British Geological Survey

REGIONAL GEOPHYSICS RESEARCH GROUP

Report 86/15

HYDROGEOPHYSICAL STUDIES IN WOLLO PROVINCE, ETHIOPIA

I. F. Smith, C. M. Jewell, Yetnayet Negussie, Kefyalew Tilahun

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Hydrogeophysical studies in Wollo Province, Ethiopia

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Cover photograph:
Queuing for water at Kelala, Wollo, Ethiopia

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1. BACKGROUND

1.1 Introduction

In October 1985, the Overseas Development Administration of H.M. Government (ODA), in response to the appalling deprivation caused by drought and the consequent famine in parts of Ethiopia, sent borehole drilling equipment to the province of Wollo. The equipment, consisting of two drilling rigs and ancilliary materials, under the supervision of ODA drilling consultants, was to be used by the Ethiopian Water Works Construction Authority (EWWCA) in its programme of well drilling for drought relief. In order to improve the site selection of the wells, geophysical survey equipment consisting of a resistivity meter, a magnetometer and aneroid altimeters were also purchased. A British Geological Survey (BGS) geophysicist was sent to Wollo province to train the local hydrogeological staff in the use of this equipment in the search for water. OXFAM has had a water team in the area for some time, which has worked closely with both EWWCA and the ODA drilling consultants. This report describes results from a number of potential well sites at which geophysical studies were carried out, with the dual purposes of training and exploration. It conveys the scientific results of the visit, which were secondary to the training of the EWWCA staff: the success of the latter aspect can only be judged from the appropriate and successful application of geophysical methods by those individuals in the future.

The BGS geophysicist (IFS) visited all the sites, with one or other of the EWWCA hydrogeologists (YN or KT); the OXFAM hydrogeologist (CMJ) visited several sites and helped in planning the rest of the programme.

The Wollo water-supply region (shown in Fig.1) stretches from the Tekeze River in the west to the Red Sea coast, and includes the part of Eritrea known as the Assab awraja (administrative area). Within this region there are three main hydrogeological provinces: the plateau, the escarpment and the rift valley floor.

The plateau is composed of Oligocene to Miocene extrusive rocks, predominately flood basalts but also including trachytes, rhyolites and tuffs. It forms the watershed between the Tekeze-Abay river system, draining into the Blue Nile, and the Awash, which flows north-east towards the Red Sea. The plateau is quite heavily populated despite the effects of the famine but the inhabitants are widely dispersed in small hamlets. The plateau is deeply dissected so that access, even to the few towns, is difficult in the dry season and frequently impossible in the wet seasons. The main sources of water on the plateau are hand-dug wells and springs, tapping the thin colluvial deposits overlying the bedrock. Although there is considerable potential for the development of small-scale borehole supplies of water from the basalts, the scattered population and the difficulty involved in getting the available drilling rigs into these areas has so far precluded this type of development.

The escarpment consists of a series of small grabens and horsts, with, in Wollo, an approximate north-south trend. Many of the faults are still active and most of the grabens have a deep fill of recent alluvium. Highway 1, the main north-south road built by Italian engineers in the 1930's, works its way along the escarpment, following the grabens where possible, and zig-zagging over the intervening horsts where necessary. Most of the larger towns in Wollo are located along this road and it is the escarpment zone which has seen the greatest development of groundwater from boreholes, almost entirely from the alluvial graben-fill deposits. Many of these towns now have some sort of modern water distribution system.

Between the foot of the escarpment and the Red Sea stretches the rift floor - an arid landscape of acacia scrub and dry water-courses, broken by the almost lunar barrenness of recent lava flows. Through the centre runs the Awash River, draining generally to the north-east into the land-locked salt lakes of Gamari, Afambo and Abe. This area is populated mainly by the Afar nomads, and traversed by Wollo's only other surfaced highway, running from Kombolcha to Assab. Along this road a series of booming truck-stop towns has grown up. Few of these towns have an adequate local water supply, and considerable effort has been expended on trying to locate suitable water sources for them. The road ends in Assab and in this area, and the coastal strip to the south a thin coastal aquifer is threatened by saline intrusion. A Failing CF15 drilling rig donated by UNICEF has been deployed in this area in an attempt to develop water resources for the small towns and other developments on the coast.

1.2 Availability of geologic and topographic information

Geological mapping is available only at a reconnaissance scale of 1:2 000 000. Good topographic maps at a scale of 1:250 000, covering the whole of Wollo are available from the Survey Department in Addis Ababa.

Aerial photography at scales of 1:50 000 and 1:80 000, flown in 1958 and 1964 respectively is available for most of Wollo. Due to the difficulty in obtaining prints, coverage of only a few areas wasavailable to us. Good LANDSAT imagery for both dry and wet seasons was obtainrd from the UK.

Thus in no case was more than outline geological information available on which to base borehole site selection. Geological observations have been made where appropriate, but their detail was limited by the time available at each site. The fundamental importance and value of basic geological investigations in this type of work must be stressed.

1.3 Geophysical methods

Three methods were applied during this project:

- vertical electrical soundings
- ground conductivity mapping
- gravity profiling

Vertical electrical soundings (VES) were the most widely used method. Soundings were obtained using the ABEM Terrameter SAS 300B and the Barker Geophysical Soundings 256 cable, which provided a very efficient technique for collecting offset Wenner sounding data (Barker, 1981). In addition the Schlumberger array was used at one site. The results were reduced using Fortran computer programs, implemented on a portable Data General One micro-computer, and interpreted using a program developed by Pedley (1985). This latter is based on the linear filter methods of Ghosh (1971) and are calculated using the coefficients of Johannsen (1975) for Schlumberger arrays, and those of Koefoed (1979) for Wenner arrays. The program generates a theoretical sounding curve from a given model of horizontally layered earth. Results from the surveys are presented in the appendix to this report, which show the comparison between the theoretical and the observed curves. Closeness between the two shows only that the model produces a similar curve to the field data: because of the ambiguity caused by equivalence, and because of the assumption of horizontal layering, the solution is not unique, and the real skill in interpretation of VES data comes in relating the model or range of models to real geological structures.

Ground conductivity mapping was carried out using the Geonics EM34-3 system, which uses twin coils separated by 10m, 20m, or 40m, giving variable search depths. The coils may be used with their axes in either vertical or horizontal mode, which controls the depth of investigation. The conductivity results can be directly related to the VES results, since conductivity is the reciprocal of resistivity:

1 mmho/m = 1000 ohm.m

The EM34 can be used to map conductive zones, which have been identified from VES data; or conversely, VES may be measured at sites which the EM34 may indicate to be most suitable, so as to provide better definition of the resistivity depth section.

At one site the gravity method was carried out along a straight, topographically-levelled profile, using Lacoste and Romberg gravity meter no. G 280. Field stations were related to an arbitrarily selected base station which was visited at the beginning and end of a section of profile. Latitude corrections were estimated from oriented and scaled aerial photographs, using the International Gravity Formula (1967). A density of 2.7 Mg/m**3 was used for the elevation correction, which gave a minimum correlation between topography and Bouguer gravity anomaly.

2. ELIWOHA

2.1. Introduction

The village of Eliwoha (lat 11° 15.5'N, long. 40° 22.5'E, elevation 650m) lies 108 km east of Dessie on the Assab road. At this point the road crosses the seasonal river called the Gelaha Shet, and the scarp of the Ethiopian plateau gives way to the plains of the Rift Valley. The population is about 4000, largely of settled Afars, but a large and variable number of nomads gather in the area.

There have been a number of attempts to provide the village with a reliable source of potable water. Not all these exercises have been fully documented, but it is clear that they have met with variable success and the inhabitants still await an adequate supply. At present the wealthier members of the community buy water supplied from a borehole, which is pumped to a tank above the town; others use crudely protected hand-dug wells, located in the river bed. In 1985 a further drilling programme was implemented. This section of the report has gathered all available data for the area and attempts to provide guidelines for further exploration.

2.2 Previous work

The earliest recorded work in the area was in 1962, when the Ethiopian Water Resources Administration (EWRA) drilled a well some 300 m south-east of the village. The location of this, and other sites referred to, is shown on Fig. 2. The geological log is shown in Fig. 3. It was reported (Hadwen and others, 1974) to have a poor yield (perhaps 1 l/s), with a draw-down to the bottom of the well, and a slow recovery. In 1972 it was cleaned and a new pump was fitted. In that state it was pumped to exhaustion 2 to 3 times per day, and took 6 - 7 hours to recover. Static water level was at 20 m, although the water strike was deeper. Much shallower hand-dug wells were noted in the stream-bed, which indicated perched water tables beneath the bed. The catchment area is about 50 km**2, over which less than 500 mm of annual rainfall would be expected. Hadwen and others recommended the siting of two 75 m boreholes adjacent to the river, the first north of the river, and the second 150 m south-east of the EWRA well. Both were expected to intesect a succession of sands, gravels and clays.

Last and others (1976) measured a Wenner resistivity depth sounding about 450 m south-east of the bridge, on the north of the river. They concluded that beneath 17.5 m there was a layer of saturated, poorly-sorted, clay-rich alluvium, extending to a depth of at least 150 m. The water level in the Universities Famine Relief and Rehabilitation Organisation (UFRRO) hand-dug well was at 11.7 m, which substantiated their conclusions. They recommended a borehole closer to the river and village, and deep enough to penetrate the full alluvial thickness.

In 1980 the United Nations Childrens Fund (UNICEF) drilled two new boreholes on sites chosen on the basis of the previous work, and they deepened the EWRA well. There is a difference of 6 m in the depth of this well as reported by Hadwen and others (1974) and that recorded in the 1980 drilling report. A well some 600m south-east of the bridge proved to be productive, and the pump from the EWRA well was installed. A second bore north of the bridge was dry. Logs from these are shown in Fig. 3.

In 1981 two further wells were drilled about 2 km west-south-west of the village in a shallow valley. No records are presently available, but one well (provided with a large tank and cattle trough) has been abandoned. The other has a pump installed and currently provides water via a pipe-line to a tank above the village.

2.3 Work carried out in 1985

A Halco V666 drilling rig, provided for EWWCA by the British Government, drilled a borehole in the broad valley to the west of the settlement, and about 700 m north of the producing well. It was hoped to prove and extract water from alluvial deposits in the valley. Water was struck at 26 m depth, at the top of basalt underlying the alluvium. A simple air-lift produced about 0.5 l/s. The simplified geological log is reproduced in Fig. 3.

Fig.4 shows the main drainage and vegetation patterns derived from LANDSAT imagery and aerial photographs. The notable parallelism of the drainage around Eliwoha, and its concordance with the regional tectonic trend, suggests structural control of run-off, possibly along joints.

On the basis of the imagery and aerial photographs, and an assessment of the hydrogeology, the following geophysical studies were proposed:

1: an investigation of the area adjacent to the Gelaha Shet, south-east of Eliwoha

2: investigation of the areas where dry season vegetation occurs

3: a study of the Ledi Shet, 3 km east of Eliwoha

4: calibration using the 1985 borehole

A total of 11 VES were measured, and on the basis of the geo-electric soundings some 5 km of ground conductivity traverses were measured. Positions of the measurements are shown on Fig.2, and the VES results and interpretations are presented in Appendix 1, figs. A1.1 to 11.

2.4 Geological observations

The foothills to the west of Eliwoha have a fair amount of outcrop, which consists of basalt, weathered basalt and a white-to-buff tuff-like rock. The volcanic rocks are covered locally by well-cemented and poorly-sorted alluvial deposits. Small exposures of bluish and greenish clays have been noted within the volcanic rocks. This succession was also found in the 1985 borehole. Examination of the drill cuttings from the laminated claystones encountered from 72 to 99 m, indicated that it is probably a tuff. Clays recorded higher in this, and other, boreholes may be of pyroclastic origin.No outcrop was seen in the low hills to the south of the village, but they are covered with colluvium consisting of angular blocks of basalt. To the east and north is an extensive plain, largely covered with wind-blown loess and scattered angular pebbles. Where it is exposed in river banks the loess can be seen to form a layer about 1 m thick. Sands and gravels, with some rounded blocks, mainly of basalt, are found in active river channels and in river banks. At several points in the river banks there are exposures of unlaminated, or crudely laminated, uniform grey-cream clay, usually overlain by sands and gravels.

At sites 1 and 2 (Fig.2) the river channels are approximately 40 m wide with bouldery beds, but downstream at site 3 it has reduced to 2-3 m wide, with a sandy bed. This indicates that the water flow reduces in quantity and energy away from the hills, presumably as a result of loss of water to the underlying rocks. At site 3 the river has entered a broad flat area of grassland and umbrella acacia, which stretches towards the dry-season vegatation of the Helem Das Shet (Fig.3a).

2.5 Geophysical studies

Site 1
There is useful borehole and well control available in this area, which made it an obvious area both for training and for extending the sub-surface information. Five depth soundings (including one measured by Last and others, 1974) have been made. With the exception of sounding 11 (measured in the river channel) all show a 'K-type' geo-electric section. The surface layer of moderate resistivity is usually less than 2 m thick, whereas the second layer is of variable thickness. Beneath the low resistivity layer, high resistivity values are found: these may not represent a high resistivity layer at depth, but may result from the 'skin effect', or from lateral variations in resistivity. Similar effects have often been noted in arid terrains (e.g. Evans, 1964). In general the lateral variation (as determined by the offset method) is not large in this area, and the resistivity method can provide useful data.

Following the depth soundings the lateral variations at depths between 10 and 20 m were investigated along 4 traverses using the EM 34 ground conductivity meter. A 40 m coil separation and a vertical dipole was used, giving an exploration depth of about 60 m, and a pek response from around 18 m.. The contoured results are shown in Fig.5.

Site 2
Following the wadi downstream, 3 soundings were made, but it proved difficult to reach the dry-season vegetation area. Soundings 3 and 4 are both 'K-type' but sounding 6 (where the channel was narrow) has a 2-layer geo-electric profile, with rather poor data quality, and large lateral errors.

Site 3
Three soundings were measured where the Assab road crossed the Ledi Shet about 3 km east of Eliwoha. The geo-electric profiles were all different, although a low resistivity layer beneath 15 m was apparent on each. Four ground conductivity traverses were made in an attempt to map the variations.

Site 4
A resistivity depth sounding was made, centred on the 1985 borehole. Large lateral errors resulted, because of the impossibility of obtaining a suitable flat site, with uniform ground contact conditions. However, the geo-electric section was sufficiently systematic to allow an interpretation to be made.

2.6 Discussion of results

Site 1
Fig.5 indicates that south of the river channel are areas of low conductivity (corresponding to high resistivity), in an area covered by rounded boulders and an abandoned river channel. The cross-section based on depth soundings (Fig.6) shows a thickening of a high resistivity layer, which corresponds to the sands and gravels intersected in the EWRA bore, and which produced water. It is suggested that this area is underlain by water-bearing sands and gravels to a maximum depth of about 20 m. To the north of the wadi the UNICEF bore penetrated non-water bearing sand overlying clay. Water was produced from sands at 46 m depth. The resistivity results are consistent with these results, although the water producing horizon could not be discriminated. Sounding no. 1 and that by Last and others (1974) indicates that the sands and gravels do not stretch far north of the river. If, as is likely, the gravels to the south of the river are in hydraulic continuity with those in the river bed, then they should be recharged by the periodic floods, or contain sub-surface flowing water. This could best be exploited by a number of dug wells, the production rate of which could be improved by radial collectors drilled from the bottom of the wells.

Site 2
Resistivity soundings in this area suggest that beneath a dry surface layer up to 5 m thick, a saturated layer with a similar resistivity to the alluvial sand and gravel at Site 1 is present, and overlies low resistivity clays (Fig.7). Because there are no boreholes in this area it is not possible to calibrate the resistivity findings. It is considered unlikely that the sands and gravels would form extensive deposits at this distance from the foothills, and it is more probable that the layer with a resistivity between 12 and 18 ohm m consists of saturated clayey sand. It is not clear what the low resistivity material comprises, although it is probably unlaminated clay. Although the clayey sand has sufficient permeability to allow the flood-waters to disperse to depth, it is unlikely to be sufficient for a productive borehole.

Site 3
The investigations around the Ledi Shet indicate a dry surface layer of about 2 m thickness, overlying a layer which, on the argument presented for Site 2, may be a saturated clay-bearing sand, which overlies clay as shown on Fig.8. The ground conductivity survey shows no significant variation, so it is unlikely that the coarse sands and gravels of the river channel extend laterally. It is not likely that a drilled well would be productive in the area

Site 4
The rather poor results from this sounding near the 1985 borehole indicate a high resistivity surface layer of about 2 m thickness, which corresponds to what is described in the drillers log as 'clay gravel'. The high resistivity layer must be presumed to represent the layer above the water table. Beneath this zone is a low resistivity layer described as a mixture of sands and gravels, clays and silts. The apparent correspondence of the high resistivity readings with the depth at which the bore intersects basalt and water may be fortuitous, and is a product of the 'skin effect'. This sounding serves to show the limitation in resolution of this resistivity method, and the difficulty which can arise in correlating drillers logs with a geo-electric section.

There are a number of wells in this shallow valley, one of which is no longer in operation, as well as the recent well which has a low production rate from a basalt. It does not therefore appear that the alluvial deposits are significantly aquiferous. Mr Kalidas Ray of UNICEF (oral communication) suggested that the water in the basalt may not be regularly recharged and is being effectively 'mined' without being replaced.

Fig.9 shows a correlation between sites along the Gelaha Shet, suggesting that the sands and gravels interfinger with a finer succession, both overlying the low resistivity clay-rich layer.

2.7 Conclusions

Sands and gravels to the south-east of Eliwoha may be recharged from the periodic river and a test should be carried out to site a number of protected dug-wells in this area. These should be close to the river and could use horizontal adits possibly extending beneath the river bed to collect water from a wider area, and thus improve production.

REcharge to these shallower arenaceous deposits could be improved by the construction of subsurface barriers within the Gelaha Shet, south-east of Eliwoha, but such a structure would need to extend to at least 10 m, and would therefore be a major undertaking.

Although a study of the drainage pattern suggested structural control on the drainage, there is no geophysical evidence to confirm this.

There is no evidence that substantial thicknesses of sands and gravels are to be found close to the Ledi Shet, or beyond the vicinity of Eliwoha.

Although the 1980 UNICEF drilling recorded arenaceous deposits to a depth of 80 m, this study cannot confirm this finding: it seems more likely that the whole area is underlain by volcanic or volcaniclastic rocks at a relatively shallow depth.

Further drilling in the area is not recommended.

3. KELALA

3.1 Introduction

Kelala (lat 39° 59.8'E, long 10° 35.0'N, elev. 2540m) lies in Borena awraja, about 160 km south-west of Dessie. The town has an estimated population of 2500 and, although it is the wereda administrative centre, there was no protected water supply until recently. EWWCA has drilled two boreholes near the town, each of which proved water, but unfortunately both have been abandoned, when drilling tools were lost down-hole.

In October 1985 two springs to the south-east of the town were developed, one being fully protected and fitted with a Mono hand-pump. However, the area remains seriously short of water and, in view of the difficult access, the most appropriate solution was to construct more dug-wells.

Four potential sites were chosen, the criteria used being a combination of access to the town, catchment area and anticipated overburden thickness. A short geophysical programme was instigated to ascertain that, at each site, there was indeed adequate depth of overburden to accommodate the well. It was hoped thus to avoid wasted abortive digging. The position of each test is shown on Fig. 10.

3.2 Geology and Hydrogeology

Kelala lies on the basalt plateau, on a low ridge between two broad valleys. Another similar valley lies to the south-east. Hills with a maximum relief of about 150m lie to the north and east of the town and form the main catchment areas. Basalt crops out in low cliffs around the summits, but the hillsides are generally covered in vegetated soil and patches of colluvium. The valleys are smooth in profile, and carry small streams which have cut steep gullies up to 2m deep into the soil and overburden. Drainage is to the south-west, eventually into the Abay Wenz (Blue Nile).

The two EWWCA boreholes penetrated a succession consisting of overburden, basalt, weathered basalt, tuff and 'shale' (possibly laminated tuff). In general it is difficult to estimate the overburden thickness from the topography.

The main spring is now much more heavily used than before the protection works were carried out; it gives about 4 hours supply in the morning and the same again in the afternoon. It flows all year round, though with a much reduced yield in the dry seasons. All the other springs and watercourses flow in the wet season only.

3.3 Geophysical work

As shown in Fig. 10, 5 sites were investigated with VES, out to a maximum electrode spacing of 96m. Results and interpretations are shown in figs. A1.12-16 in Appendix 1. No problems were encountered, although at site no. 5 the electrode contact resistance was high because of the dessicated and cracked soil.

In general the field curves show a thin top layer, with a moderate resistivity of about 20 ohm m. This overlies a layer with a resistivity between 6 and 8 ohm m, to a maximum spacing of 20m; beyond this the resistivity increases again. Lateral variation at depth is not large, although in some cases the computed values at 96m are unreliable as a result.

Rapid calculations of depths were made in the field to ensure that the particular site was suitable as a well site. Later the curves were interpreted using the automatic model curve generation program. Final results are in the appendix. At sites no.1 and 3, 3-layer models produced satisfactory matches between observed and calculated curves. Other sites required a 4-layer solution: at sites no.2 and 4 a high resistivity layer was introduced at depth; at site no.5 a very high resistivity upper layer was required.

3.4 Discussion of results

The geo-electric section at site no.4 and the borehole geological log compare well, which allows some confidence in assigning rock-types to resistivity values, and hence in interpreting the other soundings in terms of geology.

At site no.1, a stream has cut into the topsoil, and the saturated material could be seen at about 1m depth. The resistivity of the unsaturated topsoil is between 20 and 30 ohm m, except where it is very dry, as at site no.5, where it has a resistivity of 150 ohm m, and overlies a layer of typical value for topsoil. At site no. 4 the topsoil was saturated as the site was in an area of water seepage: here the resistivity was low. Saturated overburden generally shows a resistivity of 6 to 8 ohm m. The bedrock shows a variation in resistivity from 150 ohm m for solid basalt, to between 30 and 60 ohm m in weathered basalt or tuff.

The generally low level of lateral variation suggests that the resistivity layering is close to the horizontal, which must reflect the geological layering. If a well site were selected within a reasonable distance of the sounding site, then a similar depth section might be anticipated.

3.5 Conclusions

All the sites apart from no.4 have a thin layer of unsaturated topsoil.

Site no.1: saturated overburden to 5.5m, overlying weathered basalt to at least 120m. It was decided to dig a well near the abandoned borehole:this was successful.

Site no.2: saturated overburden to 6.5m, overlying about 15m of basalt, overlying weathered basalt or tuff to 120m. A successful well was dug close to the centre of the resistivity spread.

Site no.3: 7.5m of saturated overburden, overlying weathered rock or tuff to about 50m. It was decided to reserve this site for future drilling.

Site no.4: corroborated borehole record

Site no.5: Saturated overburden between 1.5 and 26.5m. Beneath this is a layer of hard basalt. In view of its proximity to the town, this is a good site for a well. The catchment is small and the thickness of overburden present could not have been deduced from the topography - it is not an obvious location. On the basis of the geophysical work, a successful - though deep - well was constructed.

4. KUTABER

4.1. Introduction

Kutaber is a small town about 25 km north-west of Dessie on the minor road leading to Wegel T'ena. It lies on the watershed between the Blue Nile and Awash catchments. Its water supply is from a number of protected hand-dug wells furnished with hand-pumps, and from streams. There is a proposal to drill a borehole to supply water to Kutaber, and this investigation was conducted to identify a suitable site.

4.2 Geology and hydrogeology

An inspection of the 1:50 000 aerial photography provided an invaluable base map (Fig.11), but also allowed a rapid assessment of the geology to be made. The country rock consists of a number of sub-horizontal basalt flows, which form steep cliffs. They are interbedded with softer rock forming ramps between the cliffs. This rock was not identified but possibly consists of weathered basalts and volcanic ashes. The rocks are cut by sub-vertical faults, which cause significant features, along north-south and east-west trends. River valleys, which often follow the fault trends, have cut deeply into the volcanic pile, creating a spectacular landscape and difficult access.

Kutaber lies across an important watershed. The steep valley to the west shows a number of alluvial terraces high on the valley walls, which consist of poorly sorted, well-rounded material. This appears to be evidence of rejuvenated rivers, cutting into earlier valleys filled with alluvium. To the east, the river meanders in a shallow gully through several flat bottomed valleys arranged en echelon. Sandy clays are exposed in the river, with little sign of coarser material, except in the river bed itself. The clays are reputed to be swelling, montmorillonitic in type.

Rainfall in the area is probably over 1000 mm/year. A number of minor (permanent?) streams run into the valleys. It is to be expected that the valley fill is saturated, and that at depth the material would become coarser-grained. A borehole into the alluvium might be expected to yield significant quantities of water. The geophysical survey was carried to determine the thickness of the valley fill, and to investigate the type of material beneath the clay at the surface.

4.3 Geophysical survey

Three Schlumberger VES were measured along the axis of the broad alluvial terrace south-east of Kutaber as shown on Fig.11, and the results are shown in figs. A1.17 - 19). It was hoped that the resisitivity would provide information on the structure of the alluvium and its thickness. The soundings were oriented along a bearing of 120 N, approximately along the axis of the valley, so that the assumption of horizontal layering was likely to be valid. The maximum separation of the current electrodes was 2km in the case of sounding no. 1, and 1km for 2 and 3.

A gravity traverse was measured across the valley through the centres of each of the soundings, and extending a good distance from the alluvial fill on to solid rock, so as to provide control on the regional field. These results would provide an independant estimate of the thickness of the valley fill.

The gravity survey was reduced to datum of sea level using a density of 2.70 Mg/m**3, which is low for basalt flows, but may be a preferable value for the mixture of rocks in the area as demonstrated by the minimal correlation between elevation and Bouguer gravity anomaly, and is often used for such situations. A regional field, dipping from west to east, has been removed, thus taking account of the exposed rock on the eastern end of the traverse and the proximity to exposed rock on the west. Whilst this may contradict the direction of the previously published field, on such a local scale considerable variations are likely. For the purposes of interpretation, the valley fill has been assigned two densities, representing the range of possible values: a minimum of 1.80 Mg/m**3 and a maximum of 2.20 Mg/m**3. A density of 2.70 Mg/m**3 has been used for the country rock. A 2.5D gravity interpretation program (Busby, 1986) implemented on a PERQ2 workstation computer has been used to calculate and plot the result (Fig.12). One data point close to the stream is probably in error, and has not been fitted by the interpretation as may be seen on the figure.

4.3 Discussion of results

Depths estimated from the resistivity soundings vary from 70m to 130m, but these values represent the minimum distance between the spread centre and the dipping bed-rock surface, not a vertical depth, even assuming that the spread was aligned along strike.

The depths shown in Fig.12 from the gravity interpretation cover the range of likely depths. It can be seen that the maximum depth (deriving from a density of 2.20 Mg/m**3) corresponds most closely to the resistivity-derived depths. Sounding 3 indicated a depth of rather greater than the gravity would indicate, possibly resulting from large lateral variations of resistivity.

Thus there is a fair degree of confidence in this interpretation, suggesting a more or less symmetrical valley, possibly with the deepest part of the buried valley being about 160 m beneath the stream bed. There is little evidence on which to base any assessment of rock type, so it is not possible to decide whether the succession coarsens with depth.

4.4 Conclusions

The gently-sloping grassy plain to the south-east of Kutaber conceals a buried valley filled with alluvium, cut into a country rock of basalts. The buried valley reaches a maximum thickness along the traverse of possibly 160m beneath the centre of the plain. Presumably the depth decreases towards the watershed in the west. The surface layer consists of a swelling clay (possibly montmorillonitic). The density of 2.2 Mg/m**3 suggests that the concealed alluvium may also be clay, or if it consists of sands and gravel it would have a porosity less than 30%. Although the alluvium is probably

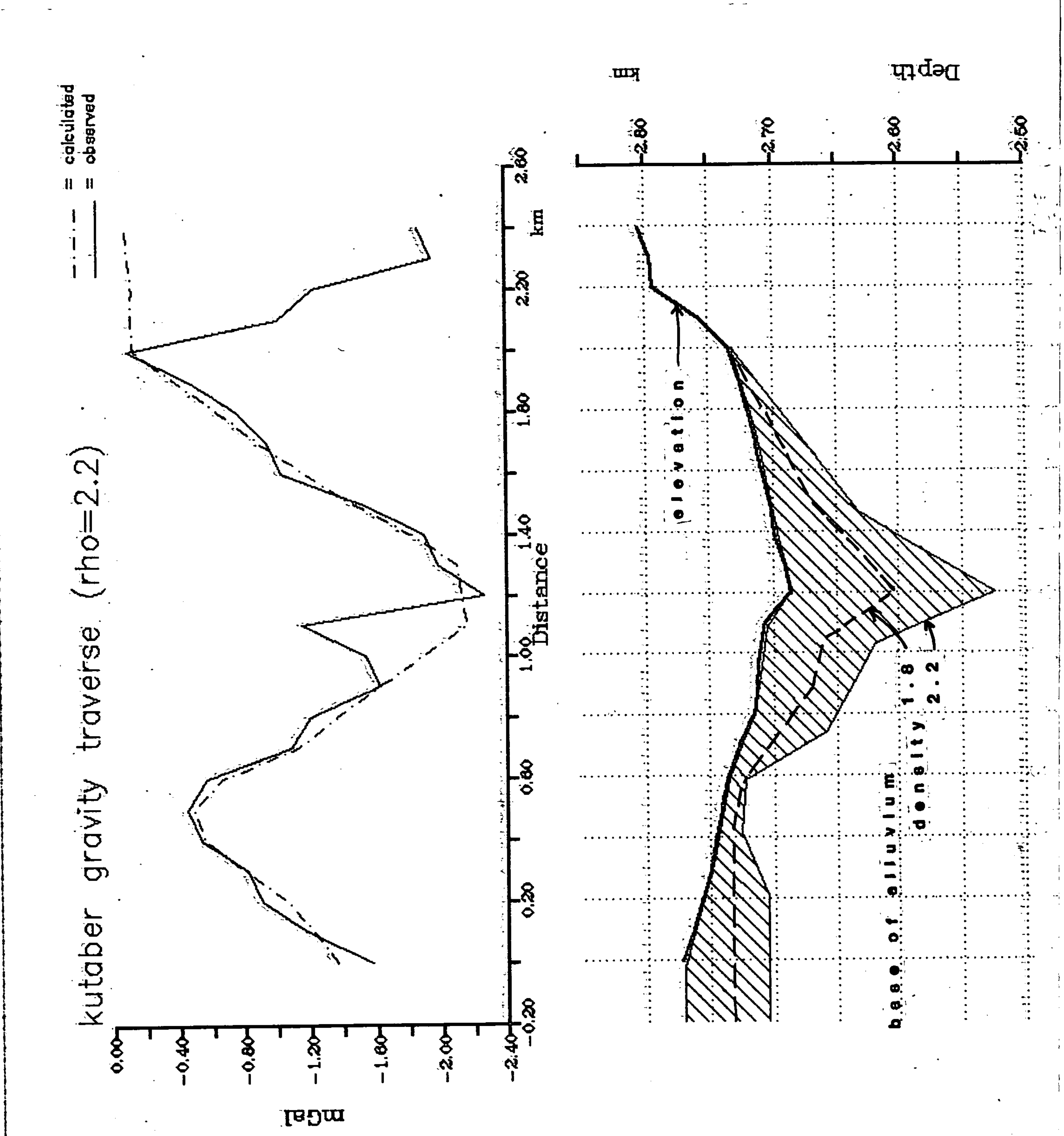

Figure 12. Kutaber gravity traverse, showing observed and model results

saturated at a shallow depth, because the lithology is not known, it is not possible to predict the water production rate.

It is recommended that, in view of the depth of alluvium indicated by this study and the dry-season storage thus available, that a borehole is drilled on a protected sitre near the centre of the valley.

5. DICHEOTO (HAYU)

5.1 Introduction

The community of Dicheoto (11° 54.8'N 41° 33.9'E, elevation 470 m) - otherwise known by its Afar name of Hayu - is where the Dessie to Assab road crosses the seasonal river called the Hayu Shet, a distance of 125 km from Mille. The local water supply is taken from unprotected hand-dug wells in the river bed and a large stone-built tank, which is filled when the river is in flood. A drilled well close the the bridge is now derelict. The sparse supply is supplemented by road tanker.

This survey was undertaken to establish whether geophysical methods could help to define the aquifers.

5.2 Geology and hydrogeology

The Hayu Shet runs along the dividing line between - to the west - an extensive flat sandy area with scattered vegetation, and a scarp consisting of sub-horizontal basalt flows to the east. The line possibly marks a fault between a basin of deposition and the line of hills. The periodic river drains a very large area to the south, and when in spate it floods widely across the sand flats.

The bed of the river runs between banks which are about 1.5 to 2 m high, and expose a succession which consist of rounded gravels and sands, overlain by a fine-grained soil or loess up to 1 m in thickness. The bed itself is largely composed of gravels. A band of large trees marks the line of the river.

Both the hand-dug wells and the tank are excavated into the river gravels and presumably exploit water contained in them. The water table in both the tank and wells is consistent at about 4 m below the level of the river bank.

Three boreholes have been drilled in the vicinity of the bridge. The deepest was situated close to the river bank penetrated 4 m of sand and gravel, then brown clays to 32 m, overlying dark volcanic rock to a depth of 201 m. Water was encountered at 146 m and 178 m within the volcanic rocks. The other two bores penetrated a sandy layer overlying clays, to a depth of 20 and 28 m, when basalt was intersected. Both were dry. The position of the first hole can be identified but the other two are lost, and their positions only vaguely known.

5.3 Geophysical studies

Nine VES were measured at the sites shown on Fig.13. The results and interpretations are contained in Appendix 1, figs. A1.20 -28. All except site no. 8 gave reasonable results, although lateral variation was quite large on all the soundings.

All the geo-electric profiles are of similar 'H-type' form, with a moderate resistivity top layer overlying a low resistivity layer, which in turn overlies a high resistivity substrate. Curve matching showed that the upper zone consisted of two thin resistivity zones, and in many cases that the intermediate low resistivity zone was best interpreted as two layers. In many cases it did not prove possible to accommodate the gradient of the lower limb using extremely high resistivities: in these cases either the lateral variation of resistivity, electrical coupling between the cables and ground, or a skin effect could have been responsible.

5.4 Discussion of results

Geological observations in the boreholes enable the resistivity results to be interpreted in terms of rock types. The high resistivity top layers represent dry loess and clay. The low resistivity is caused by saturated clays and the substrate of higher resistivity is due to the underlying basalts. The depth to the saturated clays is approximately consistent, within the errors inherent in the method and the variation of elevation between sounding sites. Depth to the base of the clays also is consistent (except at sounding no. 8), lying between 20 and 40 m and dipping to the south-west. At sounding no. 8 the data are poor but indicate that the base of the clay may be at 16 m.

The borehole records indicate that the clays do not produce water, even though presumably saturated. There is no evidence from the resistivity of extensive sands and gravels away from the river, which might provide a source of water. The water contained in the basalts is beyond the range of investigation of the resistivity method, although EM methods might be useful.

The pump and pipe-work are damaged, but it is not clear if the borehole is useable, or whether the water supply failed. The little information available indicates that the aquifers within the basalt sequence are small and receive little recharge. In this event they could not provide a sustainable supply.

5.5 Conclusions

This work has produced no evidence to indicate that further boreholes into the basalt would be any more successful than those drilled in the past. It has also shown that the superficial sand and gravel aquifer is thin and restricted to the river channel.

The most appropriate way to provide water supplies in this area would be to construct a series of subsurface barriers in the straight reach of river channel just upstream of the bridge. These barriers should extend the full width of the channel from 1m above surface to the top of the clay horizon about 5m below surface. Protected dug wells equipped with collector galleries should be constructed behind the barriers.

6. ELIDAR

6.1 Elidar (12° 3.2'N 41° 50.5'E, elevation 430 m) is a large trading community, situated at the confluence of the Elidar and Dengolu shets (wadis), on the Mille to Assab road, some 177 km north-east of Mille.

The barely adequate local water supply is supplemented by tanker, which serves the richer people of the community. The poorer take water from the dry river bed using boreholes equipped with hand-pumps, a protected dug-well and a number of deep hand-dug wells. Not only are the boreholes continually pumped to dryness , but many of the pumps are defective. The hand-dug wells are used exclusively by the nomadic Afar people, who deepen them to maintain the supply, but also protect them with a capping of stones and mud. This would appear to have several advantages: preservation against loss during the periodic floods, prevention of poaching the supply, ensuring sand and animals do not fall in. In an unprotected hand-dug well about 1 km north of the bridge the Afars have mined two horizontal adits of about 1 m in length beneath the water table, so extending the effective diameter of the well into a simple collector system. Fig.14 shows the position of the boreholes and wells, based on a rough plane-table survey.

6.2 Geology and hydrogeology

The stream bed largely consists of fine gravels and coarse sand. These can be seen to be very thin in places and, to the south of the road, overlie a cemented conglomerate consisting of rounded pumice pebbles, with a finer matrix. In the river banks this is overlain by a soil of weathered basalt, basalt colluvium and locally by outcrops of basalt. The contact dips gently to the north. To the north of the town, the river banks decrease in height and exhibit weathered basalt overlain locally by basalt flows. Further north solid rock disappears beneath a cover of sandy soil. About 1 km north of the bridge inliers of basalt (perhaps blisters above a lava tube) protrude through the sands and gravels of the river bed.

Borehole logs and inspections of hand-dug wells essentially supplement this information. The logs from the first phase of UNICEF drilling (UNICEF, 1980) report clay with boulders, sand and gravel, which overlies dark brown volcanic rock, which extends to the maximum drilled depth of 230 m. The second phase of drilling recognised sandy gravel overlying sandy clay, in turn overlying basalt. While it is not possible to relate the geological logs reliably with the existing wells, because of inadequate sketch maps showing their position, it is reasonable to deduce that the records are compatible with the recent observations. The driller in phase 1 apparently did not recognise the distinction between the fluvial sands and gravels, and the underlying pumice conglomerate, and grouped them as one unit. The subsequent driller recognised the difference, but identified the pumice conglomerate as sandy clay. Most of the water strikes occurred close to the base of this formation, and not in the sands and gravels, and from our observations at outcrop it appears to be moderately permeable.

To the north of the bridge two groups of unprotected hand-dug wells prove a small supply of water at shallow depths, deriving from the sand and gravels.

6.3 Geophysical studies

Eight offset Wenner VES were measured at the sites shown in Fig.14. Appendix 1 contains the results and interpretations in figs. A1.29 -36. The sites were chosen to obtain characteristic geo-electric profiles close to known water bearing formations, and to investigate the extension of these formations away from the river bed. Four of the sites were in the area south of the bridge, where entensive extraction of water was carried out; the other four were more widely distributed to the north.
Every site provided useable results, although high contact resistance was typical, as was significant lateral variation. All the observed curves are 'H' type, that is having a high resistivity surface layer, a low resistivity intermediate layer and a high resistivity basal layer.

6.4 Discussion of results

Sounding nos. 1, 2 and 3 were close together and, because the interpretations are essentially similar, provide some confidence in the reliability of the geo-electric profile. Sounding no. 1 was sited on sand, whereas sounding no. 2 was sited on exposed pumice conglomerate, with the stakes placed in holes driven into the tough rock, and sounding no. 3 was above the river channel on a dry plain covered with colluvial basalt blocks. Thus the resistivities of the surface layers are different, but beneath that a similar pattern of resistivity provides a satisfactory solution to the measured curves. The layer with a resistivity of 15 ohm m, beneath 8 m, 6 m and 9 m respectively presumably represents saturated pumice conglomerate. The observed values show an increase below 70 m, perhaps representing massive basalt. However, this does not correspond with the depth to basalt described in the borehole logs, which is around 20 to 25 m. The intervening section (between 20 and 70 m) may represent weathered basalt, or thin flows. In addition, for sounding 3 the values beneath 60 m cannot be fitted by model values, either because they derive from lateral variation or because the data are invalidated because of the skin effect. It is possible that the results from sounding nos.1 and 2 are similarily affected, although to a lesser extent, and doubt must be cast on the validity of the data beneath about 70 m.

Sounding no. 4 shows that low resistivity material is at a very shallow depth (about 1m) and extends to about 16m. This layer is probably saturated pumice conglomerate or perhaps saturated fluvial deposits.

To the north of the bridge, sounding nos. 5 and 6 were both in the river bed, close to shallow diggings which showed damp gravels. The interpretation of the curves accords with this, with thin, high resistivity material (which is the dry surface layer) overlying the saturated alluvium, with a resistivity of 2 ohm m, and which persists to a depth of 10 and 13 m respectively. Beneath this the resistive basalt is penetrated. The nearby sounding no. 7, which is away from the river bed and alluvium, shows a similar geo-electric profile, but here the low resistivity does not relate to the presence of alluvium, but to saturated pumice conglomerate or weathered basalt to a depth of about 25 m, both of which are seen in the river banks.

Sounding no. 8 is adjacent to an unprotected hand-dug about 2 m deep, with the water at about 1.5 m. The sounding curve shows that the saturated alluvium has a resistivity of 2 ohm m and is 12 m thick, and overlies basalt with a resistivity of 50 ohm m.

6.5 Conclusions

The water table can be defined using resistivity, and is at a depth of about 10m in the Elidar Shet, to the south of the confluence with Dengolu Shet. This is similar to the pumping water level in the deep dug well, and suggests local drawdown to this level. Elsewhere in the area it appears to be shallower, at about 2m or less. The water is contained in a pumice conglomerate and alluvial sands and gravels. Above the river banks, there is evidence that the conglomerate is present beneath basalt and weathered basalt.

The resistivity soundings indicate that the pumice conglomerate or weathered basalt may extend to a depth of up to 70m beneath the Elidar Shet and to at least 16m beneath the Dengolu Shet. The performance of the boreholes indicates that these deposits have a low or - at best - moderate permeability, and could therefore be most efficiently exploited by deep, large diameter dug wells.

The protected dug wells presently in use have a maximum depth of 11.5m but, now that compressors, jackhammers, dewatering pumps and ARMCO well lining are available to EWWCA in Kombolcha, there is no reason why much deeper wells could not be constructed.

To the north of the town there are sands and gravels at least 10m thick beneath the Dengolu Shet. Again, deep hand-dug wells would be the best way to exploit this aquifer.

The depth to the water table and the difficult configuration of the valleys and the road bridge at Elidar preclude the construction of a sub-surface dam at this site. Such a structure would of a necessity be a major engineering undertaking with no certainty of success.

Further wildcat drilling in the area cannot be recommended. However, although neither LANDSAT imagery nor aerial photography was available to us, coverage does exist and a detailed examination, with a view to locating structurally controlled sites, would be worthwhile.

7. BURE

7.1 Introduction

The large town of Bure (42°16.3'E 12°36.0'N, elevation 490 m) has no local water supply, relying on road tankers bringing water from Loggya. It lies 69 km south-west of Assab on the Dessie road. Some 2 km to south of the town the road crosses the intermittent Bure Shet, which drains the mountains to the south-east. Around the town is an area of sand-flats, marked on the map as a dry lake. There is no evidence for this description, although it may be subject to flash floods and standing water.

Two boreholes have been drilled in the area. One, beside the bridge over the Bure Shet, was drilled by a Russian team, and an unsucessful attempt to re-enter it was made by a EWWCA crew. No information is available on this hole. The second is 1.5 km north of the town, about 200 m west of the road in the 'dry lake'. This reached 300 m and was reported to be dry.

7.2 Geology and hydrogeology

This is an area of relatively subdued relief, of large expanses of sand-covered plains, with scattered scrub, separated by low rocky hills. The exposed rock consists largely of sub-horizontal basalt flows. The Bure Shet runs between low banks, locally exposing cemented laminated gravels, beneath a fine sandy top-soil (probably loess) and overlying an unlaminated clay. There is no information available from the boreholes, so the vertical extent of the loess and fluvial gravel cannot be determined.

Although a number of Afar tents were seen in the area, no evidence of hand-dug wells was found in the river bed. The river gravels would provide a likely source of water, because they would be recharged by periodic floods along the Bure Shet. The lack of evidence of wells may point to our brief search rather than lack of water.

7.3 Geophysical studies

Two VES were measured: one along the bed of the Bure Shet, to investigate the vertical extent of the river gravels; a second 150 m to the south, to study their lateral extent. The results are shown in figs. A1.37 and 38.

The first sounding gave good quality results with only small lateral variations, whereas the second proved to have very great lateral variations. The geo-electric profile from the first was complex, but smooth. Five layers were required to match the observed curve, producing an acceptable fit. However it is necessary to recognise that the lateral variation measured only represents that along the expansion, not normal to it. In a clearly two-dimensional feature such as a river bed, the assessment of lateral variation provided by the offset Wenner method only applies where the spread length is similar to the dimensions of the feature. The analysis of this curve may therefore be spurious beyond about 40 m (the distance to the river banks from the VES spread centre). The second sounding showed an erratic curve, requiring a 4 layer interpretation, and only an approximate match was achieved.

7.4 Discussion of results

There is necessarily ambiguity in the interpretation of the results, because no control is available. Both depth soundings indicate a high resistivity at depth, possibly due to basalt. On sounding no. 1 this is found at 30 m, and on sounding no. 2 at a depth of 13 m. On sounding no. 1 this is overlain by a dry surface layer to 1.1 m, a higher resistivity layer to 5 m, which could possibly be a clean saturated gravel aquifer, which rests on lower resistivity unlaminated clay. Above the basalt on sounding no. 2 there may be saturated clay between 2.6 m and 13 m, overlain by dry loess (to 0.6 m) and dry clay.

Clearly this speculation could be incorrect, and the value 75 to 80 ohm m could alternatively relate to a clean saturated gravel, although such rocks are not common in this region.

7.5 Conclusions

The most likely interpretation of the soundings at Bure is that saturated fluvial gravels are restricted to the Bure Shet, where they extent to a depth of about 5 m.

A test pit should be dug in the Bure Shet to prove the water level and to assess yield.

Examination of the LANDSAT imagery and aerial photographs, unavailable to us, would be very worthwhile for assessment of structural controls which may provide improved aquifer performance.

8. KILOMA

8.1 Introduction

Kiloma (42° 51.5'E 12° 48.63'N) is a small community 2 km from the Red Sea shore. A dry water course (the Rendell Wenz) passes some 2 km to the north. Water supply is from shallow hand-dug wells which are saline. A borehole is planned for the area in the near future and the present survey was aimed to guide the siting of the well, if possible identifying the depth to saline water and the thickness of any overlying fresh-water wedge.

8.2 Geology and hydrogeology

The village lies at the junction of the salty coastal sand flats and a gently sloping surface, which runs towards bare, craggy hills formed mainly of more or less flat-lying basic volcanic rocks. This peneplaned surface, which is dotted with sparse scrub, is covered with sand and areas of basalt blocks, which probably represents beach deposits left as the level of the Red Sea dropped. The hills probably therefore represent an ancient cliff-line. The sand flats are littered with shell and coral debris, and corals flourish in the nearby lagoons. It is likely that beneath the blackish sand (which is presumably a mixture of basalt and organic fragments) are coral limestones.

The Rendell Wenz is a dry river channel which drains a sizeable area of mountains to the south-west, and could channel any rainfall from this area towards the sea, and recharge the underlying rocks. Its bed is bouldery and cuts a broad shallow channel through an overburden consisting of sands and rounded blocks of basalt. A zone of lush vegetation, maybe 1 km wide, is supported where the river intersects the sand flats. The vegetation becomes sparser upstream.

8.3 Geophysical studies

Only three offset Wenner VES could be measured in the time available. These were sited along a south-westerly profile about 1 km north of the river channel as follows: no. 3 was on the sand flats, no. 2 was 500 m from the sand flats and no. 1 was 2.5 km up the peneplane (see Fig. 15). The data and interpretations are shown in Appendix 1, figs. A1.39 - 41.

Sounding no. 3 on the sand flats showed very low resistivities and the observational errors are rather large (around 10%). The second sounding indicated more moderate resistivities. The lateral variation on no. 2 is quite considerable, but is acceptable for the other two soundings.

Interpretation of the sounding no. 1 indicates a low resistivity layer beneath the more resistive surface layer, beneath which is a thick resistive layer. The lowest layer, beneath 50 m, is again of low resistivity. Sounding no. 2 indicates that the low resistivity surface layer is about 3 m thick and overlies a thick layer of moderate resistivity (around 35 ohm m), which in turn overlies a low resistivity layer. Sounding no. 3 suggests a complex layering of conductive rocks, ranging between 2 and 6 ohm m to a depth 60 m, where a 'basement' with a resistivity of 13 ohm m is encountered.

8.4 Discussion of results

The sand flats are covered with damp patches where saline waters reach the surface. The very low resistivities recorded on sounding no. 3 are a result of this effect, and it is likely that all the rocks beneath the surface will be salt-saturated. The increased resistivity with depth may result either from reduction in porosity as a result of increased depth of burial or from a different rock type. It is possible that the layer beneath 59 m, with the low resistivity of 13 ohm m, is porous, salt-saturated coral or basalt. Sounding no. 2, which was measured through the edge of the vegetated zone bordering the river-bed, indicated, beneath the thin layer of low resistivity material at the surface, a 65 m thickness of 35 ohm m resistivity. It is suggested that this may represent fresh water saturation of the sand and boulder beach deposits, and it overlies a salt-saturated layer of beach deposits or coral with a lower resistivity. Further up the old beach, sounding no. 1 penetrated to approximately 5m in low resistivity material, which is probably unsaturated material of unknown composition. Beneath is a layer of high resistivity which may be solid basalt, or unsaturated beach deposits. The low resistivity layer at a depth of 20 - 40 m must represent either fresh-water saturated beach deposits, or saline fluids saturating the basalts.

8.5 Conclusions

This survey has not produced sufficient detail to allow recommendations for borehole sites to be made, but it has demonstrated that there are resistivity variations in the sub-surface which can be mapped. A closer grid of soundings should enable this to be carried out, so that positive suggestions could be made as to the best sites and suitable depths for potable water wells. In addition, non-contacting earth conductivity mapping equipment, such as the Geonics EM34, might provide a rapid method of collecting useful data which would improve the understanding of this area.

The tentative suggestion may be made that fresh-water may be found between depths of 2 m and 30 m at sounding no. 2.

9. RAHITA (or REHITO)

9.1 Introduction

The village of Rahita (43° 05.04'E 12° 43.7'N) , close to the border with Djibouti, and 2 km from the Red Sea (Fig.15), takes its water from shallow hand-dug wells. The water from these sources is both saline and infected, so a reliable source has been sought from boreholes further from the coast in a area through which a series of seasonal rivers flow. One of these boreholes proved saline water and was abandoned, the other produced fresh water. A further pair of boreholes have been drilled in the vicinity to provide water for the Haleb Island development. These wells provided a useful opportunity to obtain control for a series of VES to investigate the depth and thickness of the fresh-water wedge.

9.2 Geology and hydrogeology

This flat-lying area lies some 20 km E of the mountains, and runs down to the shore of the Red Sea. No solid rock is evident in the immediate vicinity, although within 10 km is a number of low rocky hills, which are composed of flat-lying volcanic rocks. Much of the surface is dark sand with scattered boulders. Locally shallow periodic river channels are encountered, in which are washes of boulders. The borehole records indicated up to 52 m of sands, silts and gravels in varying proportions and of varying grade.The total thickness of the sand layer has not been penetrated, but it presumably overlies either basalt or coral. Vegetation is sparsely distributed, and often associated with dry river channels.

In all 4 boreholes drilled in the area, fresh water was intersected in considerable quantity, but in Rahita no.1 salt water was found beneath the fresh, rendering the well unusable as a potable supply. It was anticipated that geophysical methods might be able to provide information on the distribution and thickness of the fresh-water, and so this brief inspection was instigated as a pilot study. Subsequently fluid conductivity logs were run in the boreholes and a full pumping test was carried out on Haleb no.2.

9.3 Geophysical studies

A total of 4 offset Wenner VES were measured at, one at each of the borehole sites, the results of which are contained in figs. A1.42 - 44 in Appendix 1. At the Haleb boreholes (which are c.200 m apart, two soundings were measured from the same centre point but perpendicular to one another. In each case the contact resistance was high, and extreme at the Haleb boreholes, giving difficult working conditions, with large lateral variation.

All 4 curves show a similar general form, with a low resistivity intermediate layer, although 4 or more layers were necessary to get a reasonable match between the observed and modelled curve. In each case the steepness of the gradient of the lowest branch proved to be greater than theoretically possible for true results from a horizontally layered earth.

9.4 Conductivity logging

A simple fluid conductivity cell connected to the ABEM Terrameter was run in Rahita no.2 and the two Haleb boreholes to establish whether information on the presence of saline water at depth could be obtained from the conductivity profiles.

Readings were taken at 1m intervals. The Terrameter measurements of resistance (in ohms) were converted to electrolytic conductivity using the empirically derived relationship:

$$EC\ (\mu S/cm) = 3.84 \times 10\ /\ R\ (ohms)$$

The profile for Rahita no.2 is shown in Fig. A2.1, and those for Haleb no.1 and Haleb no.2 are shown in figs. A2.2 and A2.3 respectively.

The borehole probe is not temperature compensated, whereas the conductivity meters used at the well-head during the pumping test were corrected to a standard temperature of 25°C. Assuming a borehole temperature in the range 34-38°C and a conductivity/temperature gradient of 0.02, this would account for the observed difference of about 25% between these readings.

9.5 Test pumping

A pumping test was carried out on Haleb no.2 from 15th -18th February 1986. A four-stage step test was followed by a 48 hour constant discharge test and a measured recovery period.

Discharge was measured using an orifice weir and water levels by an electric contact tape. The electrolytic conductivity and temperature of the discharge were monitored throughout the tests.

During the constant discharge test the well was pumped at 6.4 l/s; total drawdown at the end of the test was 4.85m.

9.6 Discussion of results

At Rahita no. 1 borehole, the sounding data is probably invalid beneath 24 m, probably as a result of the skin effect with very conductive material beneath the very resistive overburden. This same effect is noted on the other soundings at slightly greater depths. Using the information on the borehole log as a guide allows a fair solution to the observed curve to be reached. A low resistivity layer of 3 ohm m has been introduced beneath 30 m to represent the saline water and above that two layers of intermediate resistivities represent the dry and fresh-water-saturated zones. The dry surface layer has a very high resistivity.

By applying similar parameters to the sounding at Rahita no.2 borehole, a reasonable interpretation has been made. This indicates beneath the highly resistive surface layer and about 26 m of moderately resistive material (representing dry and fresh-water bearing sands and gravels) there is saline water to at least 75 m in depth.

The conductivity log for Rahita no.2 borehole shows no clear trend. The significance, if any, of this log is not understood.

At the Haleb borehole site, the VES results are not reliable, with significant observational and lateral errors, as a result of the arid surface layer. The best solution does not bear much resemblance to the borehole log. It shows a rather complex high resistance surface layer to 4 m depth, beneath which is a layer to at least 30m with an intermediate resistivity, perhaps representing the unsaturated and fresh-water bearing sands and gravels. There is no indication from the VES of the low resistivity saline-water layer.

The conductivity log run at Haleb no.1 on 13th February, immediately after the service pump was removed, shows a clear conductivity gradient of about 20 μS/cm/m over the interval from 23 to 48 m, with the conductivity rising from 565 to 1030 μS/cm. The log taken on 17th February, after the borehole had been standing for four days, shows a much flatter trace. The gradient of 1 μS/cm/m probably reflects only the geothermal gradient. It seems likely that, as the water at the bottom of the bore is hotter than at the top because of the geothermal gradient, there has been convective overturn and mixing. The log from Haleb no.2 , taken before pumping started, shows a similar flat trace, for the same reason. Had it been possible to log Haleb no.2 after pumping, a trace similar to that shown in Haleb no.1 would probably have been obtained.

A salinity gradient such as this implies the existance of saline water at depth beneath the well, possibly in an underlying aquifer separated by an aquitard.

The VES results are rather disappointing from what appears to be a problem with a clear geophysical solution. They show that where the saline interface is above 25 m it may be detected using the Wenner VES approach described. However, for more general applications, it may be necessary to use the Schlumberger array, rather than the offset Wenner to eliminate the possibility of electrical coupling with the ground. Non-contacting methods such as the EM34, or pulse EM would eliminate the difficulty of the contact resistance, and respond directly to the lower resistivity layers.

The step-test results are illustrated in figs. A2.4 and A2.5. The plot of sw/Q against Q gives a straight line with a gradient 0.045 m/(l/s)^2 and an intercept on the sw/Q axis of 0.41 m/l/s. The well and aquifer losses are calculated and displayed on the figures. The drawdown sw in the well (in metres) at any discharge rate Q (in litres per second) is given by the expression:

$$sw = 0.41Q + 0.045Q^2$$

It can be seen that the efficiency drops from 82% at 2.0 l/s to 58% at 6.4 l/s: clearly at higher discharges the well would be still less efficient. These figures are nevertheless quite good for a well using slotted steel casing as a screen in an alluvial aquifer, and indicate that development was effective.

A well-loss correction factor of 1.85 m (derived from 6.4^2 x 0.045) must be applied to the drawdown values measured during the constant discharge test.

The log/log plot of corrected drawdown against time during the constant discharge test is shown in Fig. A2.6. Comparison with the Boulton (1963) type curves, shows the aquifer condition to be slightly leaky or semi-confined, with an r/B value of 0.1. There is no sign of a delayed yield effect. A value for the aquifer transmissivity of 79 m/day is obtained by curve matching.

Application of the Cooper and Jacob (1946) time-drawdown method (Fig. A2.7) indicates that, contrary to to the expected straight line, the data plot on a curve. This is because the aquifer is leaky, not confined. A straight line can be fitted approximately to the early part of the curve and, substituting the gradient of this line into the Jacob expression, a value for transmissivity of about 100 m/day is obtained.

Using the Cooper and Jacob (op.cit.) distance-drawdown method on the end-of-test results for Haleb nos. 1 and 2, and substituting a value of 100 m/day for transmissivity, allows an estimate of aquifer storativity of 1.7 x 10**-3 to be made. This procedure is shown on Fig. A2.8.

In summary the test indicates a leaky aquifer with a transmissivity of about 100 m/day and a storage coefficient of about 0.002.

Throughout the test the salinity of the water, as indicated by the electrolytic conductivity, remained sensibly constant at a value of 410 μS/cm at 25°C.

9.7 Conclusions

A saline interface can be identified at about 26 m beneath the surface at the two Rahita boreholes. The VES does not show the existance of this layer at the Haleb boreholes. However, the salinity gradient revealed by the conductivity log from Haleb no.1 does suggest the presence of saline water at depth below the base of the borehole, although it is not possible to say at what depth the interface lies.

While it may be useful for shallow investigations, the offset Wenner sounding method is not generally applicable in this area of arid surface layers, and very low resistivity at depth: other methods including pulse EM may be preferred.

The results obtained from the pumping test are encouraging. Transmissivity, for what is clearly a relatively thin, leaky, alluvial aquifer, is fairly high; a well drawdown of 3.2m for a discharge of 5 litres/s is not excessive. There was no sign of salinity increase with increase in pumping rate or on prolonged pumping.

It is concluded that, provided the Haleb wells are operated intermittently at a discharge not greater than 5 litres/s, then they should have a lifetime which will justify the investment in the pipelines. If the wells are operated at higher discharges, or if there is more development in the area, then this life may be reduced.

It is strongly recommended that once the wells go into production, then the salinity is monitored on a regular basis.

10. CONCLUSIONS

The aims of this project were to train EWWCA staff in the operation of geophysical survey equipment (particularily electrical), and in the interpretation and analysis of the results; to assess the usefulness of geophysical techniques in the development of water resources in Wollo; and to do this whilst carrying out some useful exploration work in the region. The requirement to carry out effective training inevitably reduced the rate at which data could be collected, so that relatively few sites were visited and insufficient results were obtained to allow completely satisfactory conclusions to be drawn. Nevertheless, some useful guidelines did emerge.

Rather than simply providing training in the use of the equipment, great emphasis was placed on teaching the choice and adoption of the most suitable approach to the various problems which may be encountered. In particular, the need to observe and record basic geological and hydrogeological was stressed.

With regard to the actual techniques used, it was found that the offset Wenner technique allowed rapid collection of data of reasonable quality, provided adequate care was taken to reduce electrode contact resistance in arid terrain. In many cases dry surface layers and poor contact limited the depth of investigation. The results allowed a good insight into the concealed structure, and in some cases enabled the depth to water table and to saline water to be defined.

The combination of resistivity and gravity or conductivity mapping was useful in providing corroborative evidence from an independant source. In the arid parts of the region EM was particularily useful because it obviated the need for ground contact.

In terms of the overall value of geophysics to water resource development in Wollo, the following points can be made:

1) On the plateau, access for drilling machinery is only possible to a very few areas. The bulk of new developments on the plateau will continue to be hand dug wells. While there is no doubt that the greatest contribution to successful siting of dug wells comes from an intelligent appraisal of the geology and existing water sources, it was demonstrated in Kelala that using the offset Wenner method it is possible to check rapidly the overburden thickness at a number of sites and to choose the optimal locations for wells. This may enable good wells to be constructed closer to population centres than would otherwise be anticipated, and will certainly avoid abortive digging, and return visits by the hydrogeologist. Considering that it can take a whole day to drive to some of these areas, a few hours with the Terrameter is time well spent if it avoids a subsequent visit.

2) In those parts of the plateau which can be reached by drilling equipment, and in the escarpment zone, where most drilling has been carried out to date, it has usually proved possible to site productive boreholes without the use of geophysics. It is thus unlikely that the introduction of geophysics will have any measurable effect on the "success rate", where this is defined simply as the proportion of boreholes which produce water in pumpable quantities.

However, the use of geophysics as a routine tool in borehole siting, particularily if combined with the use of aerial photography and a greater awareness of the variations in local geology which may be observed in the field, can have other benefits. In particular, greater understanding of the local geology in the planning stage of a drilling project would allow better and more detailed well design, ensuring that the correct equipment and materials are on site when work starts, thus reducing costly delays while extra, or different, materials are brought in. Occasionally the accurate location of a site over the thickest overburden or the deepest weathering would enable one borehole to be drilled, where otherwise two would have been necessary.

3) Although useable results were obtained at most of the sites investigated, the resistivity method can give ambiguous results which are difficult to interpret. This was true particularily for the Rift Valley, even in the coastal sites, where resistivity had been expected to provide a clear definition of the saline interface problem. In future, if further surveys by experienced geophysicists are carried out and different techniques are tried, a better understanding may emerge: at present it would be unfair to expect the hydrogeologists in Wollo, equipped only with the limited experience gained during this short project, to achieve much from the use of resistivity in the Rift Valley. The best approach by which they might increase success in this difficult area lies in the routine use of aerial photography and LANDSAT imagery, and in the adoption of improved construction techniques to exploit the groundwater present beneath seasonal watercourses.

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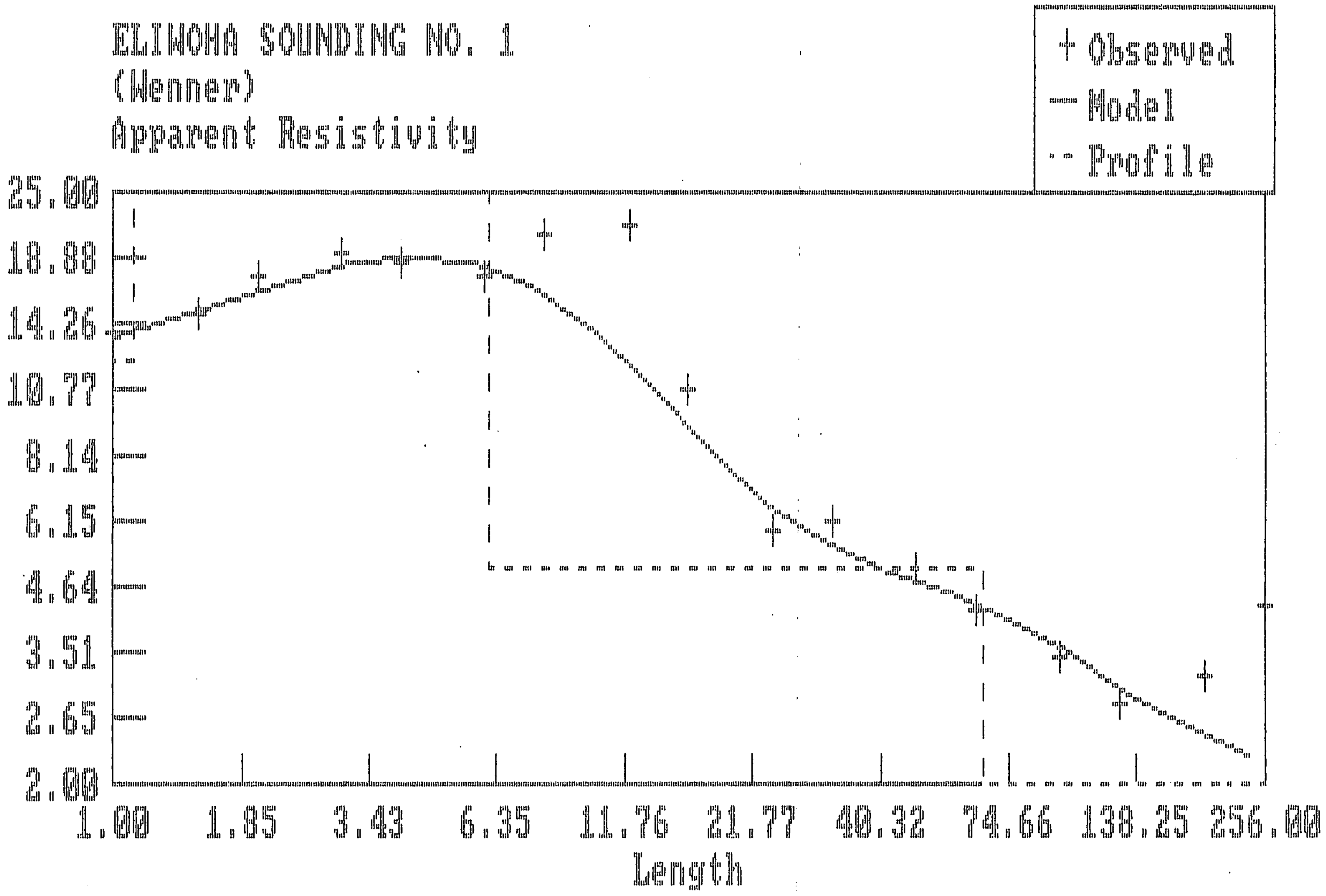

ELIWOHA SOUNDING NO. 1
(Wenner)
Apparent Resistivity
Observed
Model
Profile
25.00
18.88
14.26
10.77
8.14
6.15
4.64
3.51
2.65
2.00
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

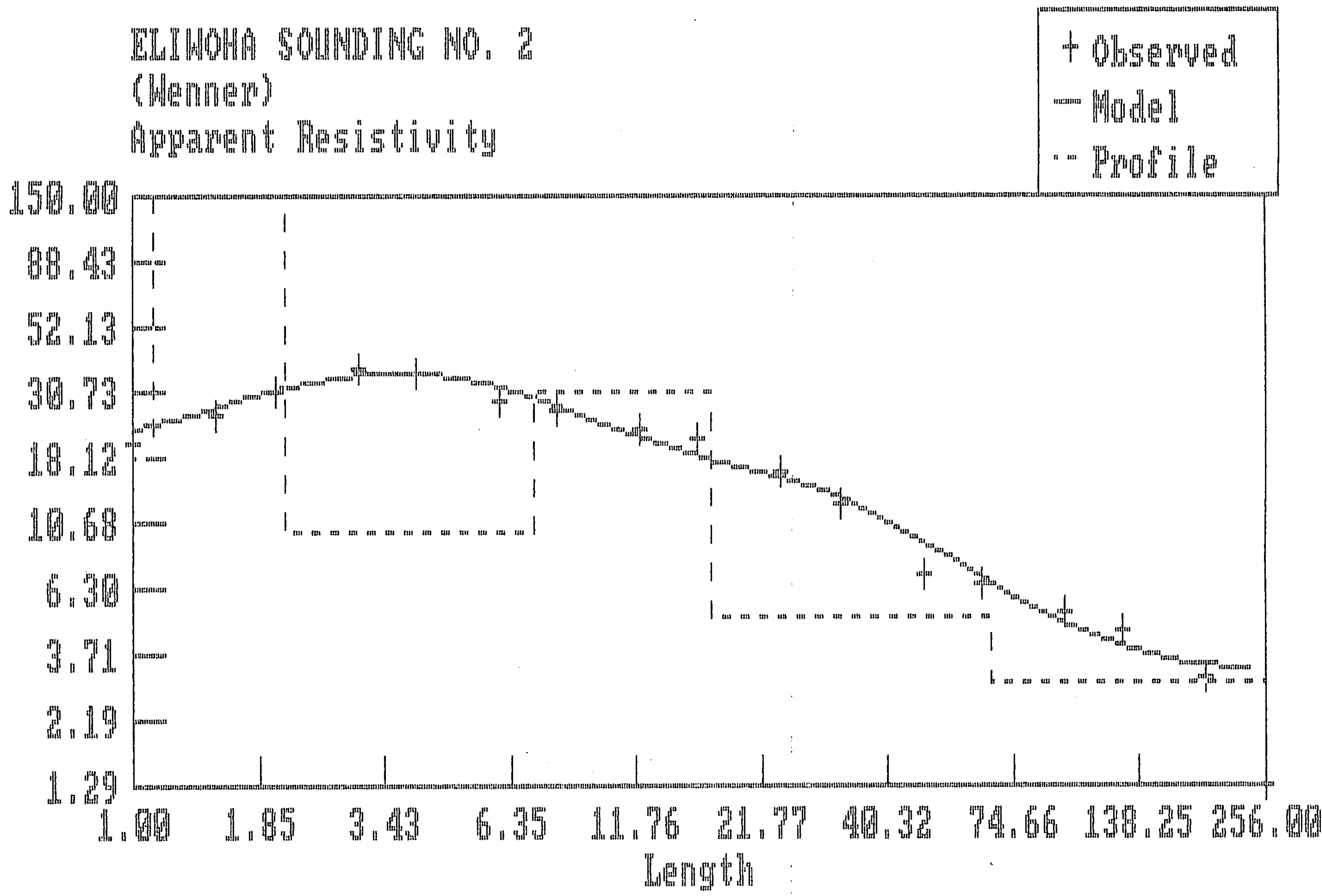
MEASURED VALUES

ELIWOHA SOUNDING NO. 1

SPACING	RESISTIVITY
1.000	13.480
1.500	14.760
2.000	17.340
3.000	18.930
4.000	18.320
6.000	17.160
8.000	20.560
12.000	21.510
16.000	10.660
24.000	5.910
32.000	6.130
48.000	4.990
64.000	4.220
96.000	3.470
128.000	2.810
192.000	3.170
256.000	4.240

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.10	12.00
2	5.00	25.00
3	60.00	5.00
4	150.00	2.00
Subst.	infinite	2.00


ELIWOHA SOUNDING NO. 2
(Wenner)
Apparent Resistivity
+ Observed
— Model
- - Profile
150.00
88.43
52.13
30.73
18.12
10.68
6.30
3.71
2.19
1.29
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

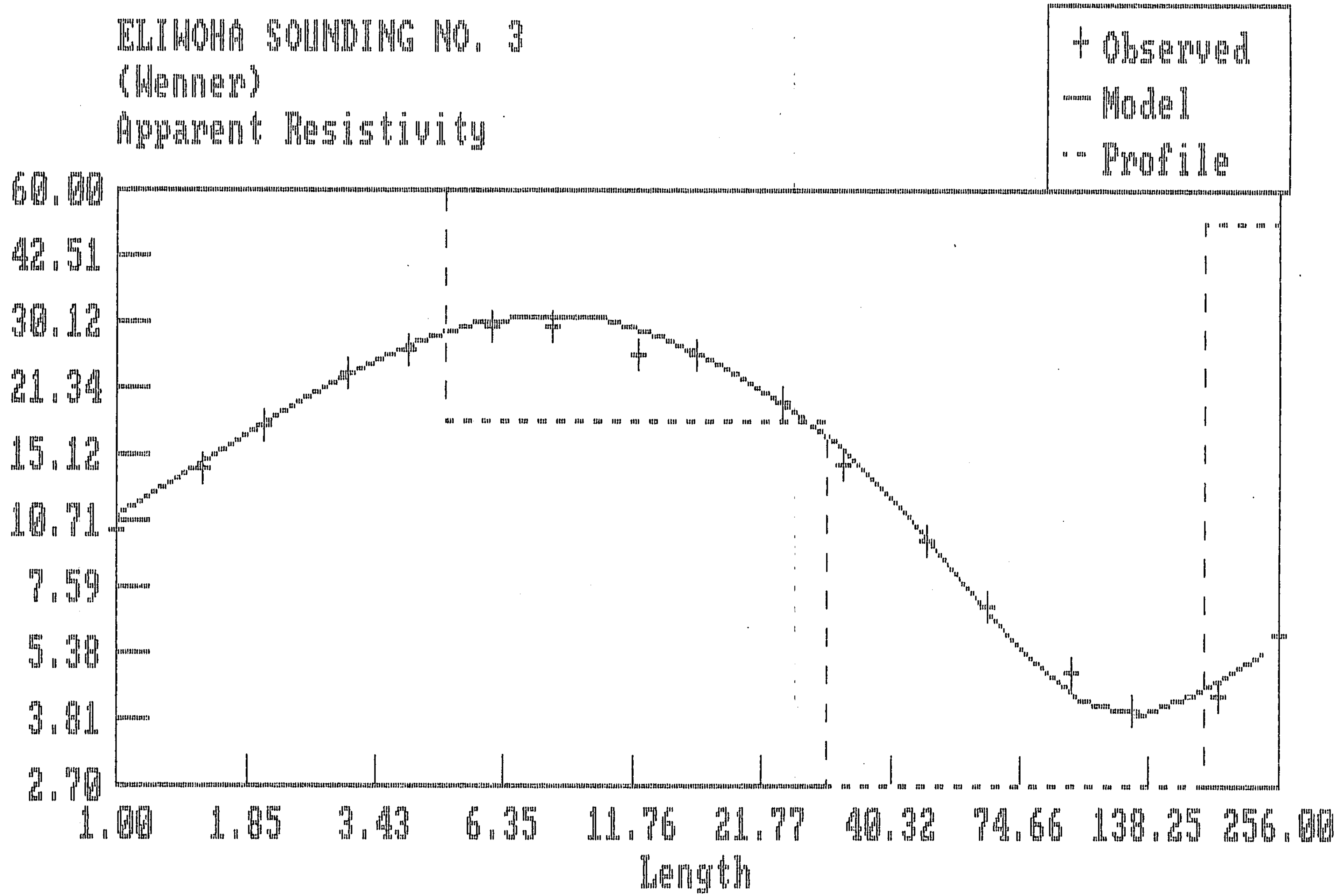
MEASURED VALUES

ELIWOHA SOUNDING NO. 2

SPACING	RESISTIVITY
1.000	20.110
1.500	25.280
2.000	30.220
3.000	36.820
4.000	35.440
6.000	28.560
8.000	26.110
12.000	22.430
16.000	20.960
24.000	15.830
32.000	12.260
48.000	7.130
64.000	6.430
96.000	5.150
128.000	4.420
192.000	3.070
256.000	1.290

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.10	18.00
2	1.00	150.00
3	5.00	10.00
4	10.00	30.00
5	50.00	5.00
Subst.	infinite	3.00


ELIWOHA SOUNDING NO. 3
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
60.00
42.51
30.12
21.34
15.12
10.71
7.59
5.38
3.81
2.70
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

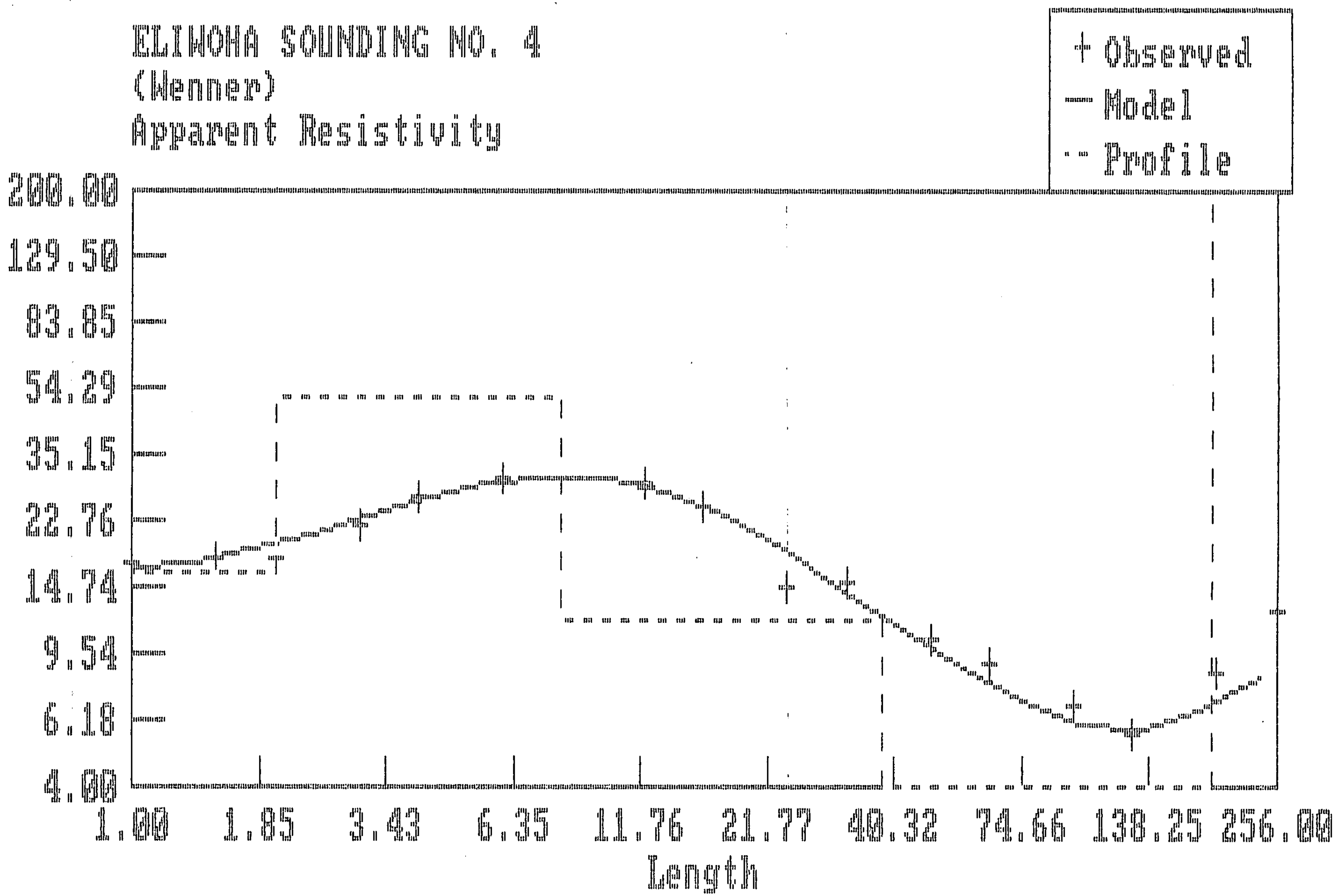
MEASURED VALUES

ELIWOHA SOUNDING NO. 3

SPACING	RESISTIVITY
1.000	10.250
1.500	13.980
2.000	17.490
3.000	23.050
4.000	25.720
6.000	29.160
8.000	29.330
12.000	25.060
16.000	25.030
24.000	19.690
32.000	14.480
48.000	9.760
64.000	6.840
96.000	4.840
128.000	4.020
192.000	4.370
256.000	5.960

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.80	7.00
2	4.00	60.00
3	25.00	18.00
4	150.00	2.70
Subst.	infinite	50.00


ELIWOHA SOUNDING NO. 4
(Wenner)
Apparent Resistivity
Observed
Model
Profile
200.00
129.50
83.85
54.29
35.15
22.76
14.74
9.54
6.18
4.00
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

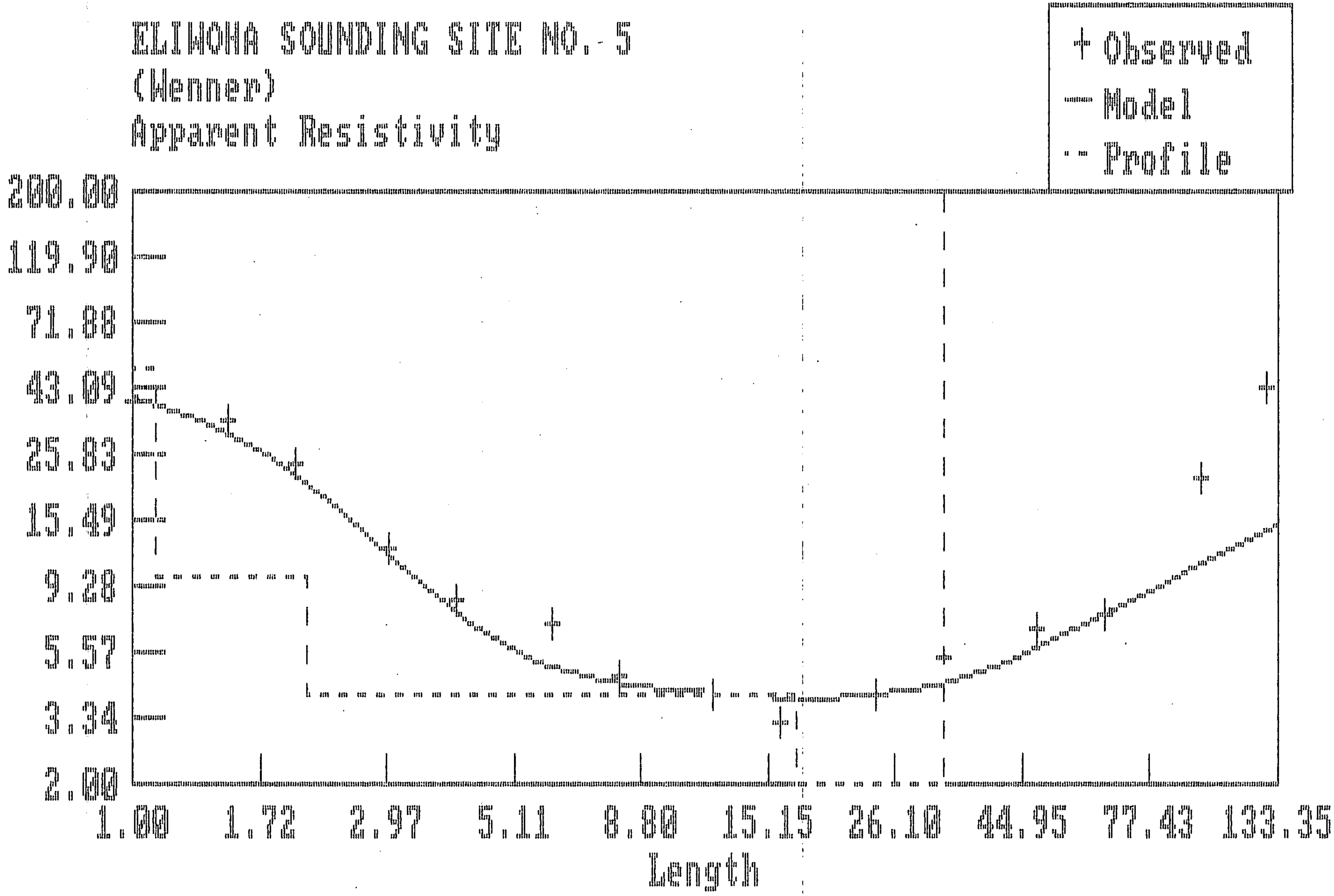
MEASURED VALUES

ELIWOHA SOUNDING NO. 4

SPACING	RESISTIVITY
1.000	17.250
1.500	17.910
2.000	17.590
3.000	22.090
4.000	26.450
6.000	30.250
8.000	29.860
12.000	29.180
16.000	24.530
24.000	14.780
32.000	14.980
48.000	10.380
64.000	9.050
96.000	6.840
128.000	5.630
192.000	8.450
256.000	12.550

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	2.00	16.00
2	6.00	50.00
3	30.00	12.00
4	150.00	4.00
Subst.	infinite	200.00


ELIWOHA SOUNDING SITE NO. 5
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
200.00
119.90
71.88
43.09
25.83
15.49
9.28
5.57
3.34
2.00
1.00
1.72
2.97
5.11
8.80
15.15
26.10
44.95
77.43
133.35
Length

MEASURED VALUES

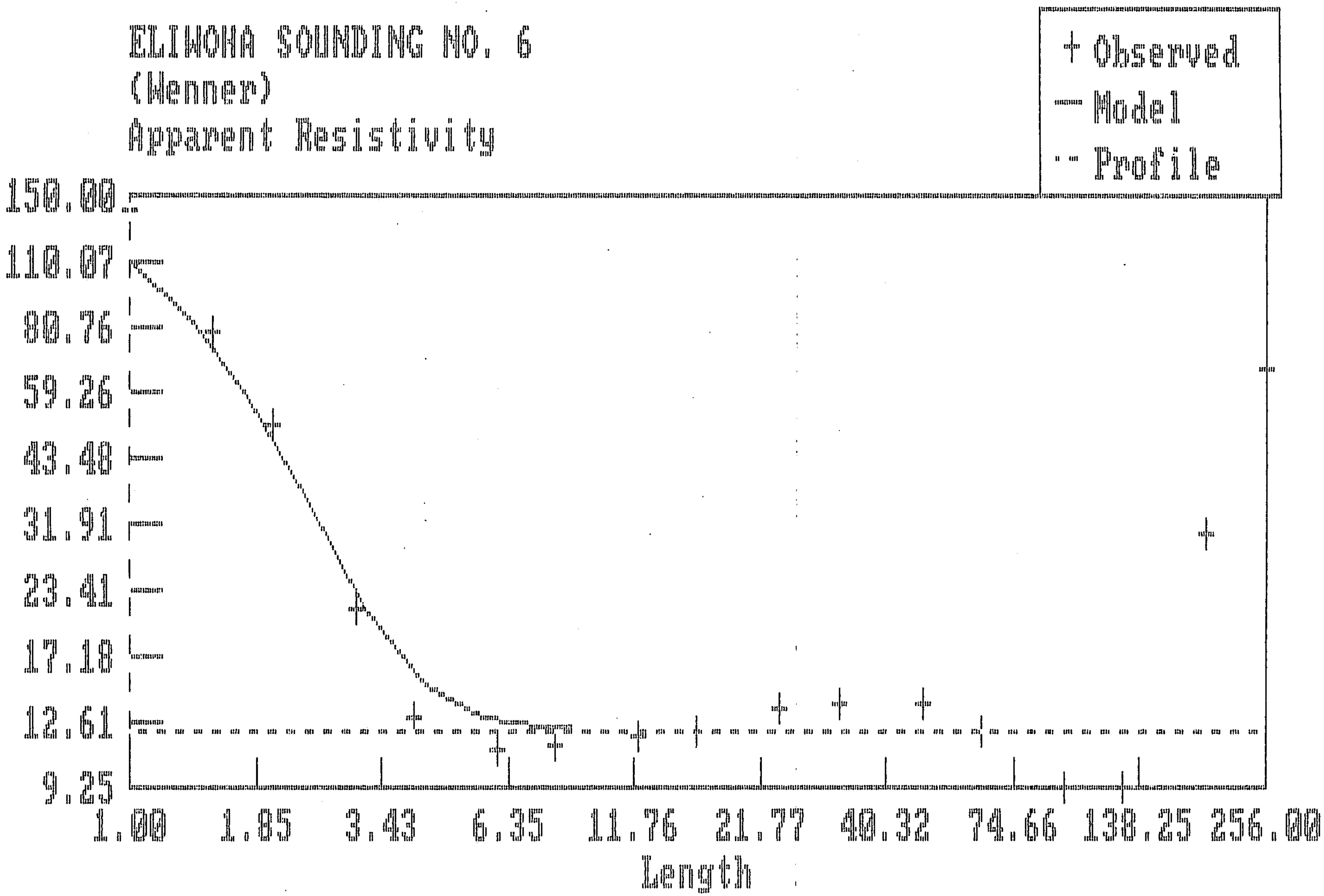
ELIWOHA SOUNDING SITE NO. 5

SPACING	RESISTIVITY
1.000	38.830
1.500	33.120
2.000	24.040
3.000	12.330
4.000	8.280
6.000	6.840
8.000	4.700
12.000	4.020
16.000	3.240
24.000	4.060
32.000	5.400
48.000	6.740
64.000	7.470
96.000	21.030
128.000	42.340

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.10	50.00
2	1.00	10.00
3	15.00	4.00
4	15.00	2.00
Subst.	infinite	200.00

ELIWOHA SOUNDING NO. 6
(Wenner)
Apparent Resistivity



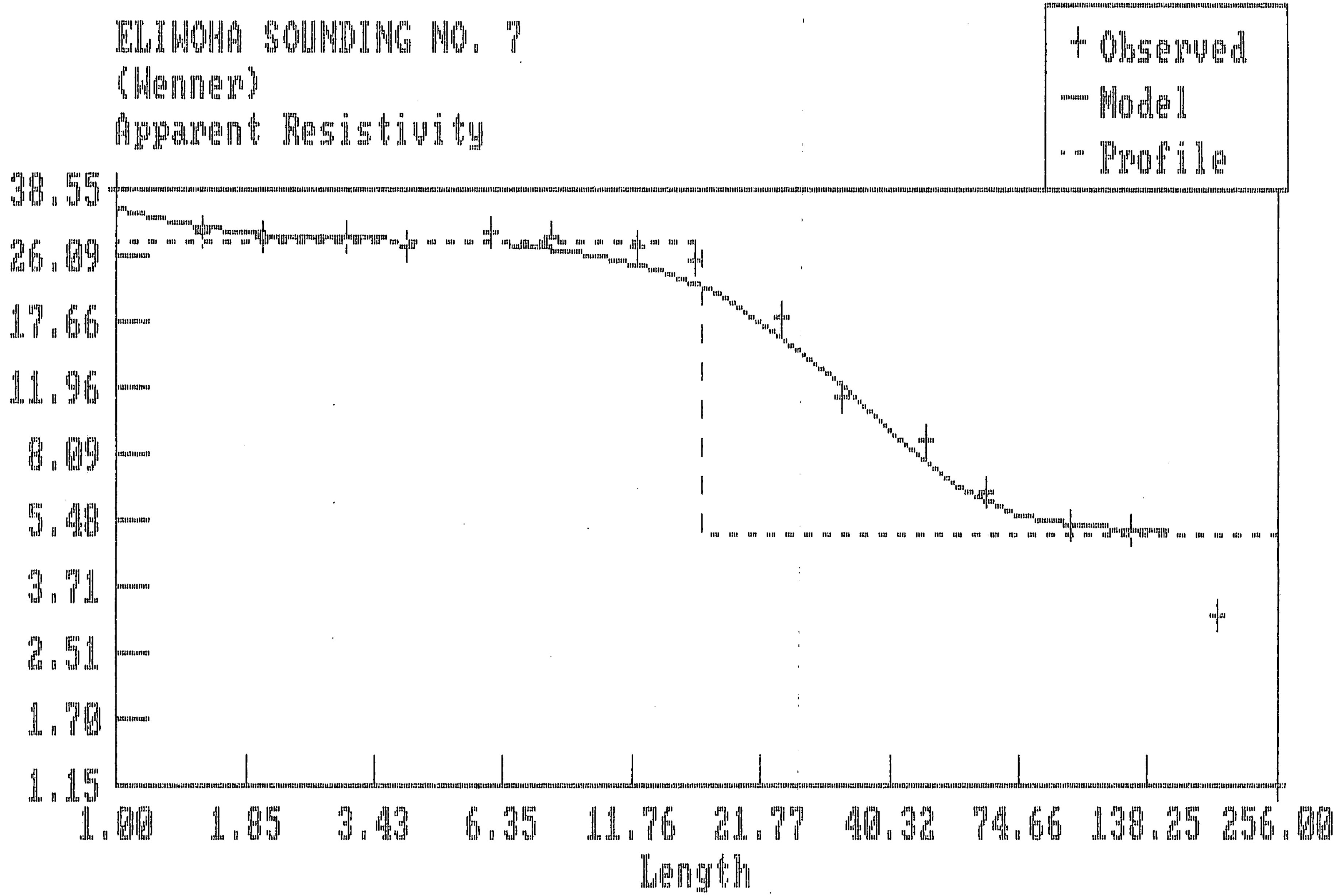
MEASURED VALUES

ELIWOHA SOUNDING NO. 6

SPACING	RESISTIVITY
1.000	137.920
1.500	78.090
2.000	49.950
3.000	21.220
4.000	12.980
6.000	11.100
8.000	11.210
12.000	11.940
16.000	12.160
24.000	13.540
32.000	13.770
48.000	13.740
64.000	12.060
96.000	9.330
128.000	9.250
192.000	30.630
256.000	65.850

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	150.00
Subst.	infinite	12.00



ELIWOHA SOUNDING NO. 7
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
38.55
26.09
17.66
11.96
8.09
5.48
3.71
2.51
1.70
1.15
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

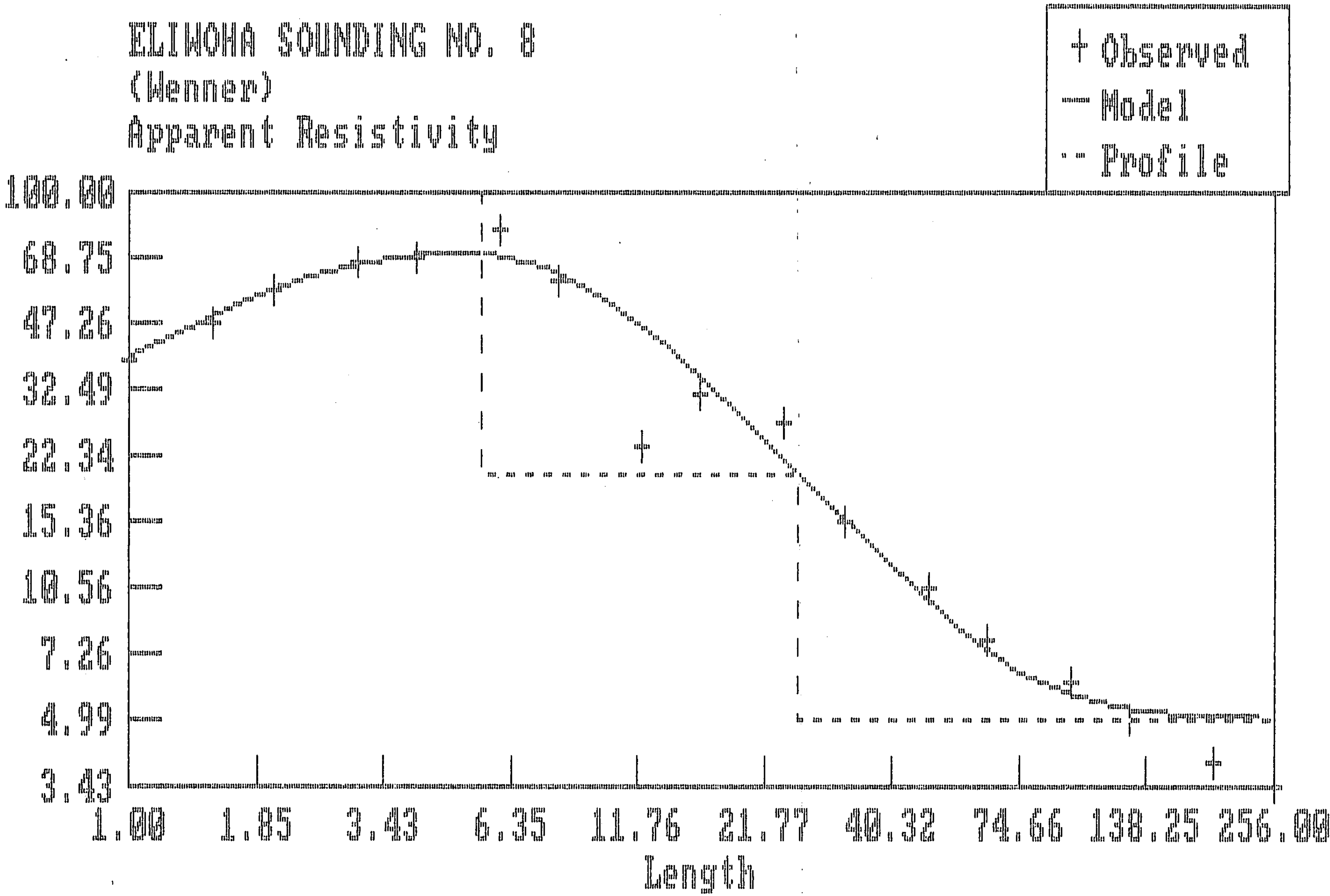
MEASURED VALUES

ELIWOHA SOUNDING NO. 7

SPACING	RESISTIVITY
1.000	38.550
1.500	29.820
2.000	28.650
3.000	28.610
4.000	26.980
6.000	29.680
8.000	29.000
12.000	27.010
16.000	25.030
24.000	18.170
32.000	11.380
48.000	8.790
64.000	6.390
96.000	5.270
128.000	5.150
192.000	3.110
256.000	1.150

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.40	50.00
2	16.00	28.00
Subst.	infinite	5.00


ELIWOHA SOUNDING NO. 8
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
100.00
68.75
47.26
32.49
22.34
15.36
10.56
7.26
4.99
3.43
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

MEASURED VALUES

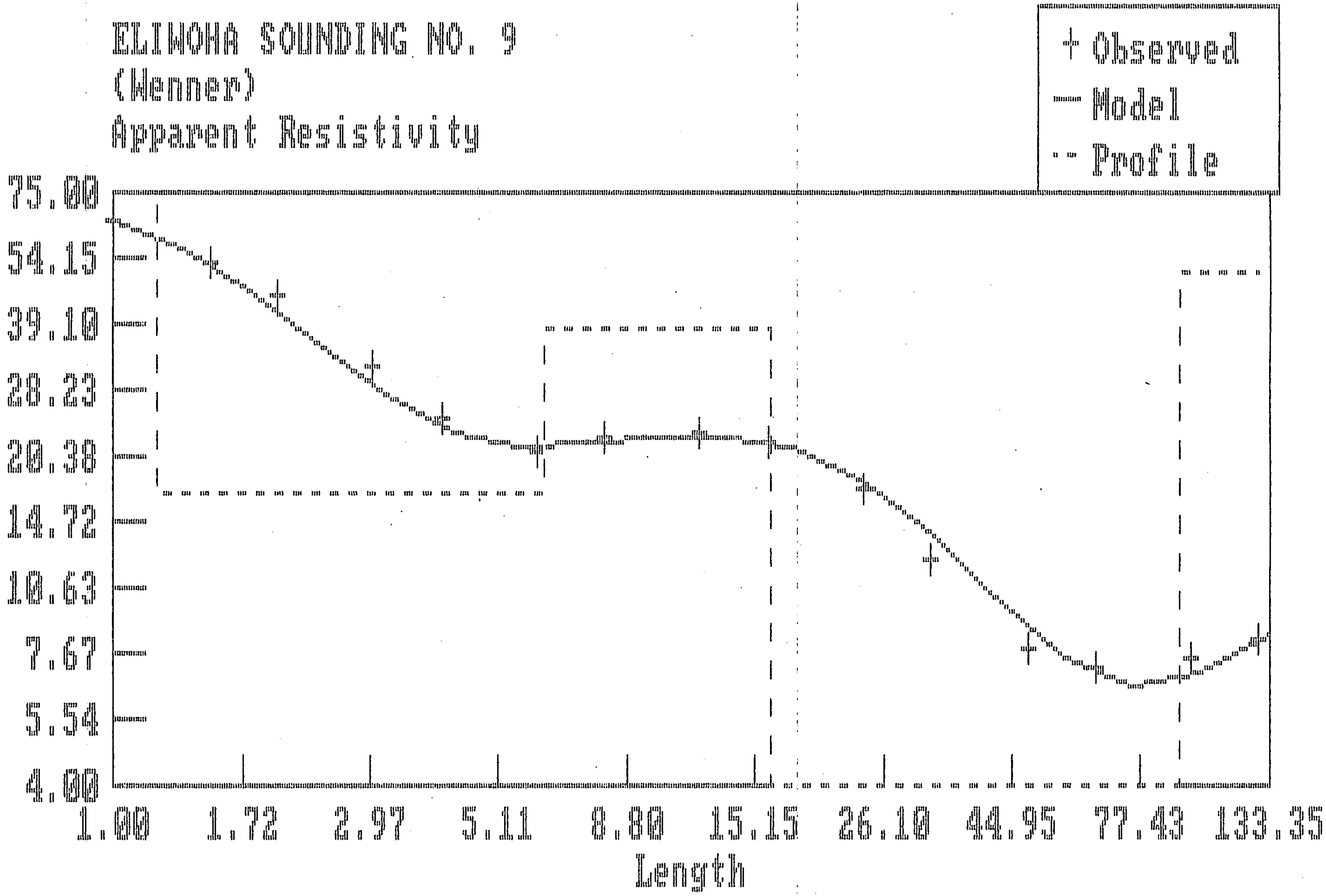
ELIWOHA SOUNDING NO. 8

SPACING	RESISTIVITY
1.000	37.570
1.500	46.240
2.000	56.860
3.000	66.580
4.000	67.610
6.000	80.070
8.000	59.640
12.000	23.290
16.000	31.060
24.000	26.800
32.000	15.480
48.000	10.610
64.000	7.930
96.000	6.110
128.000	4.990
192.000	3.960
256.000	3.430

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	20.00
2	5.00	100.00
3	20.00	20.00
Subst.	infinite	5.00

ELIWOHA SOUNDING NO. 9
(Wenner)
Apparent Resistivity



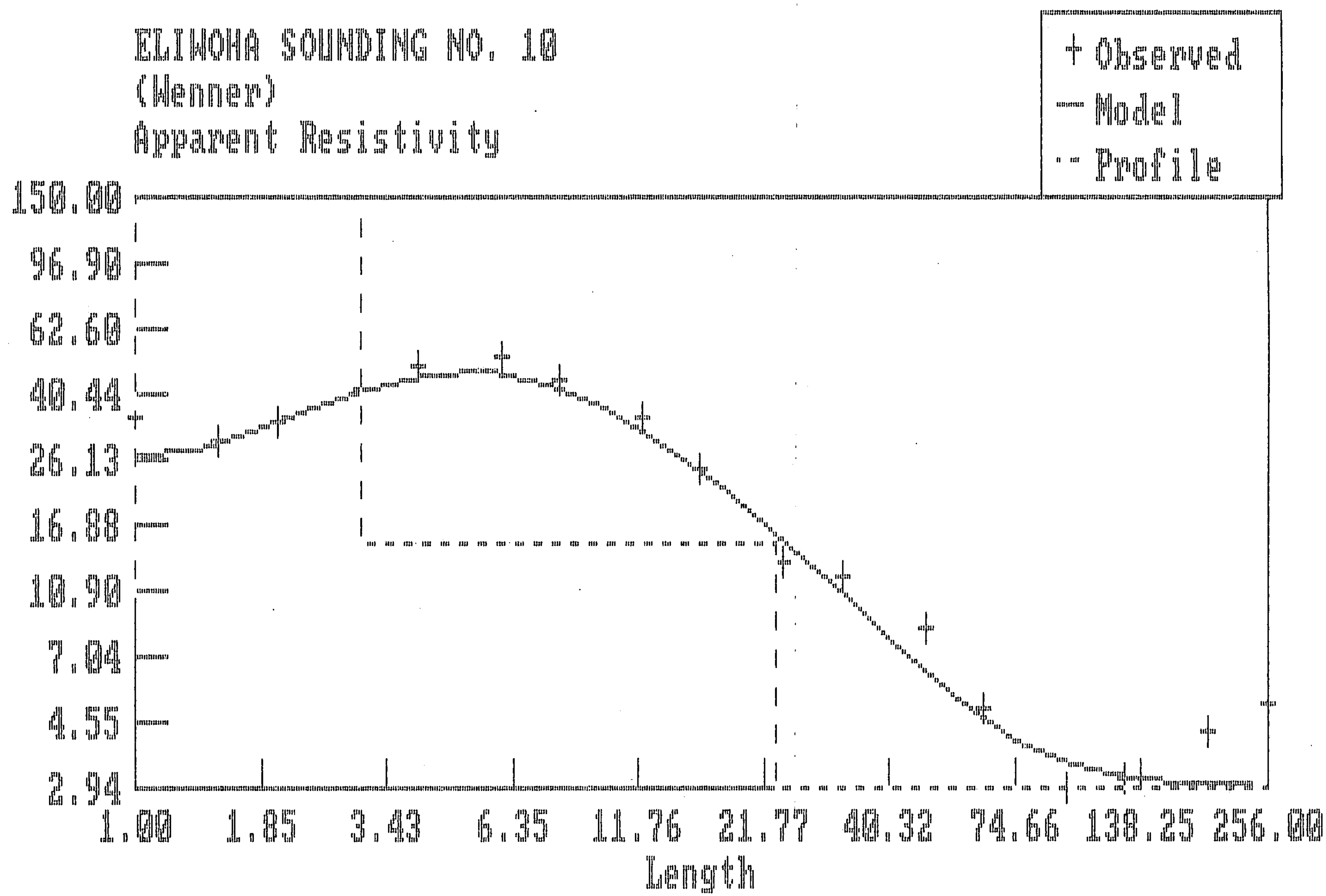
MEASURED VALUES

ELIWOHA SOUNDING NO. 9

SPACING	RESISTIVITY
1.000	65.250
1.500	52.680
2.000	44.420
3.000	31.330
4.000	24.640
6.000	20.820
8.000	22.220
12.000	22.790
16.000	21.870
24.000	17.420
32.000	12.070
48.000	7.900
64.000	7.090
96.000	7.480
128.000	8.260

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.20	75.00
2	5.00	17.00
3	10.00	38.00
4	75.00	4.00
Subst.	infinite	50.00



ELIWOHA SOUNDING NO. 10
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
150.00
96.90
62.60
40.44
26.13
16.88
10.90
7.04
4.55
2.94
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

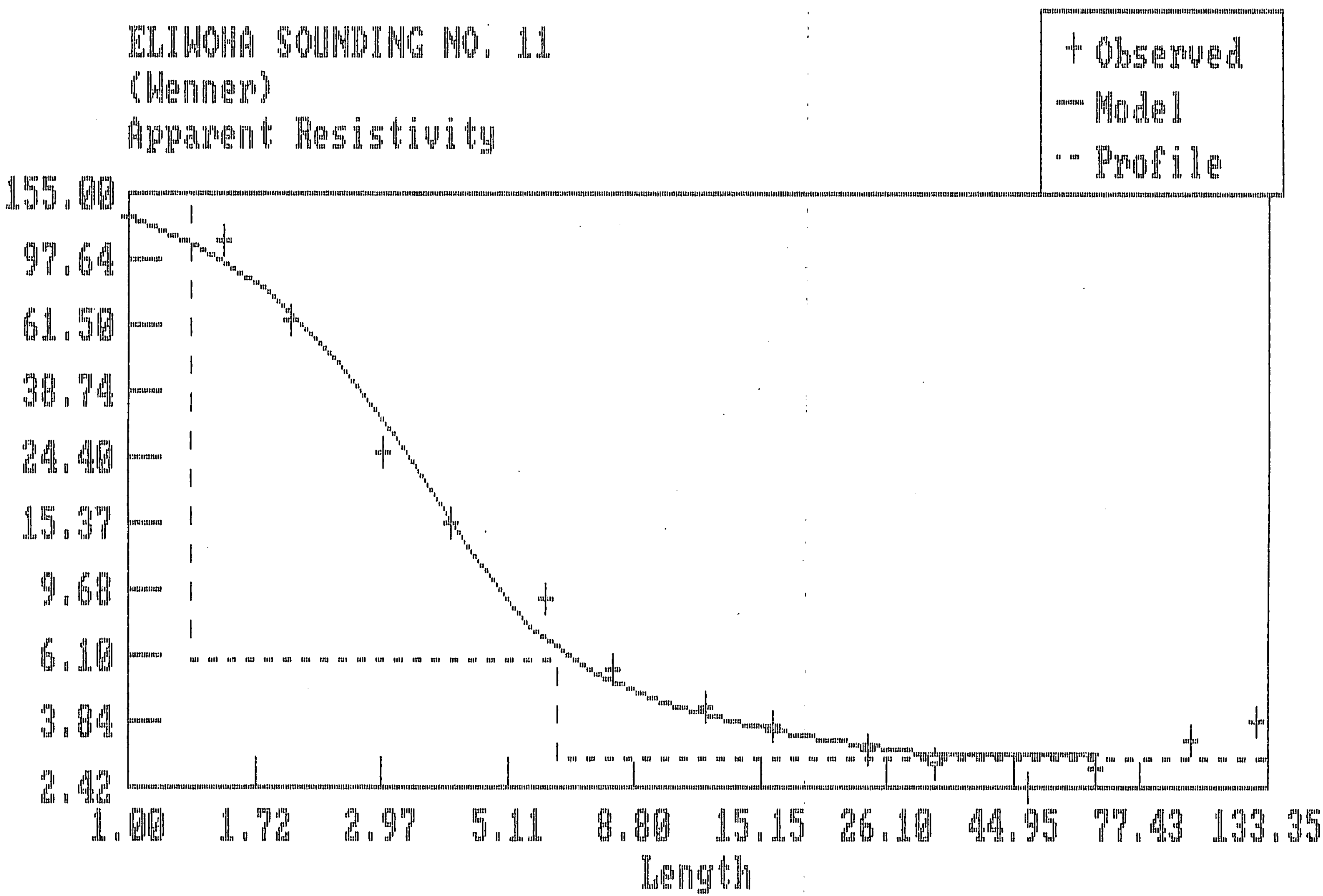
MEASURED VALUES

ELIWOHA SOUNDING NO. 10

SPACING	RESISTIVITY
1.000	34.020
1.500	29.620
2.000	33.490
3.000	41.620
4.000	48.770
6.000	51.240
8.000	44.280
12.000	34.510
16.000	24.730
24.000	13.270
32.000	11.940
48.000	8.480
64.000	4.950
96.000	2.940
128.000	3.180
192.000	4.300
256.000	5.100

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	40.00
2	.50	10.00
3	2.00	150.00
4	20.00	15.00
Subst.	infinite	3.00


ELIWOHA SOUNDING NO. 11
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
155.00
97.64
61.50
38.74
24.40
15.37
9.68
6.10
3.84
2.42
1.00
1.72
2.97
5.11
8.80
15.15
26.10
44.95
77.43
133.35
Length

MEASURED VALUES

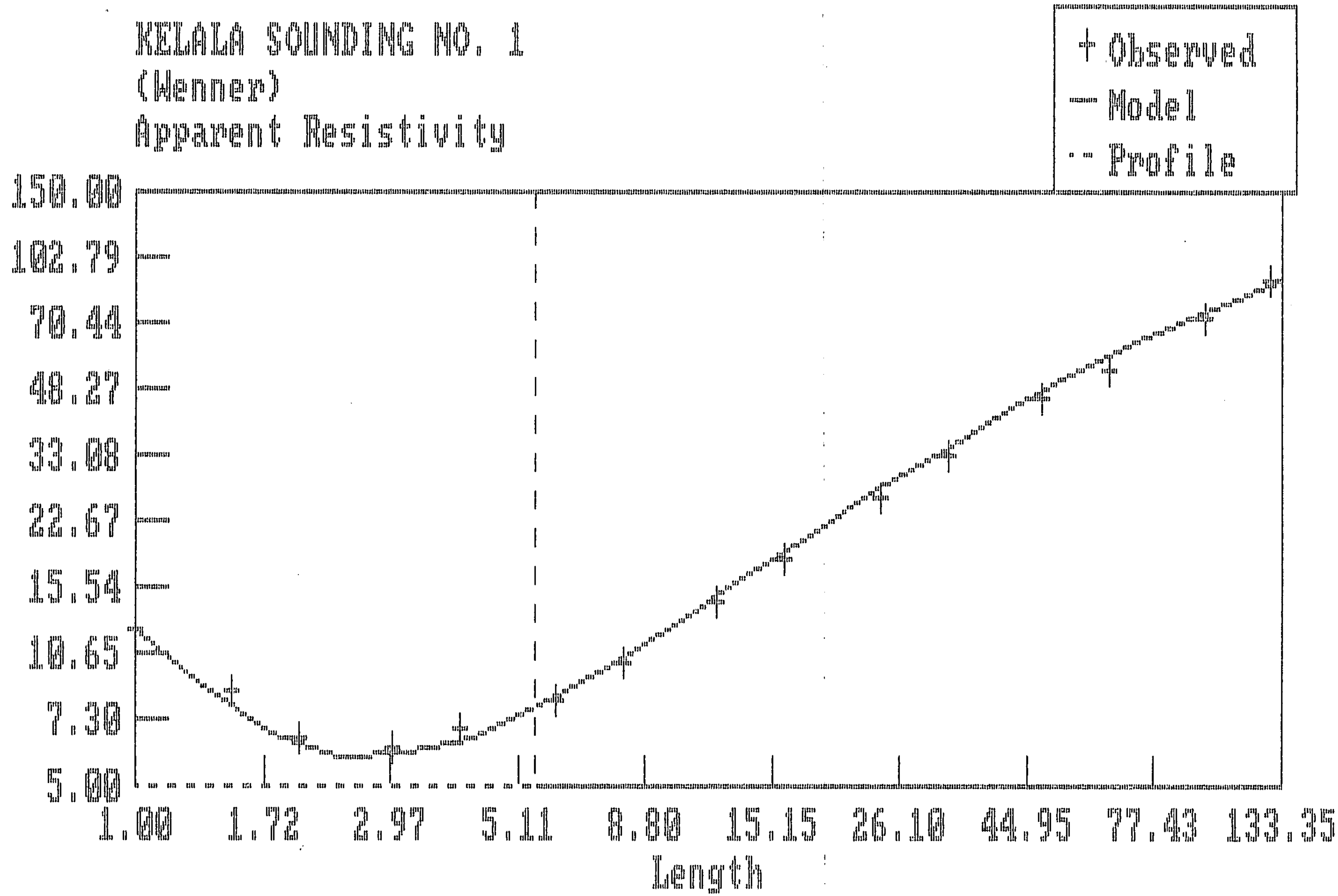
ELIWOHA SOUNDING NO. 11

SPACING	RESISTIVITY
1.000	128.180
1.500	108.550
2.000	62.890
3.000	25.420
4.000	15.410
6.000	9.200
8.000	5.520
12.000	4.210
16.000	3.740
24.000	3.140
32.000	2.830
48.000	2.420
64.000	2.810
96.000	3.360
128.000	3.870

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.30	155.00
2	5.00	6.00
Subst.	infinite	3.00

KELALA SOUNDING NO. 1
(Wenner)
Apparent Resistivity



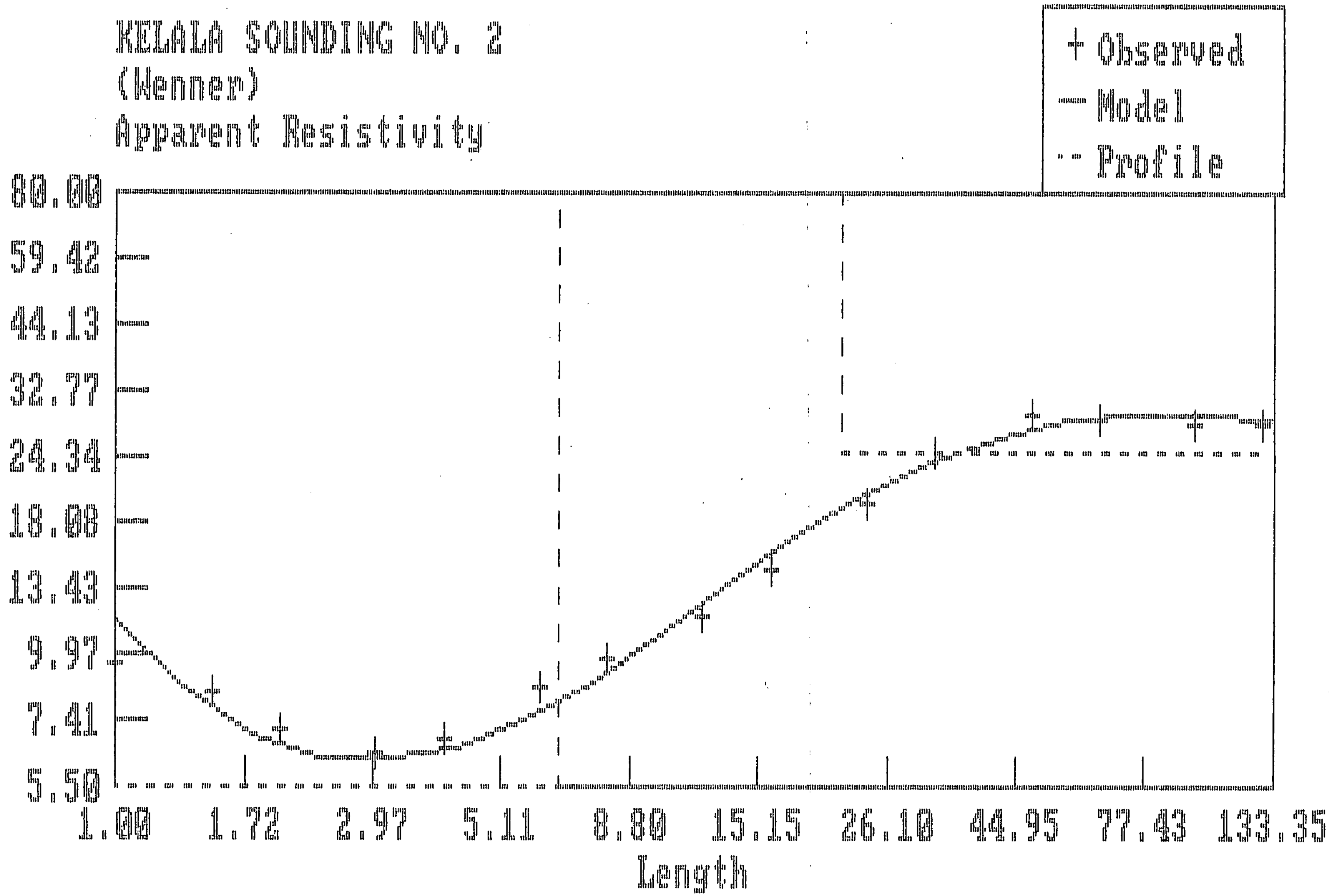
MEASURED VALUES

KELALA SOUNDING NO. 1

SPACING	RESISTIVITY
1.000	12.210
1.500	8.490
2.000	6.630
3.000	6.220
4.000	6.860
6.000	8.230
8.000	10.140
12.000	14.130
16.000	18.240
24.000	25.940
32.000	33.110
48.000	44.830
64.000	53.970
96.000	71.540
128.000	89.810

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	30.00
2	5.00	5.00
Subst.	infinite	150.00



KELALA SOUNDING NO. 2
(Wenner)
Apparent Resistivity
Observed
Model
Profile
80.00
59.42
44.13
32.77
24.34
18.08
13.43
9.97
7.41
5.50
1.00
1.72
2.97
5.11
8.80
15.15
26.10
44.95
77.43
133.35
Length

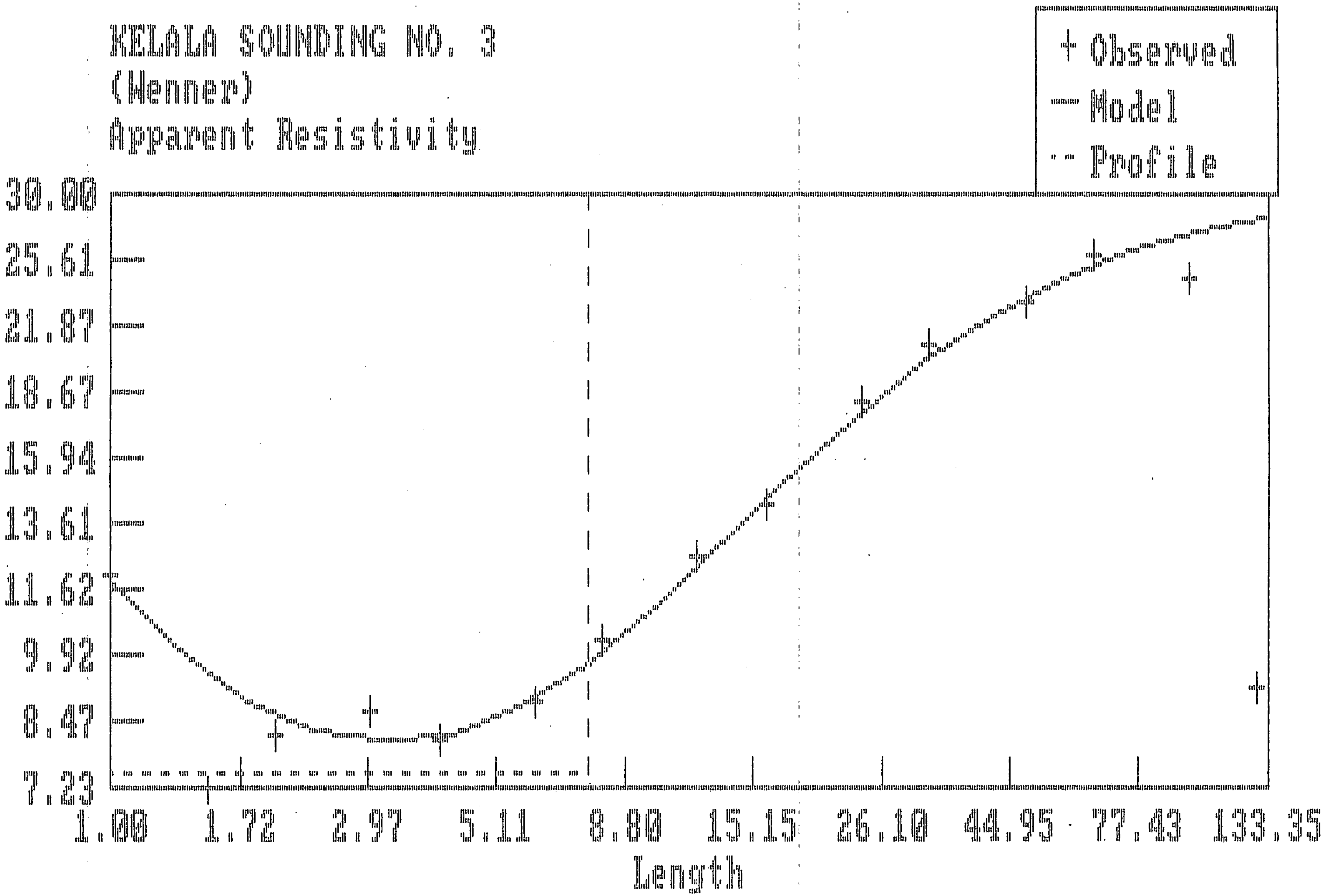
MEASURED VALUES

KELALA SOUNDING NO.. 2

SPACING	RESISTIVITY
1.000	9.640
1.500	8.390
2.000	7.040
3.000	6.430
4.000	6.750
6.000	8.560
8.000	9.800
12.000	11.760
16.000	14.520
24.000	19.740
32.000	24.640
48.000	29.180
64.000	28.610
96.000	27.890
128.000	28.300

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	25.00
2	6.00	5.50
3	15.00	80.00
Subst.	infinite	25.00


KELALA SOUNDING NO. 3
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
30.00
25.61
21.87
18.67
15.94
13.61
11.62
9.92
8.47
7.23
1.00
1.72
2.97
5.11
8.80
15.15
26.10
44.95
77.43
133.35
Length

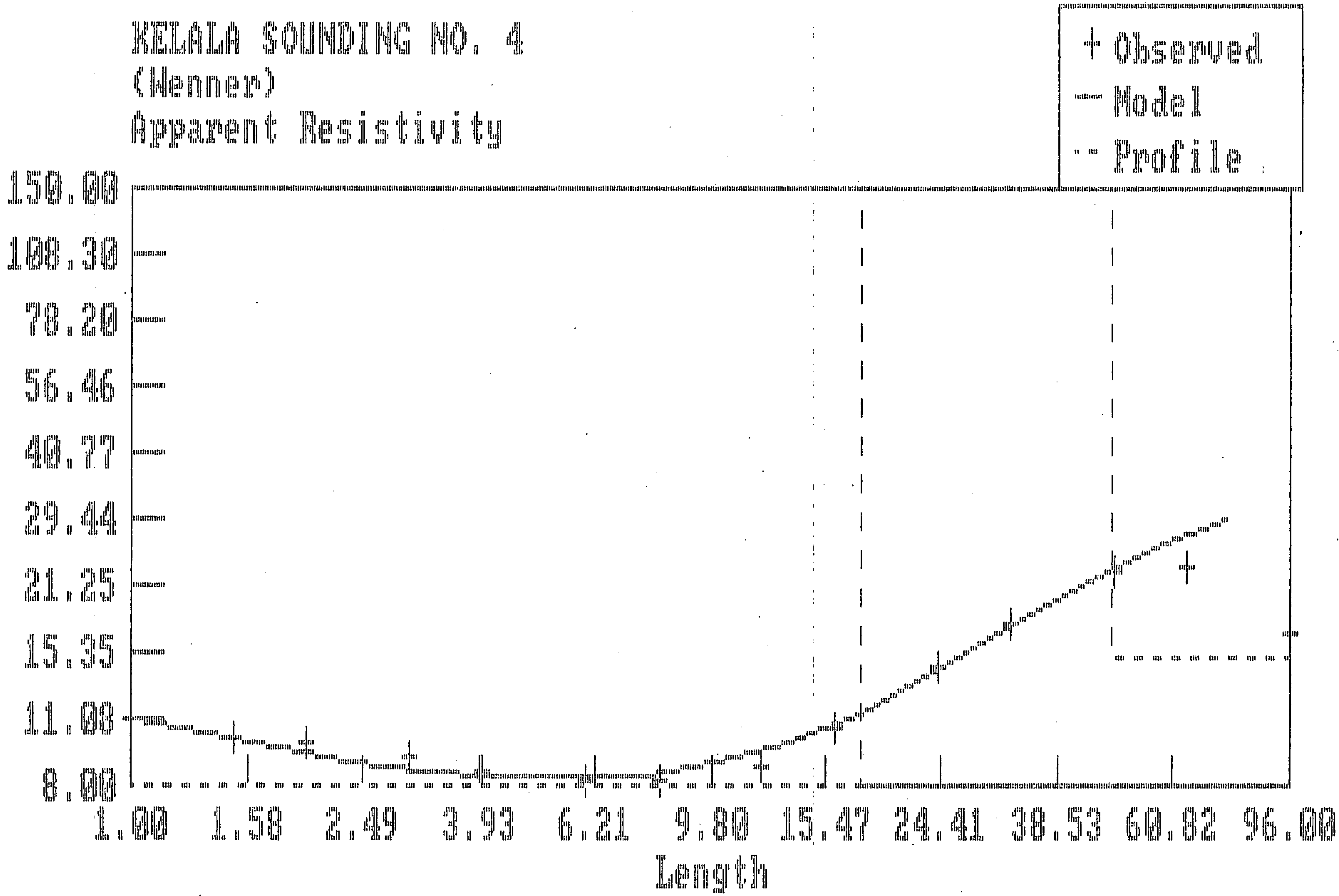
MEASURED VALUES

KELALA SOUNDING NO. 3

SPACING	RESISTIVITY
1.000	11.990
1.500	7.230
2.000	8.190
3.000	8.670
4.000	8.140
6.000	8.850
8.000	10.300
12.000	12.530
16.000	14.190
24.000	18.100
32.000	20.880
48.000	23.030
64.000	25.740
96.000	24.260
128.000	9.150

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	20.00
2	7.00	7.50
Subst.	infinite	30.00


KELALA SOUNDING NO. 4
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
150.00
108.30
78.20
56.46
40.77
29.44
21.25
15.35
11.08
8.00
1.00
1.58
2.49
3.93
6.21
9.80
15.47
24.41
38.53
60.82
96.00
Length

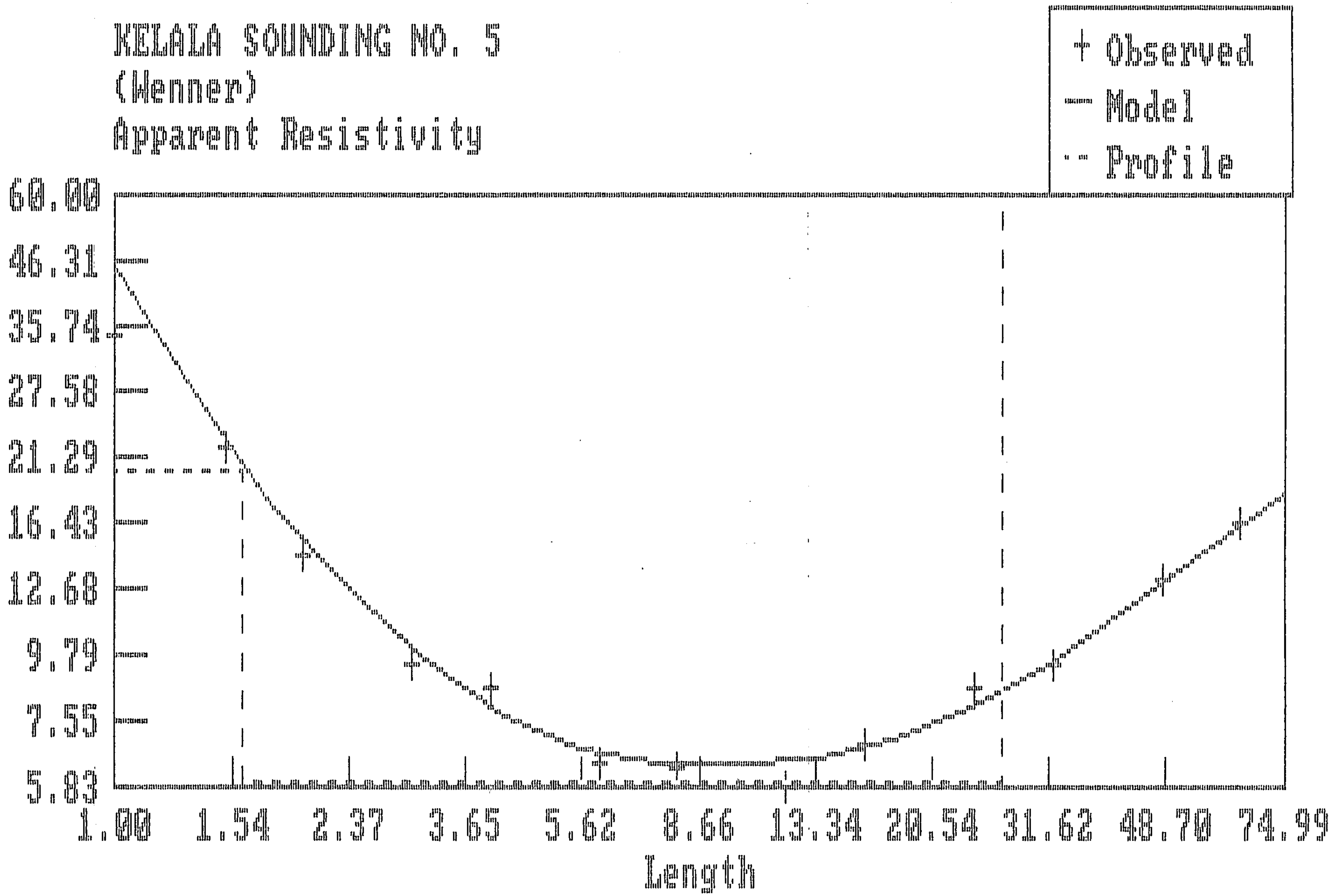
MEASURED VALUES

KELALA SOUNDING NO. 4

SPACING	RESISTIVITY
1.000	11.170
1.500	10.060
2.000	9.930
3.000	9.330
4.000	8.550
6.000	8.190
8.000	8.270
12.000	8.820
16.000	10.630
24.000	14.370
32.000	17.790
48.000	22.520
64.000	23.520
96.000	16.820

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.75	13.00
2	17.00	8.00
3	30.00	150.00
Subst.	infinite	15.00


KELALA SOUNDING NO. 5
(Wenner)
Apparent Resistivity
Observed
Model
Profile
60.00
46.31
35.74
27.58
21.29
16.43
12.68
9.79
7.55
5.83
1.00
1.54
2.37
3.65
5.62
8.66
13.34
20.54
31.62
48.70
74.99
Length

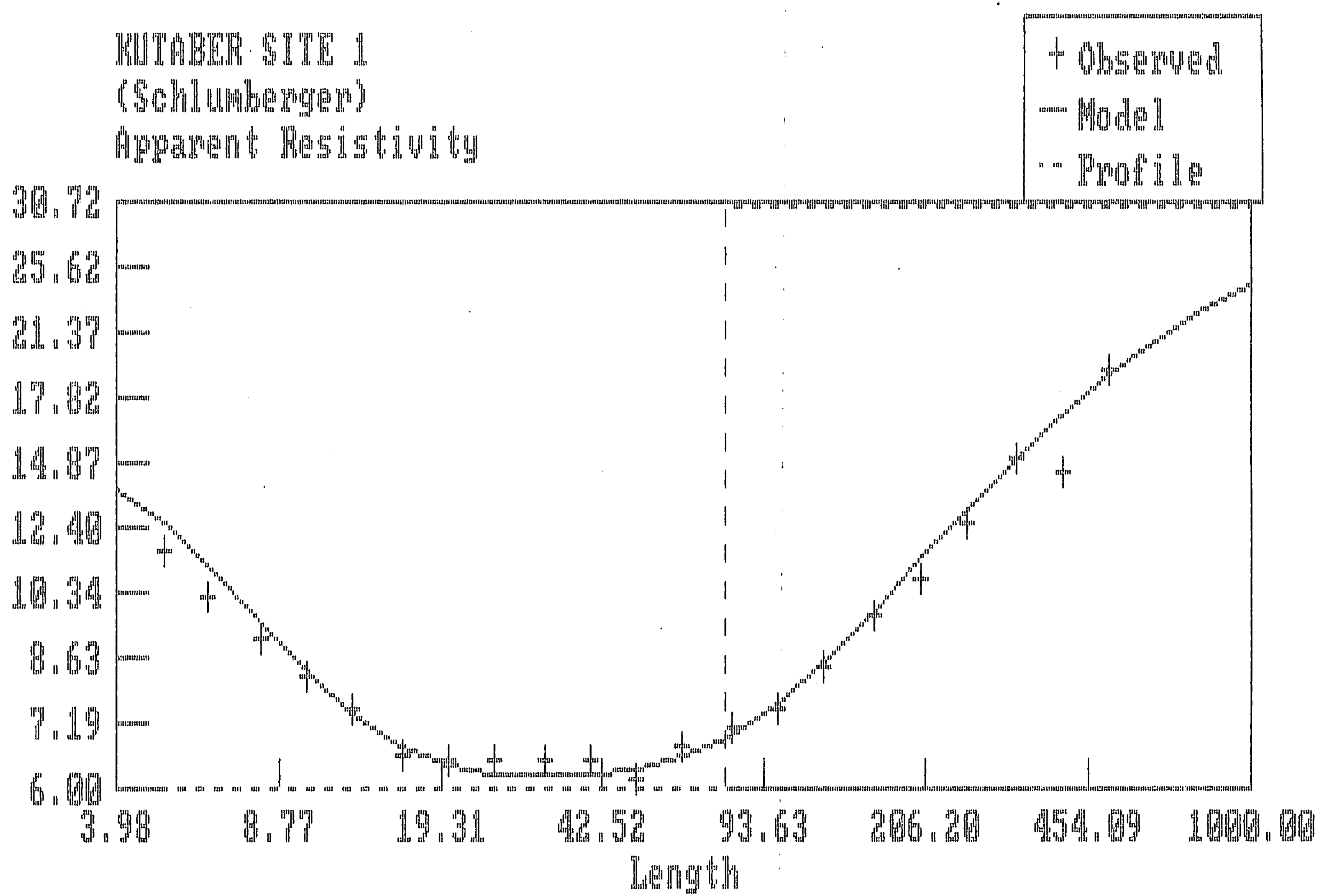
MEASURED VALUES

KELALA SOUNDING NO. 5

SPACING	RESISTIVITY
1.000	34.050
1.500	22.080
2.000	14.360
3.000	9.360
4.000	8.560
6.000	6.420
8.000	6.250
12.000	5.830
16.000	6.880
24.000	8.610
32.000	9.440
48.000	13.060
64.000	16.350

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.40	200.00
2	1.20	20.00
3	25.00	6.00
Subst.	infinite	60.00


KUTABER SITE 1
(Schlumberger)
Apparent Resistivity
Observed
Model
Profile
30.72
25.62
21.37
17.82
14.87
12.40
10.34
8.63
7.19
6.00
3.98
8.77
19.31
42.52
93.63
206.20
454.09
1000.00
Length

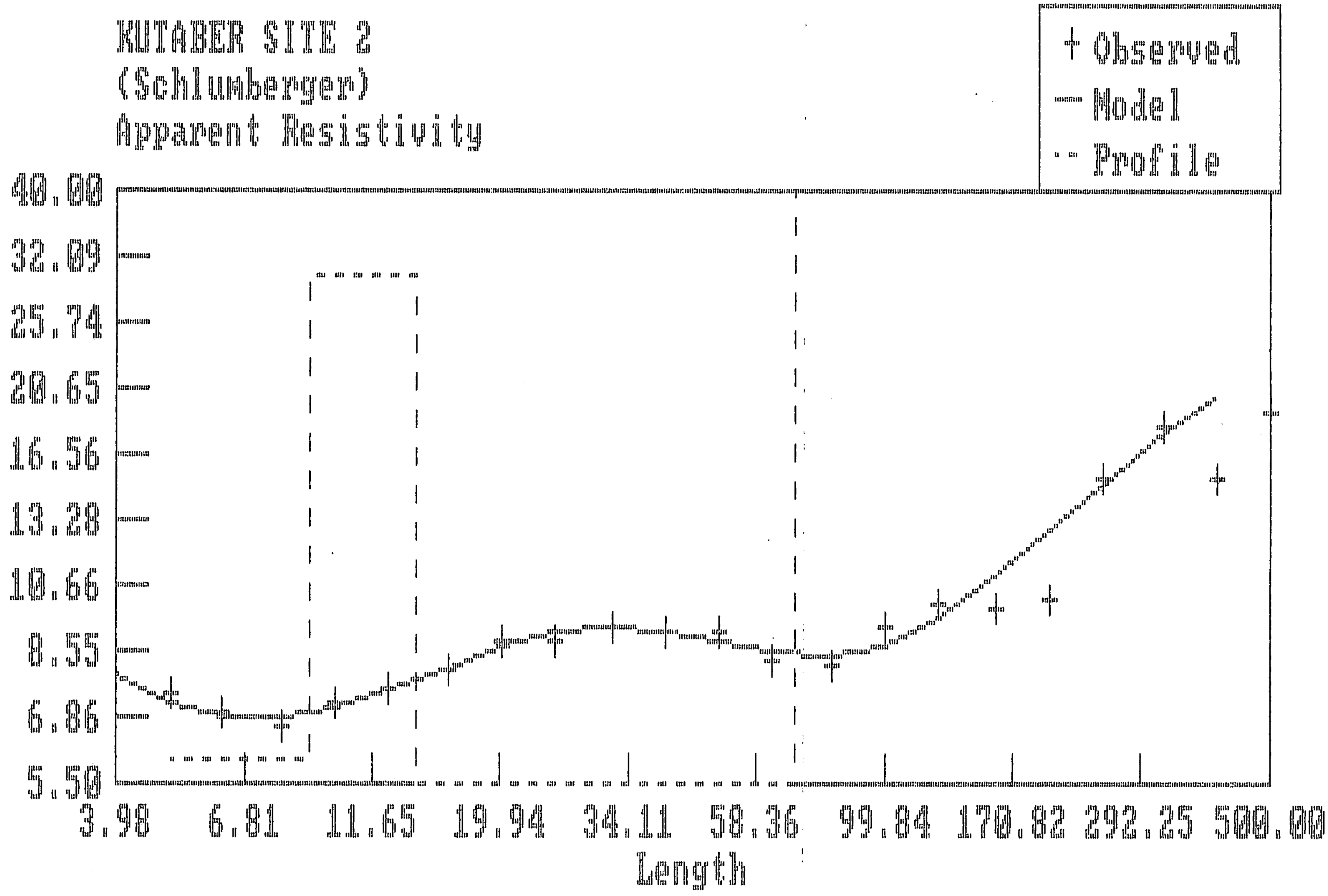
MEASURED VALUES

KUTABER SITE 1

SPACING	RESISTIVITY
5.000	11.540
6.200	10.220
8.000	9.120
10.000	8.160
12.500	7.510
16.000	6.550
20.000	6.460
25.000	6.500
32.000	6.510
40.000	6.460
50.000	6.210
62.500	6.770
80.000	7.080
100.000	7.450
125.000	8.400
160.000	9.720
200.000	10.810
250.000	12.520
320.000	15.020
400.000	14.410
500.000	19.310
1000.000	30.720

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	3.00	16.00
2	75.00	6.00
Subst.	infinite	30.00


KUTABER SITE 2
(Schlumberger)
Apparent Resistivity
Observed
Model
Profile
40.00
32.09
25.74
20.65
16.56
13.28
10.66
8.55
6.86
5.50
3.98
6.81
11.65
19.94
34.11
58.36
99.84
170.82
292.25
500.00
Length

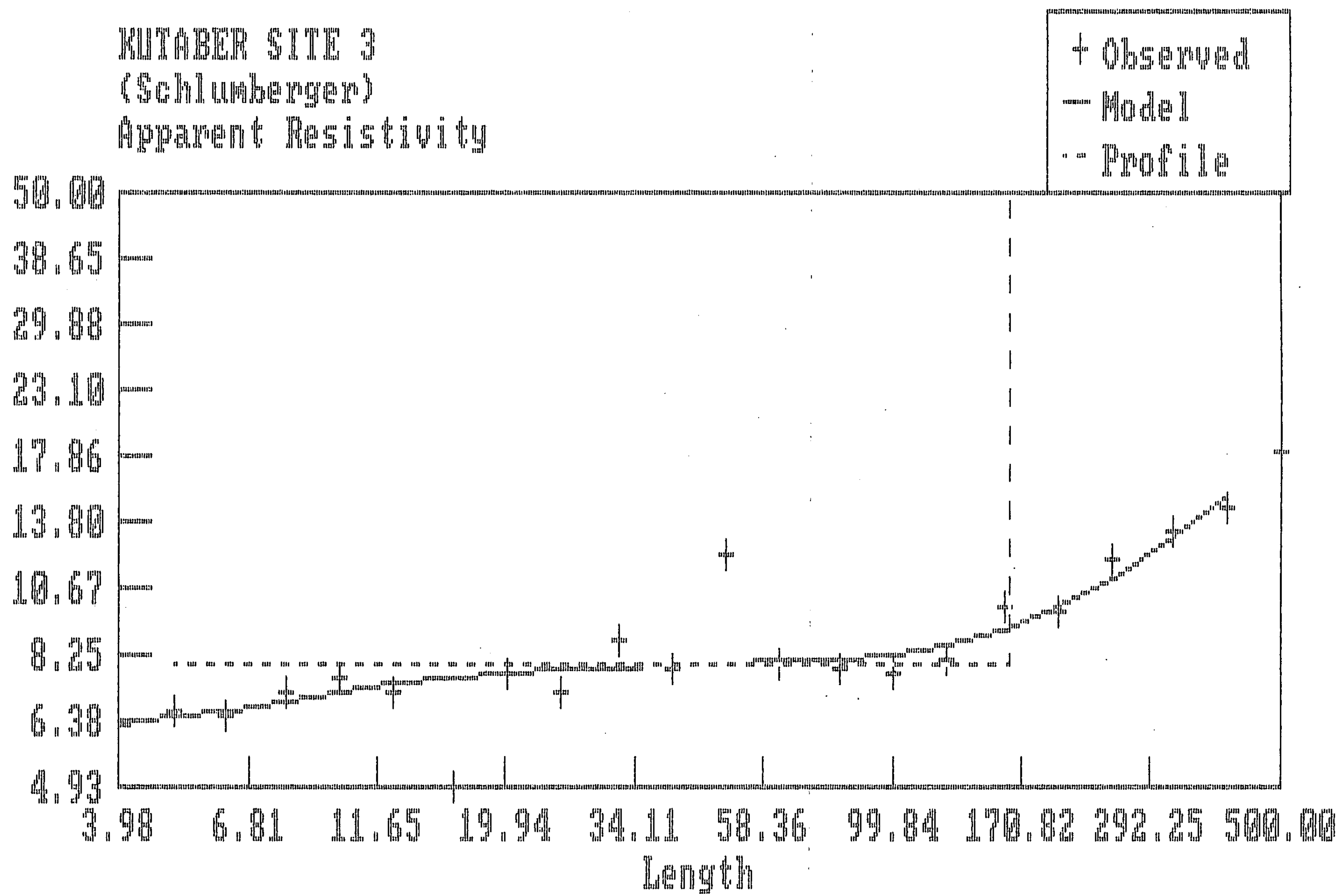
MEASURED VALUES

KUTABER SITE 2

SPACING	RESISTIVITY
5.000	7.430
6.200	6.940
8.000	6.640
10.000	7.220
12.500	7.560
16.000	8.090
20.000	8.860
25.000	8.880
32.000	9.260
40.000	9.040
50.000	9.040
62.500	8.310
80.000	8.150
100.000	9.200
125.000	9.970
160.000	9.770
200.000	10.080
250.000	15.160
320.000	18.100
400.000	15.300
500.000	18.920

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	20.00
2	8.00	6.00
3	5.00	30.00
4	55.00	5.50
Subst.	infinite	40.00



KUTABER SITE 3
(Schlumberger)
Apparent Resistivity
Observed
Model
Profile
50.00
38.65
29.88
23.10
17.86
13.80
10.67
8.25
6.38
4.93
3.98
6.81
11.65
19.94
34.11
58.36
99.84
170.82
292.25
500.00
Length

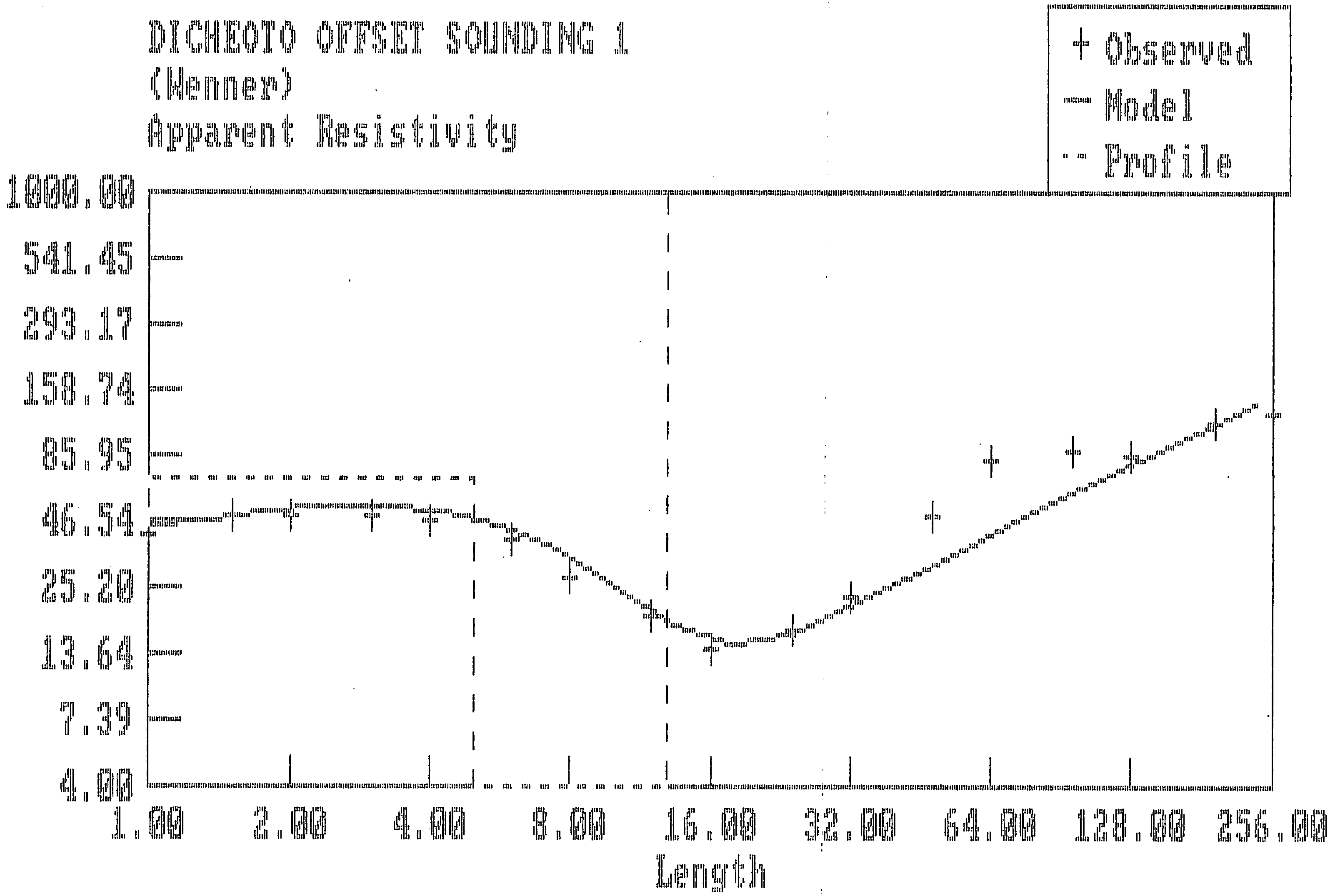
MEASURED VALUES

KUTABER SITE 3

SPACING	RESISTIVITY
5.000	6.680
6.200	6.550
8.000	7.080
10.000	7.570
12.500	7.120
16.000	4.930
20.000	7.710
25.000	7.130
32.000	8.760
40.000	7.840
50.000	12.010
62.500	8.000
80.000	7.770
100.000	7.720
125.000	8.090
160.000	9.970
200.000	9.800
250.000	11.820
320.000	13.210
400.000	14.530
500.000	18.200

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	3.00	6.00
2	160.00	8.00
Subst.	infinite	50.00


DICHEOTO OFFSET SOUNDING 1
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
1000.00
541.45
293.17
158.74
85.95
46.54
25.20
13.64
7.39
4.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

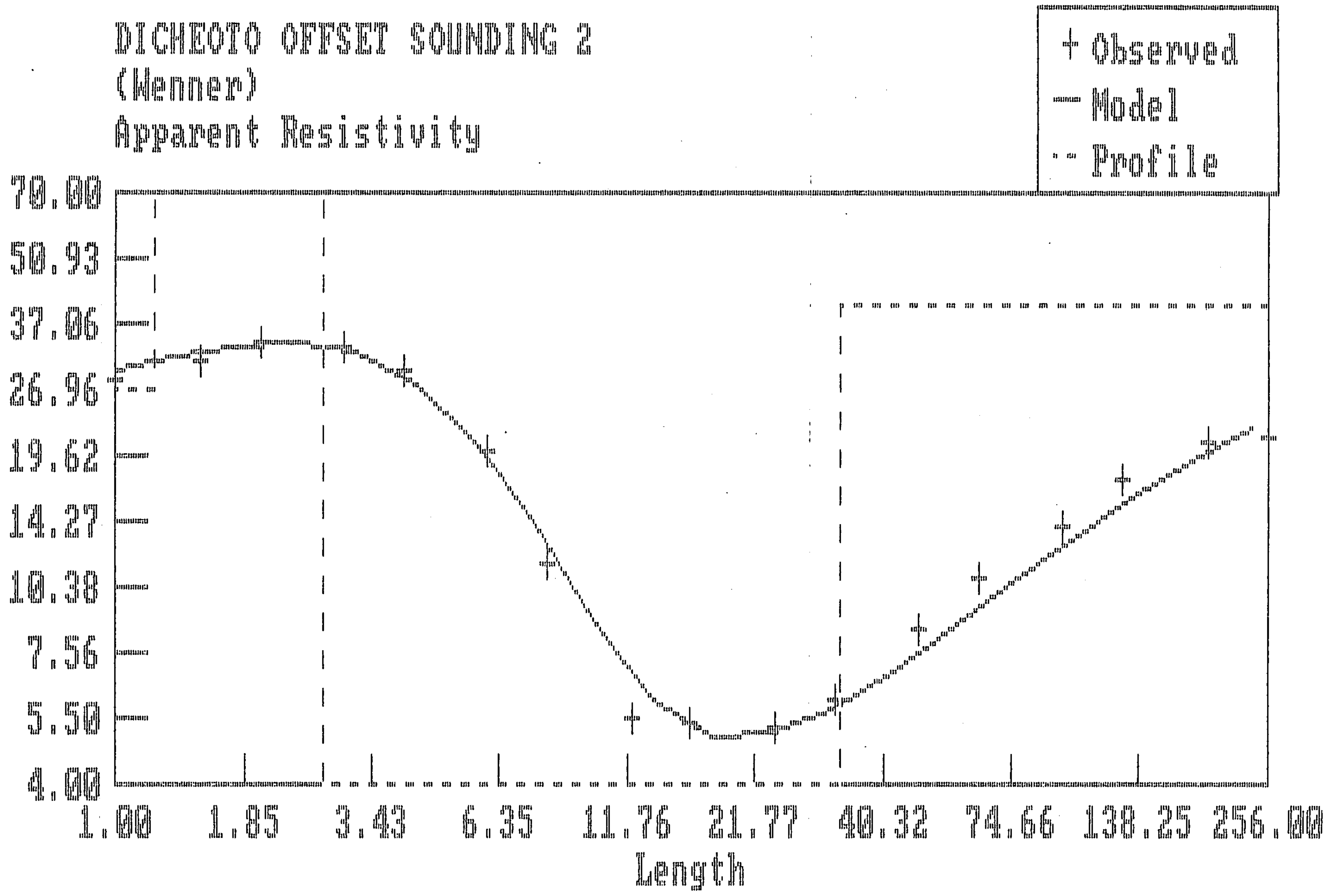
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 1

SPACING	RESISTIVITY
1.000	41.410
1.500	47.520
2.000	47.560
3.000	48.770
4.000	46.960
6.000	39.430
8.000	27.970
12.000	19.030
16.000	14.000
24.000	16.870
32.000	23.010
48.000	47.710
64.000	81.390
96.000	87.440
128.000	83.840
192.000	114.480
256.000	128.440

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	40.00
2	4.00	70.00
3	8.00	4.00
Subst.	infinite	1000.00


DICHEOTO OFFSET SOUNDING 2
(Wenner)
Apparent Resistivity
70.00
50.93
37.06
26.96
19.62
14.27
10.38
7.56
5.50
4.00
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length
+ Observed
— Model
·· Profile

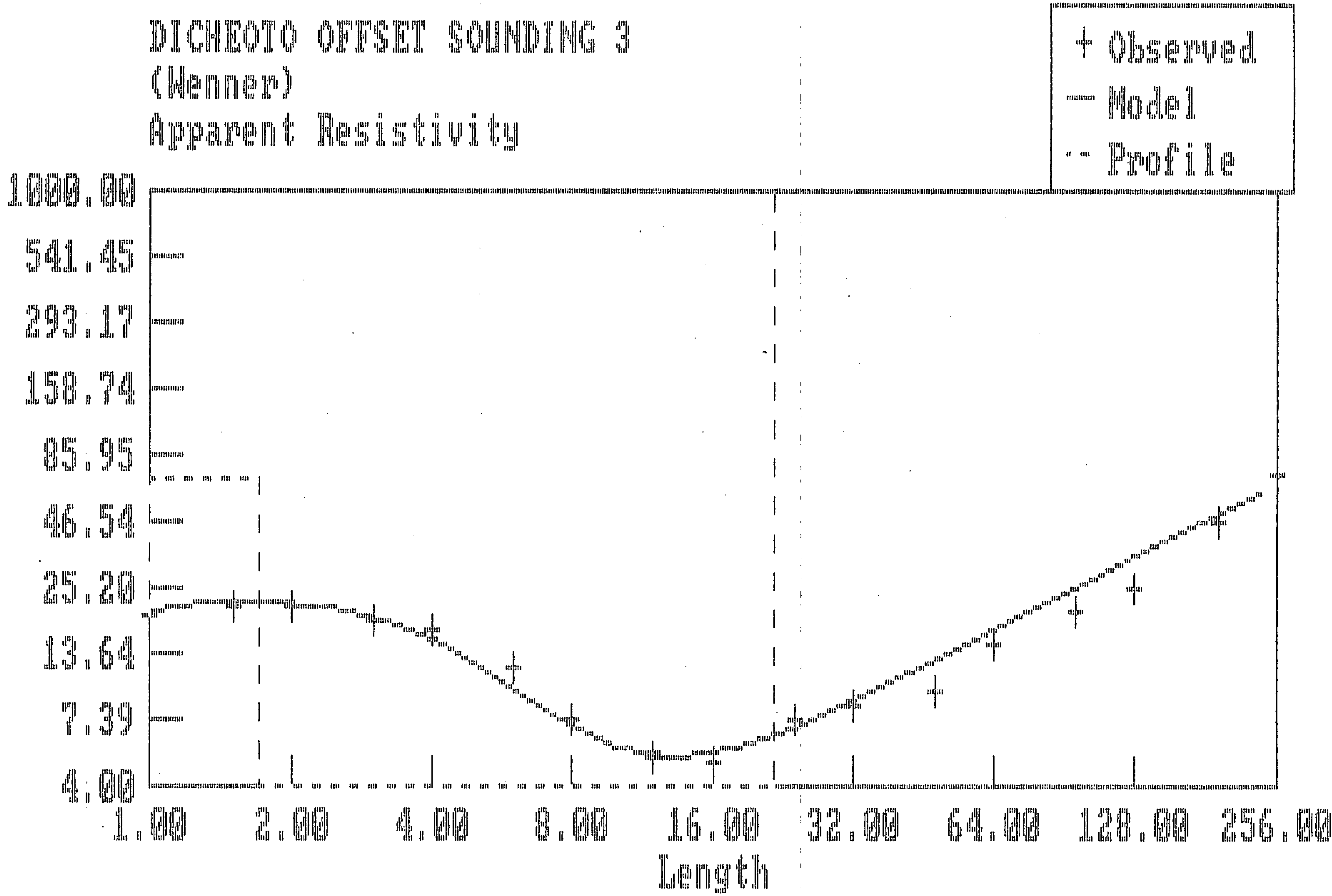
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 2

SPACING	RESISTIVITY
1.000	28.050
1.500	30.460
2.000	33.490
3.000	33.200
4.000	29.440
6.000	19.940
8.000	11.560
12.000	5.560
16.000	5.350
24.000	5.230
32.000	6.010
48.000	8.460
64.000	10.740
96.000	13.970
128.000	17.410
192.000	20.840
256.000	21.570

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.20	27.00
2	1.50	70.00
3	30.00	4.00
Subst.	infinite	40.00



DICHEOTO OFFSET SOUNDING 3
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
1000.00
541.45
293.17
158.74
85.95
46.54
25.20
13.64
7.39
4.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

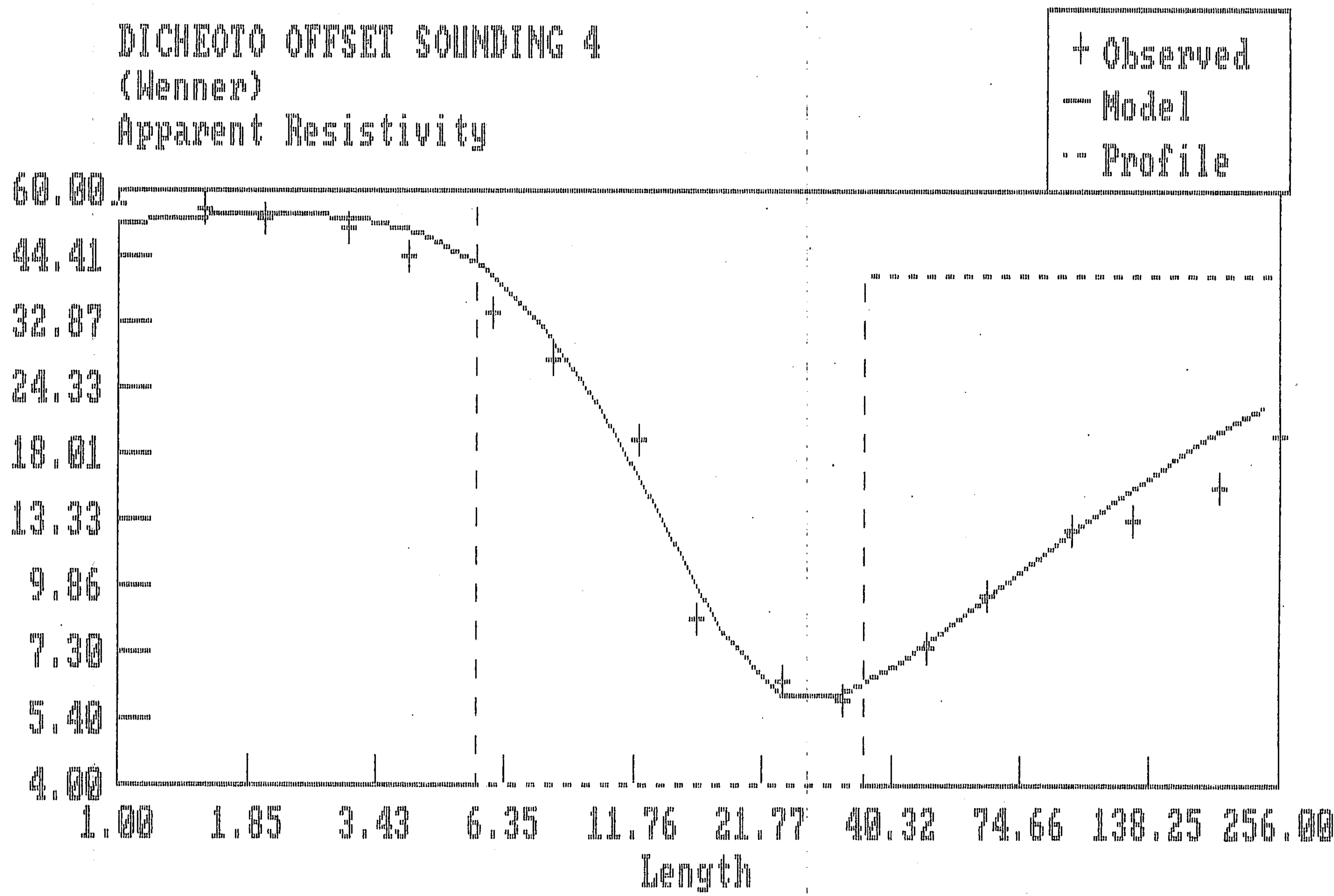
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 3

SPACING	RESISTIVITY
1.000	19.260
1.500	20.760
2.000	21.250
3.000	18.370
4.000	16.900
6.000	12.140
8.000	7.490
12.000	5.280
16.000	4.940
24.000	7.260
32.000	8.360
48.000	9.810
64.000	14.680
96.000	20.170
128.000	25.660
192.000	46.040
256.000	71.870

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	18.00
2	.70	70.00
3	20.00	4.00
Subst.	infinite	1000.00



DICHEOTO OFFSET SOUNDING 4
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
60.00
44.41
32.87
24.33
18.01
13.33
9.86
7.30
5.40
4.00
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

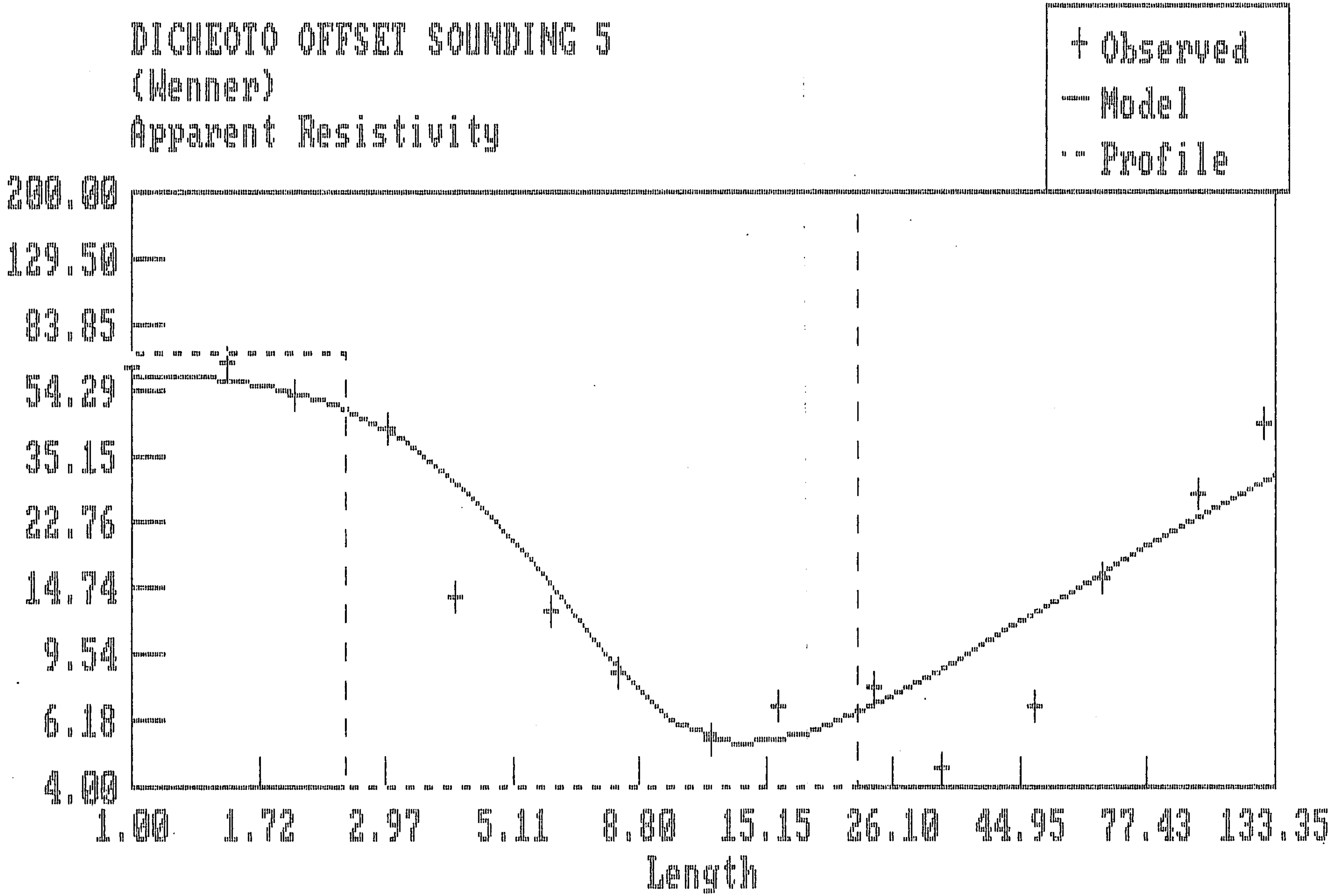
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 4

SPACING	RESISTIVITY
1.000	55.290
1.500	54.140
2.000	52.530
3.000	50.220
4.000	43.880
6.000	34.320
8.000	27.500
12.000	18.990
16.000	8.450
24.000	6.470
32.000	5.870
48.000	7.500
64.000	9.390
96.000	12.610
128.000	13.350
192.000	15.300
256.000	19.660

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	50.00
2	4.50	60.00
3	30.00	4.00
Subst.	infinite	40.00


DICHEOTO OFFSET SOUNDING 5
(Wenner)
Apparent Resistivity
Observed
Model
Profile
200.00
129.50
83.85
54.29
35.15
22.76
14.74
9.54
6.18
4.00
1.00
1.72
2.97
5.11
8.80
15.15
26.10
44.95
77.43
133.35
Length

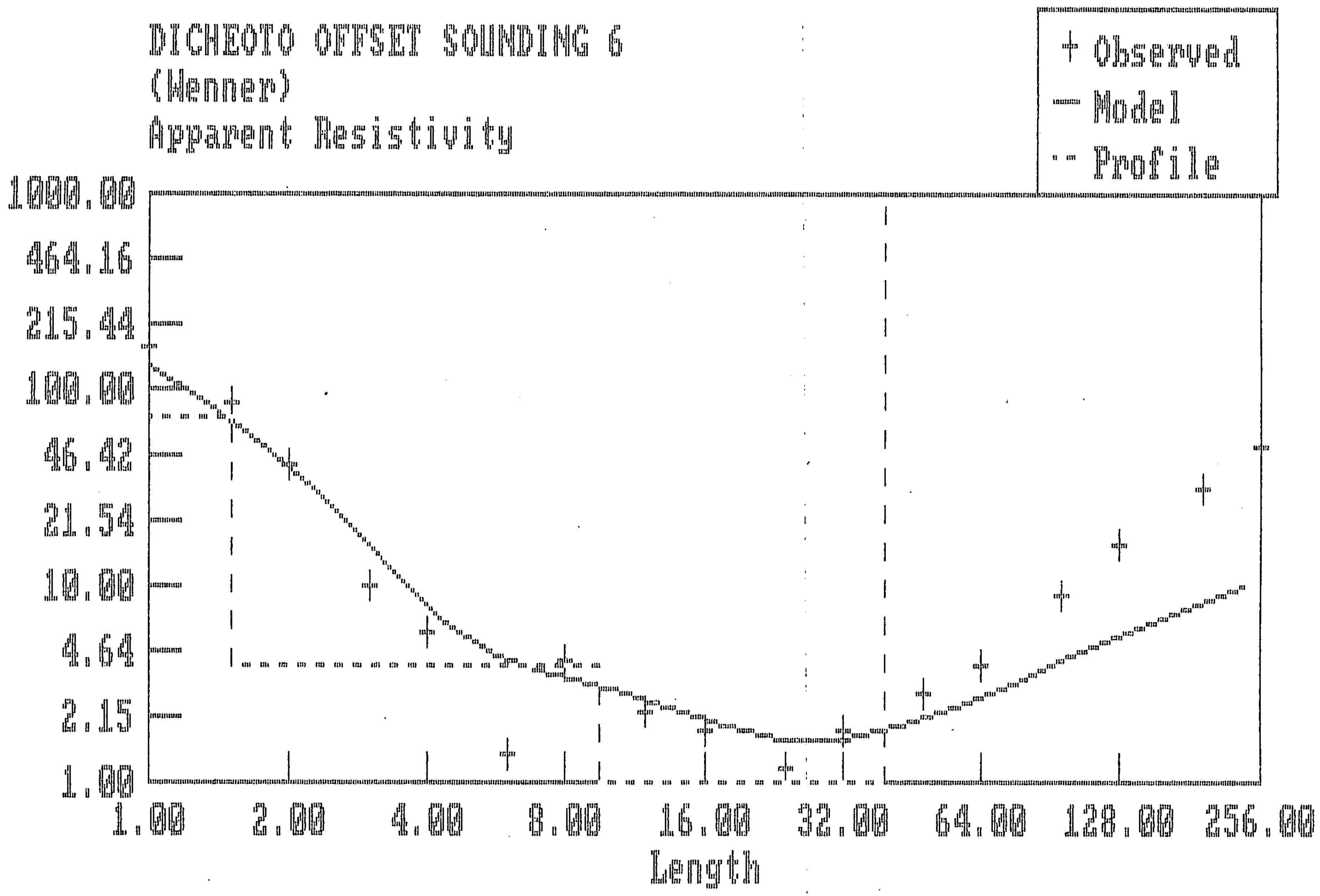
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 5

SPACING	RESISTIVITY
1.000	63.110
1.500	64.000
2.000	52.110
3.000	41.880
4.000	13.660
6.000	12.710
8.000	8.570
12.000	5.510
16.000	6.790
24.000	7.700
32.000	4.530
48.000	6.790
64.000	15.560
96.000	27.530
128.000	43.810

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	60.00
2	1.50	70.00
3	20.00	4.00
Subst.	infinite	200.00


DICHEOTO OFFSET SOUNDING 6
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
1000.00
464.16
215.44
100.00
46.42
21.54
10.00
4.64
2.15
1.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

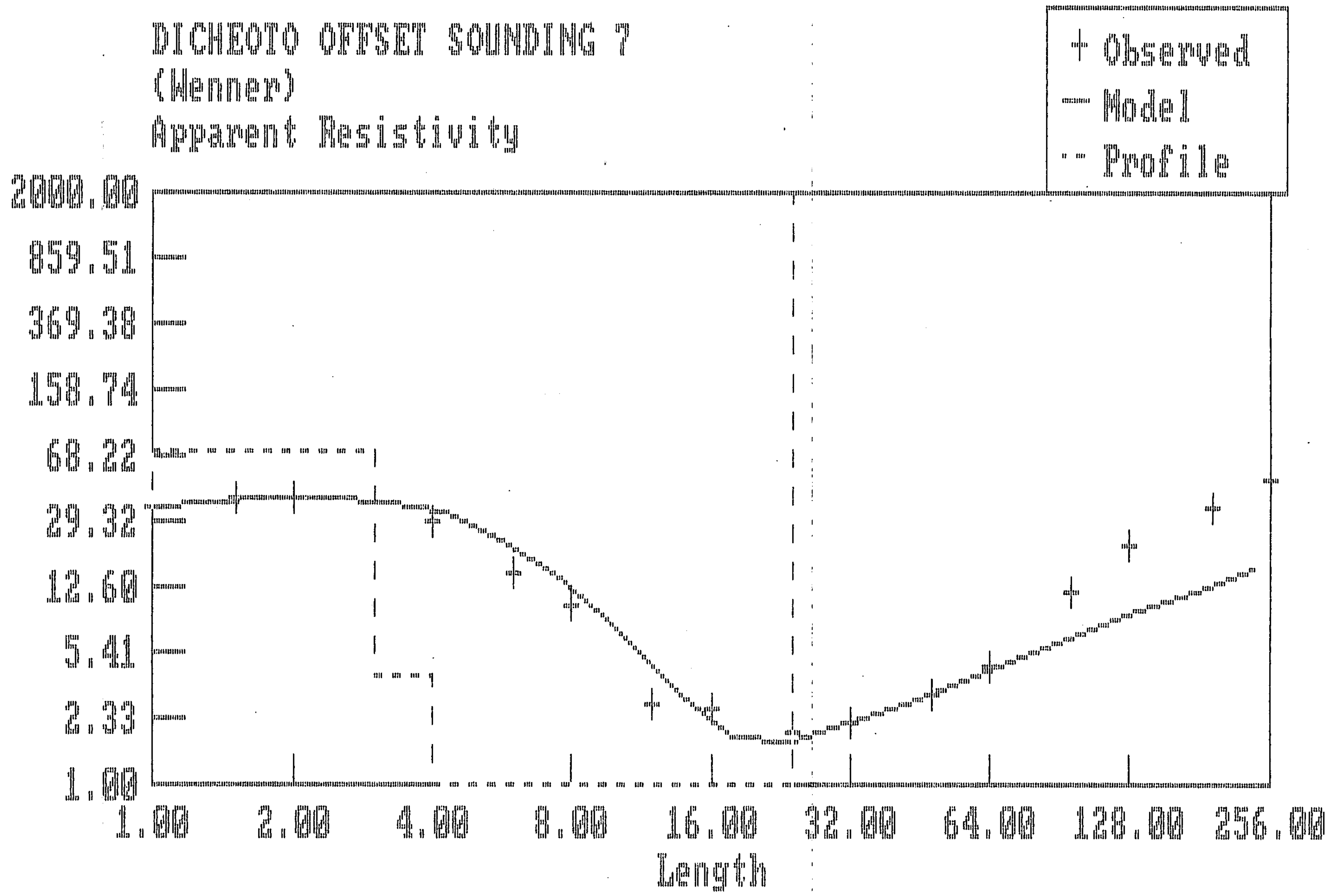
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 6

SPACING	RESISTIVITY
1.000	158.020
1.500	83.710
2.000	40.650
3.000	9.740
4.000	5.910
6.000	1.410
8.000	4.270
12.000	2.330
16.000	1.810
24.000	1.190
32.000	1.860
48.000	2.870
64.000	4.000
96.000	8.990
128.000	16.240
192.000	31.060
256.000	50.070

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	300.00
2	1.00	70.00
3	8.00	4.00
4	30.00	1.00
Subst.	infinite	1000.00


DICHEOTO OFFSET SOUNDING 7
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
2000.00
859.51
369.38
158.74
68.22
29.32
12.60
5.41
2.33
1.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

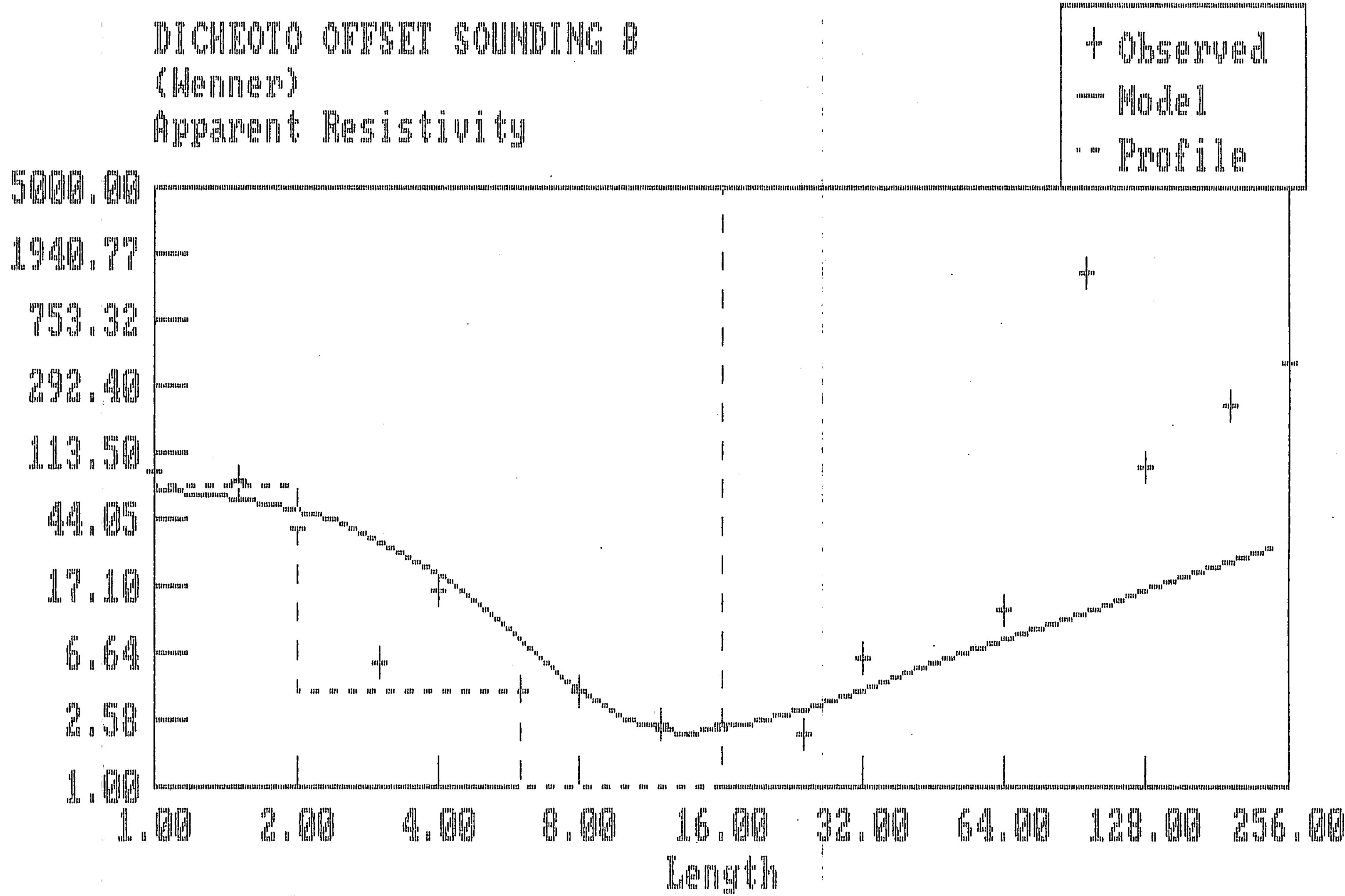
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 7

SPACING	RESISTIVITY
1.000	35.560
1.500	39.510
2.000	38.200
3.000	37.660
4.000	29.180
6.000	15.430
8.000	10.010
12.000	2.730
16.000	2.570
24.000	1.950
32.000	2.210
48.000	3.240
64.000	4.570
96.000	11.830
128.000	22.170
192.000	35.740
256.000	49.910

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	30.00
2	2.00	70.00
3	1.00	4.00
4	20.00	1.00
Subst.	infinite	2000.00


DICHEOTO OFFSET SOUNDING 8
(Wenner)
Apparent Resistivity
Observed
Model
Profile
5000.00
1940.77
753.32
292.40
113.50
44.05
17.10
6.64
2.58
1.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

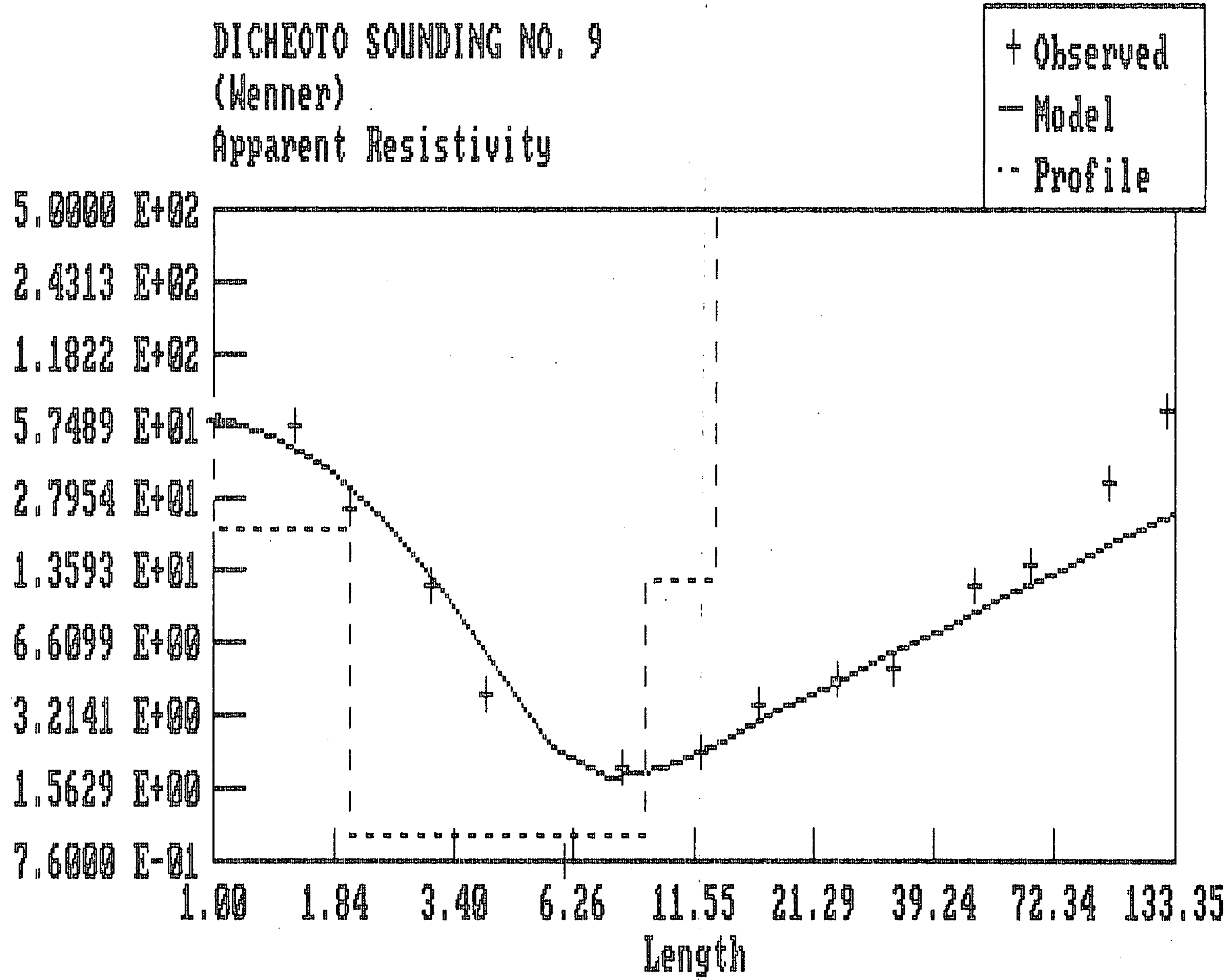
MEASURED VALUES

DICHEOTO OFFSET SOUNDING 8

SPACING	RESISTIVITY
1.000	85.770
1.500	72.420
2.000	37.450
3.000	5.670
4.000	15.960
6.000	3.800
8.000	3.850
12.000	2.390
16.000	2.440
24.000	2.090
32.000	6.210
64.000	12.320
96.000	1446.430
128.000	94.470
192.000	213.790
256.000	407.150

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	70.00
2	1.50	70.00
3	4.00	4.00
4	10.00	1.00
Subst.	infinite	5000.00


DICHEOTO SOUNDING NO. 9
(Wenner)
Apparent Resistivity
Observed
Model
Profile
5.0000 E+02
2.4313 E+02
1.1822 E+02
5.7489 E+01
2.7954 E+01
1.3593 E+01
6.6099 E+00
3.2141 E+00
1.5629 E+00
7.6000 E-01
1.00
1.84
3.40
6.26
11.55
21.29
39.24
72.34
133.35
Length

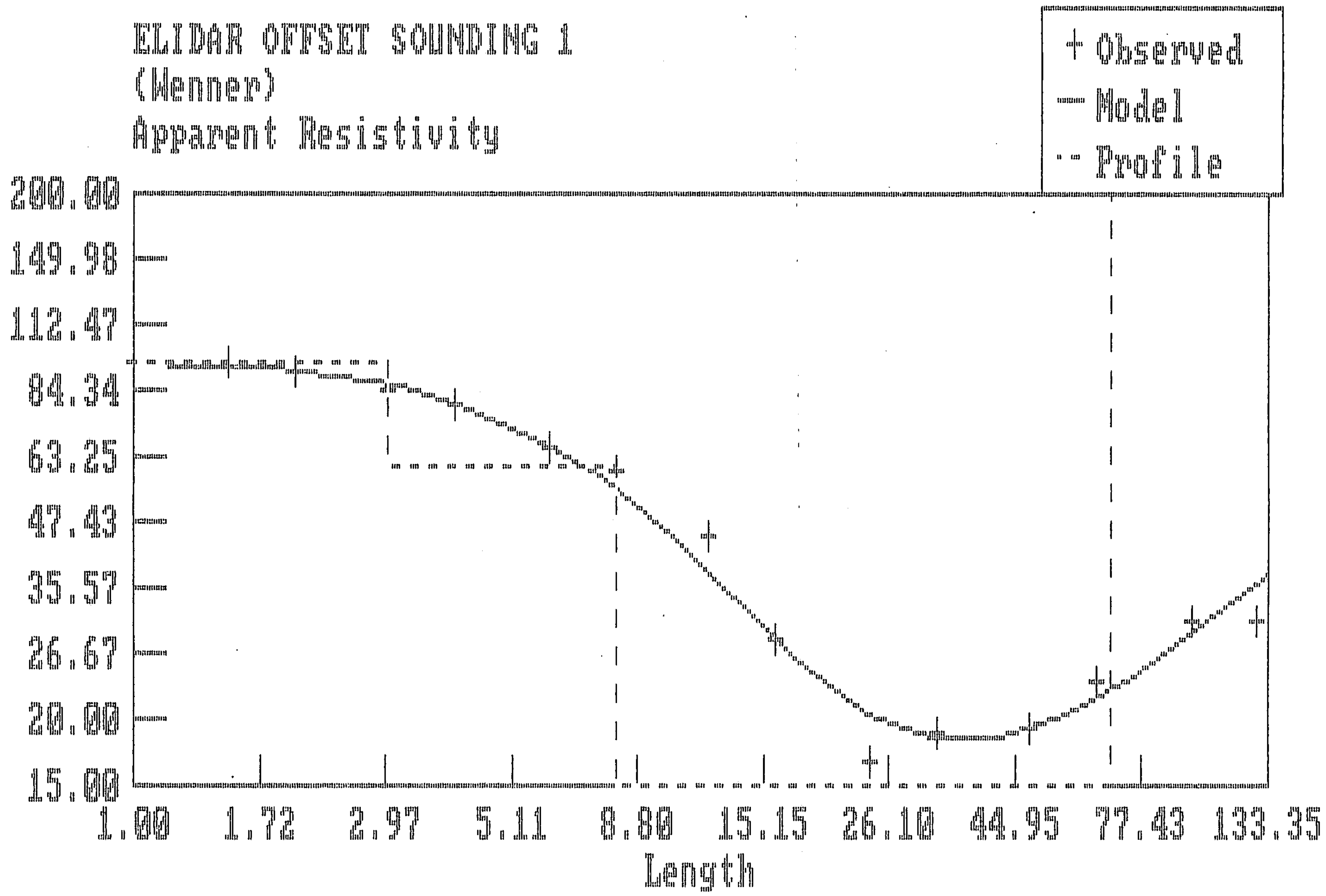
MEASURED VALUES

DICHEOTO SOUNDING NO. 9

SPACING	RESISTIVITY
1.000	58.310
1.500	55.440
2.000	24.640
3.000	11.760
4.000	3.930
6.000	.760
8.000	1.950
12.000	2.240
16.000	3.490
24.000	4.510
32.000	5.100
48.000	11.400
64.000	14.170
96.000	32.310
128.000	65.710

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	83.00
2	1.00	20.00
3	7.00	1.00
4	4.00	12.00
Subst.	infinite	500.00



ELIDAR OFFSET SOUNDING 1
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
200.00
149.98
112.47
84.34
63.25
47.43
35.57
26.67
20.00
15.00
1.00
1.72
2.97
5.11
8.80
15.15
26.10
44.95
77.43
133.35
Length

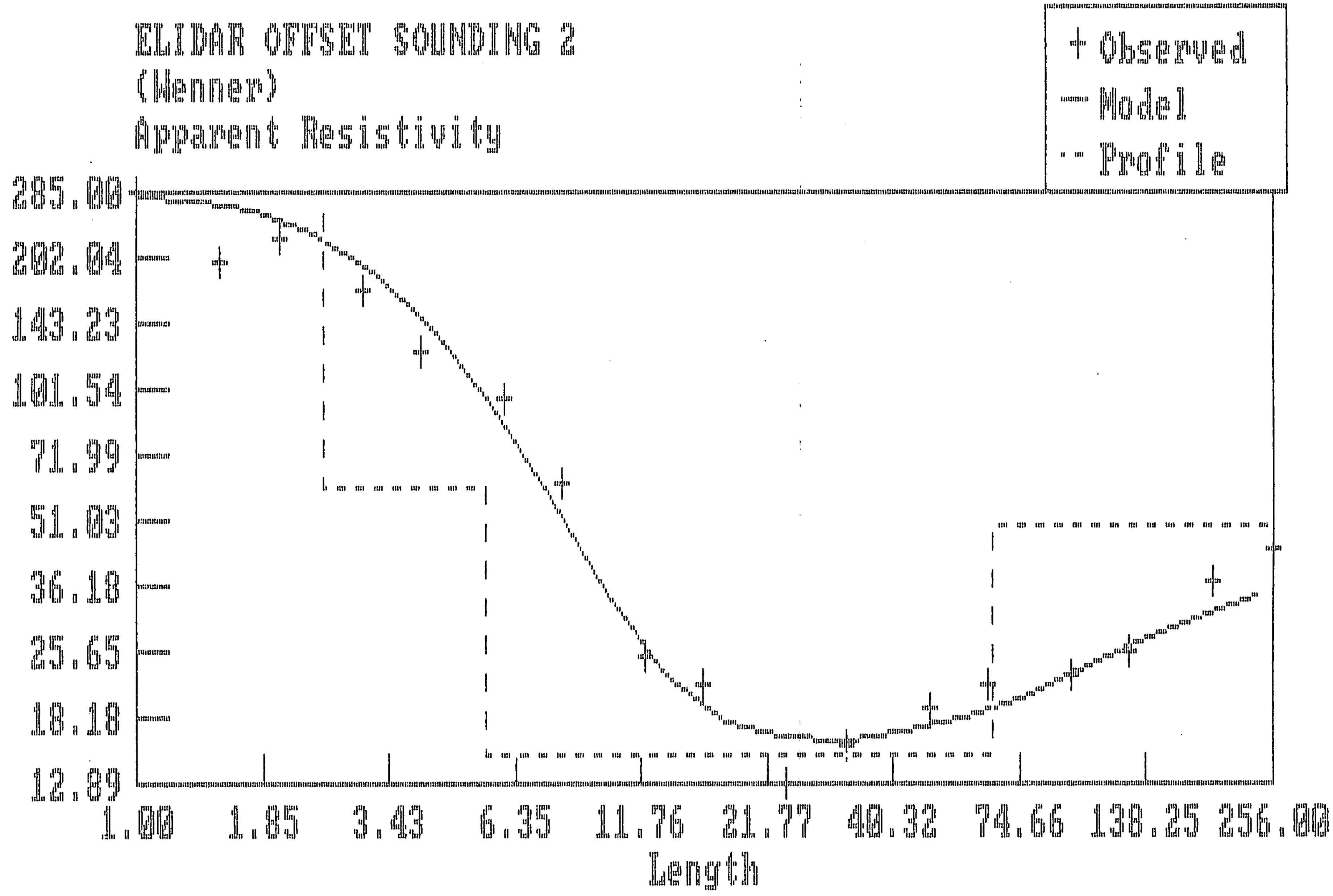
MEASURED VALUES

ELIDAR OFFSET SOUNDING 1

SPACING	RESISTIVITY
1.000	95.410
1.500	94.810
2.000	90.350
3.000	83.820
4.000	79.670
6.000	65.930
8.000	59.310
12.000	44.590
16.000	28.600
24.000	16.590
32.000	18.670
48.000	19.420
64.000	23.600
96.000	31.080
128.000	30.960

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	3.00	95.00
2	5.00	60.00
3	60.00	15.00
Subst.	infinite	200.00


ELIDAR OFFSET SOUNDING 2
(Wenner)
Apparent Resistivity
+ Observed
— Model
- - Profile
285.00
202.04
143.23
101.54
71.99
51.03
36.18
25.65
18.18
12.89
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

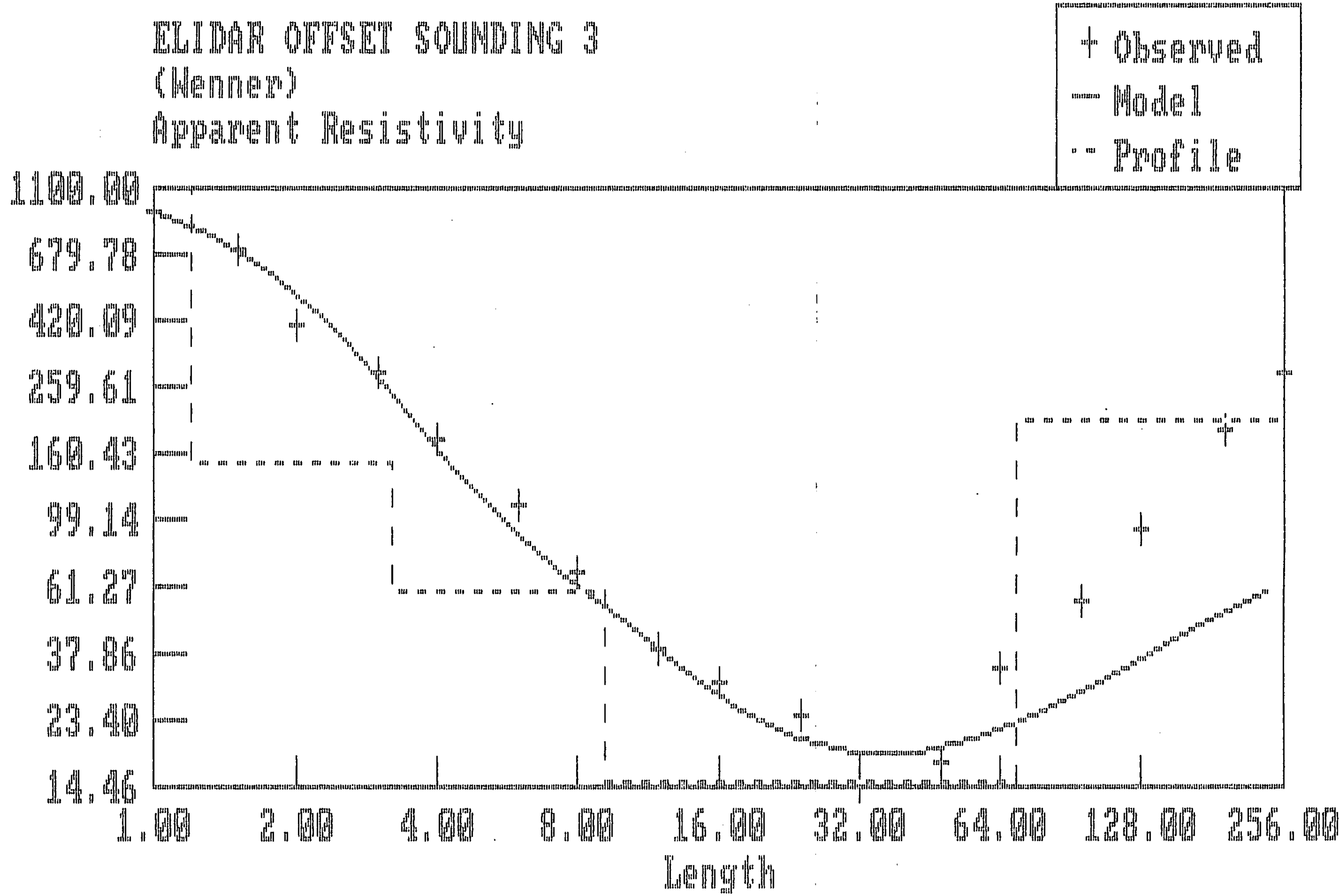
MEASURED VALUES

ELIDAR OFFSET SOUNDING 2

SPACING	RESISTIVITY
1.000	284.940
1.500	197.360
2.000	221.230
3.000	167.930
4.000	123.020
6.000	96.280
8.000	62.300
12.000	25.200
16.000	21.560
24.000	12.890
32.000	15.800
48.000	19.360
64.000	21.650
96.000	22.970
128.000	25.410
192.000	36.890
256.000	44.120

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	2.50	285.00
2	3.00	60.00
3	60.00	15.00
Subst.	infinite	50.00


ELIDAR OFFSET SOUNDING 3
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
1100.00
679.78
420.09
259.61
160.43
99.14
61.27
37.86
23.40
14.46
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

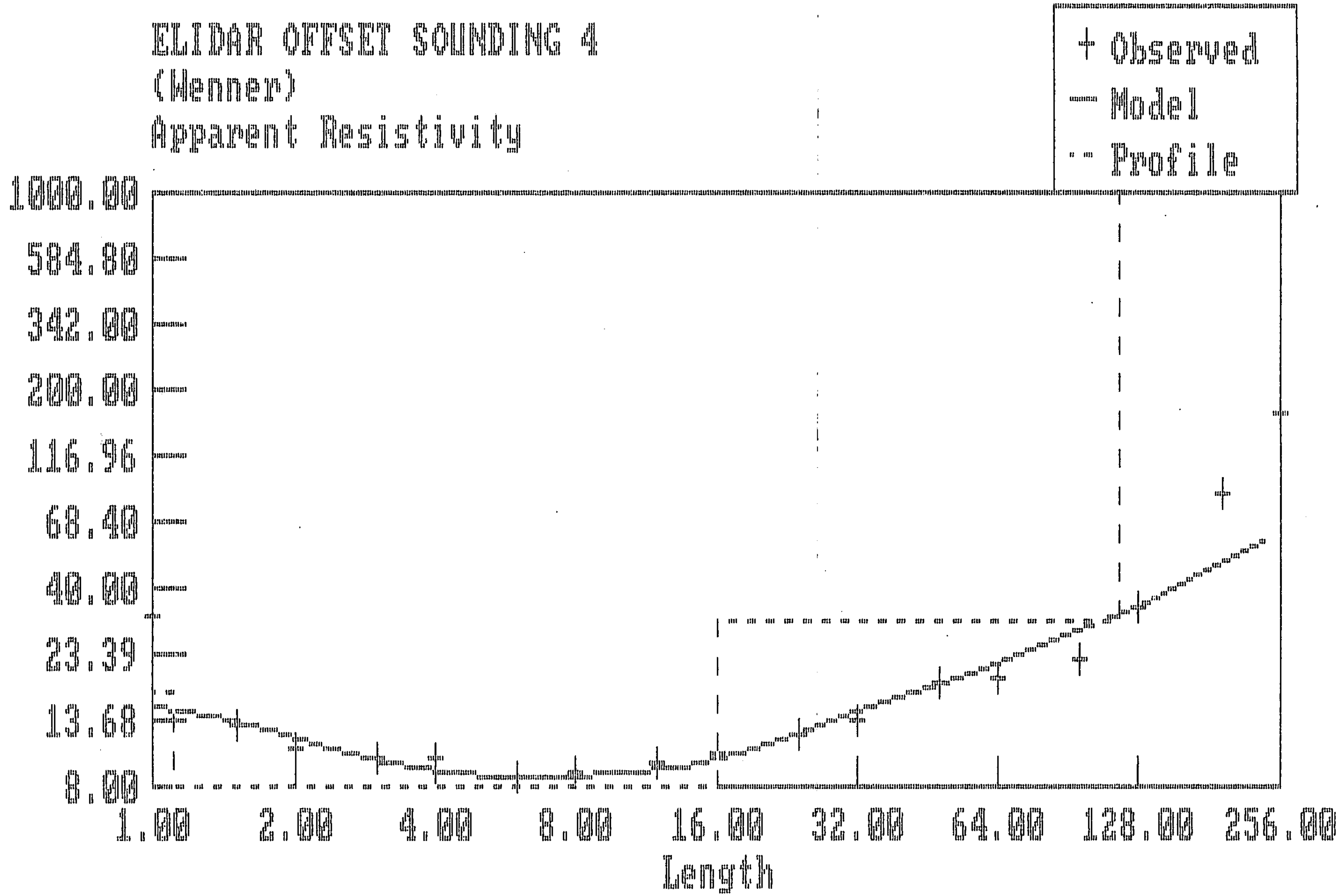
MEASURED VALUES

ELIDAR OFFSET SOUNDING 3

SPACING	RESISTIVITY
1.000	916.090
1.500	703.960
2.000	395.210
3.000	280.690
4.000	179.200
6.000	111.250
8.000	68.080
12.000	39.590
16.000	31.320
24.000	24.320
32.000	14.460
48.000	17.350
64.000	34.420
96.000	55.090
128.000	92.650
192.000	186.770
256.000	280.980

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.20	1100.00
2	2.00	150.00
3	6.00	60.00
4	60.00	15.00
Subst.	infinite	200.00



ELIDAR OFFSET SOUNDING 4
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
1000.00
584.80
342.00
200.00
116.96
68.40
40.00
23.39
13.68
8.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

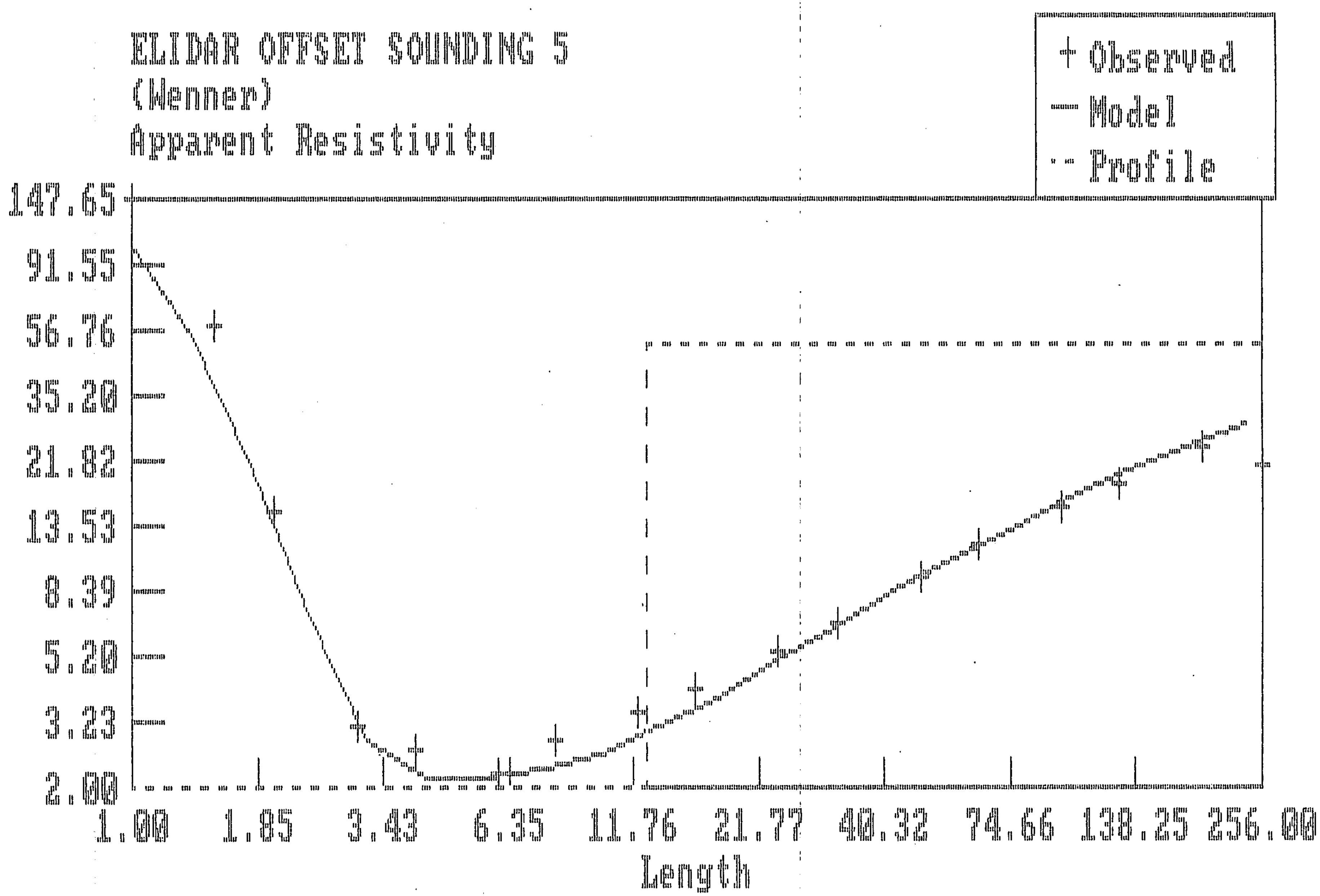
MEASURED VALUES

ELIDAR OFFSET SOUNDING 4

SPACING	RESISTIVITY
1.000	31.950
1.500	13.340
2.000	10.970
3.000	10.020
4.000	10.300
6.000	8.620
8.000	9.180
12.000	9.890
16.000	10.690
24.000	12.190
32.000	13.820
48.000	18.590
64.000	19.620
96.000	22.900
128.000	34.660
192.000	86.870
256.000	166.710

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.10	17.00
2	15.00	8.00
3	100.00	30.00
Subst.	infinite	1000.00


ELIDAR OFFSET SOUNDING 5
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
147.65
91.55
56.76
35.20
21.82
13.53
8.39
5.20
3.23
2.00
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

MEASURED VALUES

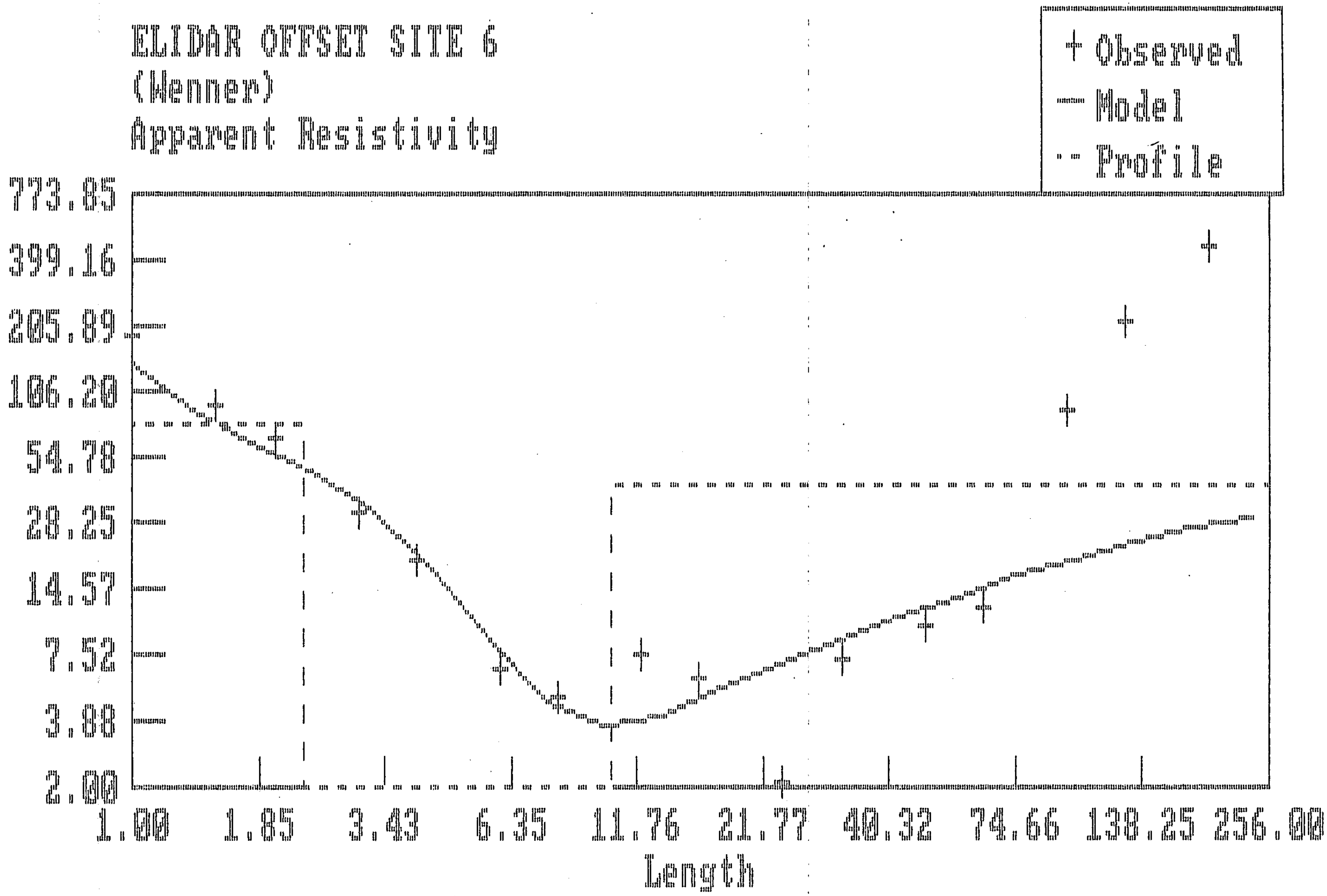
ELIDAR OFFSET SOUNDING 5

SPACING	RESISTIVITY
1.000	147.650
1.500	58.750
2.000	14.810
3.000	3.150
4.000	2.600
6.000	2.240
8.000	2.780
12.000	3.430
16.000	4.140
24.000	5.360
32.000	6.600
48.000	9.290
64.000	11.880
96.000	15.370
128.000	18.480
192.000	23.830
256.000	21.280

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.60	300.00
2	12.00	2.00
Subst.	infinite	50.00

ELIDAR OFFSET SITE 6
(Wenner)
Apparent Resistivity



MEASURED VALUES

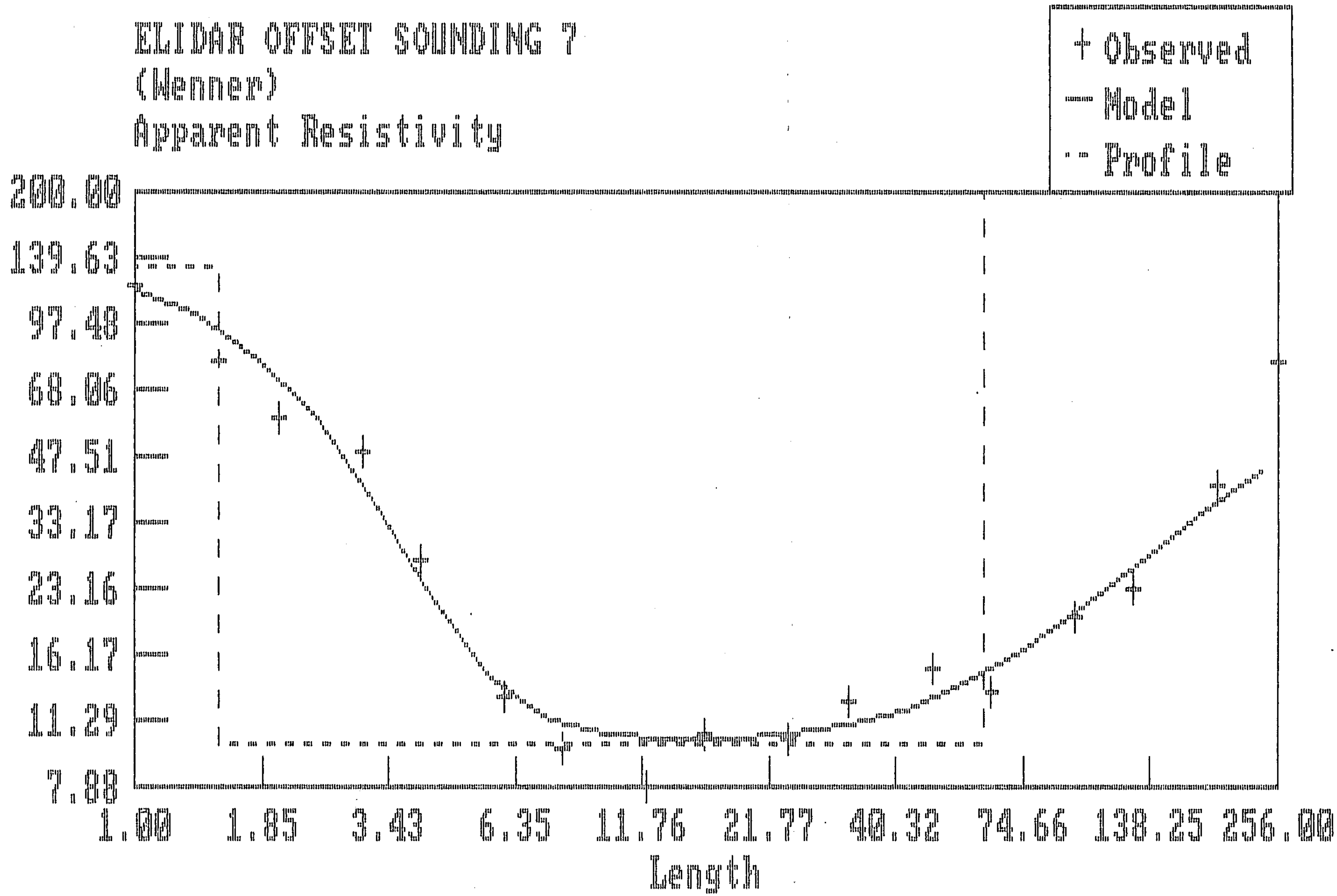
ELIDAR OFFSET SITE 6

SPACING	RESISTIVITY
1.000	184.100
1.500	91.560
2.000	64.590
3.000	30.600
4.000	19.550
6.000	6.580
8.000	5.010
12.000	7.410
16.000	5.830
24.000	2.160
32.000	7.220
48.000	9.870
64.000	11.880
96.000	86.680
128.000	211.030
192.000	446.030
256.000	773.850

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.30	1500.00
2	2.00	75.00
3	8.00	2.00
Subst.	infinite	40.00

ELIDAR OFFSET SOUNDING 7
(Wenner)
Apparent Resistivity



MEASURED VALUES

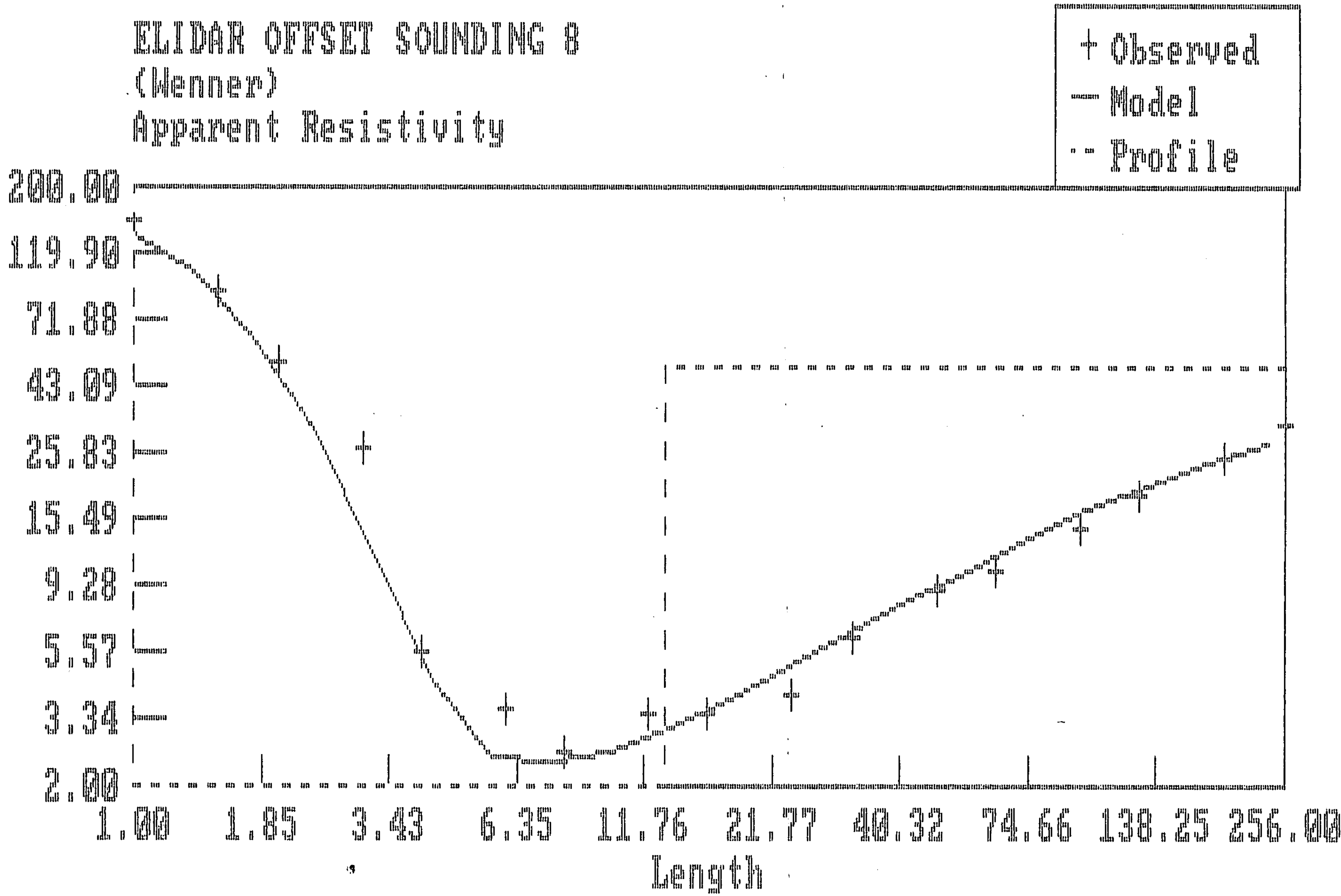
ELIDAR OFFSET SOUNDING 7

SPACING	RESISTIVITY
1.000	119.660
1.500	78.990
2.000	58.500
3.000	47.950
4.000	26.640
6.000	12.860
8.000	9.660
12.000	7.880
16.000	10.520
24.000	10.230
32.000	12.680
48.000	14.910
64.000	13.170
96.000	20.030
128.000	23.080
192.000	40.850
256.000	79.750

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.50	130.00
2	60.00	10.00
Subst.	infinite	200.00

ELIDAR OFFSET SOUNDING 8
(Wenner)
Apparent Resistivity



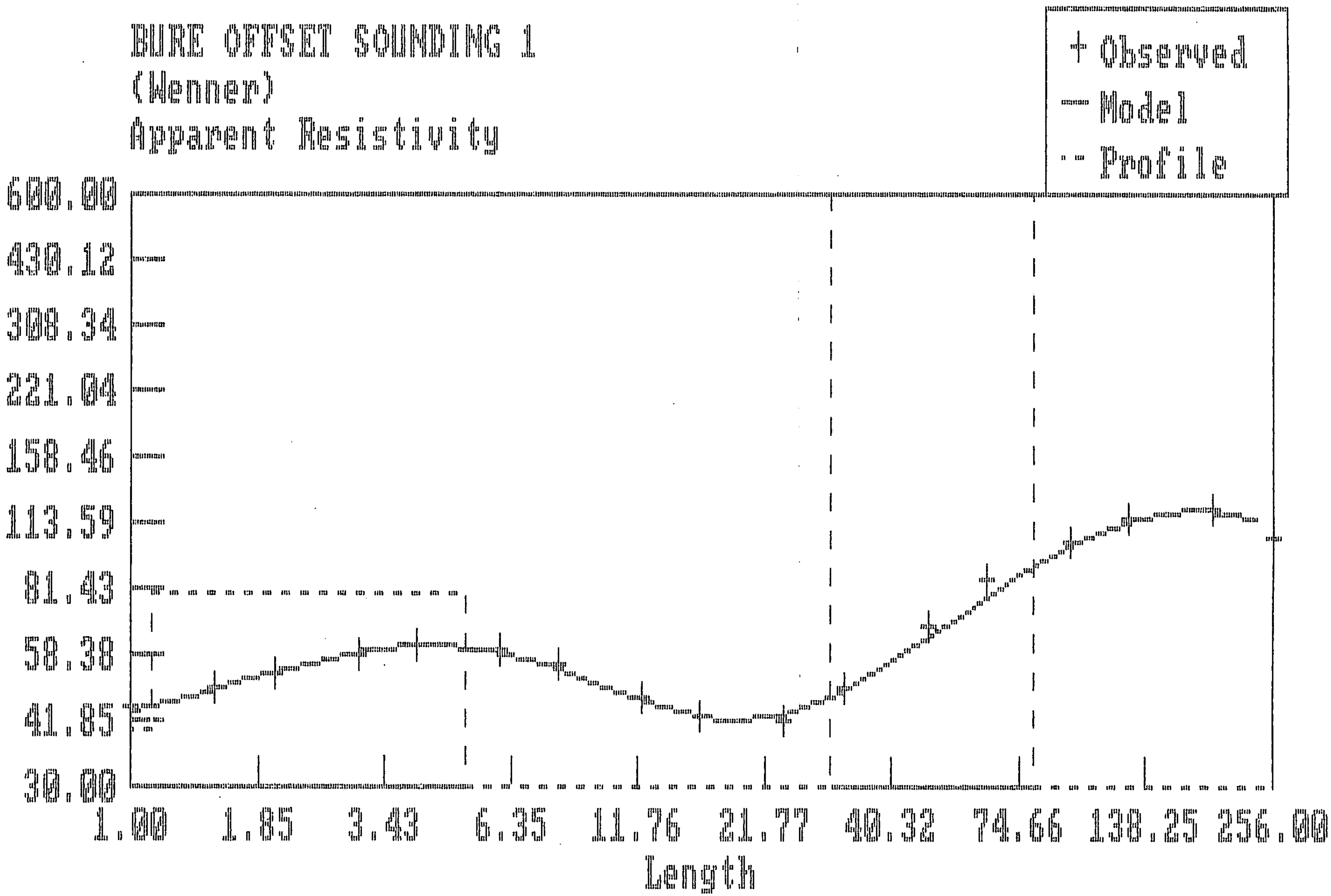
MEASURED VALUES

ELIDAR OFFSET SOUNDING 8

SPACING	RESISTIVITY
1.000	154.880
1.500	86.910
2.000	50.450
3.000	26.310
4.000	5.580
6.000	3.580
8.000	2.620
12.000	3.410
16.000	3.450
24.000	4.010
32.000	6.270
48.000	8.940
64.000	10.390
96.000	14.590
128.000	18.380
192.000	24.700
256.000	31.920

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	200.00
2	12.00	2.00
Subst.	infinite	50.00


BURE OFFSET SOUNDING 1
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
600.00
430.12
308.34
221.04
158.46
113.59
81.43
58.38
41.85
30.00
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

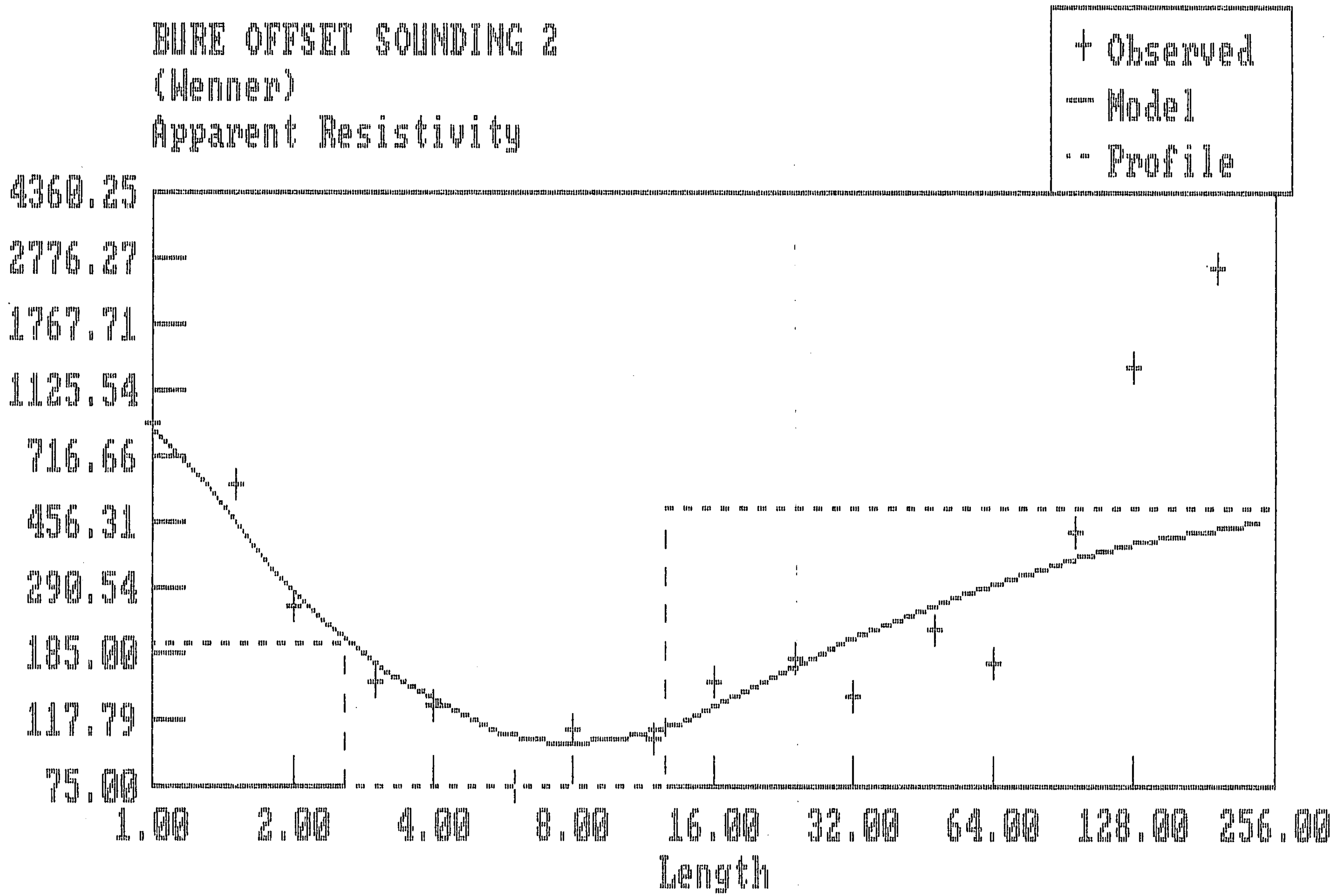
MEASURED VALUES

BURE OFFSET SOUNDING 1

SPACING	RESISTIVITY
1.000	45.490
1.500	49.520
2.000	52.590
3.000	58.770
4.000	61.700
6.000	60.220
8.000	55.820
12.000	47.640
16.000	43.080
24.000	42.360
32.000	49.660
48.000	67.470
64.000	85.150
96.000	103.690
128.000	114.930
192.000	121.410
256.000	104.790

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.10	40.00
2	4.00	80.00
3	25.00	30.00
4	50.00	600.00
Subst.	infinite	30.00



BURE OFFSET SOUNDING 2
(Wenner)
Apparent Resistivity
Observed
Model
Profile
4360.25
2776.27
1767.71
1125.54
716.66
456.31
290.54
185.00
117.79
75.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

MEASURED VALUES

BURE OFFSET SOUNDING 2

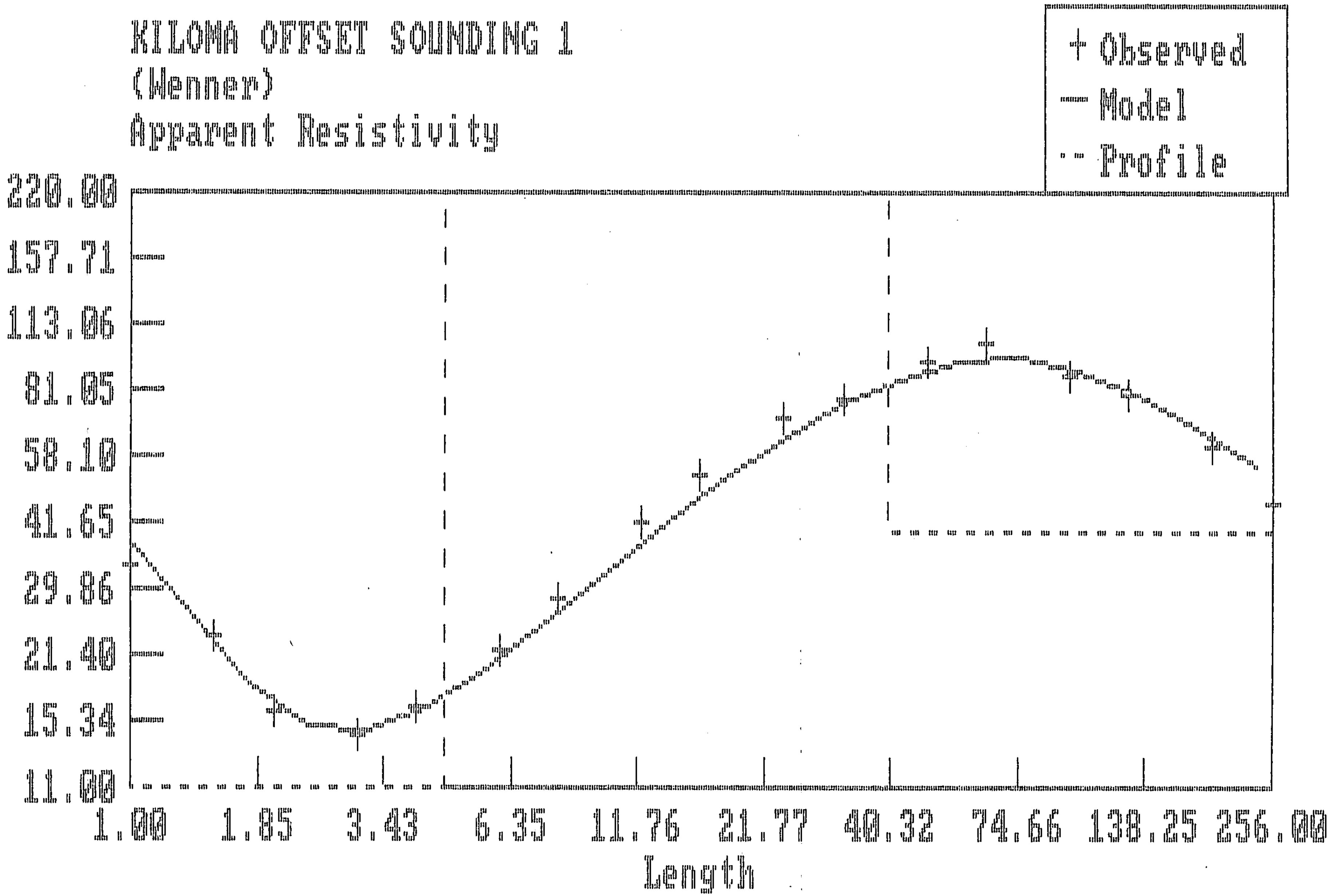
SPACING	RESISTIVITY
1.000	897.240
1.500	591.850
2.000	251.580
3.000	153.790
4.000	131.820
6.000	75.160
8.000	110.840
12.000	102.950
16.000	151.500
24.000	181.210
32.000	137.120
48.000	215.690
64.000	172.910
96.000	419.560
128.000	1293.230
192.000	2562.570
256.000	4360.250

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.60	2000.00
2	2.00	200.00
3	10.00	75.00
Subst.	infinite	500.00

/

KILOMA OFFSET SOUNDING 1
(Wenner)
Apparent Resistivity



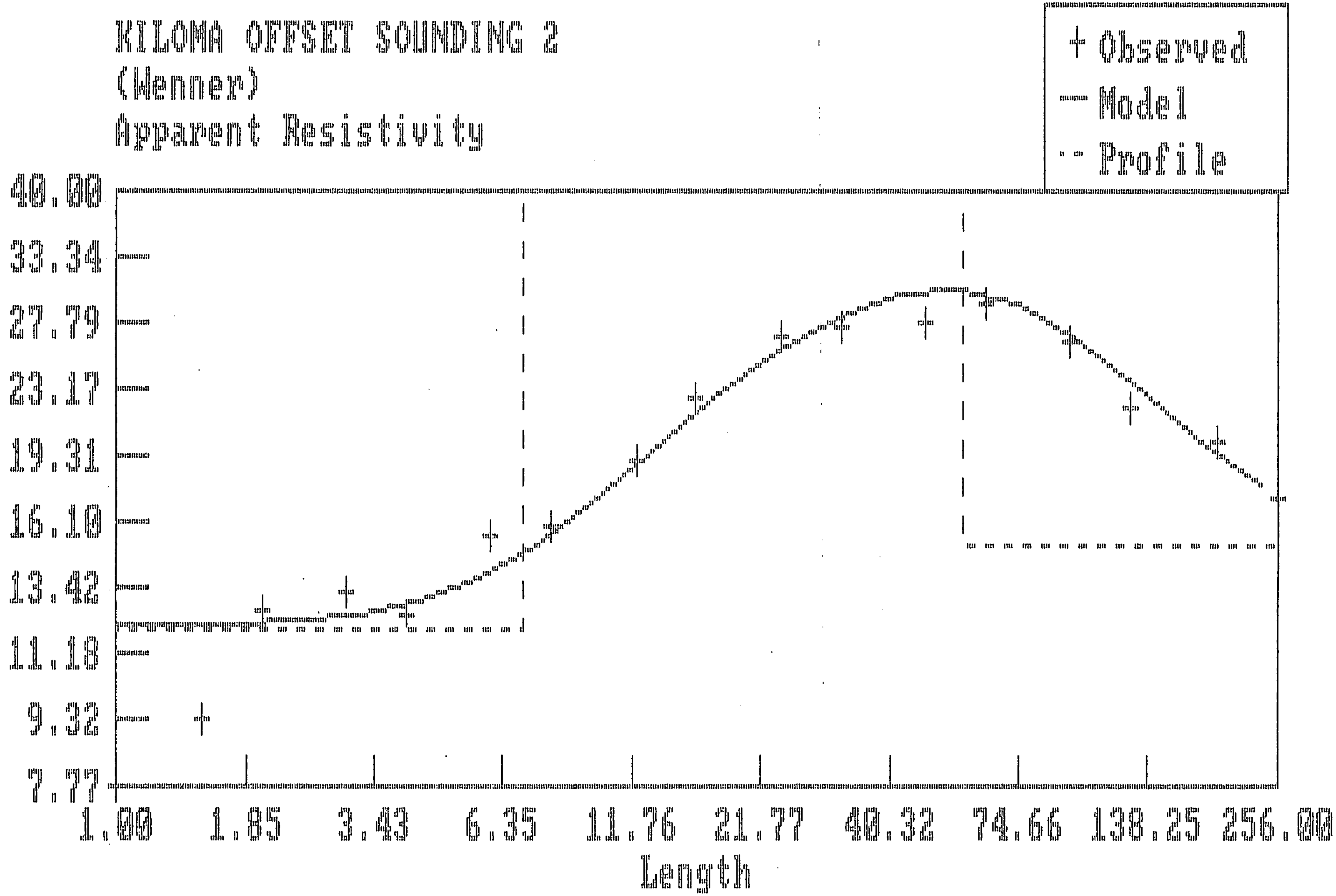
MEASURED VALUES

KILOMA OFFSET SOUNDING 1

SPACING	RESISTIVITY
1.000	33.800
1.500	23.360
2.000	15.960
3.000	14.350
4.000	16.660
6.000	21.880
8.000	28.150
12.000	41.250
16.000	53.080
24.000	70.390
32.000	77.510
48.000	93.450
64.000	101.740
96.000	86.760
128.000	77.810
192.000	60.280
256.000	45.860

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.60	80.00
2	4.00	11.00
3	35.00	220.00
Subst.	infinite	40.00


KILOMA OFFSET SOUNDING 2
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
40.00
33.34
27.79
23.17
19.31
16.10
13.42
11.18
9.32
7.77
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

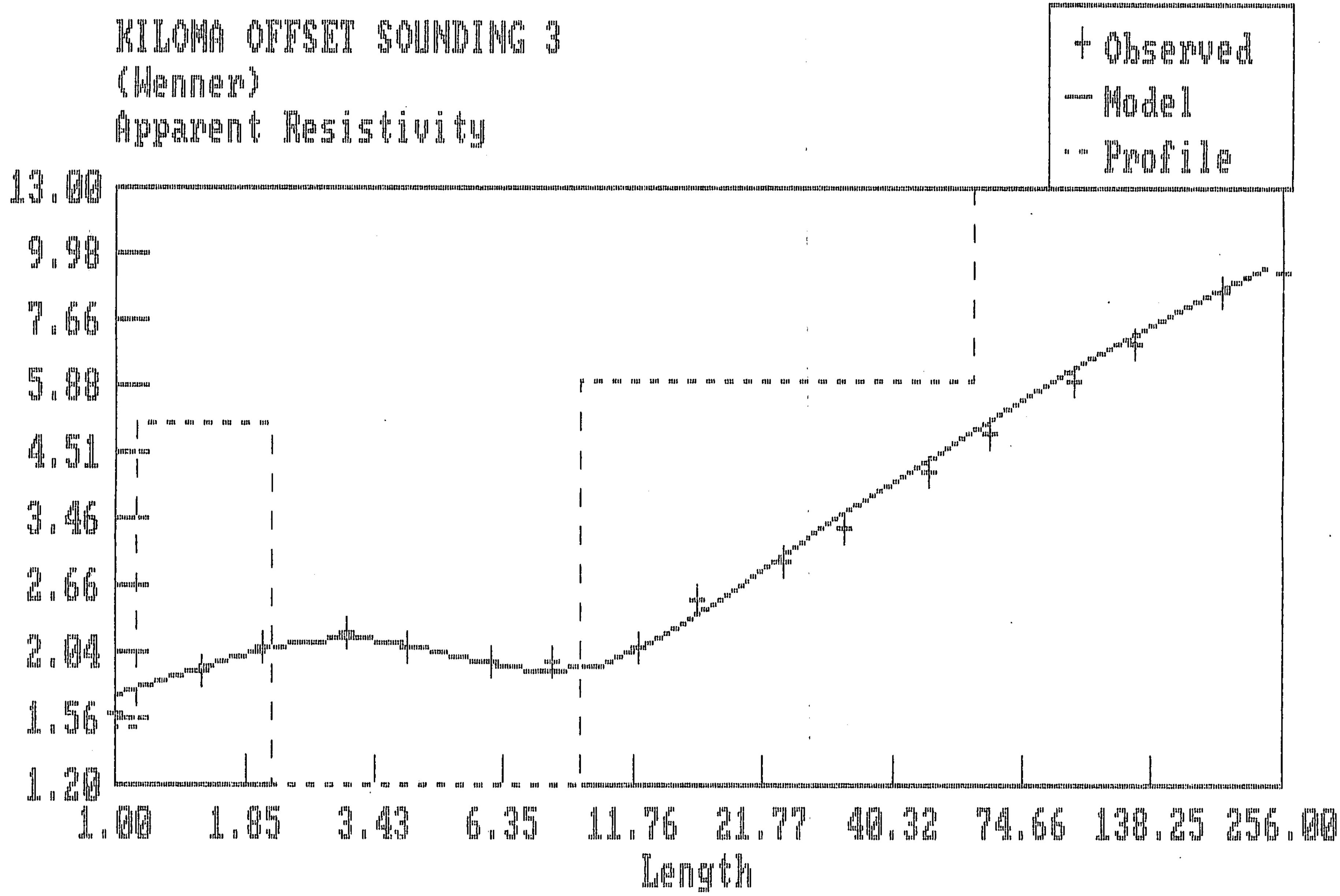
MEASURED VALUES

KILOMA OFFSET SOUNDING 2

SPACING	RESISTIVITY
1.000	7.770
1.500	9.340
2.000	12.540
3.000	13.310
4.000	12.370
6.000	15.390
8.000	15.880
12.000	19.010
16.000	22.590
24.000	26.550
32.000	27.390
48.000	27.670
64.000	29.050
96.000	26.220
128.000	21.880
192.000	20.120
256.000	17.090

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	7.00	12.00
2	50.00	40.00
Subst.	infinite	15.00


KILOMA OFFSET SOUNDING 3
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
13.00
9.98
7.66
5.88
4.51
3.46
2.66
2.04
1.56
1.20
1.00
1.85
3.43
6.35
11.76
21.77
40.32
74.66
138.25
256.00
Length

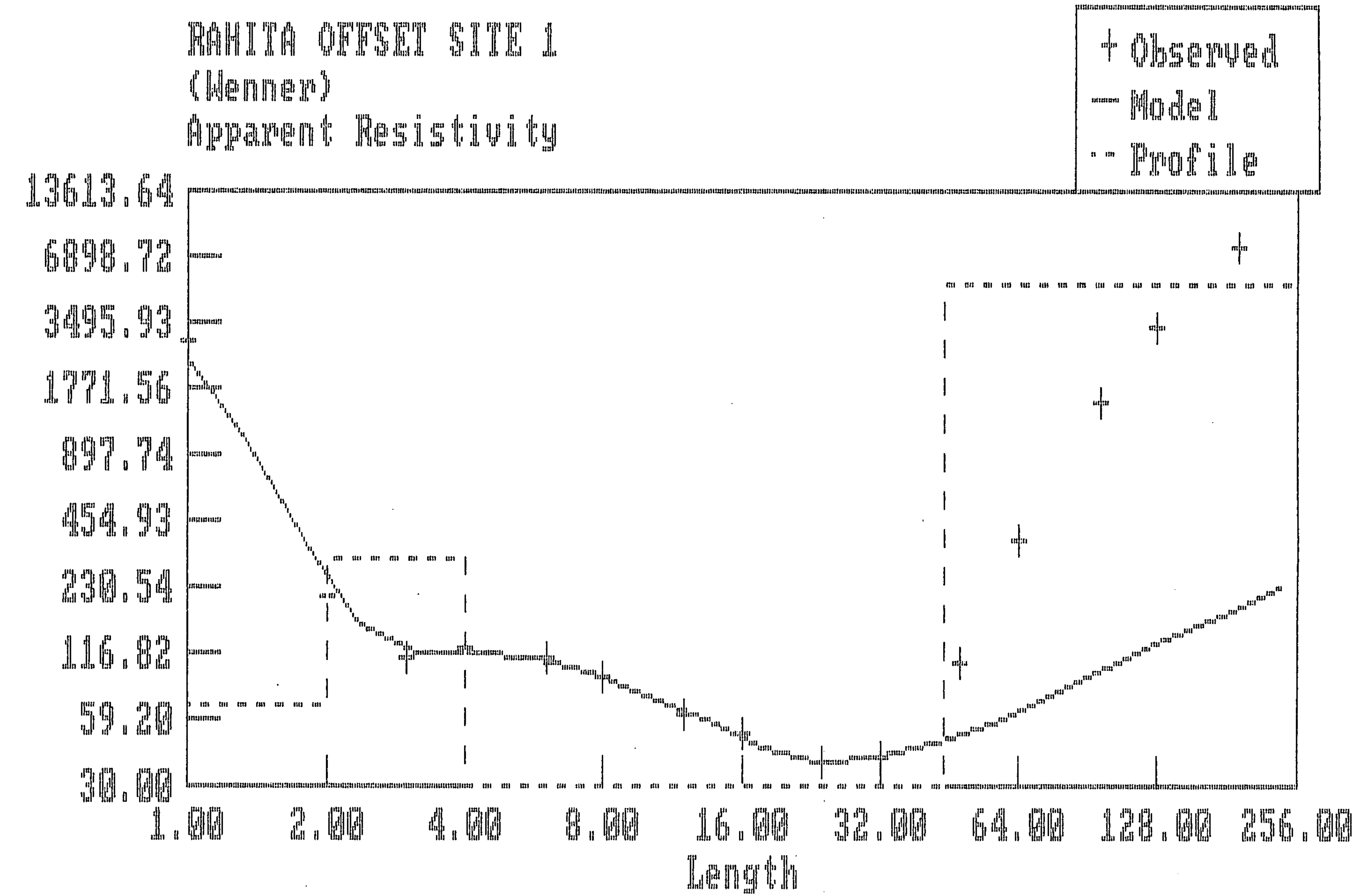
MEASURED VALUES

KILOMA OFFSET SOUNDING 3

SPACING	RESISTIVITY
1.000	1.610
1.500	1.880
2.000	2.090
3.000	2.200
4.000	2.060
6.000	1.960
8.000	1.950
12.000	2.080
16.000	2.490
24.000	2.900
32.000	3.350
48.000	4.150
64.000	4.820
96.000	5.920
128.000	6.870
192.000	8.530
256.000	9.120

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.10	1.50
2	1.00	5.00
3	7.00	1.20
4	50.00	6.00
Subst.	infinite	13.00


RAHITA OFFSET SITE 1
(Wenner)
Apparent Resistivity
Observed
Model
Profile
13613.64
6898.72
3495.93
1771.56
897.74
454.93
230.54
116.82
59.20
30.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

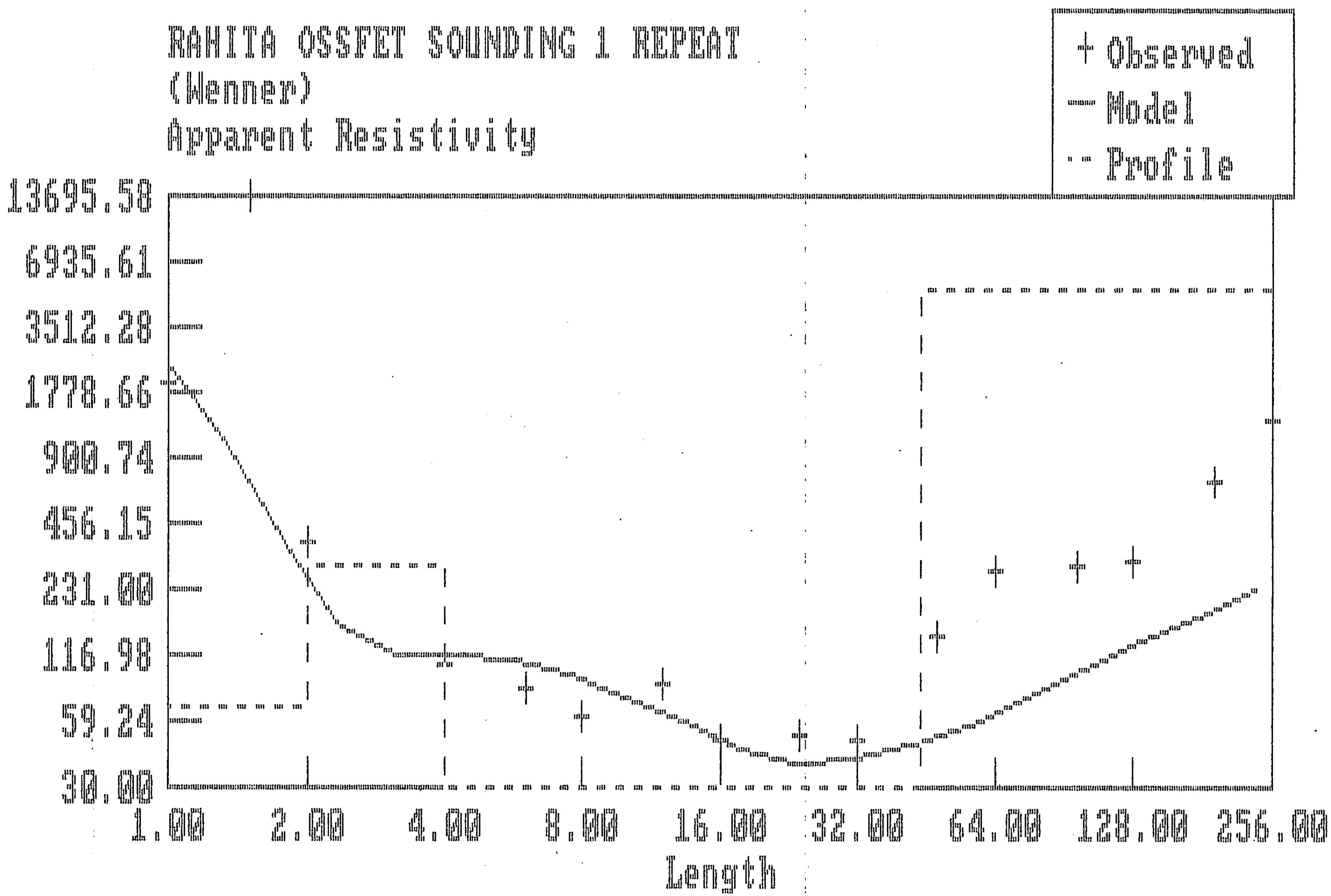
MEASURED VALUES

RAHITA OFFSET SITE 1

SPACING	RESISTIVITY
1.000	2819.580
2.000	211.120
3.000	113.720
4.000	120.640
6.000	111.930
8.000	90.910
12.000	62.220
16.000	50.570
24.000	37.890
32.000	40.200
48.000	106.880
64.000	367.940
96.000	1482.960
128.000	3221.010
192.000	7611.300
256.000	13613.640

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	10000.00
2	1.50	70.00
3	2.00	300.00
4	40.00	30.00
Subst.	infinite	5000.00


RAHITA OSSFET SOUNDING 1 REPEAT
(Wenner)
Apparent Resistivity
+ Observed
— Model
·· Profile
13695.58
6935.61
3512.28
1778.66
900.74
456.15
231.00
116.98
59.24
30.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

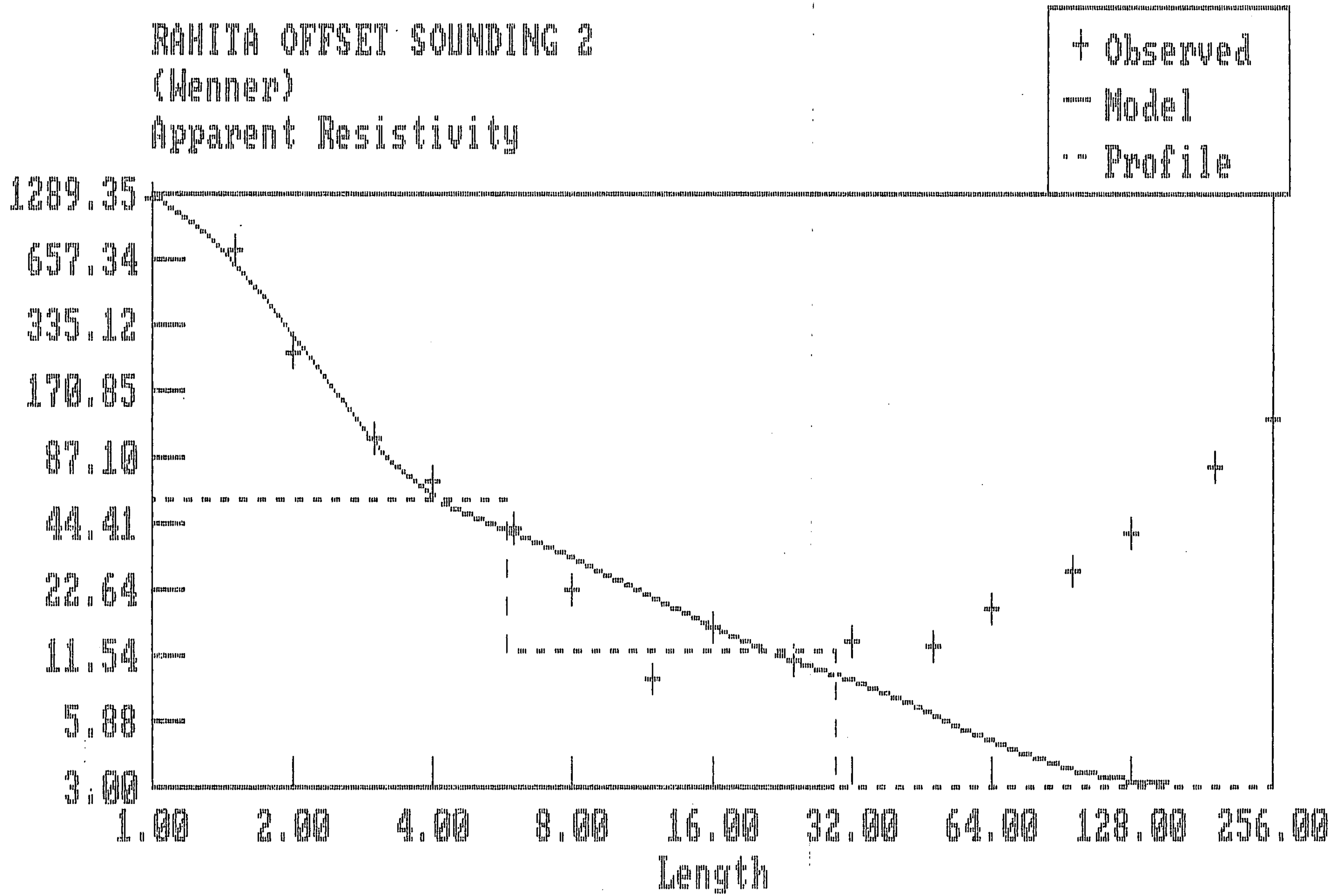
MEASURED VALUES

RAHITA OSSFET SOUNDING 1 REPEAT

SPACING	RESISTIVITY
1.000	1903.810
1.500	13695.580
2.000	365.050
4.000	107.440
6.000	82.170
8.000	63.890
12.000	88.040
16.000	49.910
24.000	52.000
32.000	48.660
48.000	144.390
64.000	280.080
96.000	294.410
128.000	302.600
192.000	713.410
256.000	1285.980

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.50	10000.00
2	1.50	70.00
3	2.00	300.00
4	40.00	30.00
Subst.	infinite	5000.00


RAHITA OFFSET SOUNDING 2
(Wenner)
Apparent Resistivity
Observed
Model
Profile
1289.35
657.34
335.12
170.85
87.10
44.41
22.64
11.54
5.88
3.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

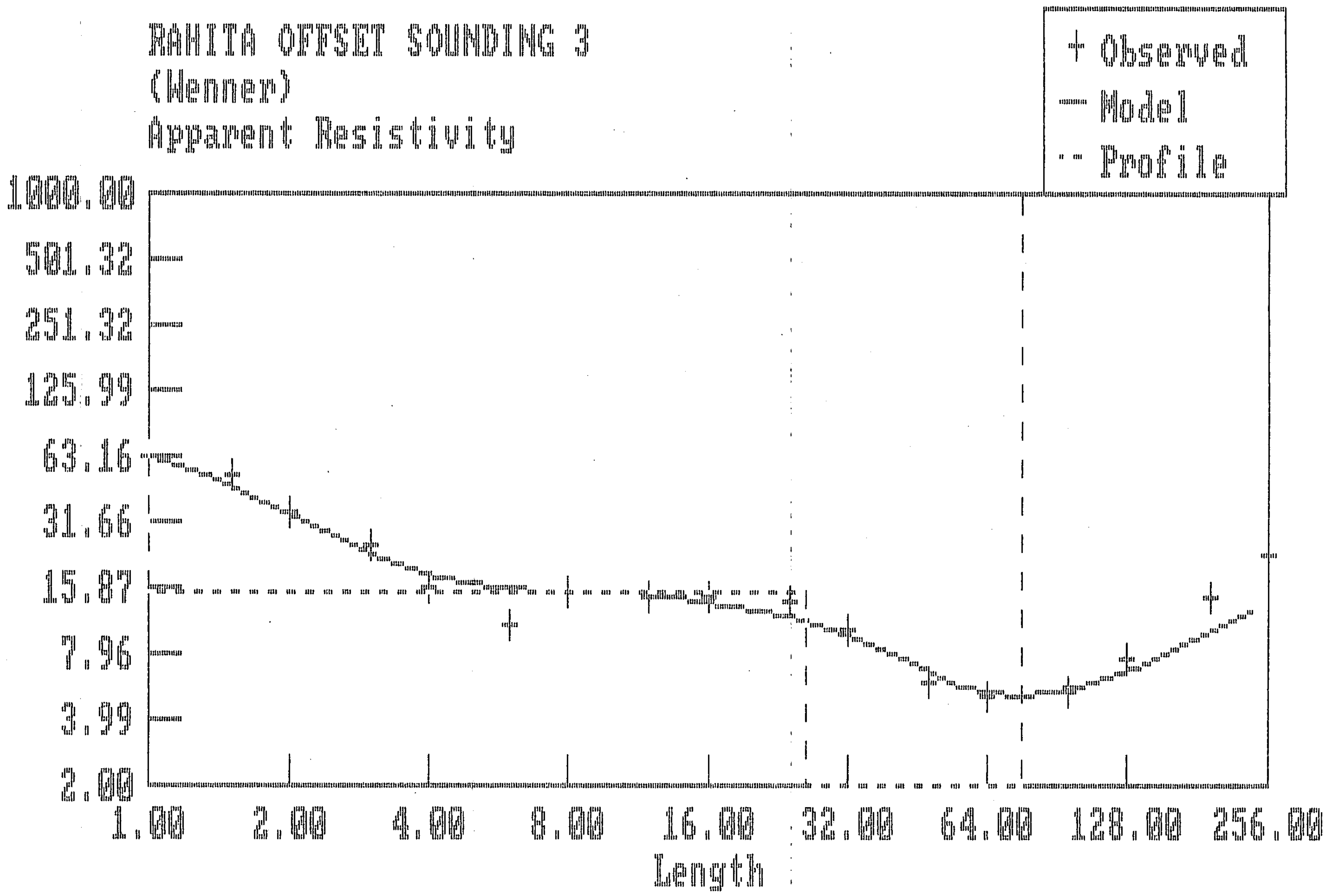
MEASURED VALUES

RAHITA OFFSET SOUNDING 2

SPACING	RESISTIVITY
1.000	1180.610
1.500	717.130
2.000	243.160
3.000	106.190
4.000	66.350
6.000	42.830
8.000	22.090
12.000	9.180
16.000	15.270
24.000	11.040
32.000	13.170
48.000	12.820
64.000	18.420
96.000	27.730
128.000	40.050
192.000	78.950
256.000	125.230

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	.75	2500.00
2	5.00	55.00
3	24.00	12.00
Subst.	infinite	3.00


RAHITA OFFSET SOUNDING 3
(Wenner)
Apparent Resistivity
+ Observed
— Model
-- Profile
1000.00
501.32
251.32
125.99
63.16
31.66
15.87
7.96
3.99
2.00
1.00
2.00
4.00
8.00
16.00
32.00
64.00
128.00
256.00
Length

MEASURED VALUES

RAHITA OFFSET SOUNDING 3

SPACING	RESISTIVITY
1.000	61.670
1.500	52.190
2.000	35.440
3.000	24.360
4.000	15.750
6.000	10.690
8.000	14.780
12.000	14.560
16.000	14.180
24.000	13.640
32.000	10.110
48.000	6.050
64.000	5.030
96.000	5.400
128.000	7.580
192.000	14.420
256.000	22.740

LAYER DESCRIPTIONS

Layer	Thickns.	Restvty.
1	1.00	80.00
2	25.00	15.00
3	50.00	2.00
Subst.	infinite	1000.00

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Report 86/15

HYDROGEOPHYSICAL STUDIES IN WOLLO PROVINCE, ETHIOPIA

I. F. Smith, C. M. Jewell, Yetnayet Negussie, Kefyalew Tilahun

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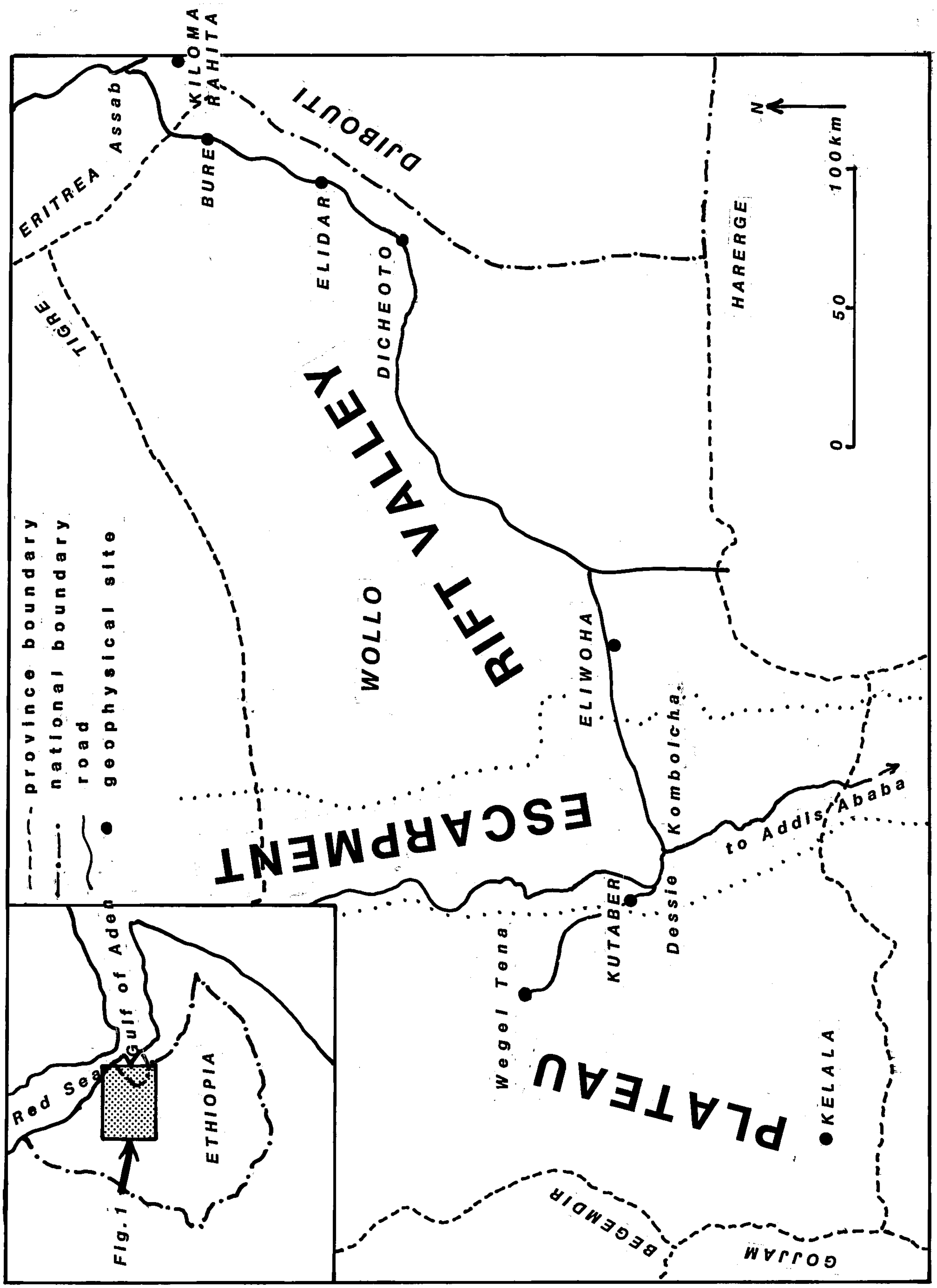

Figure 1. Map of Wollo Province, Ethiopia, showing geophysical sites visited for this study

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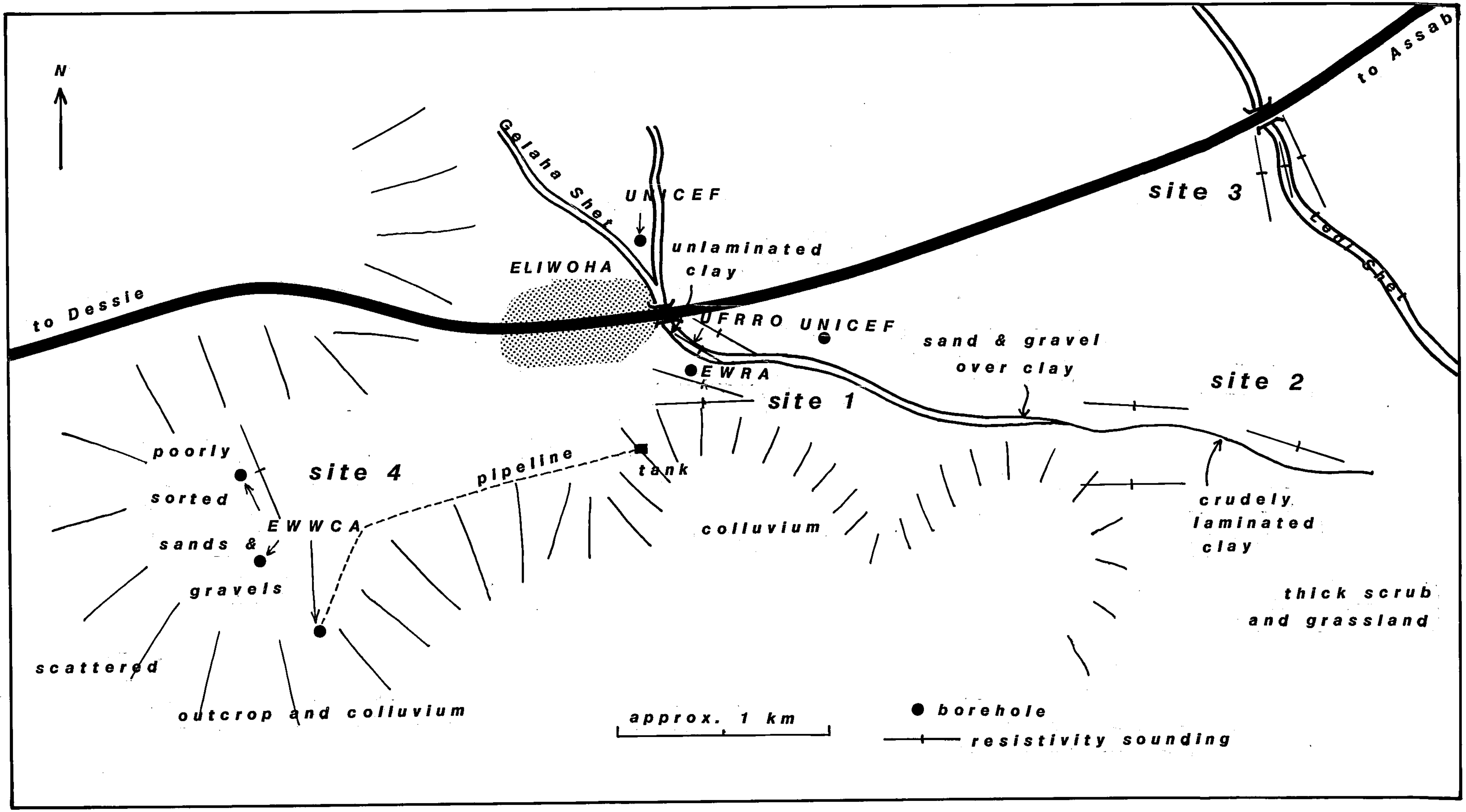

Fig.2 Position of wells, geophysical sites and geological observations at Eliwoha

WK/RG/86/15

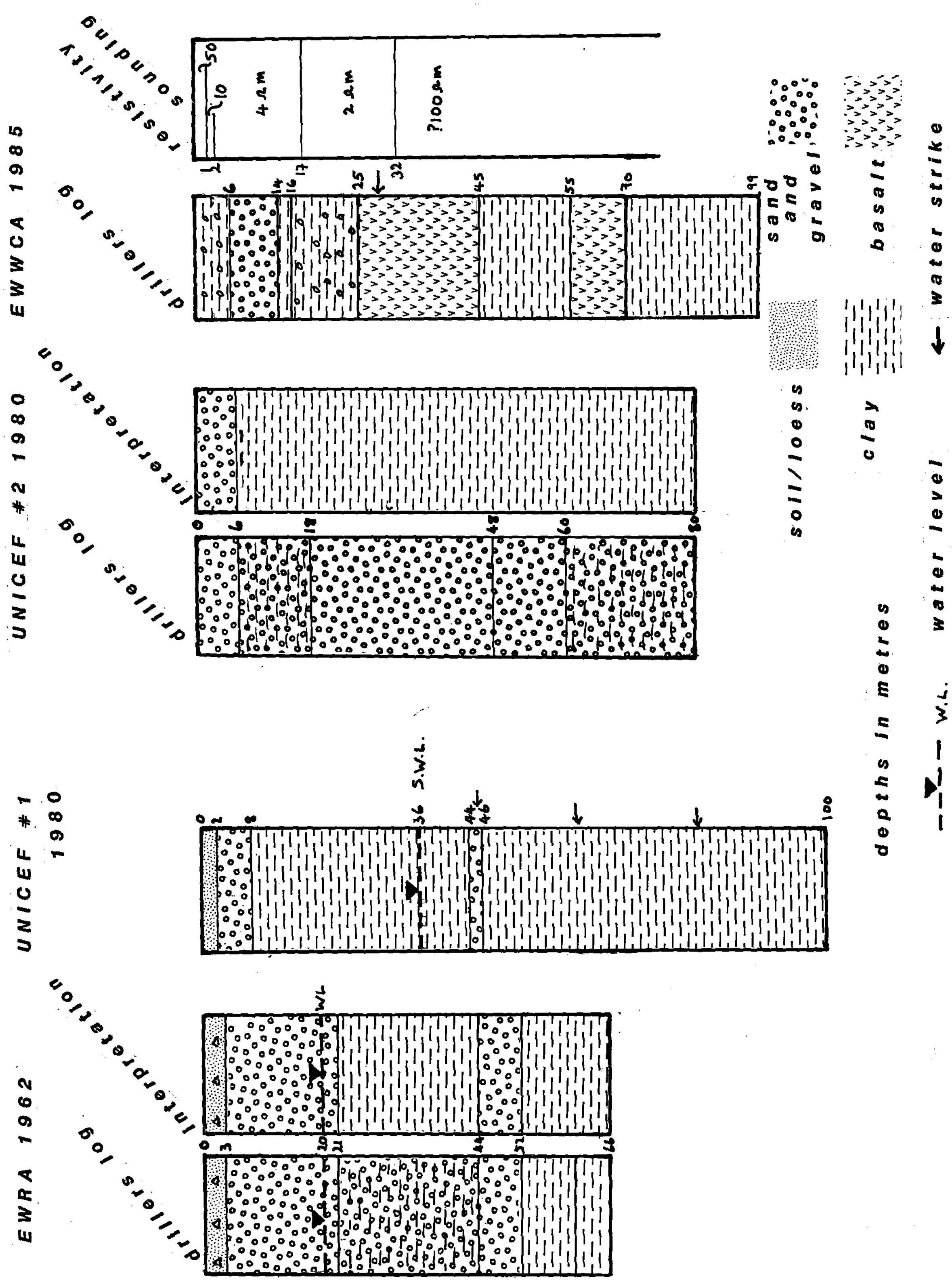

Fig.3 Simplified borehole logs from Eliwoha

WK/RG/86/15

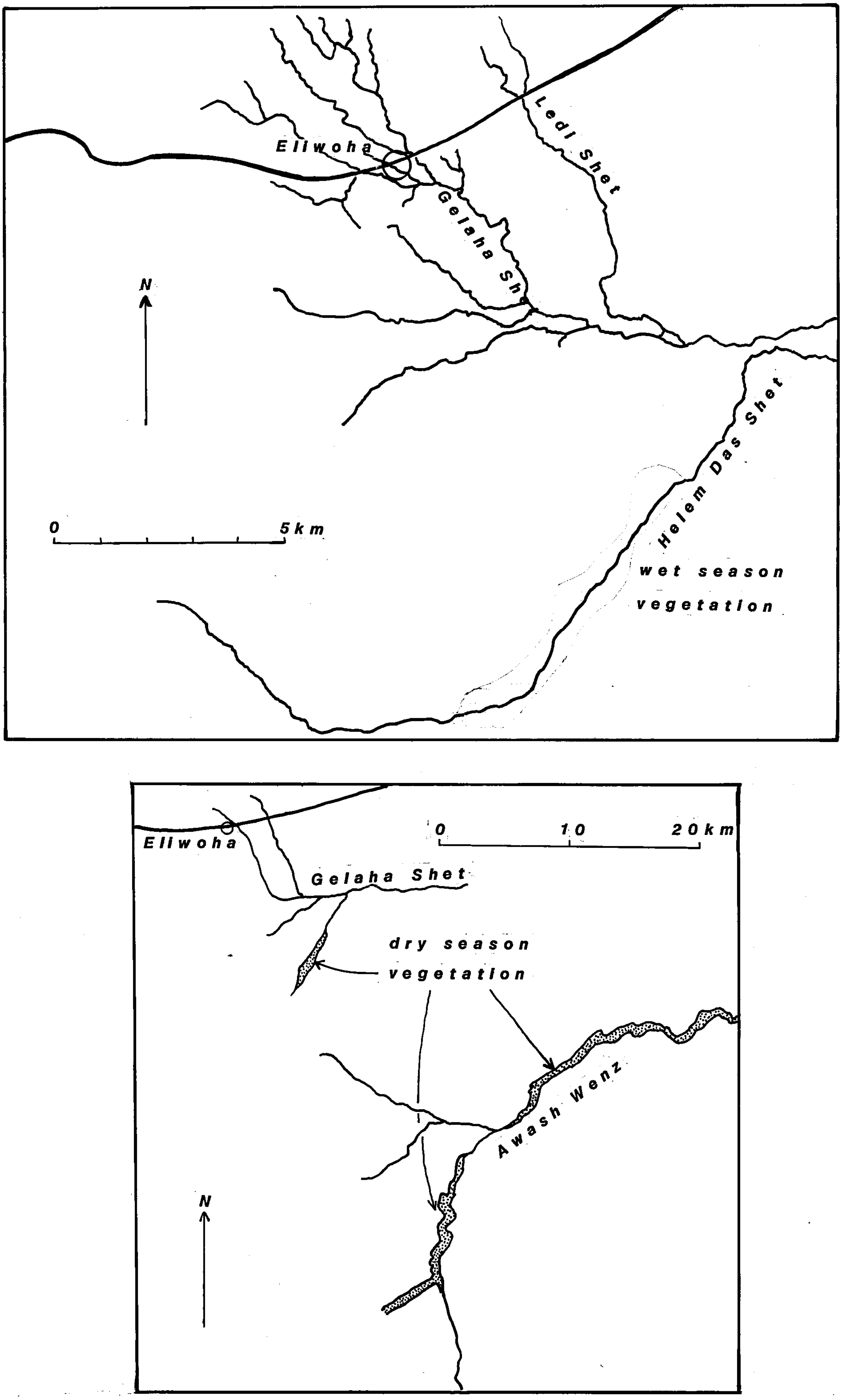

Fig.4 a. Drainage patterns from aerial photography
b. Main drainage derived from LANDSAT imagery

WK/RG/86/15

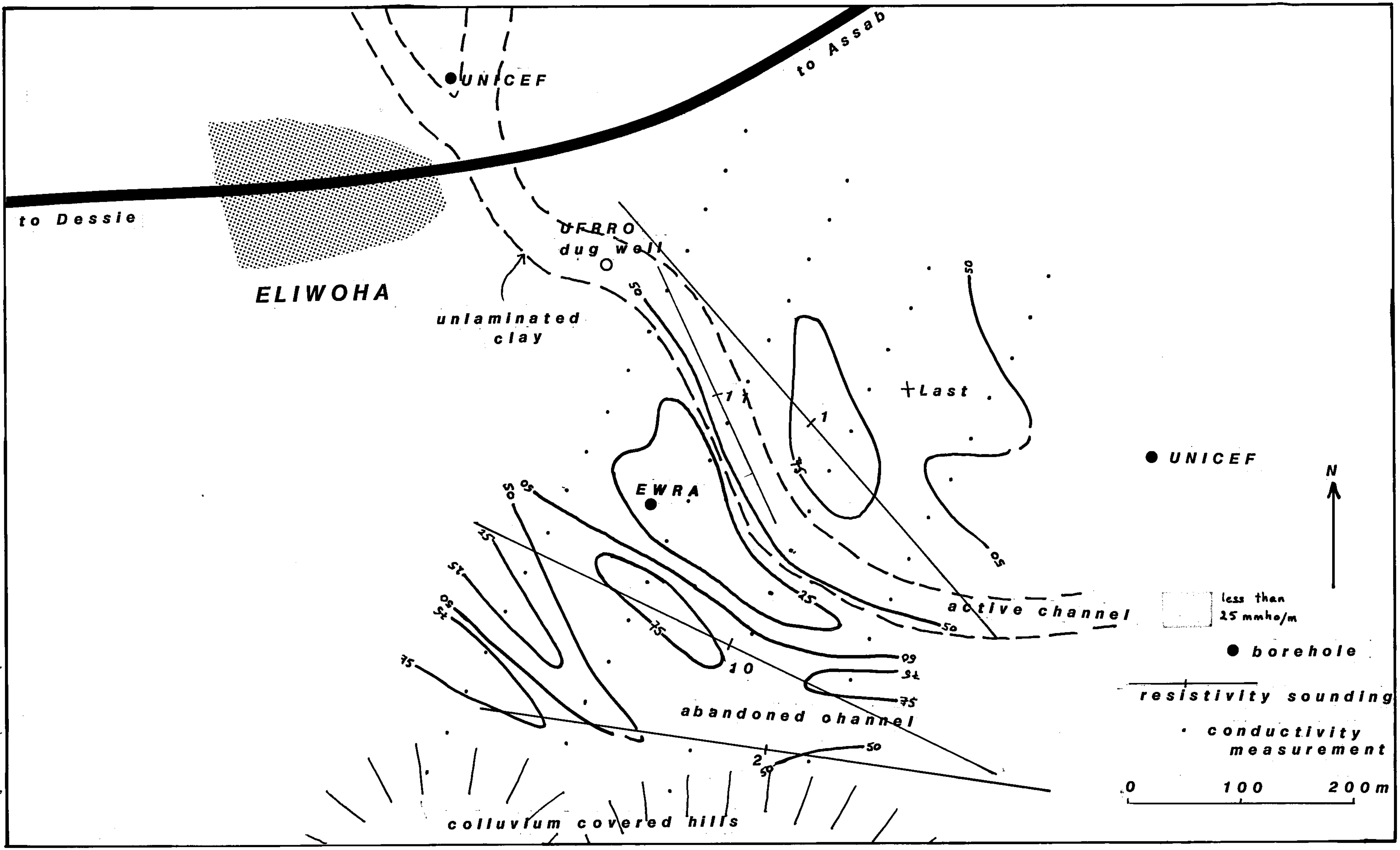

Figure 5. Contours of ground conductivity at Eliwoha

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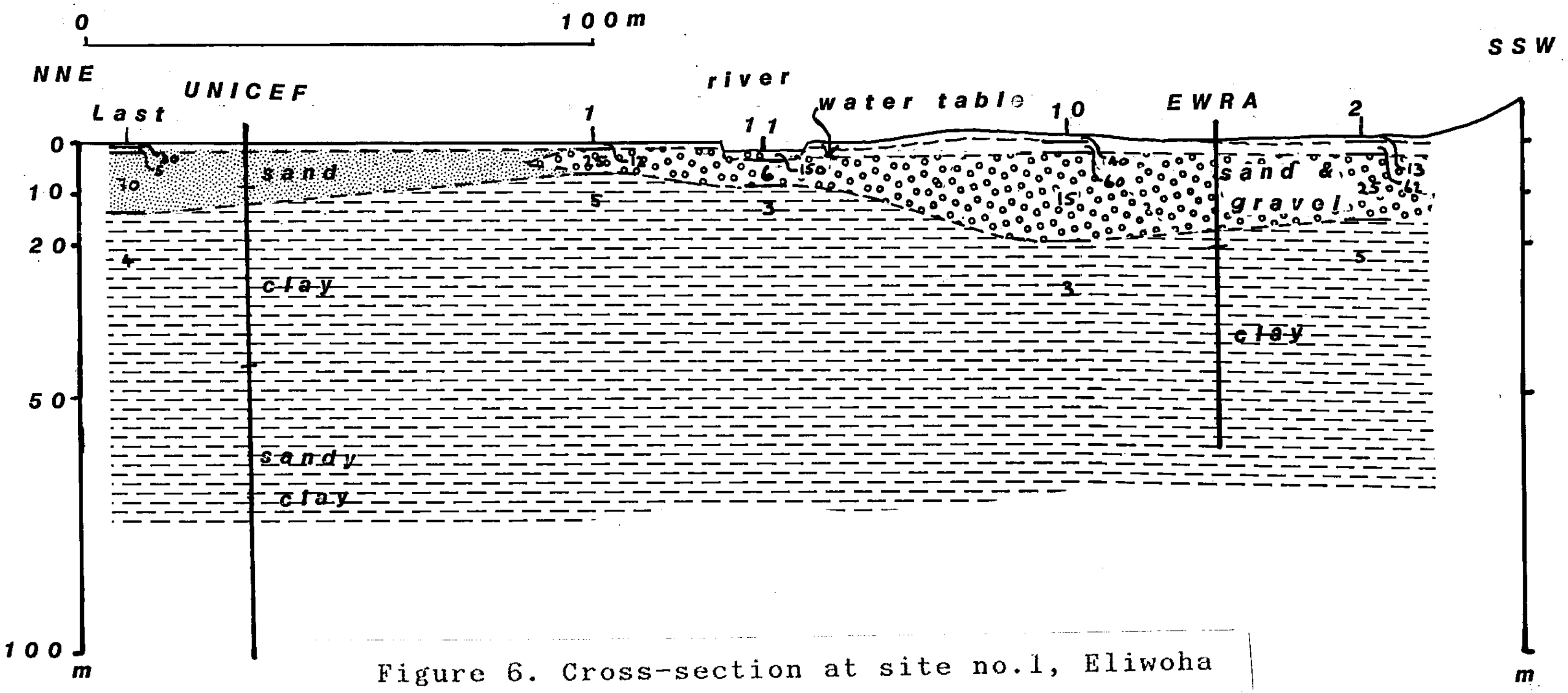

Figure 6. Cross-section at site no.1, Eliwoha

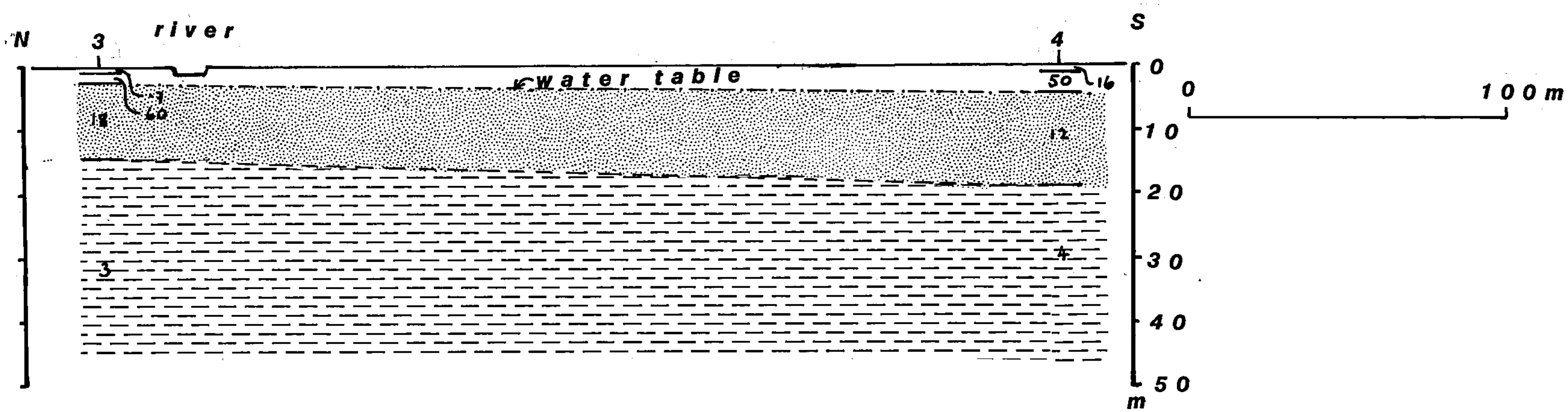

Figure 7. Cross-section at site no.2, Eliwoha

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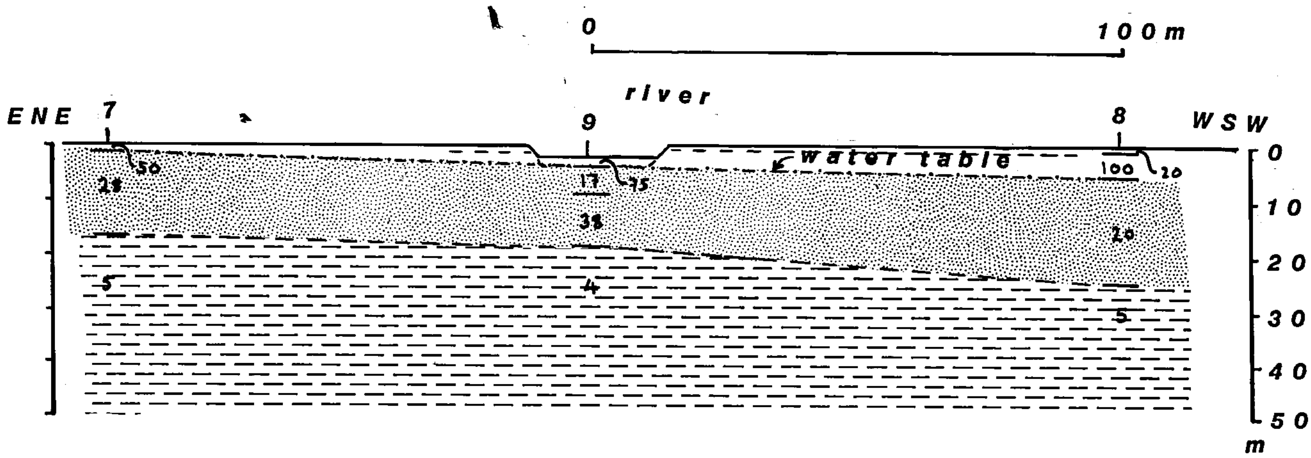

Figure 8. Cross-section at site no.3, Eliwoha

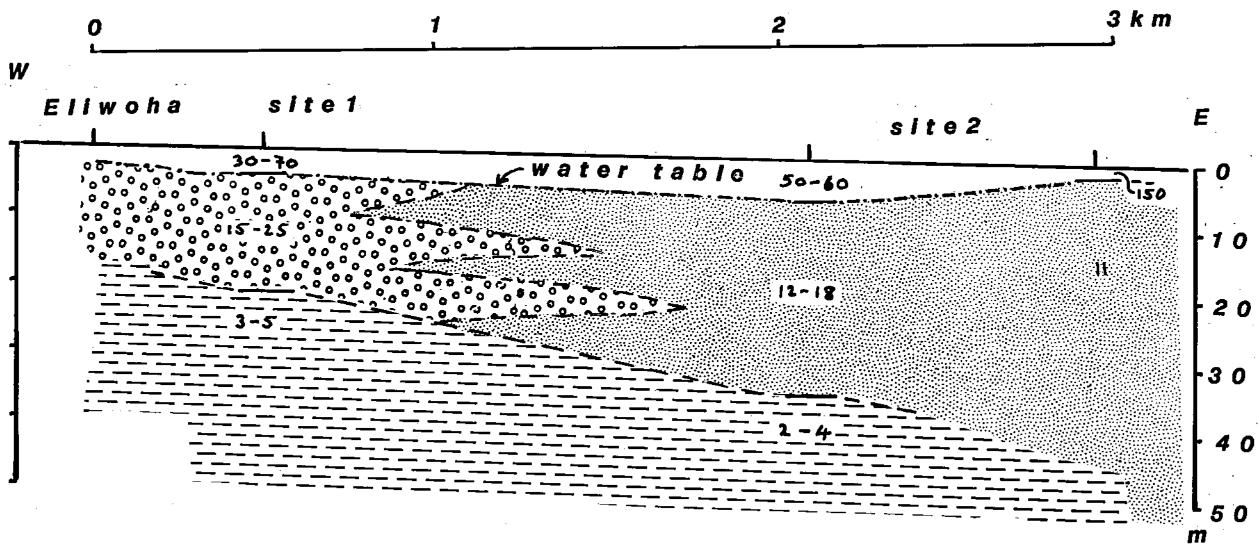

Figure 9. Correlations between soundings along the Gelaha Shet, Eliwoha

WK/RG/86/15

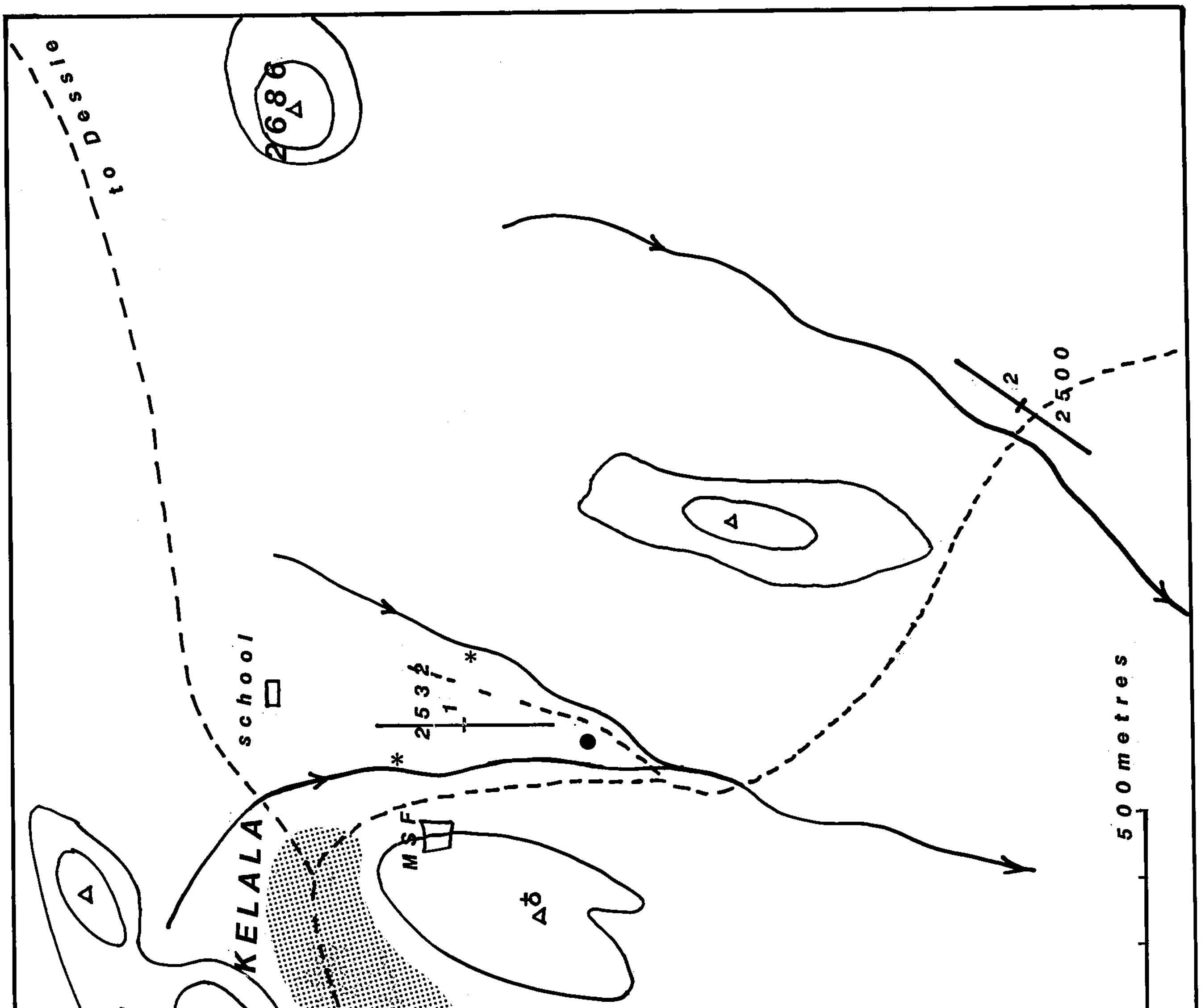

Figure 10. Sites of geophysical observations at Kelala

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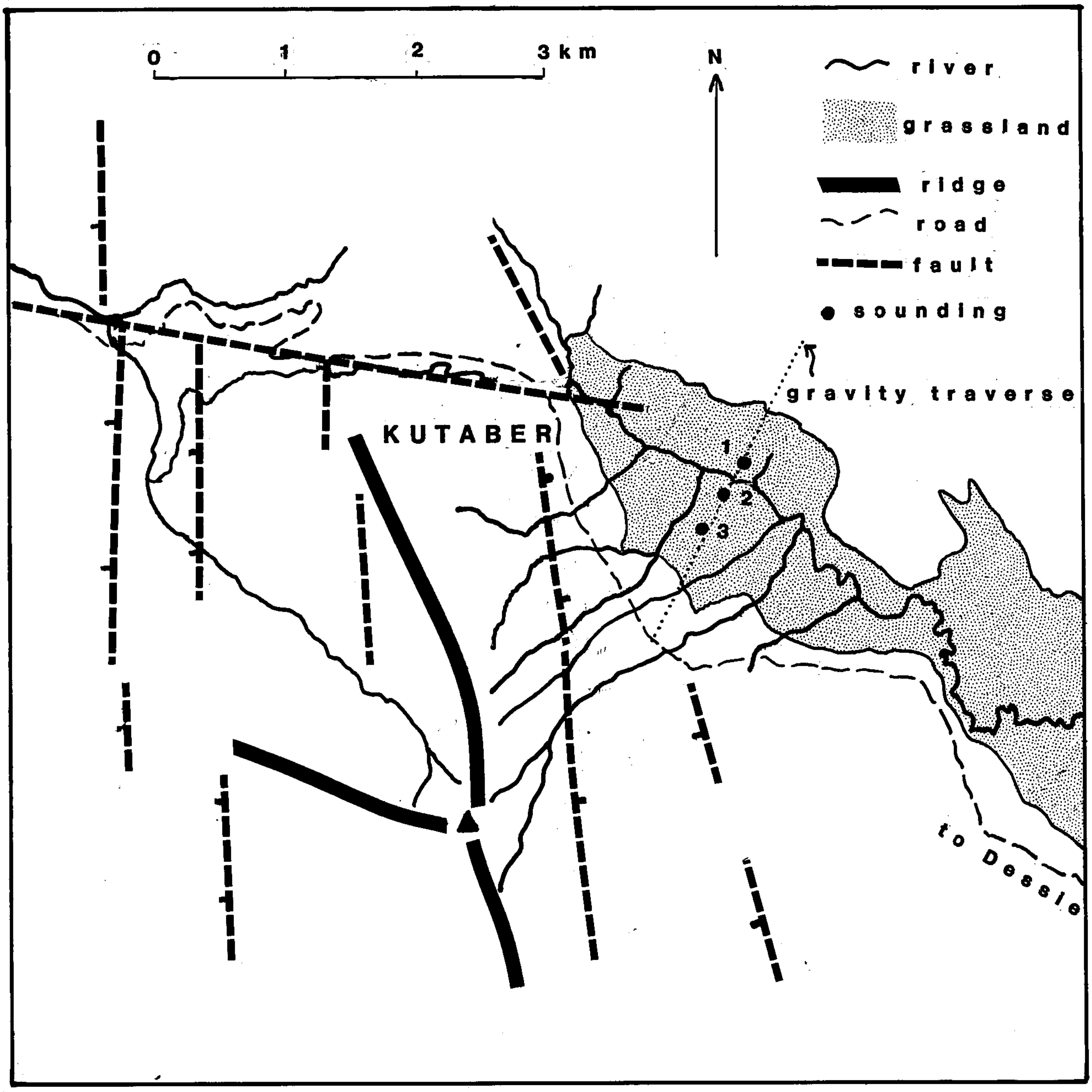

Figure 11. Map of Kutaber area, showing structural lines derived from aerial photographs

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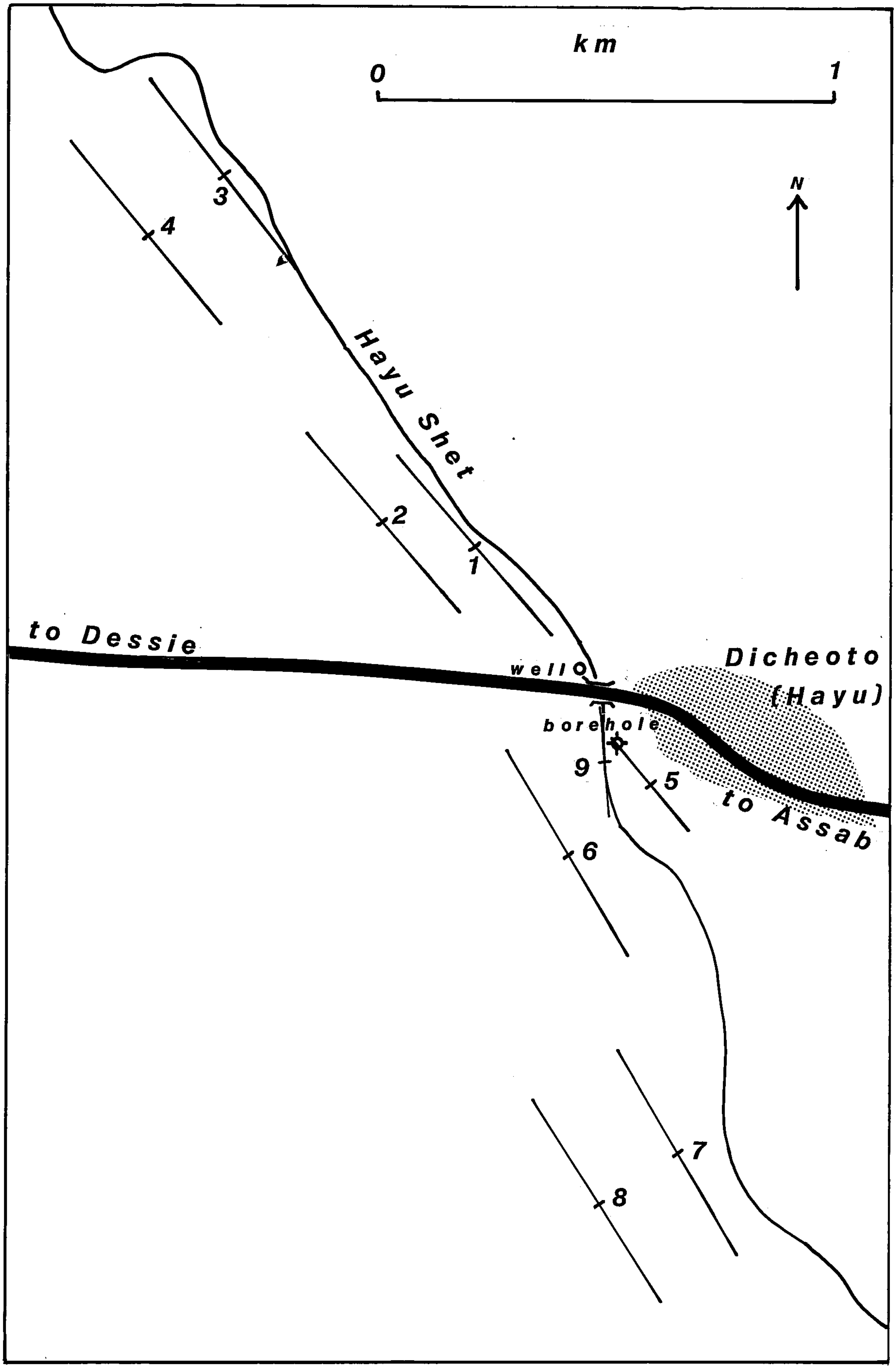

Figure 13. Position of geophysical measurements, Dicheoto

WK/RG/86/15

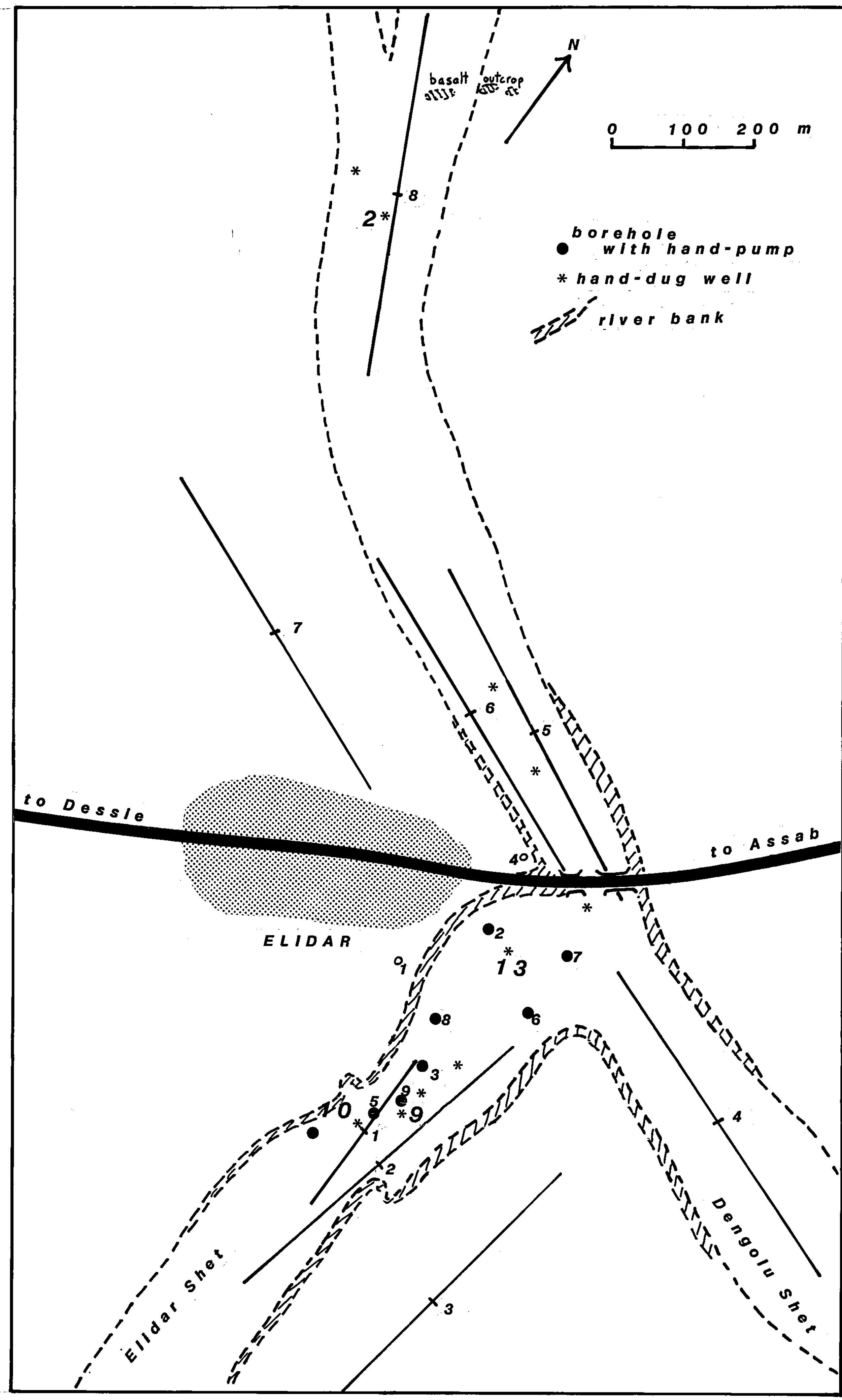

Figure 14. Position of bores and geophysics at Elidar

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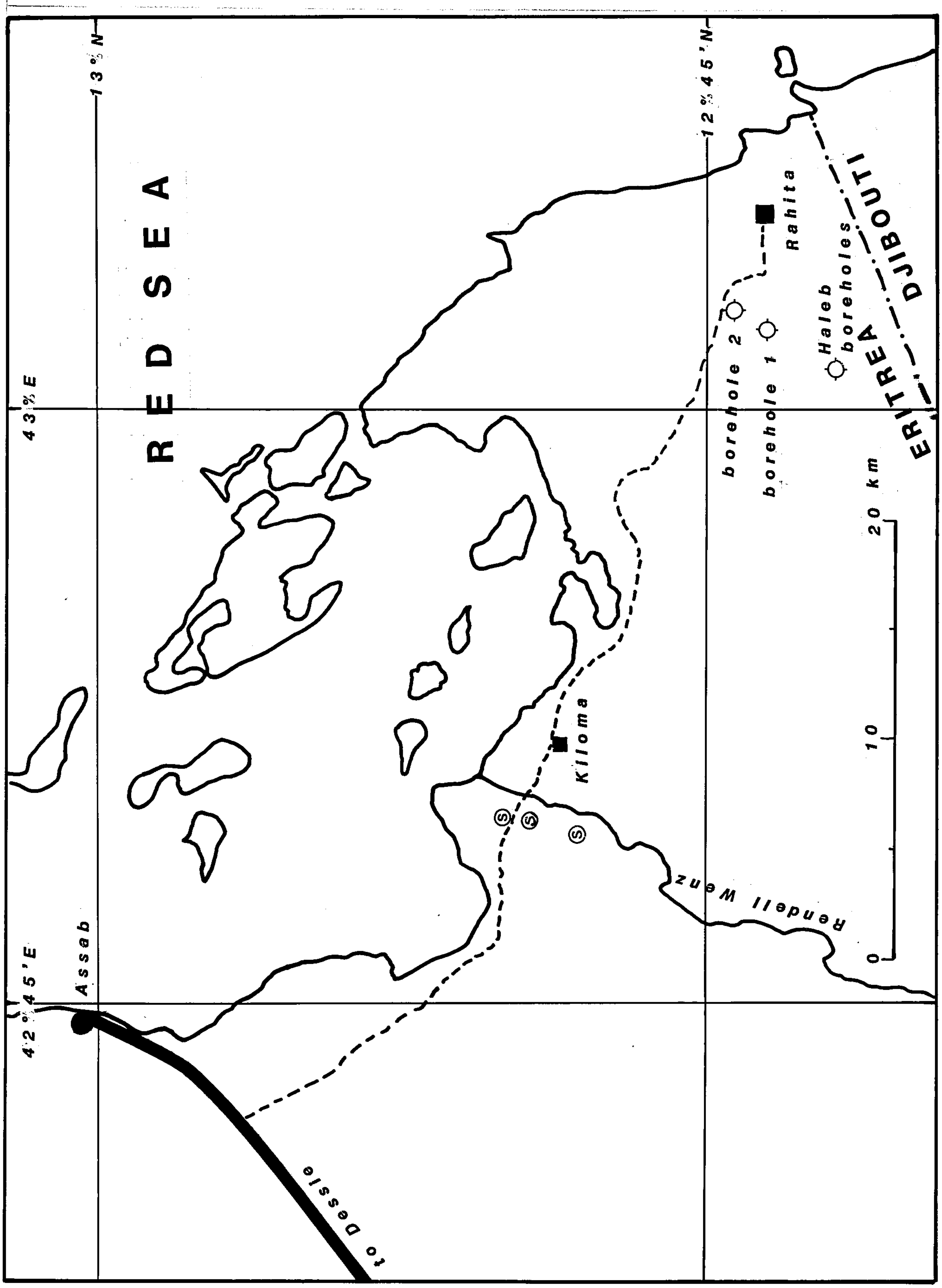

Figure 15. Geophysical sites at Kiloma and Rahita

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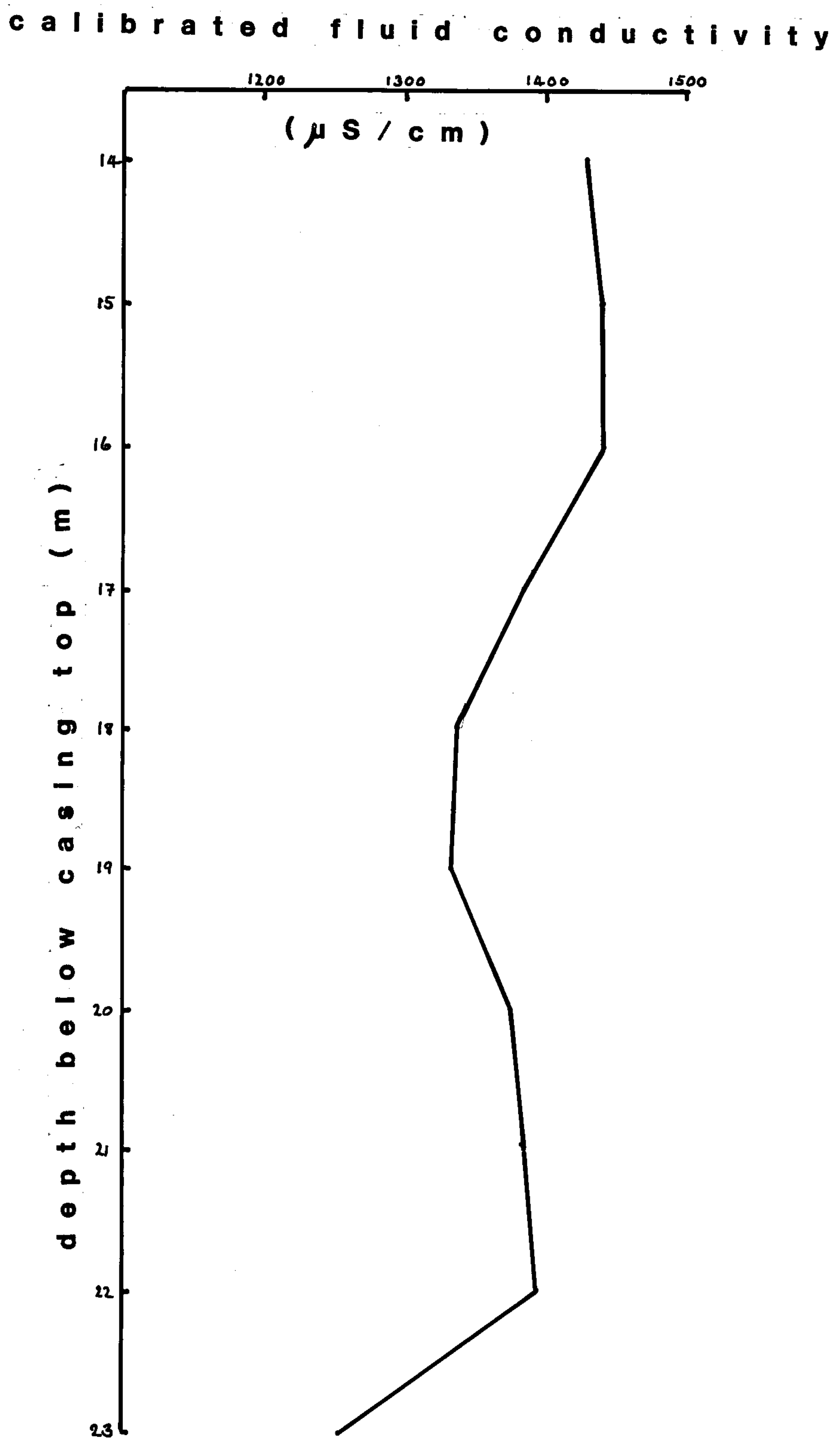

Fig.A2.1 Rahita no.2 borehole fluid conductivity log

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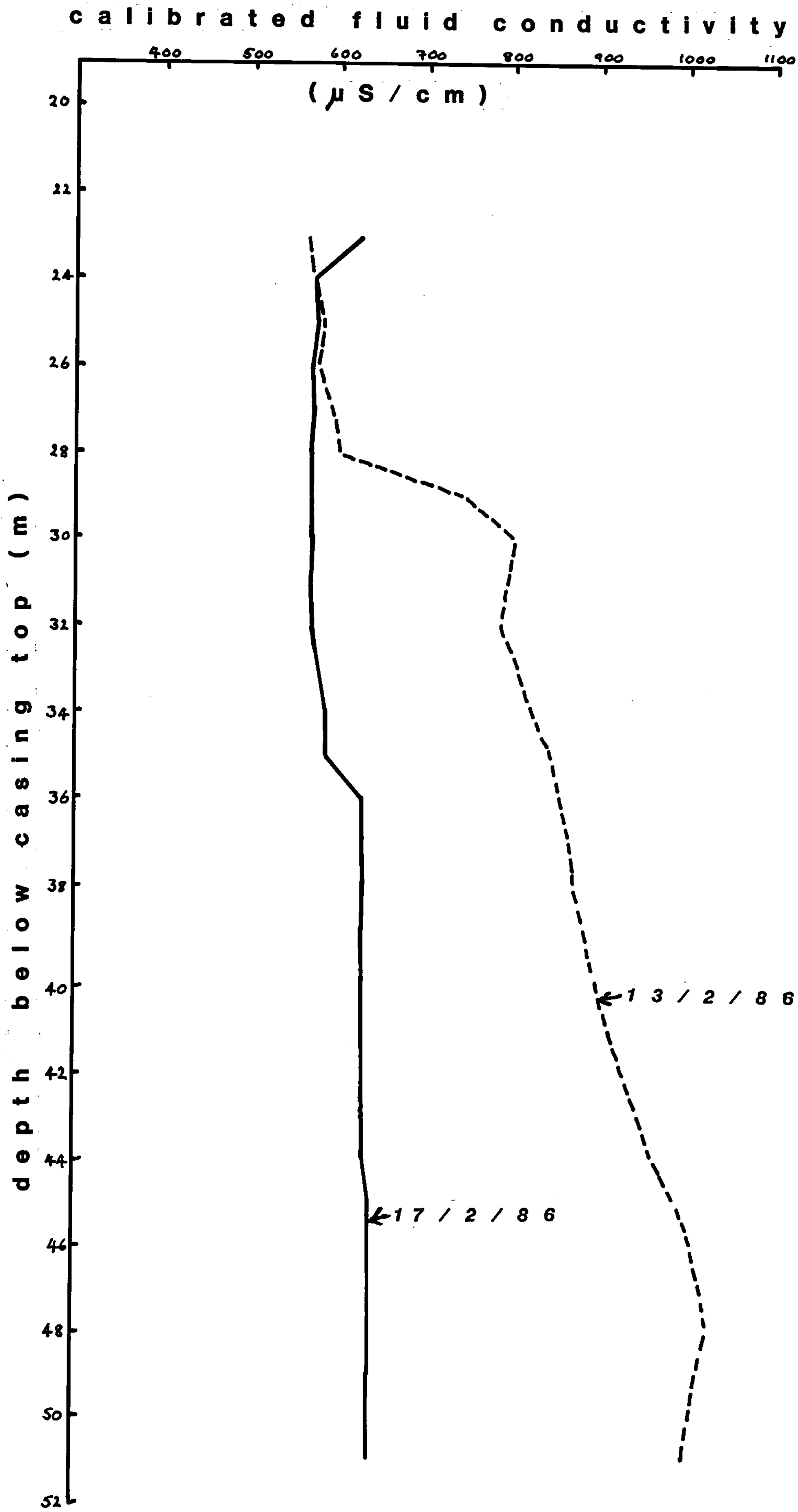

Fig.A2.2 Haleb no.1 borehole fluid conductivity logs, measured on two different occasions

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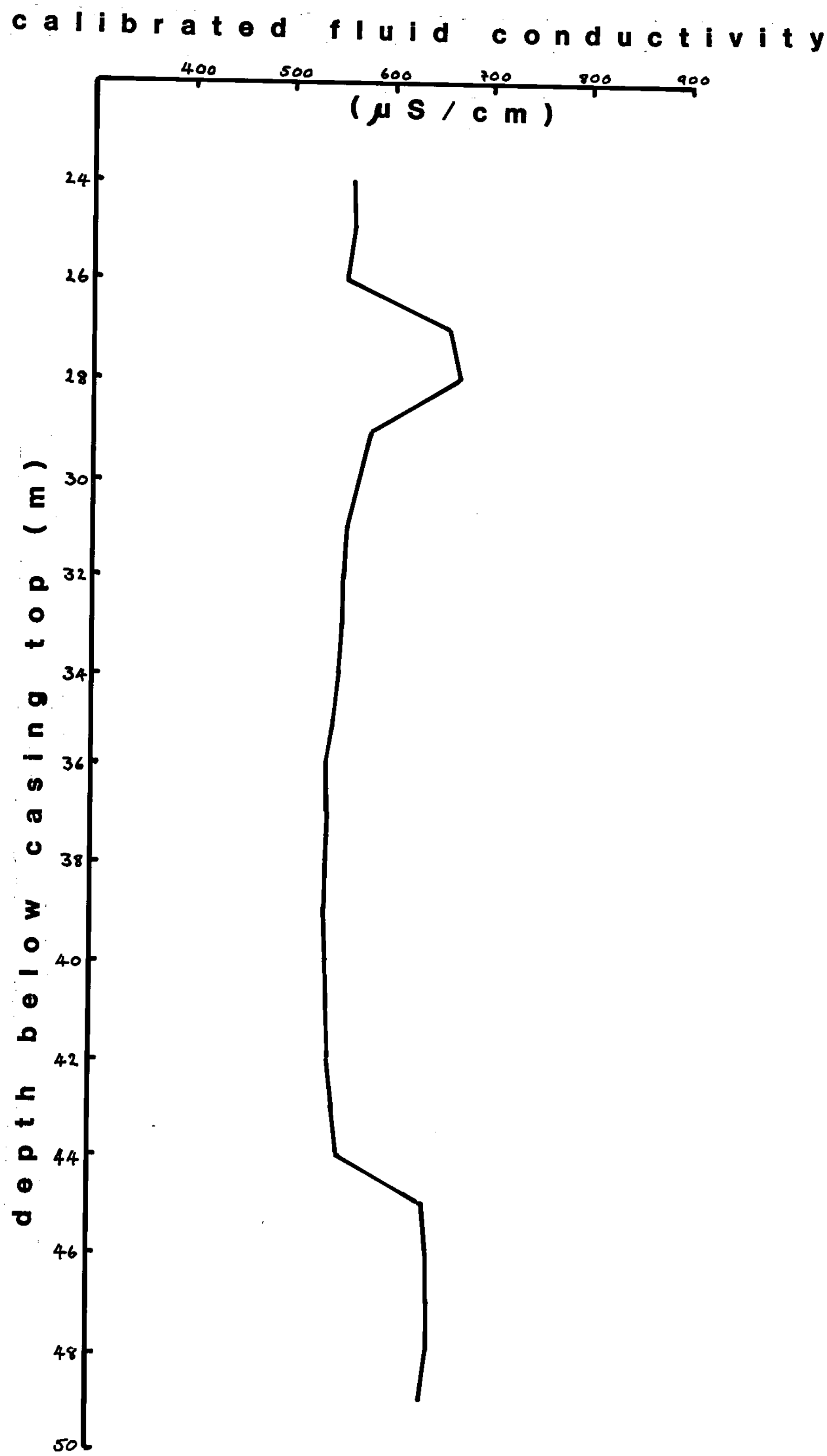


Fig.A2.3 Haleb no.2 borehole fluid conductivity log

WK/RG/86/15

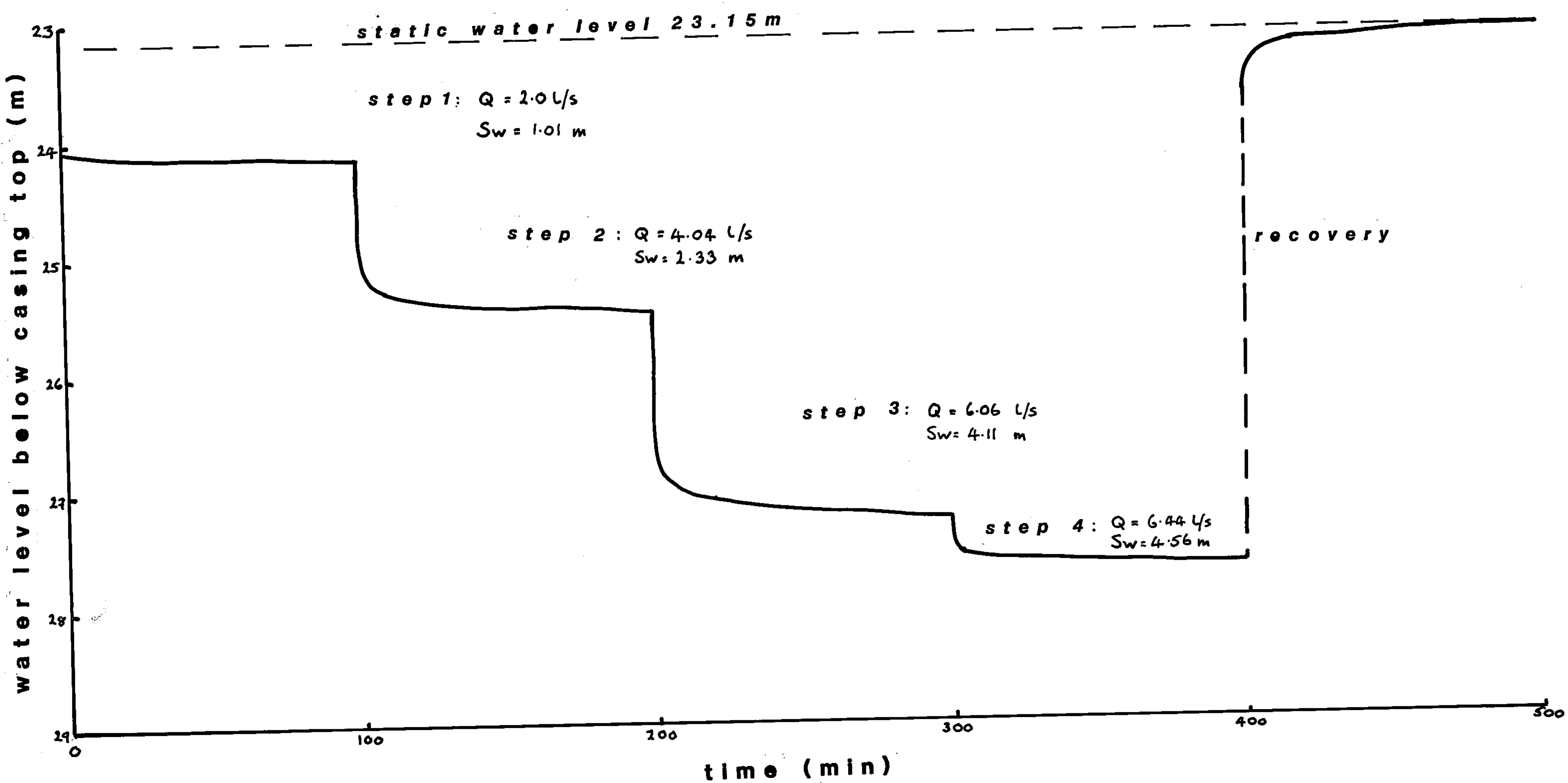
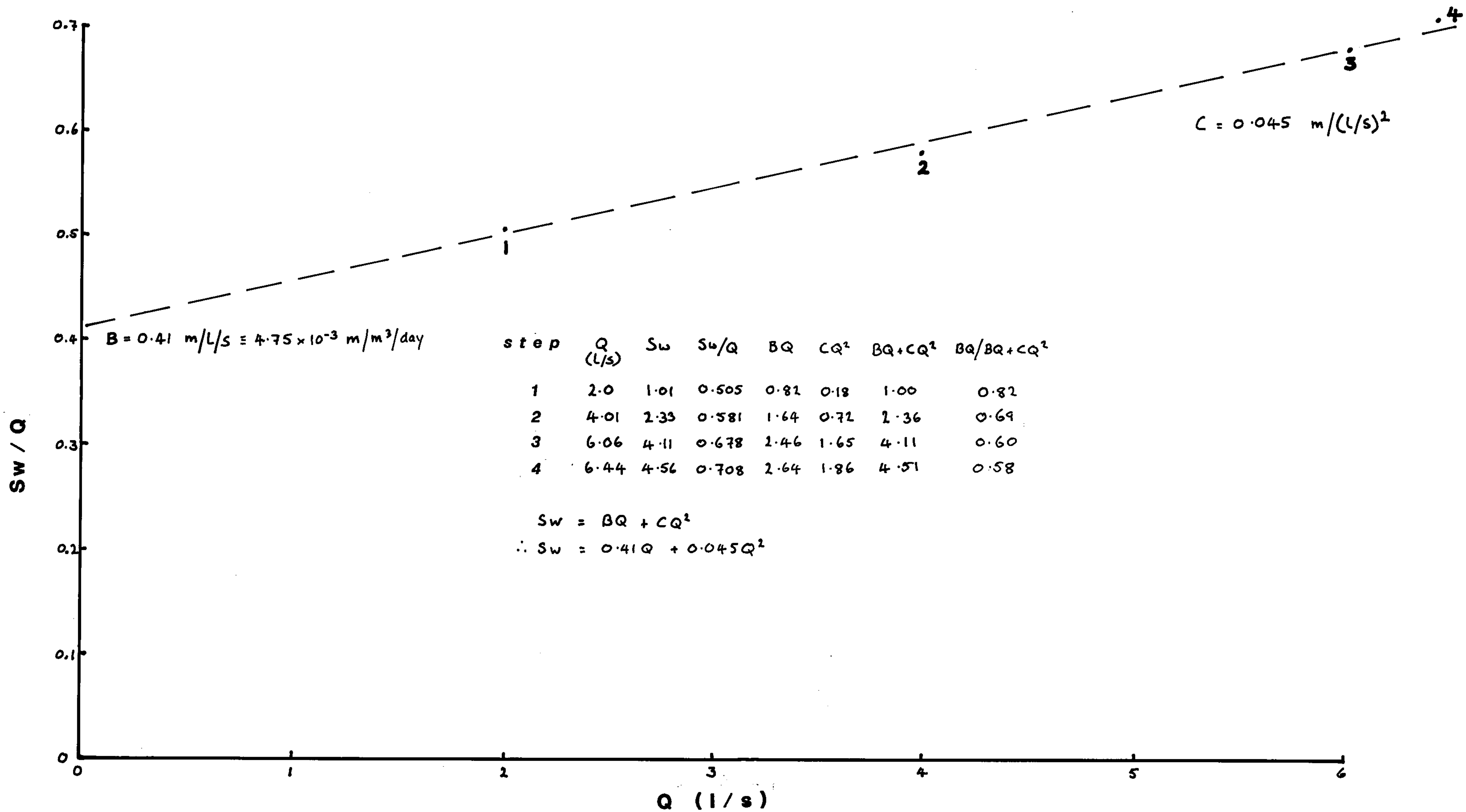


Fig.A2.4 Haleb no.2 borehole step test results

WK/RG/86/15



step	Q (L/s)	Sw	Sw/Q	BQ	CQ^2	$BQ+CQ^2$	$BQ/BQ+CQ^2$
1	2.0	1.01	0.505	0.82	0.18	1.00	0.82
2	4.01	2.33	0.581	1.64	0.72	2.36	0.69
3	6.06	4.11	0.678	2.46	1.65	4.11	0.60
4	6.44	4.56	0.708	2.64	1.86	4.51	0.58

$$Sw = BQ + CQ^2$$
$$\therefore Sw = 0.41Q + 0.045Q^2$$

Fig.A2.5 Haleb no.2 borehole step test analysis after Cooper and Jacob (1946)

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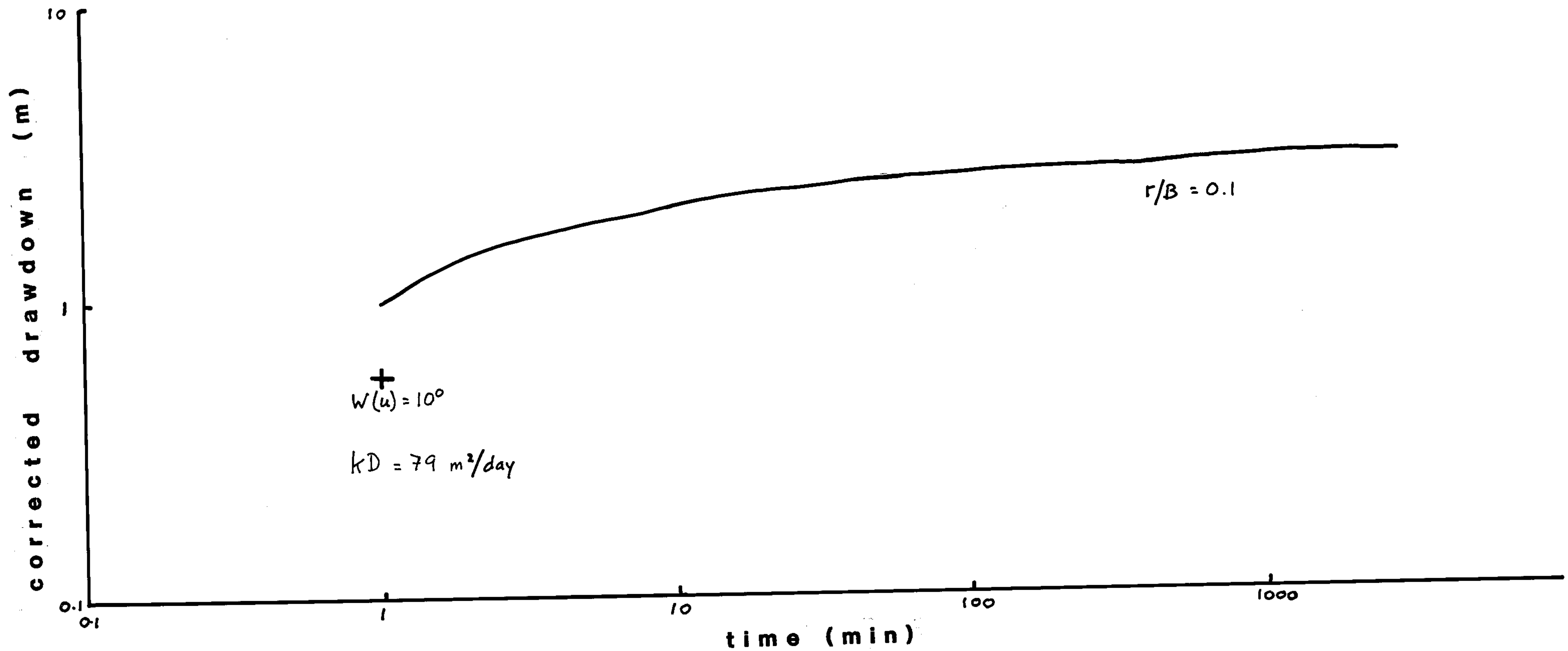

Fig.A2.6 Haleb no.2 borehole constant discharge test, plot of corrected drawdown against time

WK/RG/86/15

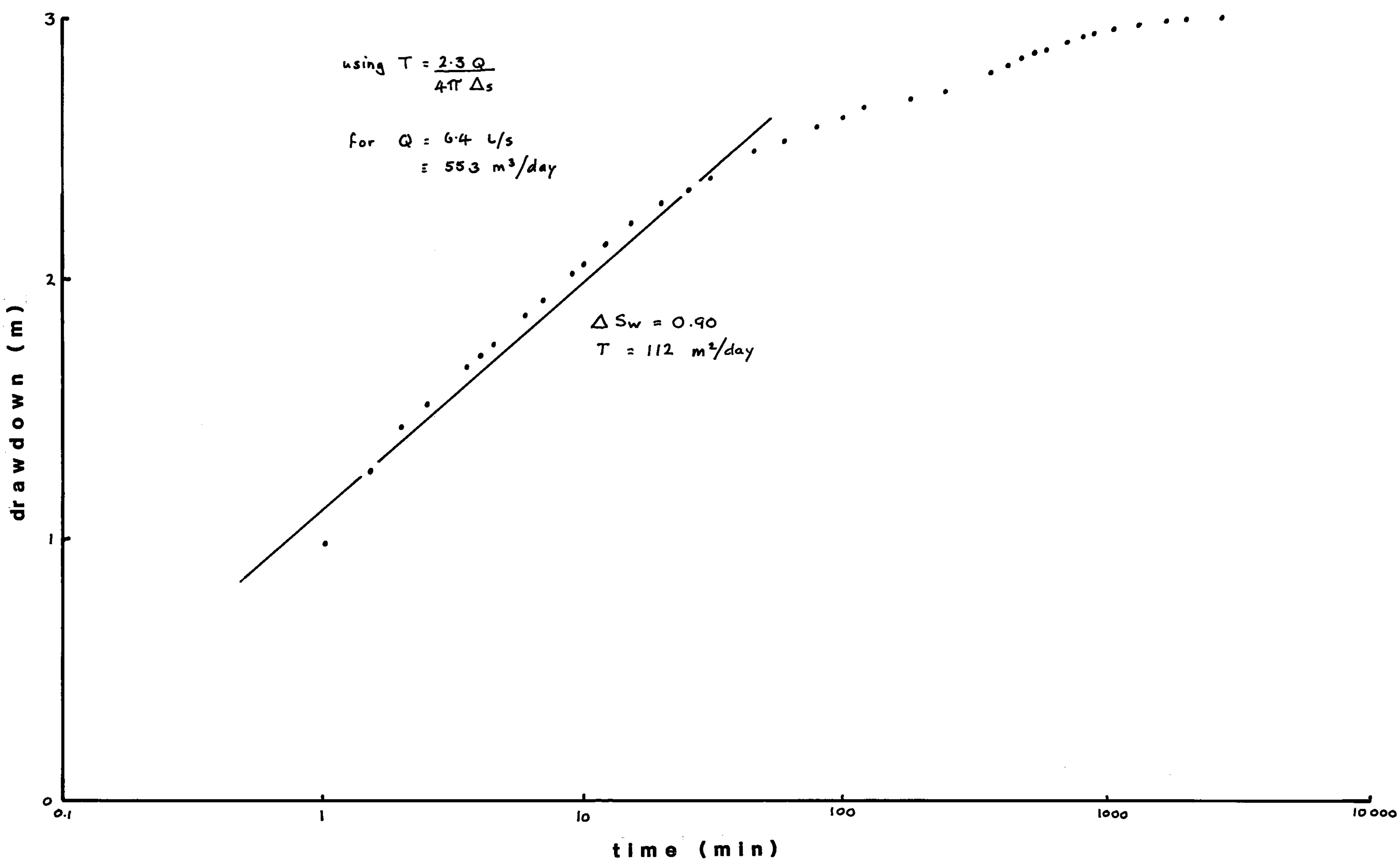

Fig.A2.7 Haleb no.2 borehole constant discharge test, analysis using Jacobs time/drawdown method

WK/RG/86/15

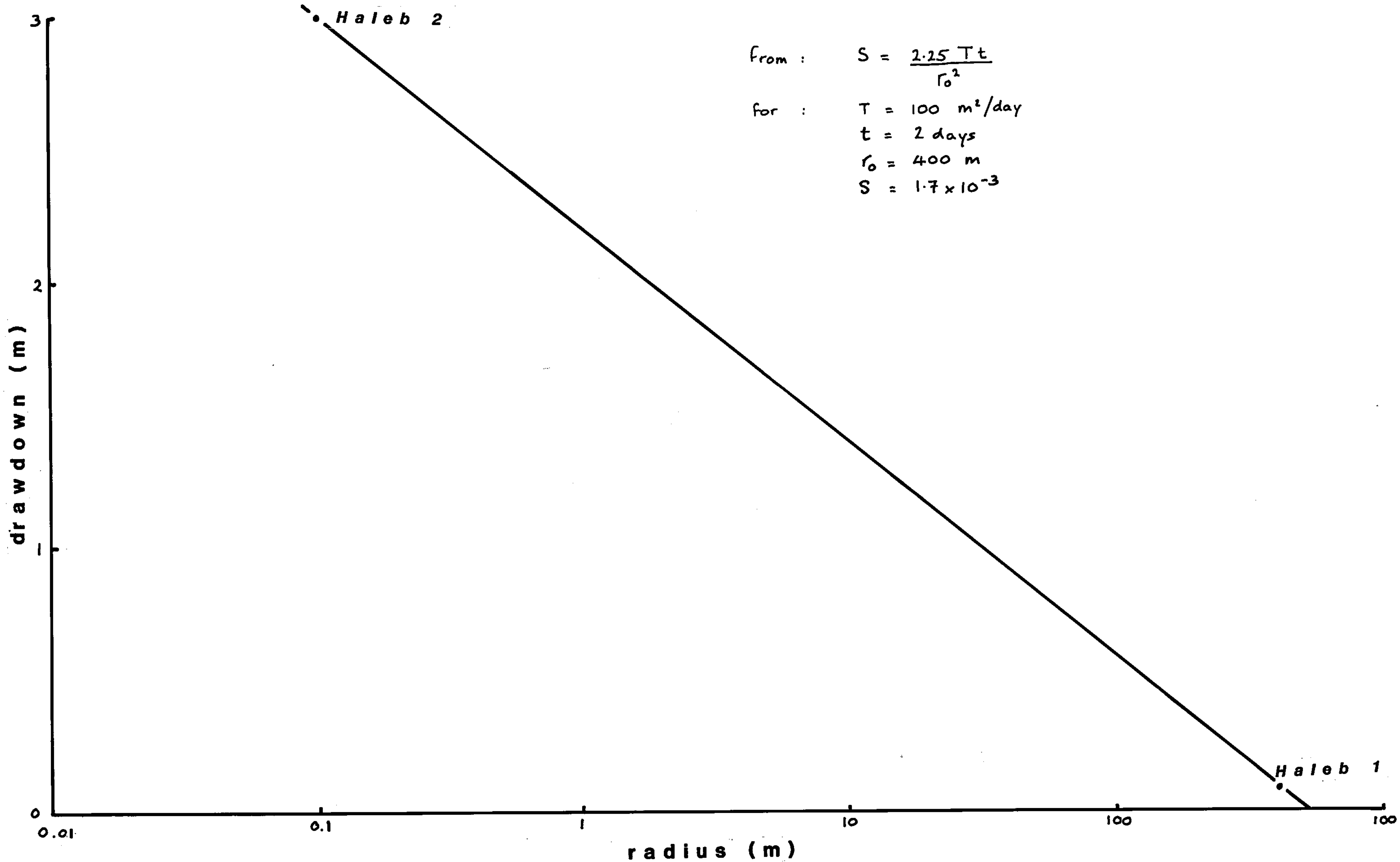

Fig.A2.8 Haleb no.2 borehole constant discharge test, analysis using Jacobs distance/drawdown method

WK/RG/86/15