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TIME-DOMAIN GEOELECTRIC SOUNDINGS IN JACKSON HOLE, WYOMING: PART A - RESULTS

by

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INTRODUCTION

During September 13-17, 1993, 9 time-domain electromagnetic (TDEM) soundings were made in Jackson Hole, a valley in Teton County, northwestern Wyoming. The crew consisted of David L. Campbell, B. Thomas Nolan and John Holland of the USGS and Kevin R. Boyce of the Wyoming State Engineer's Office. At all these sounding sites deep geoelectrical units were detected that had electrical resistivities of 30 ohm-m or less. We interpreted these low-resistivity rocks to be Cretaceous(?) marine shales. Surficial units, having resistivities in the range of 100-400 ohm-m, were interpreted to represent glacial and fluvial sands and gravels that make up the surficial aquifer in Jackson Hole. The deep low-resistivity unit is probably a much poorer aquifer than the surficial units. The TDEM soundings, therefore, suggested a way to plumb the depth of the surficial aquifer, and thereby help estimate ground water resources in Jackson Hole.

Most of the 1993 TDEM soundings were made in open sage and grasslands of the Grand Teton National Park, in the northern part of Jackson Hole valley. The area of highest concern for ground-water resources, however, is in the southern part of the valley, where housing developments are proposed on present-day hay and cattle ranches. The ranches have large fields enclosed by wire fences, and some have irrigation installations with electrical pumps. Fences and electrical power lines near TDEM sounding stations can induce noise in TDEM data and make it unreliable. For that reason, we recommended that Audio-frequency Magnetotelluric (AMT) soundings be done on the ranch lands in the southern part of the valley -- AMT gear can be set up in less area than TDEM loops, and consequently may be less sensitive to electromagnetic noise from nearby cultural sources. A general reference on TDEM method is Nabighian and Macnae (1991), and on AMT method is Strangway and others (1973). Table 1 compares TDEM and AMT methods, indicating some of the trade-offs associated with the two techniques.

During winter 1993-94, B. Thomas Nolan of the USGS Water Resources Division's Cheyenne Office put together a consortium to fund the recommended work. In late May and early June of 1994, R. M. Senterfit, Marilla Senterfit and B. Thomas Nolan of the USGS made 81 AMT soundings in Jackson Hole, mostly in the south valley. In September 12-15, 1994, we returned to Jackson Hole, repeated 7 AMT soundings and made 4 new TDEM soundings.

This report covers the TDEM work in the project, and consists of Part A, where we present interpreted results, and Part B, where we present tables showing details of the interpretation. We felt that general readers mainly would be interested in Part A, but that knowledgeable geophysicists may wish to use the information in Part B to judge our work, or to try to extend our interpretations. A companion report by Senterfit and others (1995) discusses the AMT work.

Table 1.-- Comparison of TDEM and AMT

BOTH TDEM and AMT

1. Explore to **intermediate depths**, about 1000-2000 ft. Do not explore shallow depths (<100 ft) very well.
2. Yield **electrical resistivities**; most likely geology/hydrology is inferred.
3. Detect **major geoelectric interfaces**; tops of thick layers where electrical resistivity changes significantly.
4. Can not be used near wire fences, power lines, buried cables, railroad tracks, and other sources of electrical noise.
5. Are **available** through either USGS or contractors. (AMT used here is a special USGS system; most contractors use Controlled-Source AMT.)

TDEM FEATURES

1. Crew of 4; about 2 sites/day; typical cost: $1000/site.
2. Uses transmitter -- current in a large (1000 ft square) loop. To explore to a depth of about 1000 ft, a 1000 ft square loop typically would be used. Such loops needs large areas, with loop cables at least 500 ft from the nearest wire fences.
3. Focuses below shallow surficial layers, so will not detect the shallow section (down to 100 ft, say). Maximum depth probed is equal to about the length of one side of the square loop, but depends on resistivity distribution with depth.
4. Very vulnerable to cultural electrical noise, e.g., wire fences. Such noise invalidates all data from that site.
5. Fairly insensitive to lateral geoelectric inhomogeneities outside outside the loop.
6. Standard interpretation package fits three "best" layers; thin layers in complex geoelectric sections are usually not resolved by the TDEM method.
7. Measured apparent resistivities are reasonably correct.
8. Interface depths typically correct to ± 15%.

AMT FEATURES

1. Crew of 2; about 4 sites/day; typical cost: $250/site.
2. (USGS system) No transmitter -- signals used are due to lightning from distant storms. Can be done in small (40 Acre) fields.
3. Depth probed is typically 1 km; depends on resistivity distribution with depth.
4. Less vulnerable than TDEM to cultural noise from nearby

sources, but power lines can be a problem. Some data from "bad" sites may still be usable.

5. Influenced by geoelectric structures that may be present off to the side as well as underneath. Double soundings (N-S and E-W) are made at each site; these can be used to infer nearby faults or other conditions causing lateral variations.
6. Standard interpretation computer program shows up to 16 "layers", but many of them may have similar resistivities and so may represent the <u>same</u> geoelectric unit.
7. Measured apparent resistivities can be biased up or down from true values.
8. Interface depths typically correct to ± 20%.

EQUIPMENT, FIELD CONDITIONS, AND DATA REDUCTION

The TDEM soundings were made using equipment owned by the USGS, Branch of Geophysics, consisting of matched EM-37 transmitter and receiver units manufactured by Geonics Ltd., Mississagua, Ontario, Canada. TDEM measurements involve first energizing a transmitter loop so as to induce currents in the ground, then stopping transmission and using a receiver loop to measure electromagnetic fields caused by the decay of those currents. At Jackson Hole, TDEM signals were transmitted into the ground via square loops of insulated #10 wire, and resulting signals were measured at a receiving loop, located at its center, which had a moment of 100 m^2. The 1993 soundings (TCW01-TCW09) were made with square-transmitter loops measuring 1000 ft on a side, but most of the 1994 soundings were made with square loops measuring 500 ft or 250 ft on a side in order to fit into the smaller farm fields. Of these, only TCW13 was in a field large enough to use a 1000 ft square loop. Ideally, the sides of all transmitter loops should be located at a distance of more than one loop-dimension (that is, 1000 ft for TCW01-09 and TCW13) from wire fences, but for TCW09-13 one side of the square-transmitter loop was only a half loop-dimension from a fence paralleling it. Most such fences had 3 or 4 strands of barbed wire stapled to wooden posts, not steel posts (less chance of grounding).

The EM-37 transmitter (Tx) can send current into the transmitter loop with either positive or negative polarity. The total duty cycle consists of four steps of equal time durations in the following sequence: Tx on with positive polarity -- Tx off -- Tx on with negative polarity -- Tx off. At Jackson Hole two duty cycles were used; one that repeated 3 times per second, and another that repeated 30 times per second. By convention, these repetition rates are denoted "3 Hz" and "30 Hz", respectively.

During the "Tx off" part of the duty cycle the EM-37 receiver measures decay voltages in the receiver loop during 20 separate time intervals (channels). It starts measuring a short time after the Tx turns off (one T/O interval), and cumulatively stacks (adds) the successive contributions in each channel for a time equal to 33.3 x 2^N msec. The value of N is chosen by the operator and was typically set equal to 8 at Jackson Hole (so that each measurement took about 8.5 sec to complete). The stacking process, of course, must be set up to make the signals from positive- and negative-polarity parts of the duty cycle reinforce, rather than cancel. To this end, the Rx unit reverses the sign of the received signal during the appropriate half of each duty cycle as it stacks. By toggling a polarity switch, the operator selects which half of the duty cycle the Rx electronics are to reverse. It is common practice to take TDEM data in pairs, with the polarity switch in opposite positions for the two members of the pair. To get good sampling statistics, 5 such data pairs were recorded for each repetition rate at all Jackson Hole stations.

The 20 EM-37 receiver channels are centered at times from 0.087 to 7.04 msec after turn-off (T/O) when using the repetition rate of 30 Hz and in 20 channels centered at times from 0.87 to 70.4 msec after T/O when using the 3 Hz repetition rate. Channels 1-10 at 3 Hz and Channels 11-21 at 30 Hz -- the nominal time interval 0.87 to 7.05 msec -- have center times and widths that are approximately equal. At most Jackson Hole sites, signal quality was poor in the 7.12-71.2 msec range, having the effect of obscuring signals due to deeper geological features.

Data was collected and pre-processed using procedures and computer programs by David V. Fitterman (USGS, 1993, unpublished TDEM manual). Fitterman's program uses pairs of measured positive- and negative-polarity voltages to calculate a particular measure of apparent resistivity that is subsequently input to the interpretation program. This measure is the so-called "late stage" apparent resistivity, and is one of several possible choices (Spies and Eggers, 1986). Late stage apparent resistivity asymptotically approaches true resistivity in its late-time channels for data taken over a uniform half space. The apparent resistivities calculated for early-time channels are usually higher than the true resistivity of the half-space, and have no direct physical significance. The pre-processed data was screened and values that had more than a 10 percent standard deviation of calculated apparent resistivity (sd%R) were deleted. This result was then reviewed, and for some sites a few channels that initially had been rejected because of high sd%R values were reinstated; in all these cases we substituted the median apparent resistivity value (only) of the 5 data pairs in place of the average apparent resistivity value. The resulting data was interpreted and plotted using "TEMIXGL", a computer program by InterpeX Limited, PO Box 839, Golden, CO.

INTERPRETED RESISTIVITY LAYERS

Plate 1 shows the locations of the 13 TDEM soundings, overlaid on a color map taken from Behrendt and others (1968). That map is used here because it shows both generalized geology and gravity anomalies in the Jackson Hole area.

Geoelectric data is usually interpreted in terms of idealized models that consist of a stack of horizontal layers.

Each layer has uniform thickness Ti and constant electrical resistivity Ri. The effect of the deepest layer is computed as if it were a layer of infinite thickness.

Figs. 1-13 show interpretations of the TDEM data taken at the 13 TDEM sounding sites in Jackson Hole. For each sounding there are two or three page-size figures. The first page (a) of each figure has a graph on the left that shows observed data (squares) and the computed curves (solid lines) that result from the "best-fit" layer model. The graph on the right shows resistivity versus depth for the best-fit model. The second page (b) shows several models whose calculated sounding curves all fit the field data from the site about equally well (the "equivalency suite"). From these models one can judge possible alternate interpretations that would be permissible. All (b) pages are plotted to the same scale to help compare between soundings.

All interpretations are conservative in the sense that only two or three layers, the minimum possible number, were used to fit the observations. Table 2 shows the models that give "best fits" to the observed data.

Table 2.--Best fit interpretations of Jackson Hole TDEM data. R1 and T1 represent the resistivity and thickness for the topmost layer, R2 and T2 for the second layer, and R3 for the third layer (assumed infinitely thick). At TCW05, 06, 07, 09, 12 and 13, only two layers were needed to adequately fit the observations. All resistivities R are in ohm-m, thicknesses T are in meters, and Fit indicates how well the calculated curve for the model agrees with the observations. Fits less than 10% are considered acceptable.

Sounding	R1	T1	R2	T2	R3	Fit
September 1993						
01--Jenny Lake	376	319	108	241	29	2.59%
02--Antelope Flats	155	250	11	188	1.7	6.58%
03--Baseline Flats	335	323	76	290	25	7.89%
04--Moosehead ranch	41	7.8	64	472	6.5	5.03%
05--Lost Creek	207	110	23	-	-	4.94%
06--Potholes	207	740	13	-	-	4.10%
07--Airport lookout	181	136	25	-	-	5.54%
08--Gros Ventre	96	139	12	160	435	5.20%
09--Oliver hay field	56	278	16	-	-	4.25%
September 1994						
10--Resor's quarry	242	275	1355	171	19	7.47%
11--Hardeman farm	391	352	73	361	1039	5.58%
12--Teton Village N	147	186	25	-	-	4.11%
13--Halpin farm	233	74	36	-	-	6.12%

A characteristic of TDEM soundings is that they usually are insensitive to shallow geoelectric units. Typically, the depth to the top of the shallowest unit that may be detected by a TDEM measurement, d', is proportional to the diffusion depth (Nabighian and Macnae, 1991)

$$\delta = \sqrt{\frac{2\tau\rho}{\mu}} \qquad (1)$$

where τ = earliest time measured by the TDEM equipment, ρ = average resistivity of geoelectric units above the shallowest detected unit, and μ = magnetic permeability. The proportionality factor depends on loop dimension, a, and on true thickness of surficial geoelectric layers, d, so that $d'<\delta$ when $a/d<1$ and $d'>\delta$ when $a/d>1$ (Spies, 1989). Setting τ = 0.086 msec and $\mu = 4\pi \times 10^{-7}$ ohm-sec/m (the permeability of free space), we find δ = 37 m if ρ = 10 ohm-m, δ = 118 m if ρ = 100 ohm-m, and δ = 372m if ρ = 1000 ohm-m. We infer that surficial units are probably not reflected in the models reported here; our interpreted first layer is likely to represent unit(s) well below the water table, which may be saturated with ground water. It appears that the 7.8 m-thick surficial unit which the modeling program found at TCW04 (Moosehead ranch) may be an artifact of the modeling process, and should not be trusted very much. In general, the TDEM method may have difficulty in resolving thin layers unless their "conductance" (thickness divided by resistivity) is high compared to those of surrounding layers. A sequence of layers having conductances that are similar (different by factors of only 2 or 3, for example) are likely to be lumped together by the TDEM interpretation program which we used. Therefore, all the above models must be regarded as generalized; they almost certainly do not reflect all of the many geologic units that may be present beneath each site.

An important feature of each interpretation is its equivalency suite -- a number of different layer models that all fit the observed data about equally well (figs (b)). Note that each "interpretation" is best regarded as the entire suite of equivalent layer models. For definiteness, though, Table 3 and the following discussions use the model at each site that had the "best" fit parameter, citing its particular resistivities and depths. Clearly, though, these values are uncertain by at least the amounts indicated by the equivalency suite for that sounding.

TDEM soundings TCW05, 06, 07, 09, 12, and 13 were modeled with only two layers, rather than the three layers used to fit the other soundings. For each of these soundings a third page (c) has been included to show the equivalency suite of three-layer models for that field sounding data. For all of them the percent fit for three layers was only a little better than for two, the first layer is practically unchanged, and the best-fit third layer is added at depth. In most cases the depth and/or resistivity of the acceptable-fit third layers can vary widely, unconstrained by the observations. Still, the three-layer solutions (figs (c)) may be useful to indicate possible thickness of the deep low-resistivity unit(s) and the possible nature of the units underlying them.

BACKGROUND INFORMATION ON RESISTIVITY VALUES

Different geological units generally have different electrical resistivities. Therefore we expect, though there is no guarantee of it, that different interpreted resistivity layers correspond to different geological units or combinations of units. Changes in resistivity usually reflect changes in lithology, but can also reflect water table or fresh-brackish water boundaries.

Water conductivities are often reported in units of micromho/cm. The relation between resistivity ρ in ohm-m and conductivity σ in micromho/cm is:

(2) $$\rho \text{ [ohm-m]} = 10{,}000 / \sigma \text{ [micromho/cm]}$$

Hem (1970) presents a graph showing water resistivity ρ_W versus dissolved-solids concentration DSC, from which we infer the rough equivalence

(3) $$\text{DSC [mg/L]} = 6200 / \rho_W \text{ [ohm-m]}$$

Here ρ_W represents resistivity of the water alone, but clean sand aquifers often have formation resistivities ρ proportional to that of the water they carry. Jackson and others (1978) fit results from experiments on marine aquifer materials using the relation

(4) $$\rho = \rho_W \Phi^{-M}$$

where Φ is the porosity and M is a coefficient depending on the shape of solid grains making up the aquifer. For equidimensional grains, M = 1.30, approximately. Equation (4) accordingly predicts formation resistivity will be about 8 times water resistivity for an equi-grained aquifer with 20% porosity, and about 20 times for one with 10% porosity. These results only hold for aquifers with high-resistivity matrix materials. If the formations are silty or clayey, the conductivity of the matrix will mask that of the pore-water. This may be the case at sounding sites such as TCW04, 08, and 09 (Moosehead, Gros Ventre, and Oliver hay field, respectively).

Keller and Frischknecht (1966, Table 10 on p. 40 and Fig. 24 on p. 41), and Keller (1966, Table 26-2 on p. 562) give general resistivity ranges for (water saturated) rocks of different geological ages. More detailed values, including Formation names, are given in Keller and Frischknecht's (1966) Table 11, pp. 44-49. These tables show that shales have lower resistivities than alluvium, and that marine sediments have lower resistivities than terrestrial ones. In particular, Keller and

Frischknecht's (1966) Fig. 24 shows that most Mesozoic and lower Eocene sedimentary rocks in the western US have resistivities less than 100 ohm-m. During most of the Mesozoic Era there was a shallow sea where the Rocky Mountains and High Plains now stand; very likely saline minerals deposited in the sediments of that sea account for their low electrical resistivities. The tables do not list resistivities for Cenozoic units found specifically in Jackson Hole, but we expect the glacial and alluvial sand and gravel deposits that form surficial aquifers there should have resistivities similar to glacial and alluvial aquifers elsewhere in the northern US; that is, between 150 and 400 ohm-m.

USGS Branch of Geophysics crews have done electrical surveys in many parts of the US over the past several decades. To our knowledge, though, no tabulation exists of resistivities that have been observed for particular geologic units. The values in Table 3 therefore represent an informed "best guess" as to resistivities of possible units in Jackson Hole.

Table 3.--Possible source rocks (generalized) for resistivities observed in this study.

Resistivity Range	Possible source rocks
< 30 Ohm-m	Marine clays and shales
30 - 150 Ohm-m	Clays, shales, silts; lacustrine deposits; brackish- to fresh-water aquifers
150 - 400 Ohm-m	Sand and gravel fresh-water aquifers; volcanic rocks
> 400 Ohm-m	Dry sands and gravels; limestones; igneous and metamorphic rocks

The TDEM interpretations show units with low resistivities (10's or 20's of ohm-m) at depth almost everywhere in the valley, presumably due to clay or shale units. Alternately, these low values could represent units containing more brackish waters. Following Keller and Frischknecht (1966), our best guess is that the low resistivity units, especially those with formation resistivities less than about 30 ohm-m, represent Cretaceous marine shales. Such units have been mapped in Jackson Hole by Love and others (1992), and our descriptions below are taken from that reference. Some possible low resistivity units are:

Tsi - Shooting Iron Formation (Pliocene). Maximum thickness greater than 100 ft; lacustrine to deep-water claystone, sandstone, and siltstone. It is not clear whether Tsi is a marine unit. From its lithologic description, Tsi may be a poor aquifer; we might expect it to have resistivities in the 20-80 ohm-m range.

There are minor exposures of Tsi along the south ends of East and West Gros Ventre Buttes, so the unit could be present at depth, especially south of the Jackson thrust fault. Tsi's thinness and scarcity make it a low-probability candidate for representing the deepest interpreted layer at most of the present sounding sites.

Tte - Teewinot Formation (upper Miocene). Thickness up to 6000 ft; soft porous limestone, claystone, and pumicite. From the lithologic description of Tte, we expect its resistivity to be in the 50-150 ohm-m range. These lithologies argue that Tte might make a fair aquifer, though the claystone layers could represent aquitards. There are good exposures of Tte on the upthrown sides of normal faults just east of soundings TCW05 and TCW07. Tte unconformably overlies older Tertiary units below it. Some units under Tte are the Colter formation (middle-to-lower Miocene, 0-4900 ft thick) and other Tertiary units whose lithological descriptions argue that they might make poor-to-fair aquifers and lead us to estimate they may have resistivities in the 100-250 ohm-m range.

Kh - Harebell Formation (Upper Cretaceous). Thickness up to 10,000 ft; marine conglomerate, sandstone, claystone, and tuff; generally dark in color; claystones are silty. Kh is probably a poor aquifer, and is the kind of unit that might have a resistivity of less than 20 ohm-m. Kh crops out on the mountains east of Jackson Hole, and so might be present at depth in the valley block. Other Cretaceous rocks (unconformably) underlying Kh are also mostly marine; some (Kmv, Mesaverde Formation) are too sandy to have such low resistivities (also, a USGS crew has measured Kmv resistivity to be about 100 ohm-m in Colorado), but others (Bacon Ridge Sandstone, Cody Shale, Frontier Formation, Mowry Shale, Thermopolis Shale...) contain much silt, clay or shale, and might be electrically indistinguishable from Kh.

DISCUSSION

To facilitate comparison with well data in Jackson Hole, geoelectric depths originally calculated in terms of meters are expressed in feet in this section.

Almost everywhere in the north valley (at TCW01, 02, 03, 05, 06, and 07) Layer 1 has moderate to high resistivities, in the range 180-375 ohm-m. Surficial units here are glacial sands and gravels (Love and others, 1992). The units making up Layer 1 appear to be thick and uniform, and likely represent an excellent aquifer. They are thickest in the north (2430 ft at Potholes (TCW06)) and thin to the south and east (about 1000 ft at Jenny

Lake (TCW 01) and Baseline Flats (TCW03); 820 ft at Antelope Flats (TCW02); about 450 ft at Airport Lookout (TCW07) and Gros Ventre (TCW08)). Layer 1 at TCW04, 08, and 09 has lower resistivities (50-100 ohm-m), possibly reflecting a higher proportion of clays and silts in the shallow geological units at those places. There are shallow wells in those areas that produce ground water, and so at least parts of Layer 1 there must represent aquifer material. Soundings made in 1994 (TCW10, 11, 12 and 13) show Layer 1 resistivities in the 150-400 ohm-m range. Wells nearby produce ground water in substantial amounts, so these units clearly represent good aquifers. At these south-Jackson-Hole locations (that is, TCW09-13), the units that comprise Layer 1 probably include alluvial deposits, lacustrine sediments, and glacial scour (Kenneth L. Pierce, USGS, oral commun., 1994). Except for TCW13, the 1994 soundings were made along the western edge of Jackson Hole. There Layer 1 again thickens to the south; about 610 ft at Teton Village (TCW12), 900 ft (or more -- see below) at Resor's quarry (TCW10), and 1150 ft near the town of Wilson (TCW11). TCW13 (Halpin's) is surrounded on three sides by hills made up of mostly Paleozoic sedimentary rocks (Love and others, 1992), but may have 240 ft of alluvial and/or other medium-resistivity units near the surface.

Eleven of the 13 TDEM soundings detected a <30 ohm-m layer at depth that we interpret to represent Cretaceous marine shales. The two soundings that did not were TCW13 (Halpin's) and TCW11 (Hardeman's, near Wilson). At TCW13, the presence of Cretaceous shales seemed geologically unlikely; we expected to detect a high-resistivity electric basement there, probably consisting of Paleozoic rocks like those in nearby hills. Instead, all solutions (Figs 14b,c) gave Layers 2 and/or 3 with resistivities in the 30-50 ohm-m range. TCW13 lies on an east-west trending, structural belt that includes both the Cache Creek thrust fault and Jackson thrust fault (recently mapped by Love and others, 1992, near where the Cache thrust of Fig. 1 projects through the valley), and these resistivities may reflect such complexities. A single TDEM sounding, as this one was, would not be able to distinguish possible steeply-dipping units or faults in the belt.

It is appropriate here to emphasize, in general, that the our interpretations of the TDEM data assume ideal geoelectric layers that are flat, uniformly thick, and infinite in extent. True geoelectric layer(s), however, may dip, change thickness, and have limited lateral extent(s) -- for example, they may be cut off by faults or pinch out stratigraphically. Geoelectric soundings that are made where the geologic units are fairly flat and uniform, and in places far from such edges, can usually be interpreted adequately using the above ideal assumptions. Interpretations of soundings made over units with limited lateral extent, however, will be more or less distorted. These TDEM soundings were made in a way that does not check for the presense of such lateral changes -- one must use geologic information or some other inference than the TDEM data itself. Except for sounding site TCW13, we have no reason to suspect our interpretations on the grounds of possible lateral effects. That possibility, though, must be kept in mind as these TDEM interpretations become synthesized with other Jackson Hole data.

The interpretation of TCW11 (Wilson) shows a 1150 ft-thick Layer 2 with 60-90 ohm-m resistivity, underlain by a high-resistivity electric basement. Layer 2 may represent shaley sands or silts, either marine or non-marine. The high-resistivity basement at 2340 ft may reflect crystalline rock.

The interpretation of TCW10 (Resor's quarry) shows a Layer 2 with resistivity that is unusually high for this area (see table 3). Unlike most other TDEM soundings in this set, its resistivity is not well determined -- it can range from about 200 to 20,000 ohm-m. Below Layer 2 is a 19 ohm-m unit which we assume to represent Cretaceous marine shales. This interpretation implies that Layer 2 is post-Cretaceous, and in turn that its "best fit" resistivity of 1355 ohm-m is too high (resistivity values that high usually reflect dry, cemented sand and gravel or crystalline rocks). A resistivity of about 400 ohm-m would also fit the data; in that case Layer 2 might represent a fresh-water aquifer mainly composed of gravels.

TCW02 has two very low-resistivity layers -- Layer 2 with 11 ohm-m and Layer 3 with 1.7 ohm-m. Both may represent marine shales. This location (Antelope Flat) is in the middle of the valley and along the axis of the Jackson Hole gravity low (Fig. 1 and next paragraph), so that a thick accumulation of fine-grained valley sediments is possible there.

Earlier geophysical work done in the Jackson Hole has been reported by Behrendt and others (1968). Their report shows seismic refraction lines, magnetic maps, and gravity maps of the valley. Their seismic line 3 extends from south of Blacktail Butte to about Moran Junction (near TCW07 to northwest of TCW04). Its interpreted seismic depths are shown on a small-scale figure that is hard to read precisely enough to make close comparisons at the places where the seismic line passes nearest to our TDEM sites; qualitatively, however, its seismically-interpreted depths agree with the interpreted TDEM depths. The magnetic map is generally featureless over the part of Jackson Hole where the TDEM soundings were made, and it is not useful to us. The gravity map, however, is valuable, for it shows a series of lows in the eastern-middle valley. That map is reproduced and included with Figure 1. Gravity lows of this kind tend to outline places of thickest and/or most porous sediments. Hence, the gravity map shows (and our TDEM soundings agree) that the valley fill thickens substantially to the north. It also argues that the deepest part of the Jackson Hole is along its east-central axis, rather than crowded against the Teton Mountain wall, as we might think. The gravity low is broken over Blacktail Butte, a thrust sheet remnant that consists of rocks of higher density than that of the sediments in the surrounding valley. Could this remnant be perched high within the valley sediments, or must it be rooted at depth? To answer this question, we note that all gravity anomalies Δg take Bouguer form

(5) $$\Delta g = 12.77\ F\ h\ \Delta d$$

where Δd = density difference in g/cm^3 between the body causing the anomaly and its background, h is the vertical thickness of the body in kft, F is a dimensionless factor usually somewhat less than 1.0 that reflects the body's shape, and Δg is in mGals. For Blacktail Butte, Δg = 15 mGal, approximately, so that h Δd ≈ 1.2 kft-g/cm^3. If Δd = 0.3 g/cm^3, then the Blacktail Butte remnant must be about 4000 ft thick; that is, it may extend about 3000 ft beneath the level of the flat valley surface around it. We infer that the keel of the Blacktail Butte remnant may extend into the deepest units detected by the TDEM soundings, and that it may affect ground-water flow in Jackson Hole.

Table 4 summarizes the above (speculative) interpretations.

Table 4.--Summary of interpretations of TDEM data in Jackson Hole, Wyoming. Depths to top of layers are in feet, and very approximate. SA+ = good surficial aquifer. SA- = poor surficial aquifer; LPZ = low permeability zone (likely aquitard); KMS = Cretaceous marine shales; XBR = crystalline bedrock.

Sounding	Layer 1	Layer 2 Depth		Layer 3 Depth	
01--Jenny Lake	SA+	1040	KMS	1840	KMS
02--Antelope Flats	SA+	820	KMS	1430	KMS
03--Baseline Flats	SA+	1060	LPZ	2000	KMS
04--Moosehead ranch	SA-	26	LPZ	1570	KMS
05--Lost Creek	SA+	360	KMS	-	-
06--Potholes	SA+	2430	KMS	-	-
07--Airport lookout	SA+	450	KMS	-	-
08--Gros Ventre	SA-	450	KMS	970	435
09--Oliver hay field	SA--	910	KMS	-	-
10--Resor's quarry	SA+	900	SA-	1460	KMS
11--Wilson	SA+	1150	LPZ	2340	XBR
12--Teton Village N	SA+	610	KMS	-	-
13--Halpin farm	SA+	240	LPZ	-	-

CONCLUSIONS

1. Most soundings detected a deep, low-resistivity layer of 2-30 ohm-m, probably representing upper-Cretaceous marine shales at depth. The conductive unit(s) represent a good mappable layer for further electrical surveys in Jackson Hole. It may or may not be an aquitard.

2. The surficial aquifer is very thick (2400 ft or more) in the north, and thins to about 450 ft near the Gros Ventre River, in the south. It may thicken along the west side of Jackson

Hole, from about 610 ft near Teton village to about 1150 ft near Wilson.

3. All soundings probed deeper than the 1000 ft limit which we had set as a minimum.

4. So far as we could determine, the data was not contaminated by nearby wire fences, power lines, etc. At TCW09, however, there were wire fences only 400 ft from two sides of the loop. We are probably fortunate that those fences had wooden posts instead of steel ones. We observed that hayfields in the southern part of Jackson Hole have wire fences and power cables for the irrigation rigs, which likely would preclude doing more TDEM there using 1000 ft square loops. A set of 82 audio-frequency magnetotelluric (AMT) soundings therefore were made in the southern part of Jackson Hole, and are presented in a companion Open-file Report by Senterfit and others (1995).

ACKNOWLEDGEMENT: We thank the Teton County Natural Resource District, the Jackson Hole Baseline Research Foundation, and the USGS Water Resources Division cooperative program for funding this work.

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Spies, Brian R., 1989, Depth of investigation in electromagnetic sounding: Geophysics, v. 54, no. 7, p. 872-888.

Fig 1a.--TCW01 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

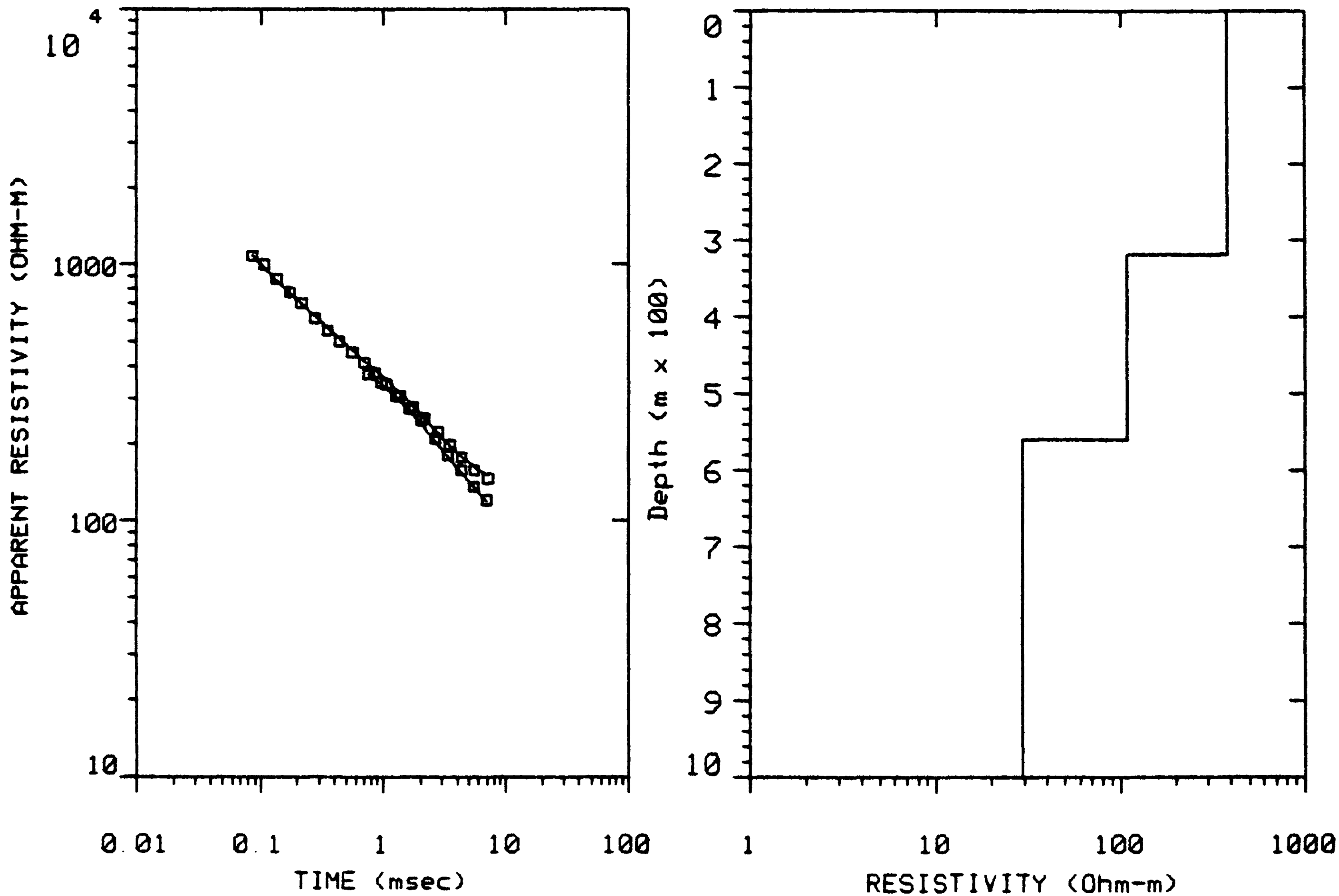


Fig 1b.--Three-layer equivalent models for TCW01. All models adequately fit the data shown on Fig 1a.

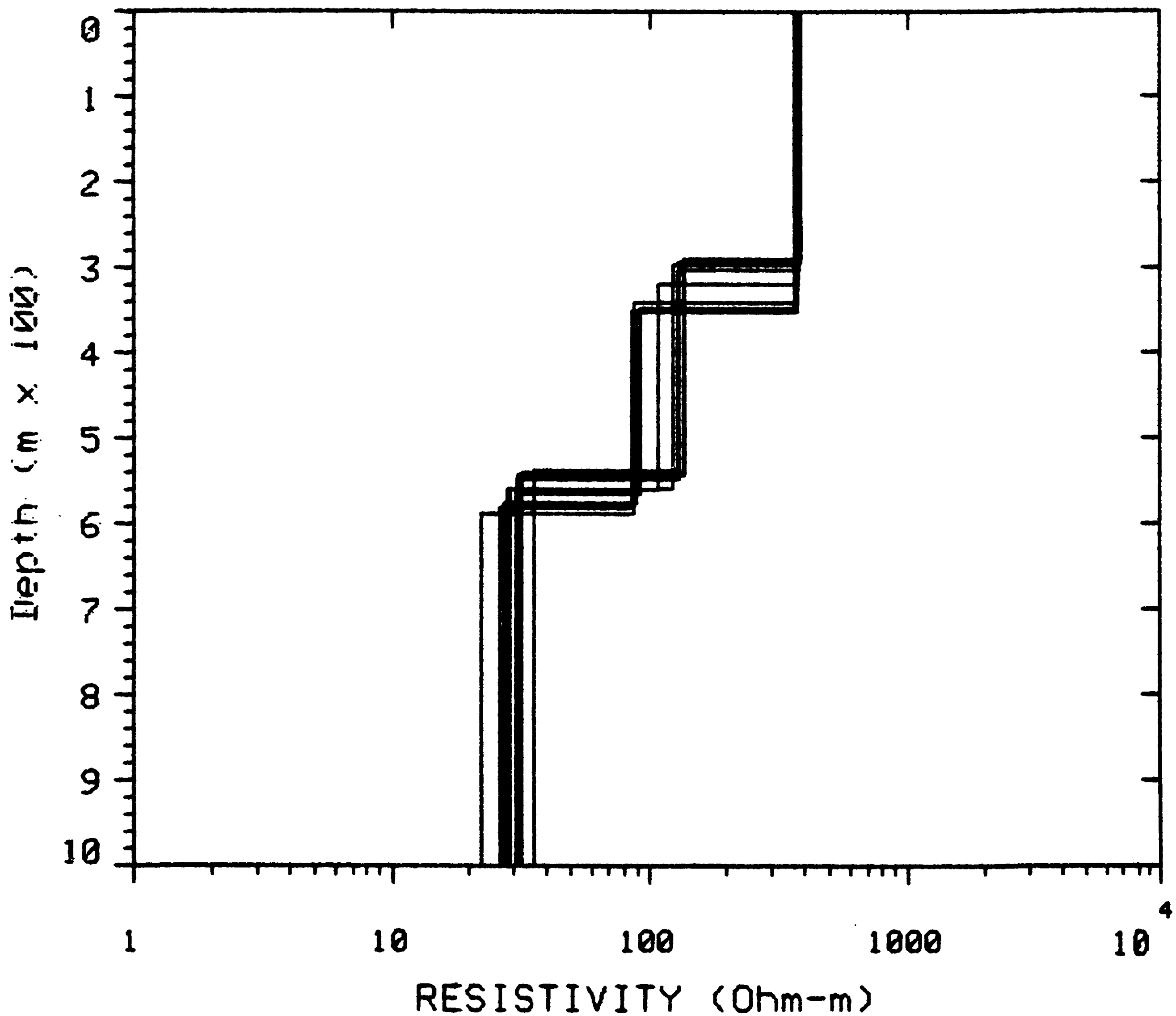


Fig 2a.--TCW02 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

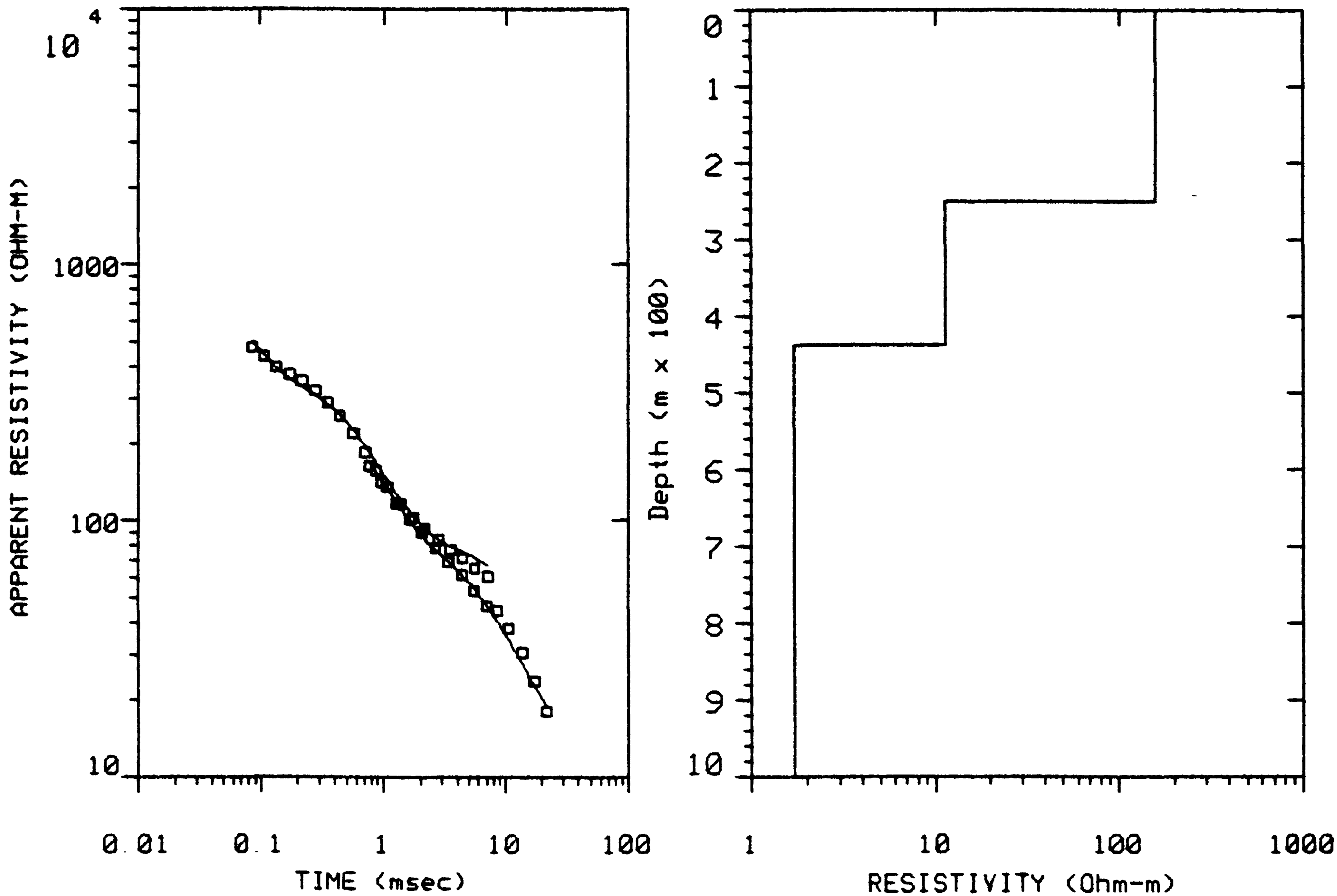


Fig 2b.--Three-layer equivalent models for TCW02. All models adequately fit the data shown on Fig 2a.

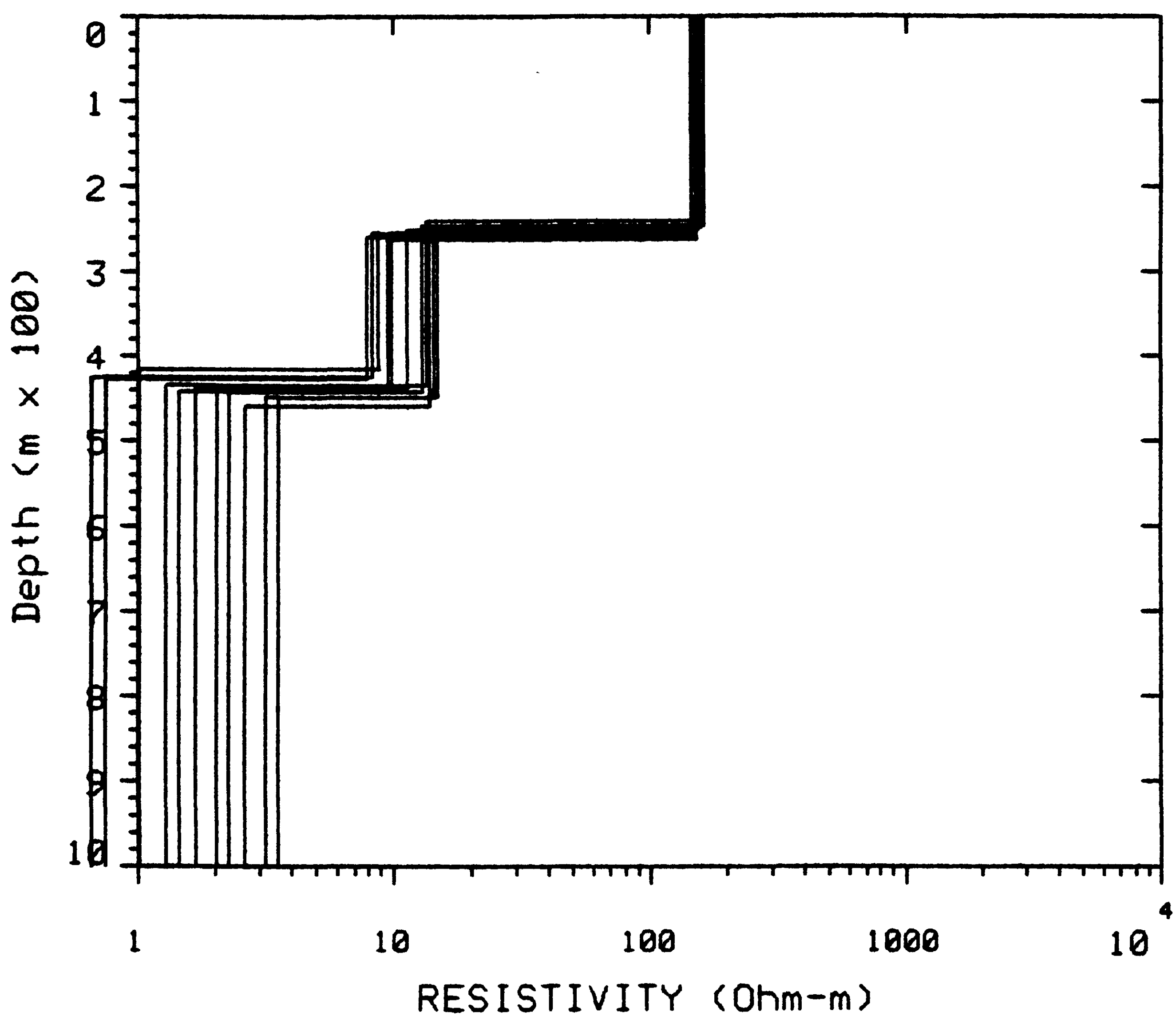


Fig 3a.--TCW03 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

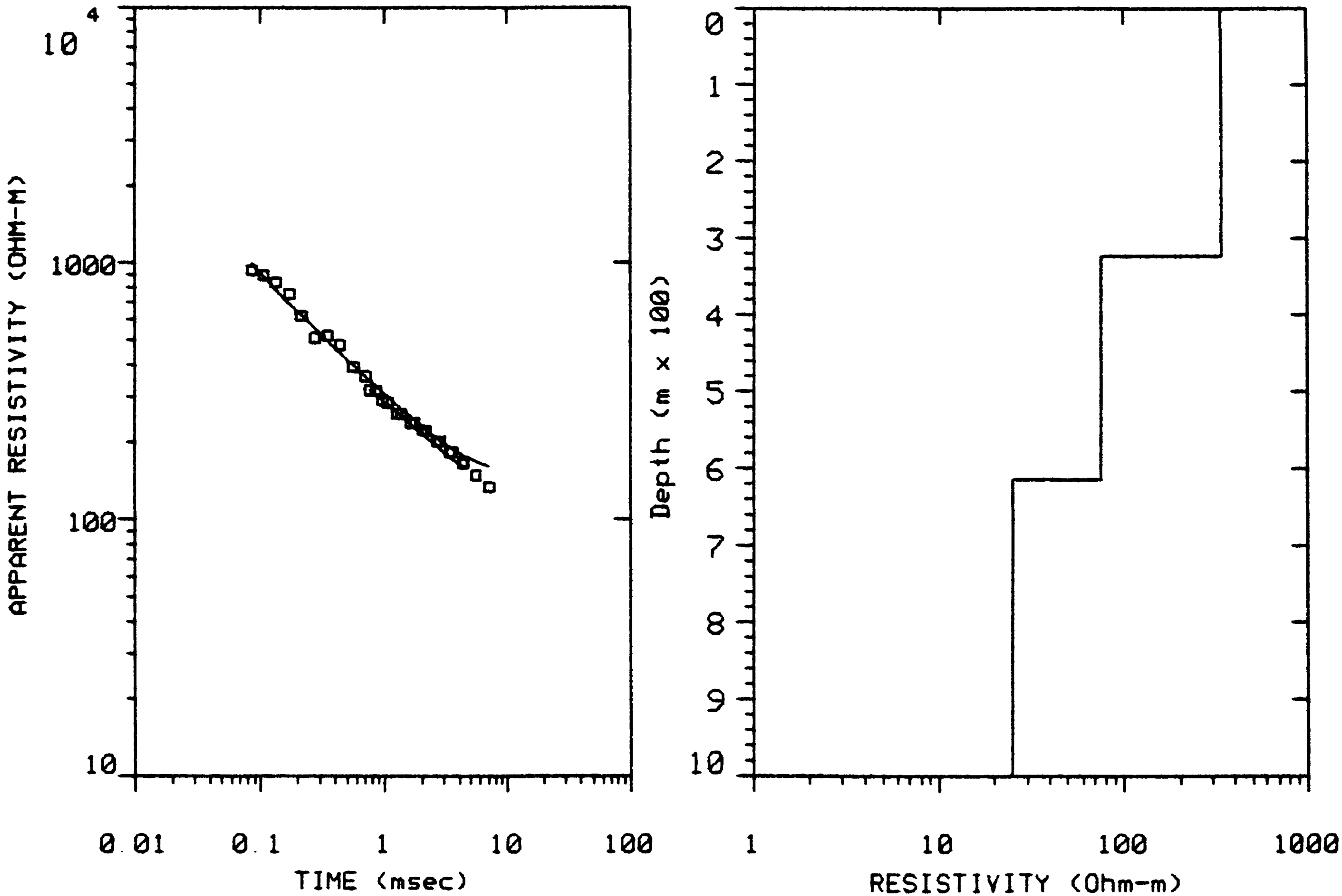


Fig 3b.--Three-layer equivalent models for TCW03. All models adequately fit the data shown on Fig 3a.

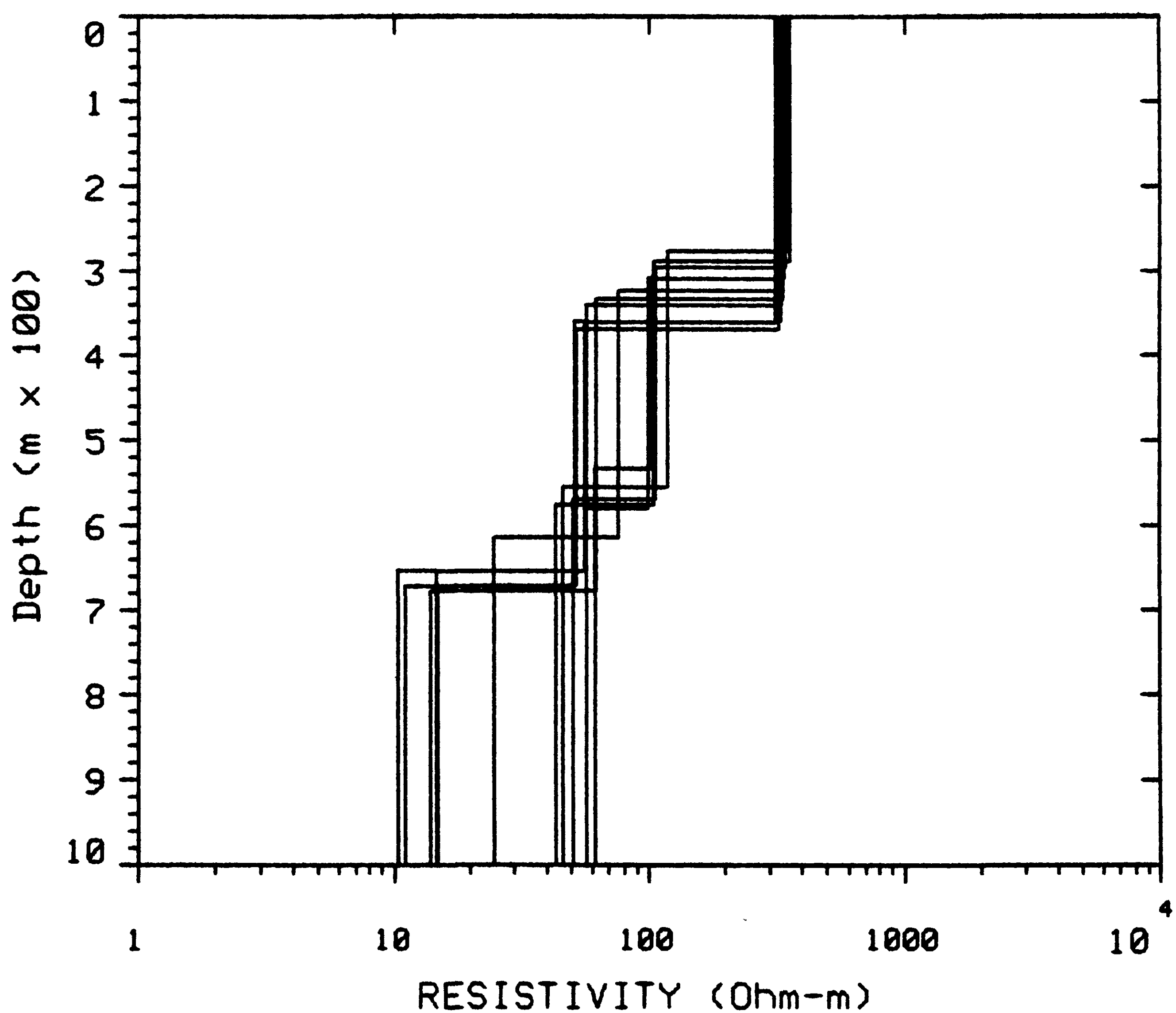


Fig 4a.--TCW04 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

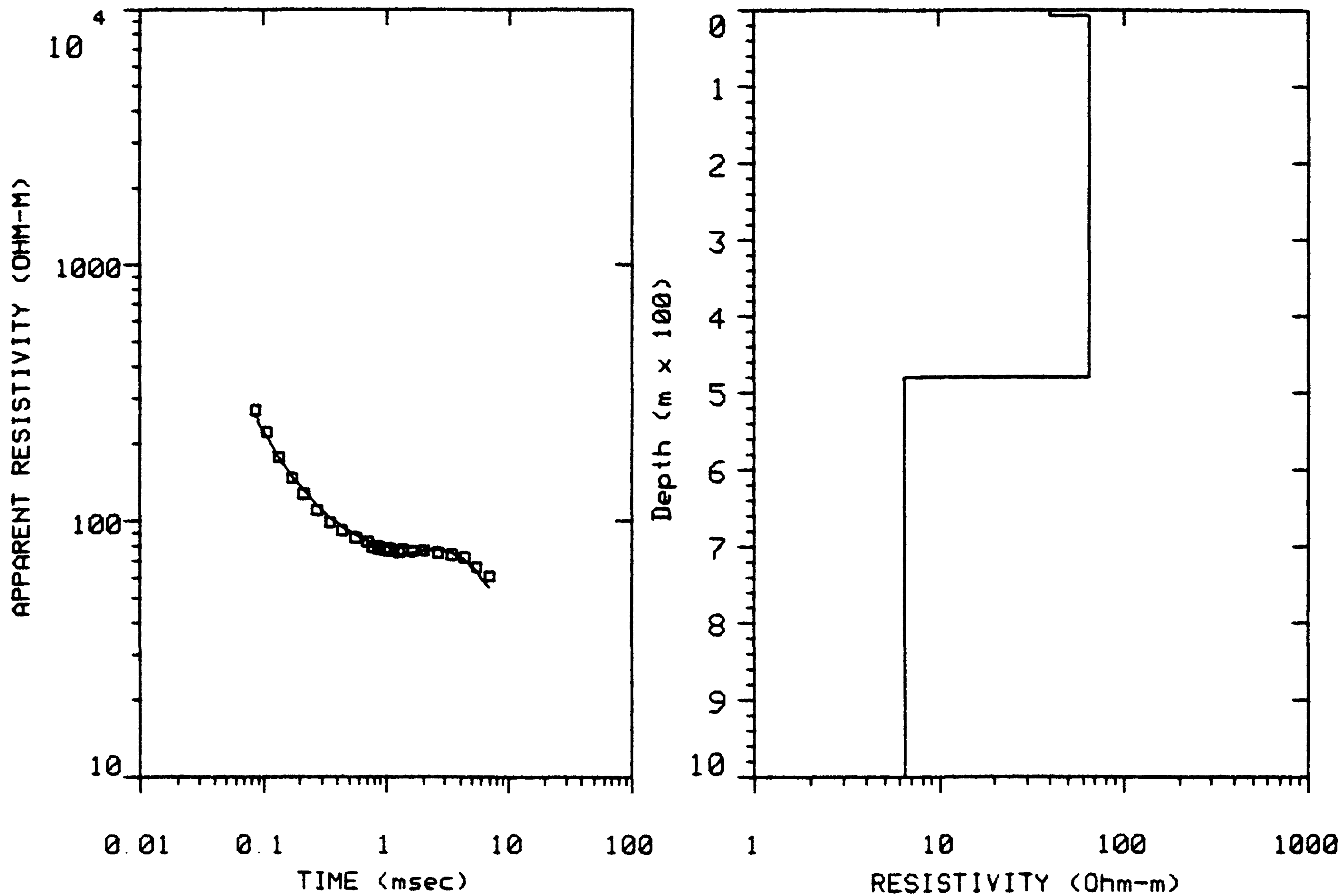


Fig 4b.--Three-layer equivalent models for TCW04. All models adequately fit the data shown on Fig 4a.

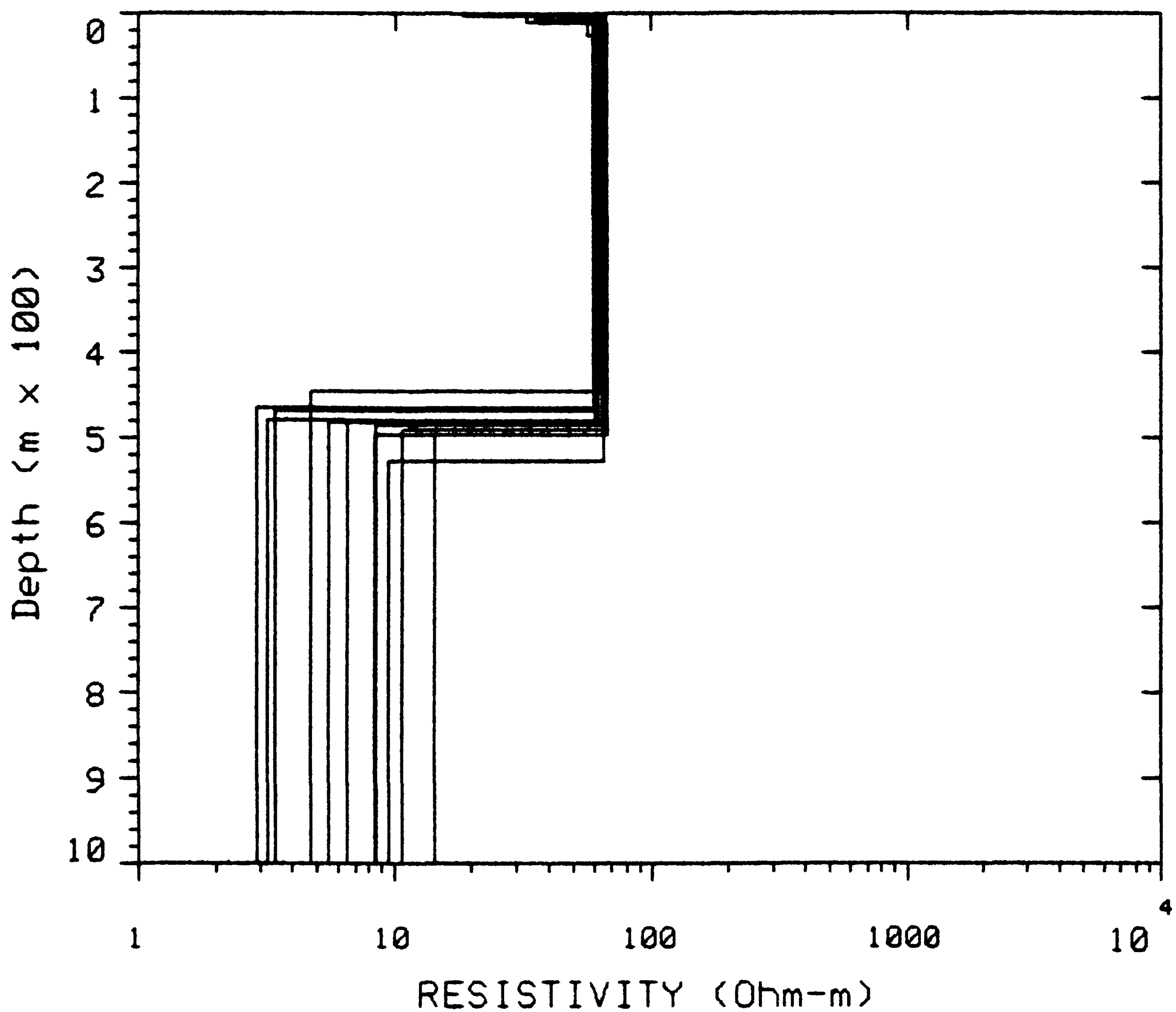


Fig 5a.--TCW05 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

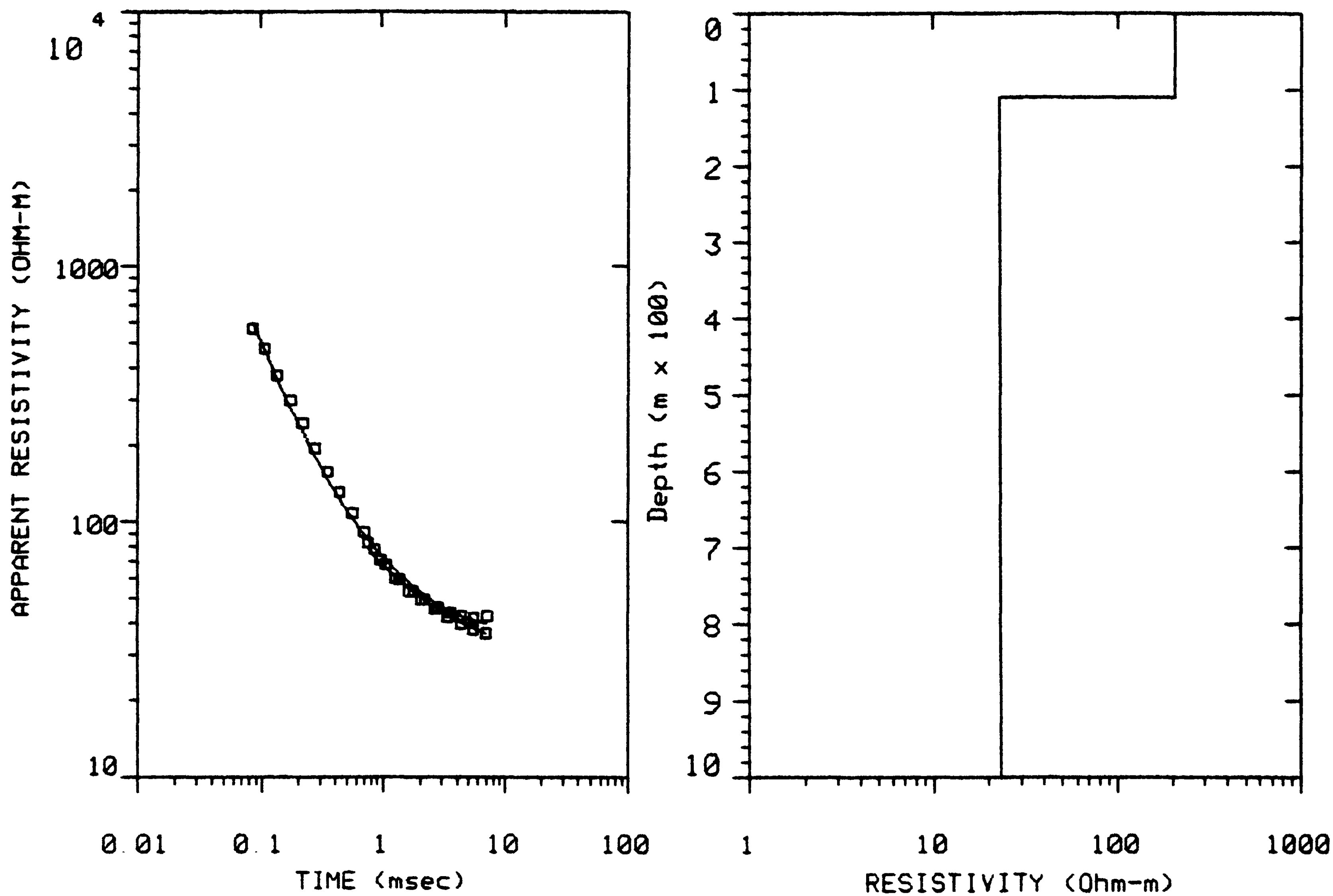


Fig 5b.--Two-layer equivalent models for TCW05. All models adequately fit the data shown on Fig 5a.

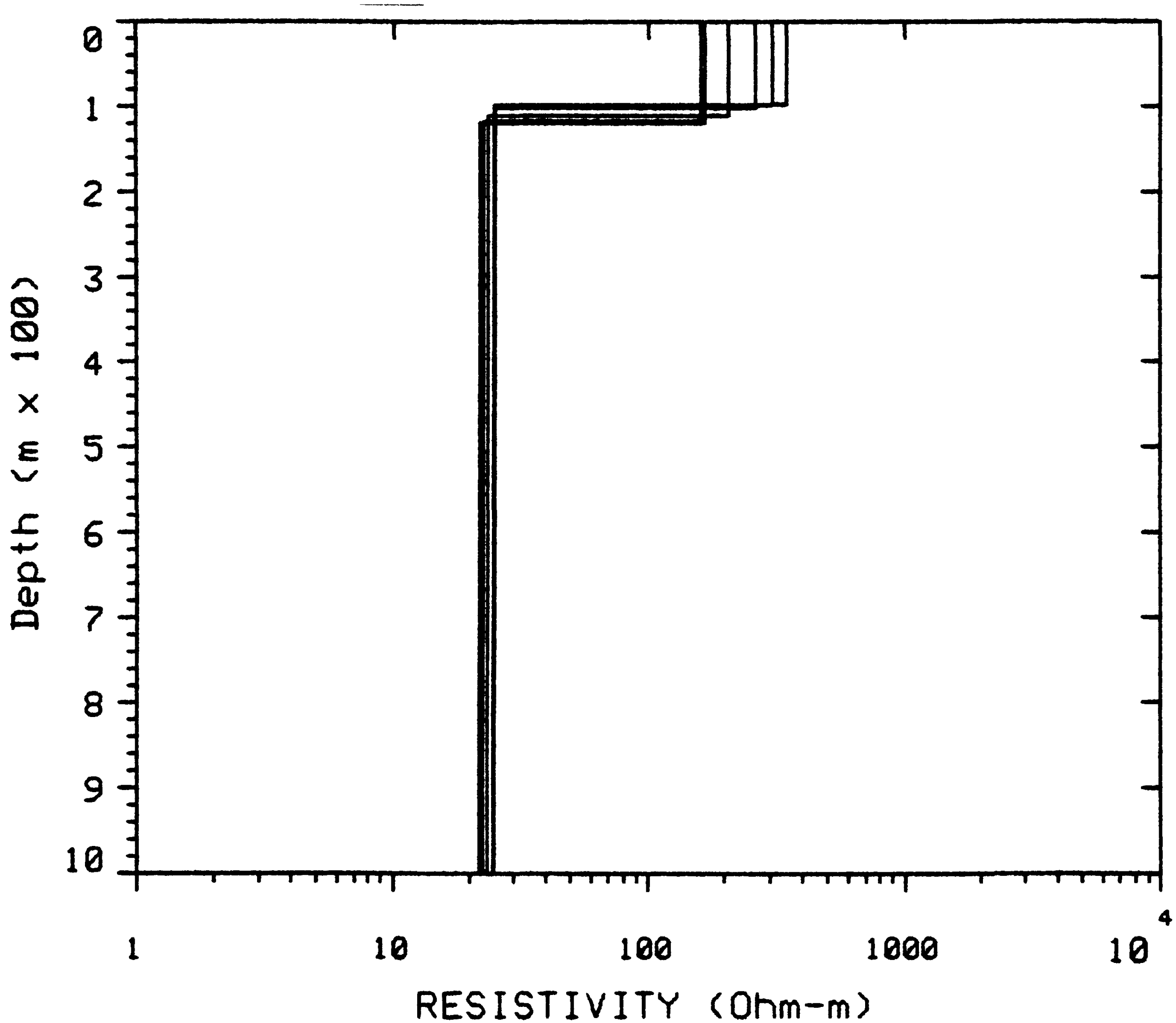


Fig 5c.--Three-layer equivalent models for TCW05. This plot helps indicate constraints or lack of them on the two-layer solution shown in Fig 5b.

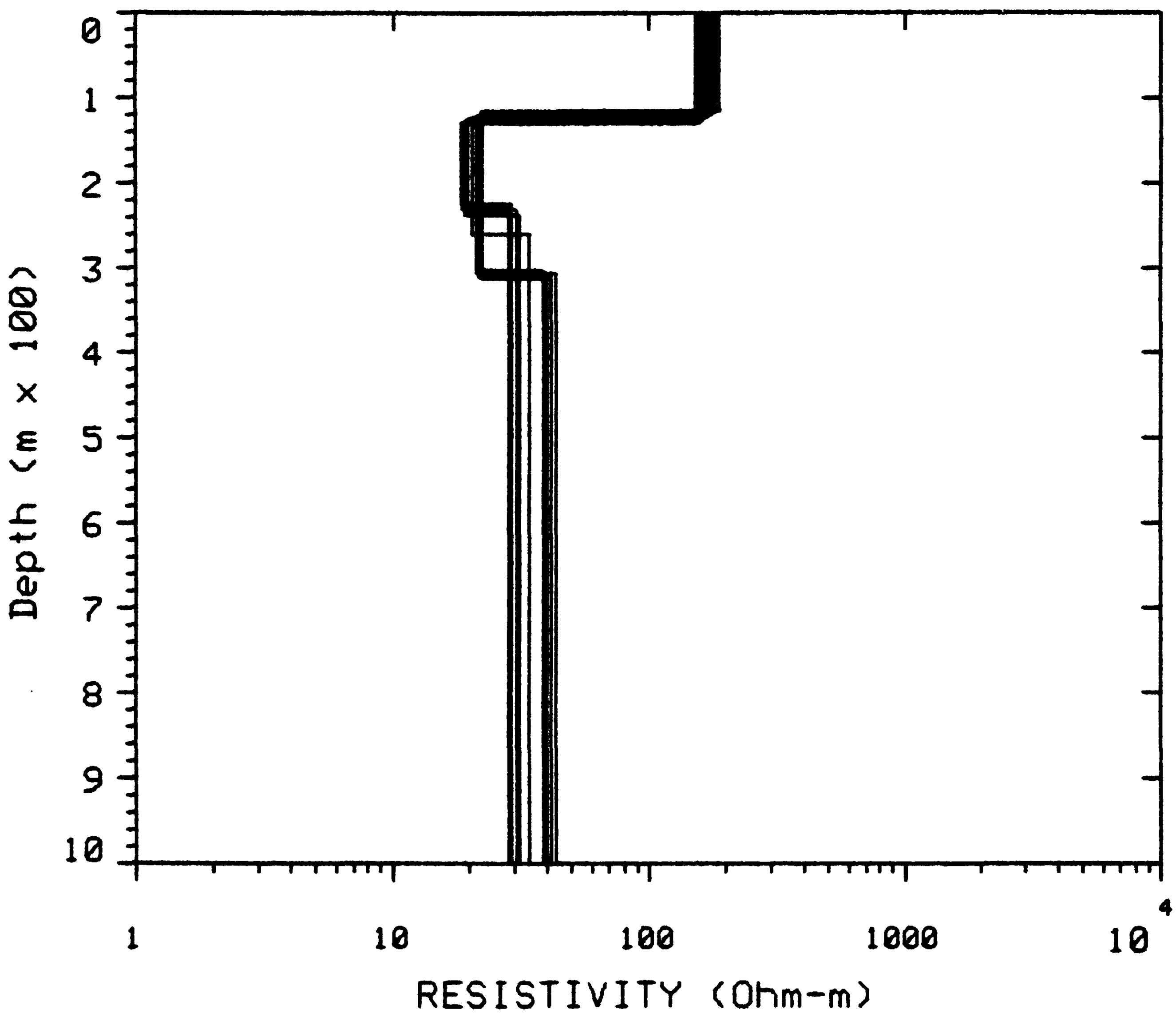


Fig 6a.--TCW06 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

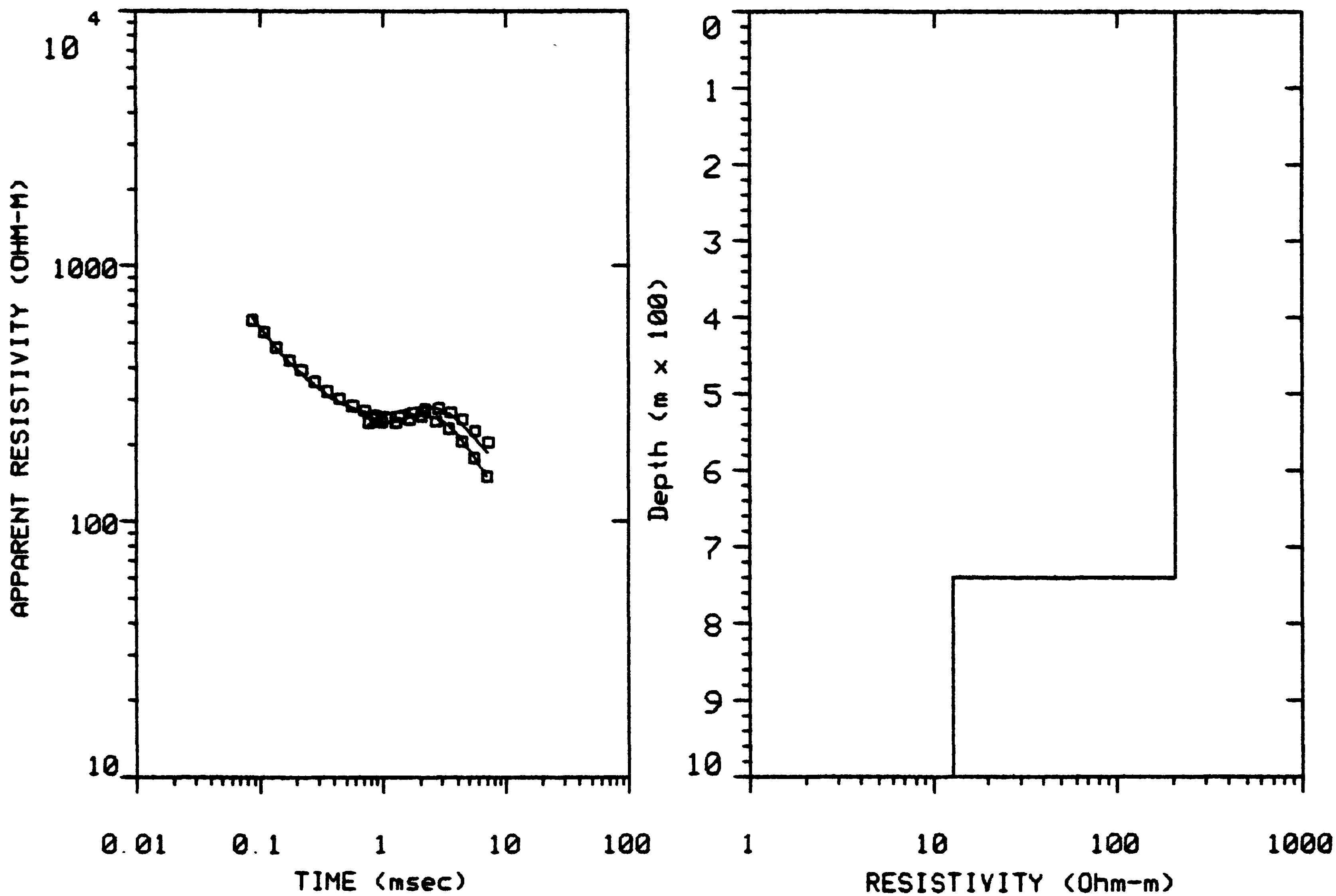


Fig 6b.--Two-layer equivalent models for TCW06. All models adequately fit the data shown on Fig 6a.

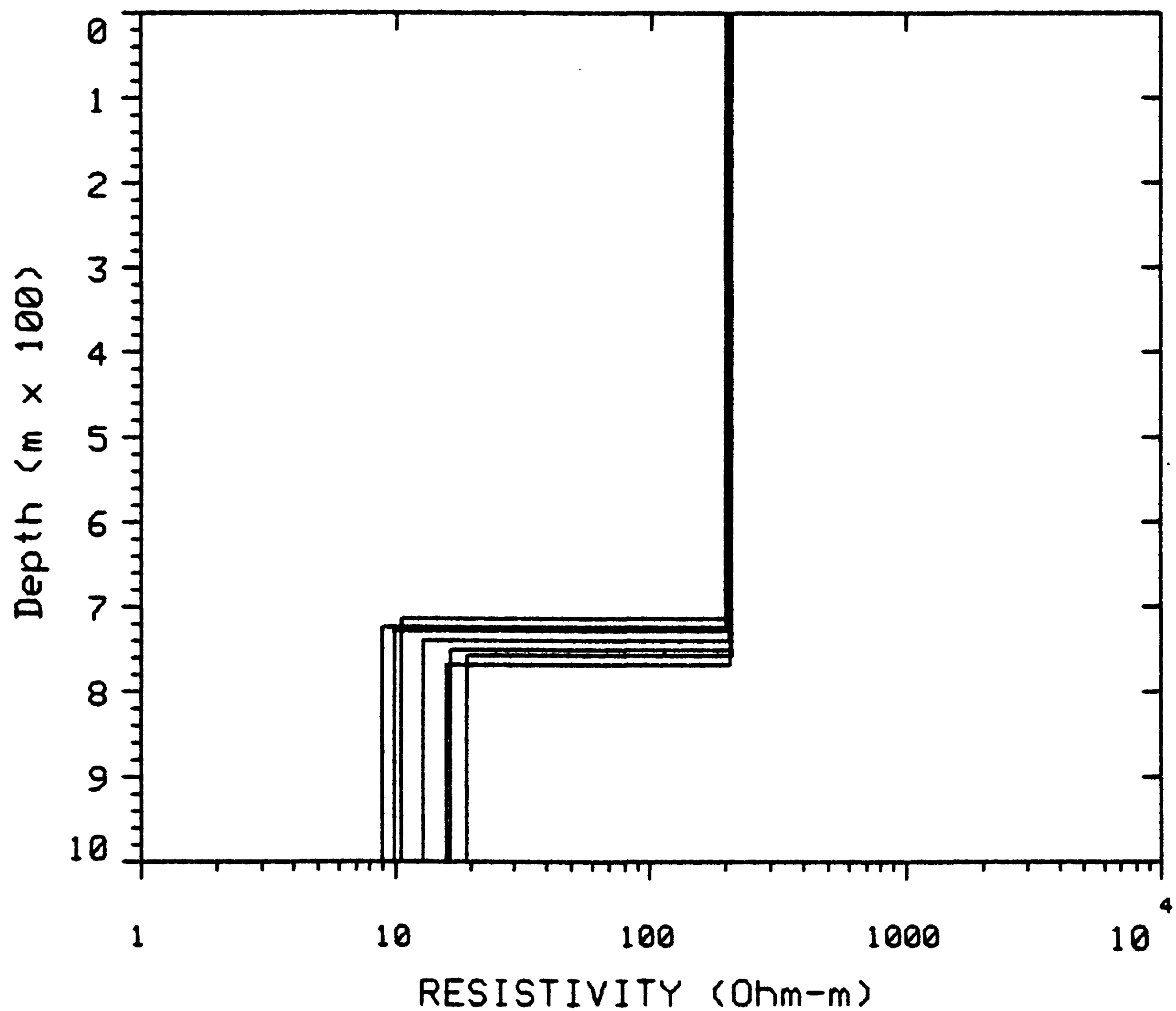


Fig 6c.--Three-layer equivalent models for TCW06. This plot helps indicate constraints or lack of them on the two-layer solution shown in Fig 6b. Note depth scale change from Fig 6b.

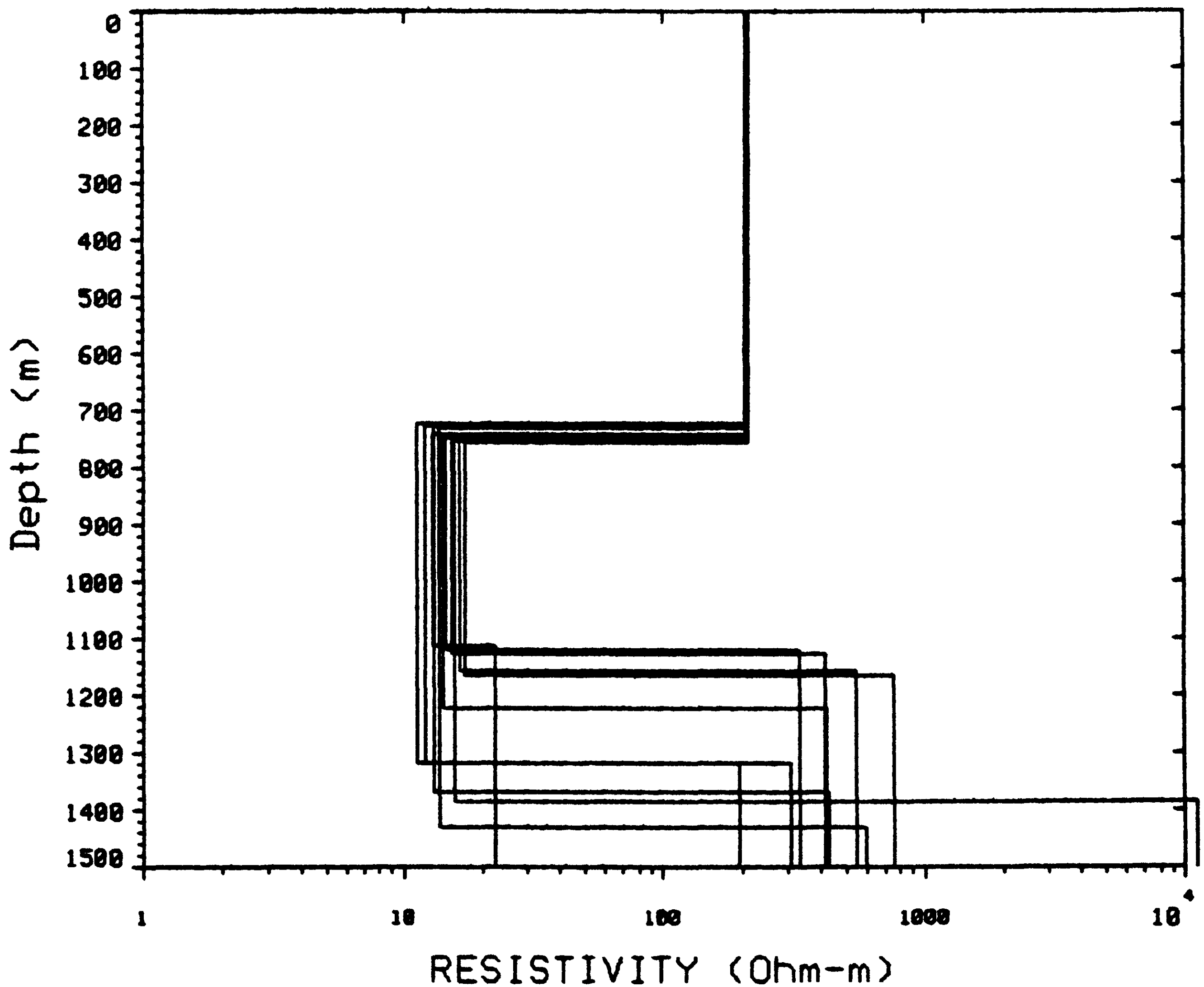


Fig 7a.--TCW07 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

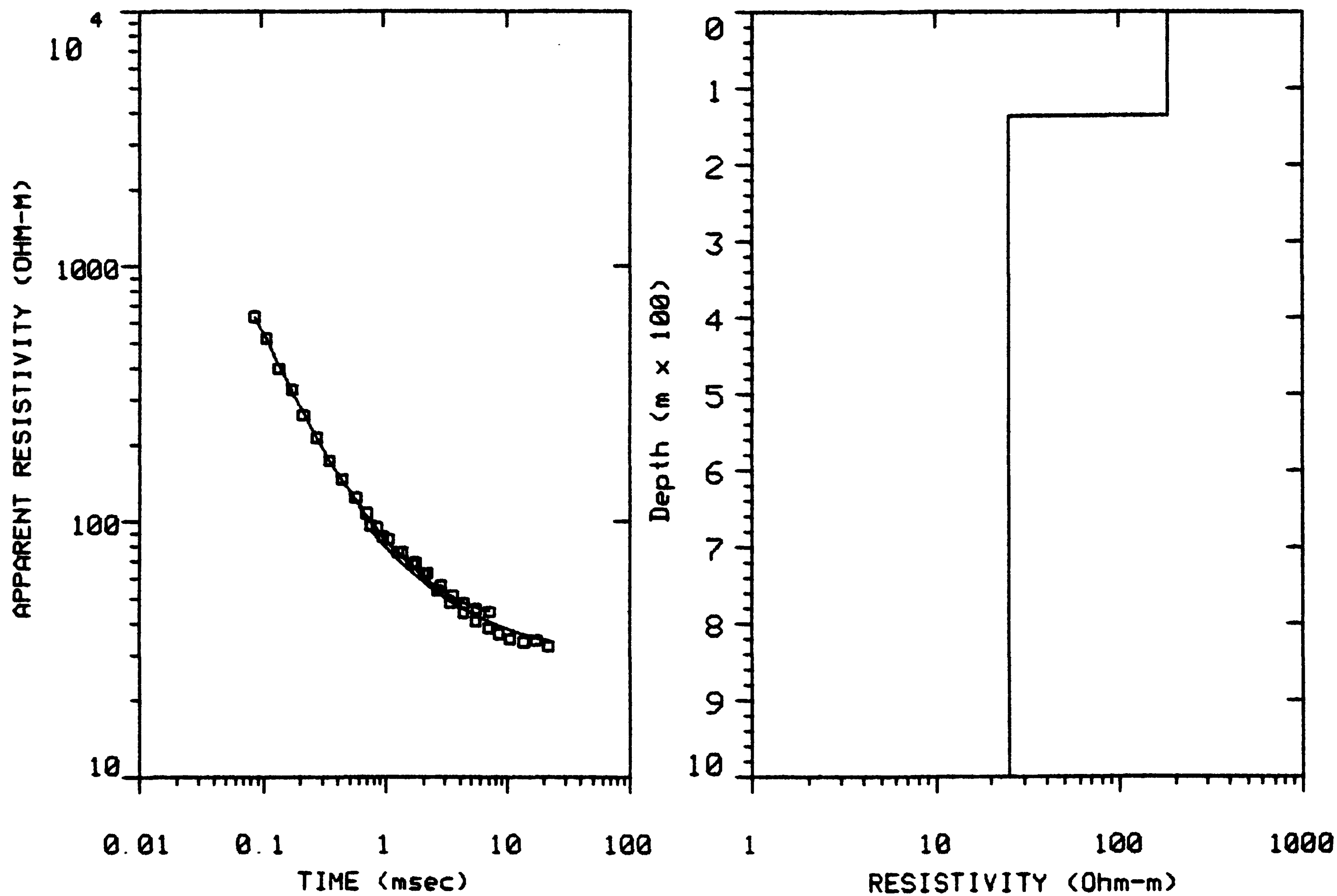


Fig 7b.--Two-layer equivalent models for TCW07. All models adequately fit the data shown on Fig 7a.

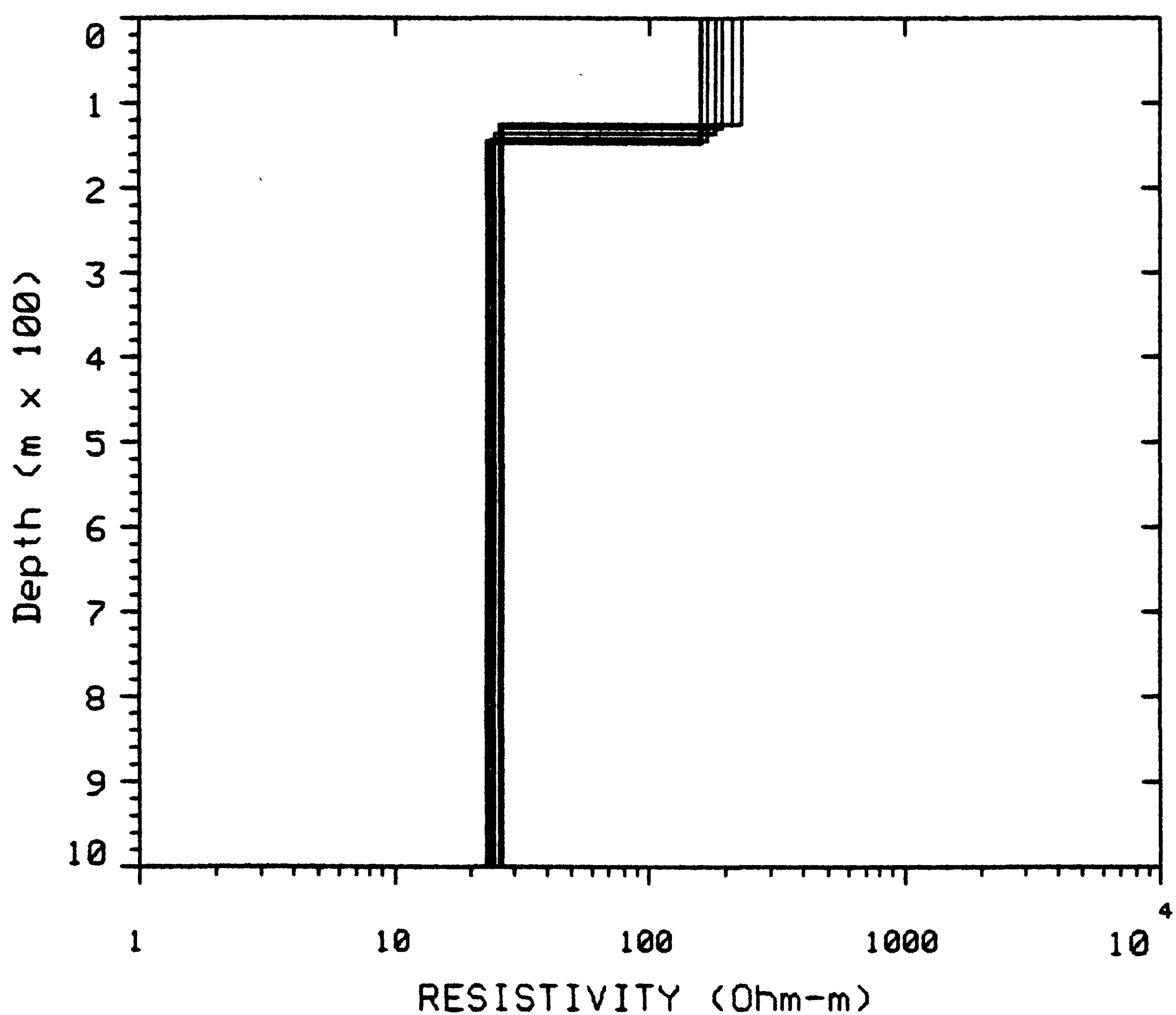


Fig 7c.--Three-layer equivalent models for TCW07. This plot helps indicate constraints or lack of them on the two-layer solution shown in Fig 7b. Note depth scale change from Fig 7b.

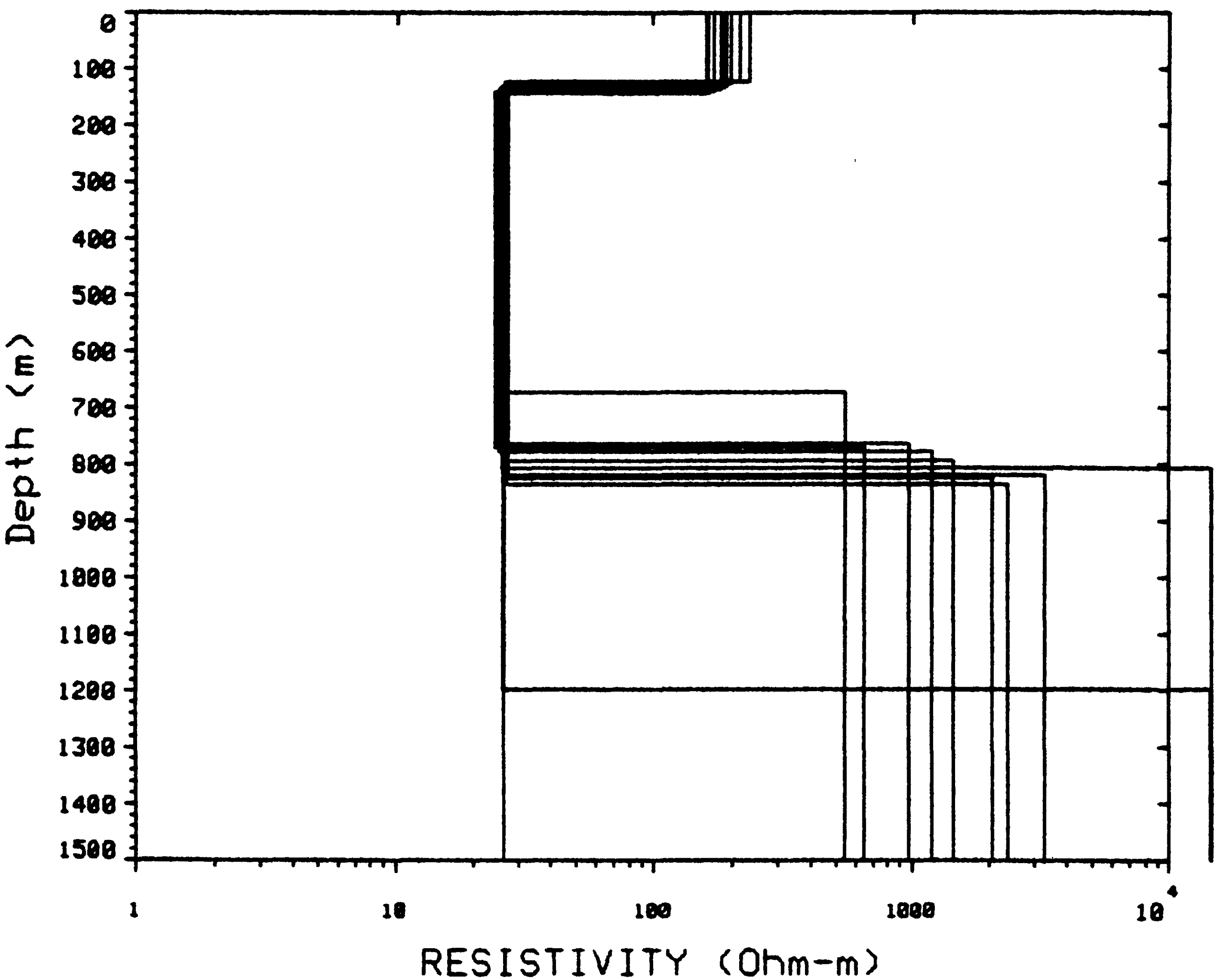


Fig 8a.--TCW08 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

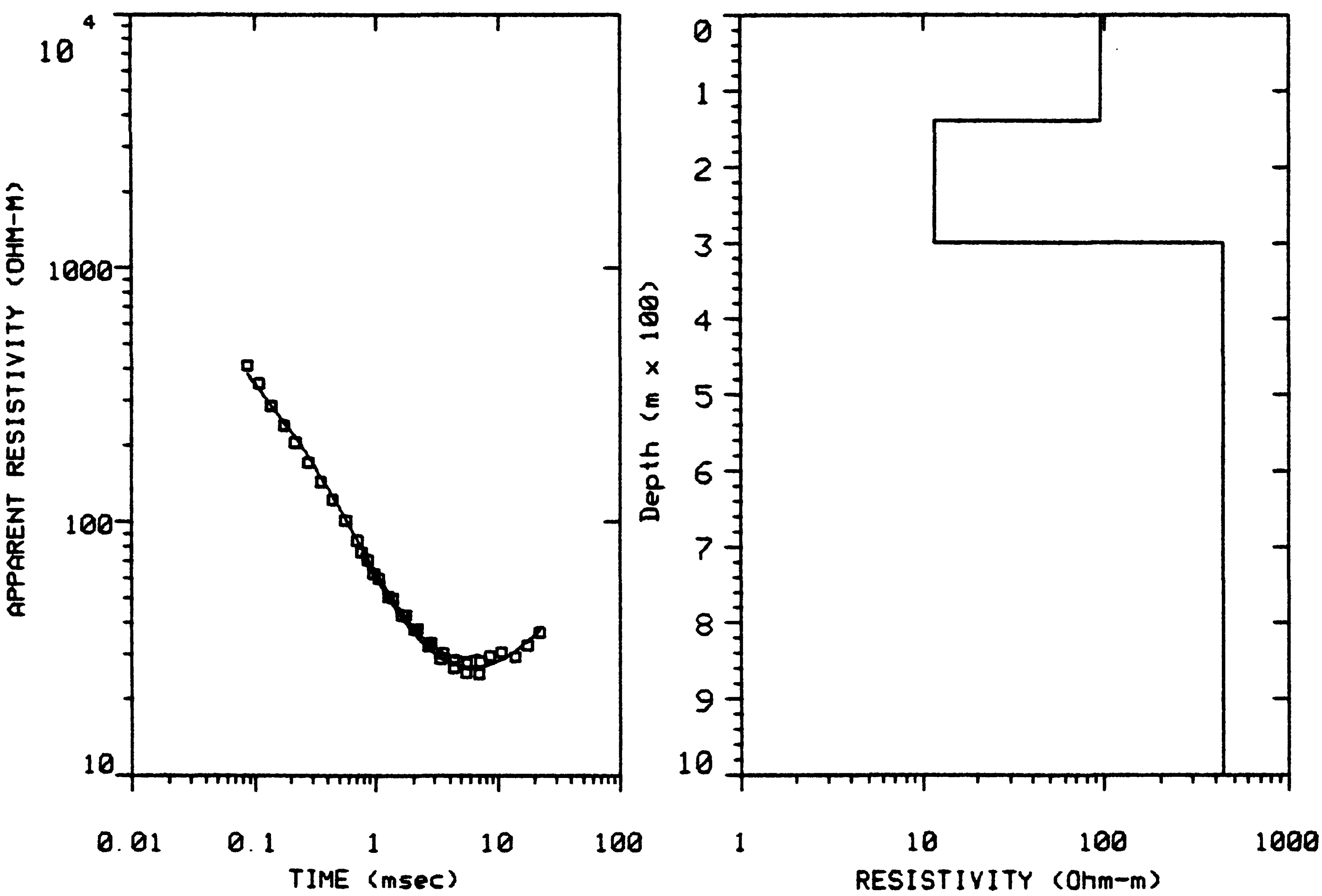


Fig 8b.--Three-layer equivalent models for TCW08. All models adequately fit the data shown on Fig 8a.

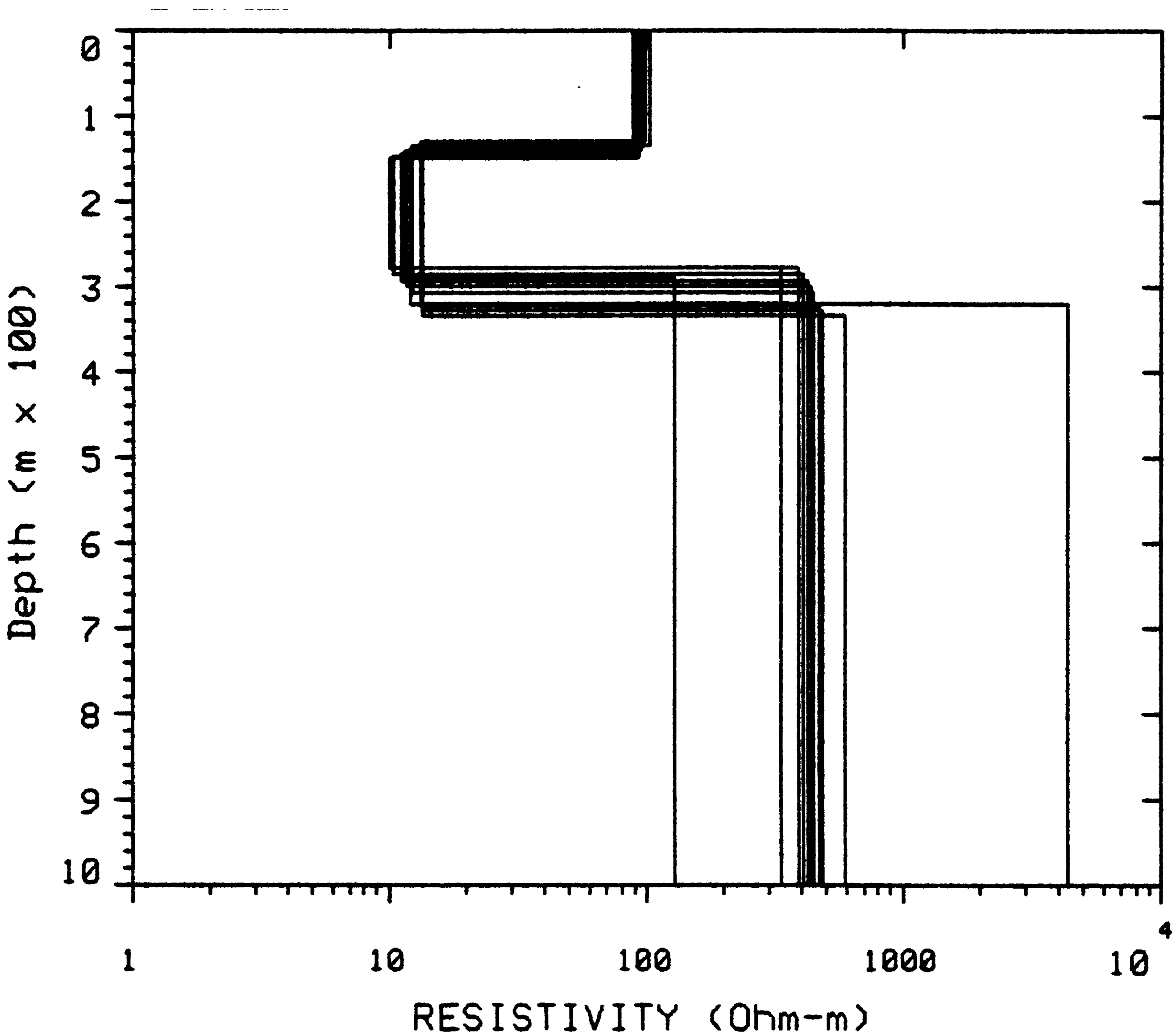


Fig 9a.--TCW09 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

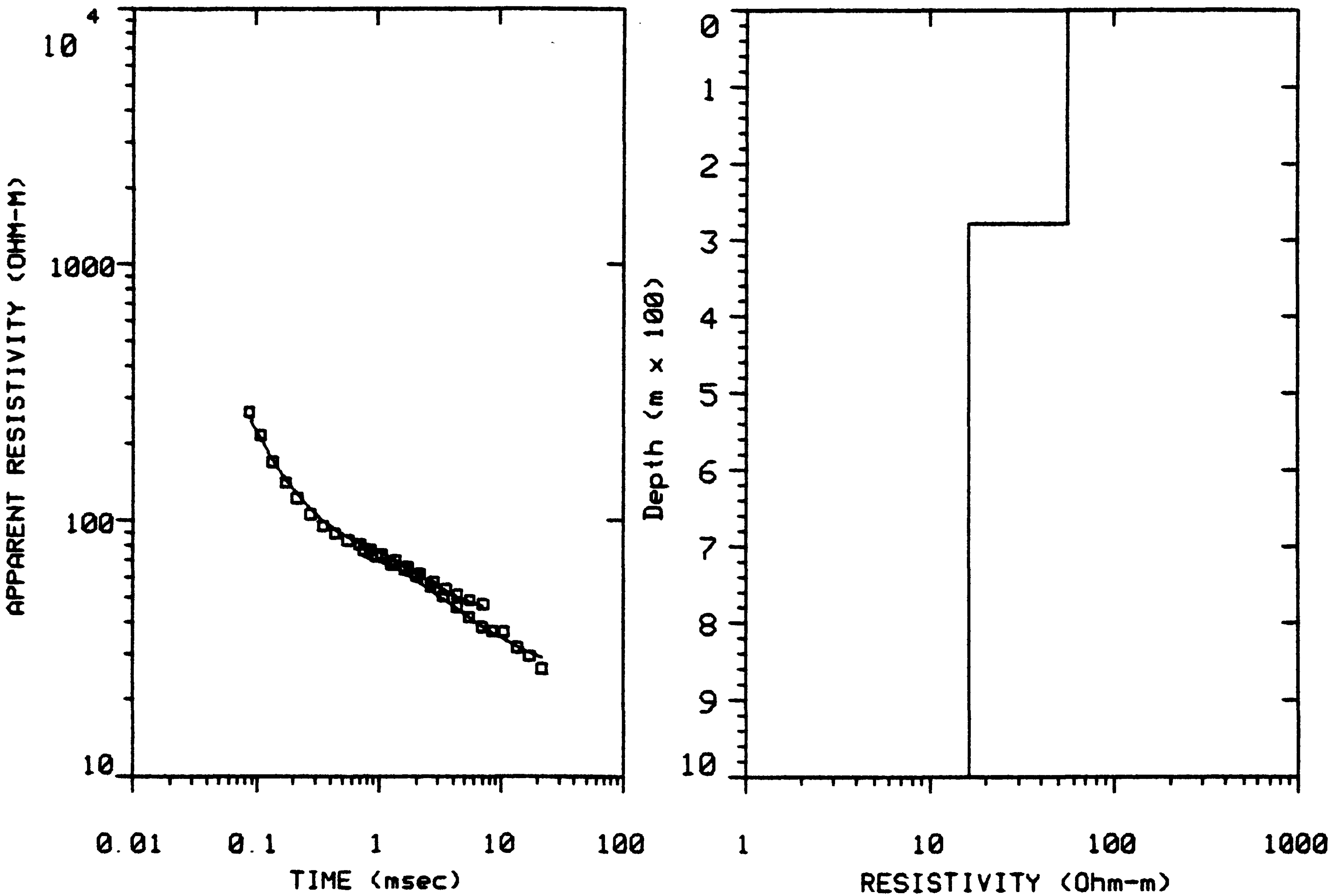


Fig 9b.--Two-layer equivalent models for TCW09. All models adequately fit the data shown on Fig 9a.

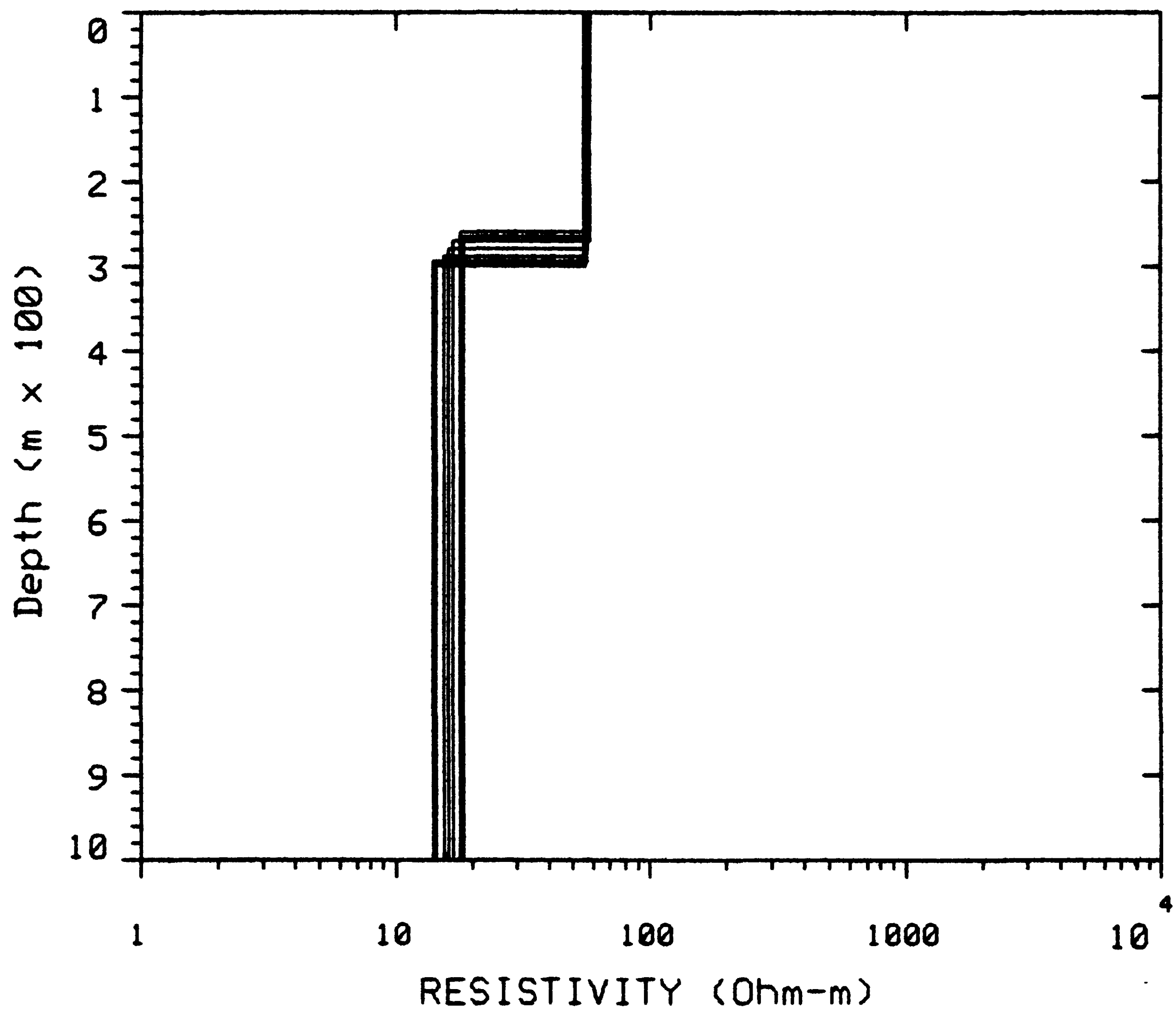


Fig 9c.--Three-layer equivalent models for TCW09. This plot helps indicate constraints or lack of them on the two-layer solution shown in Fig 9b. Note depth scale change from Fig 9b.

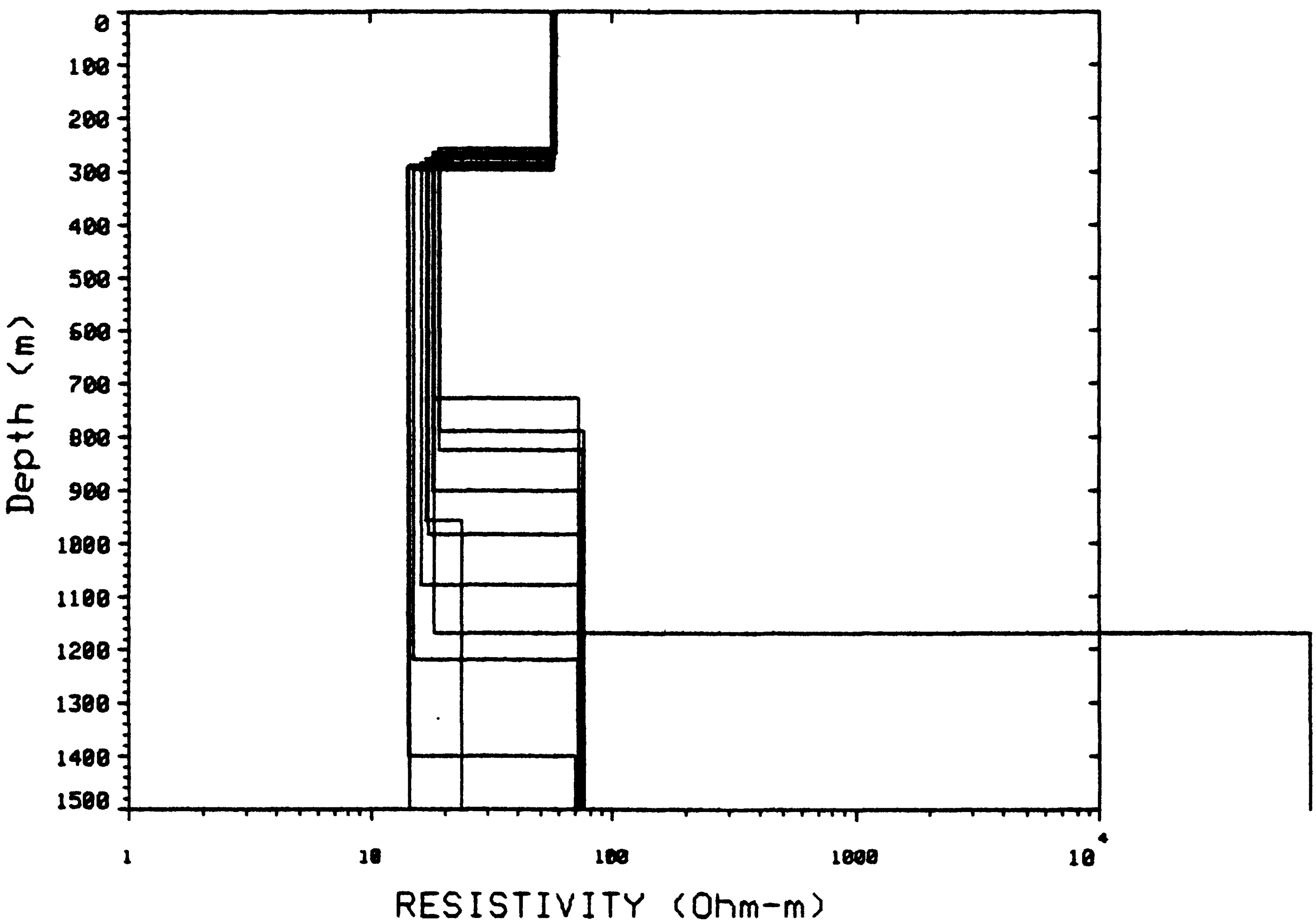


Fig 10a.--TCW10 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

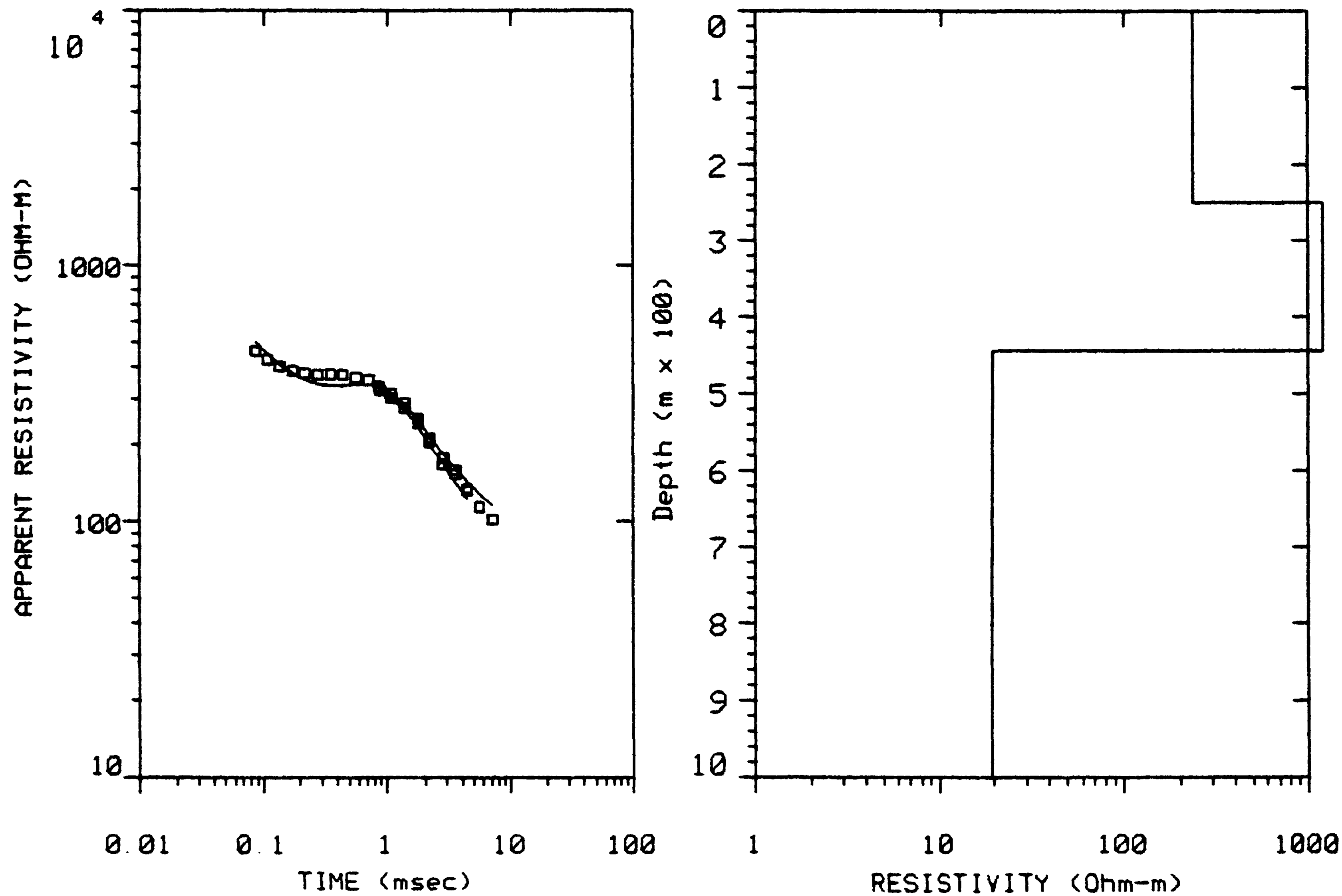


Fig 10b.--Three-layer equivalent models for TCW10. All models adequately fit the data shown on Fig 10a.

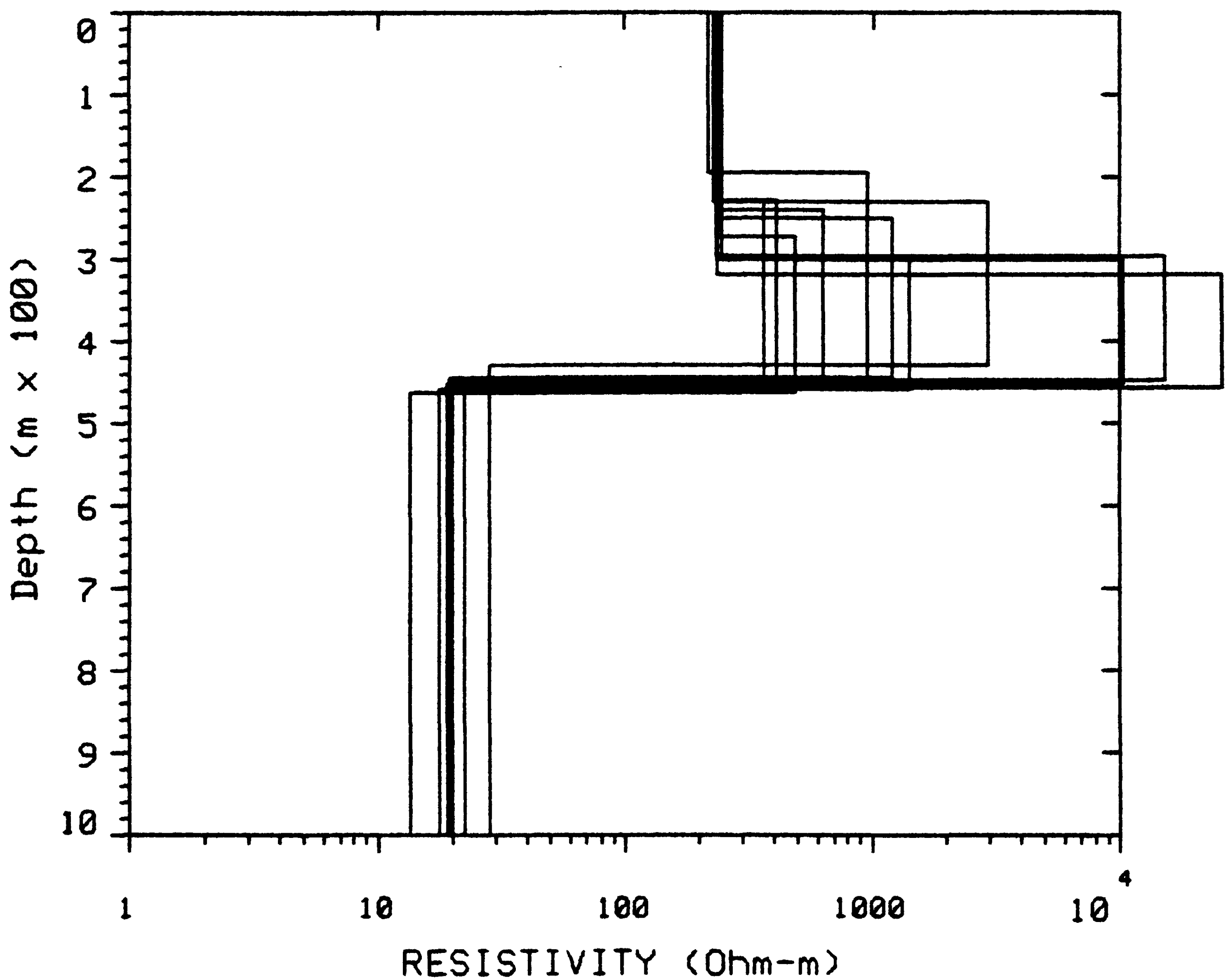


Fig 11a.--TCW11 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

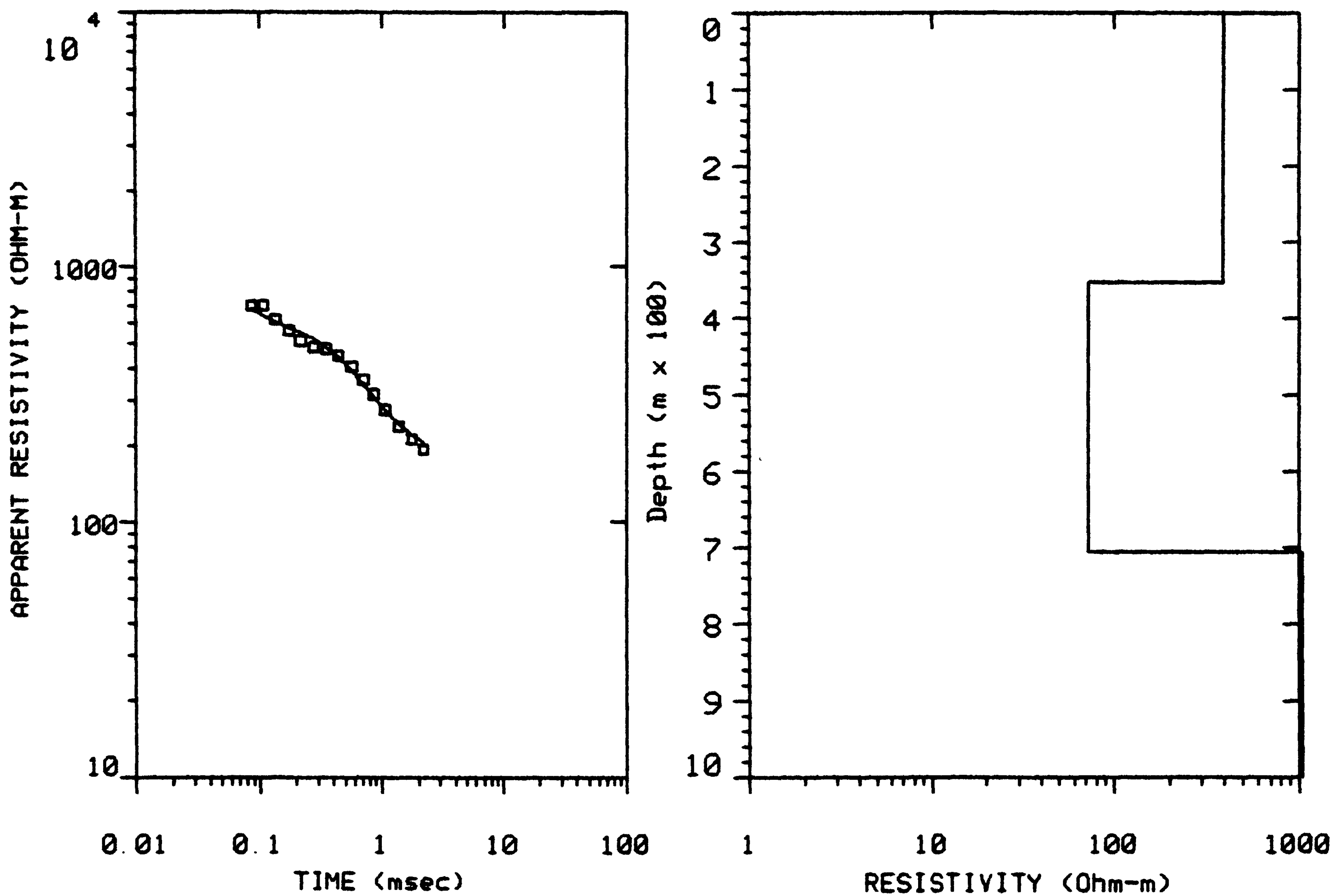


Fig 11b.--Three-layer equivalent models for TCW11. All models adequately fit the data shown on Fig 11a.

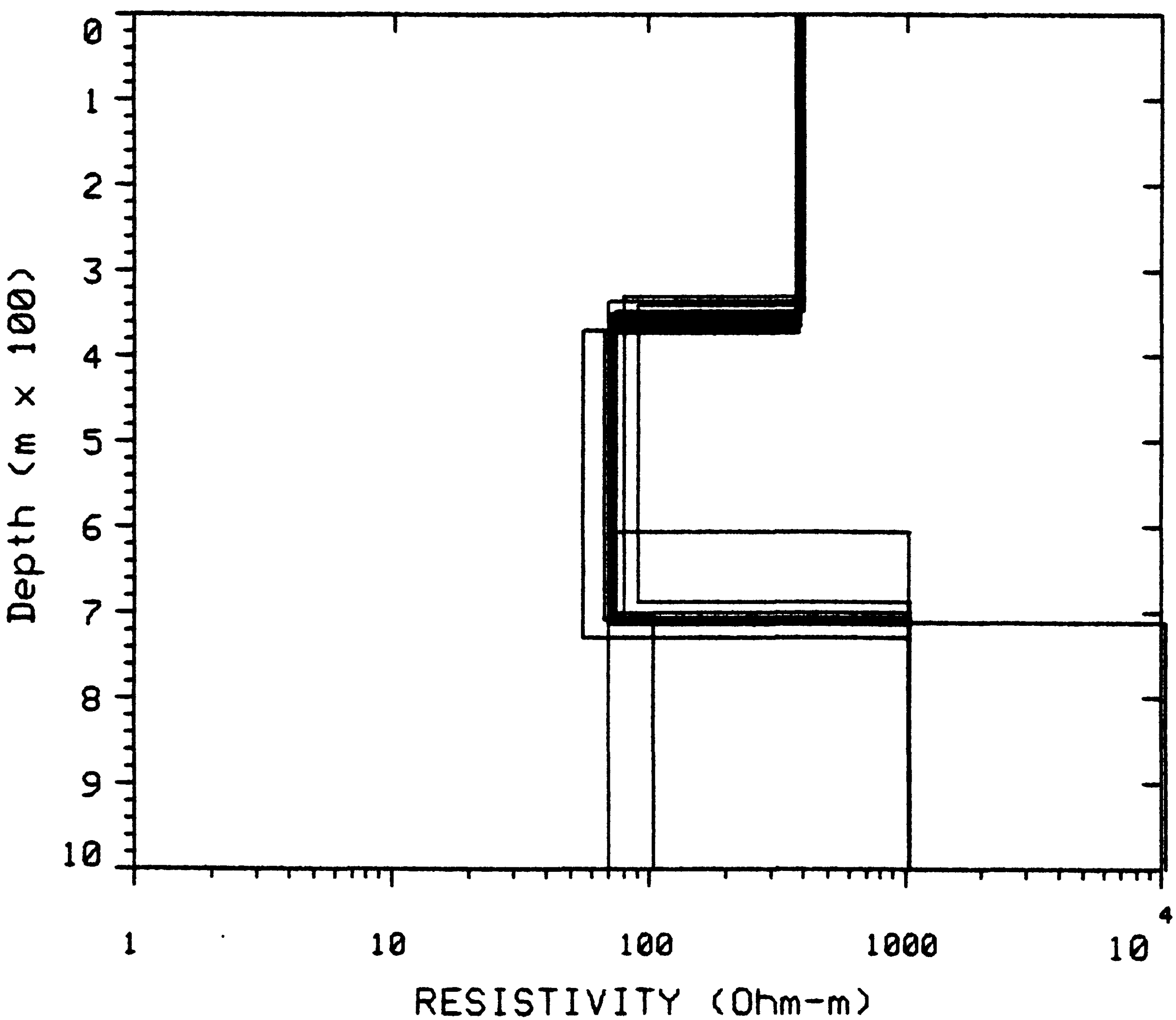


Fig 12a.--TCW12 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

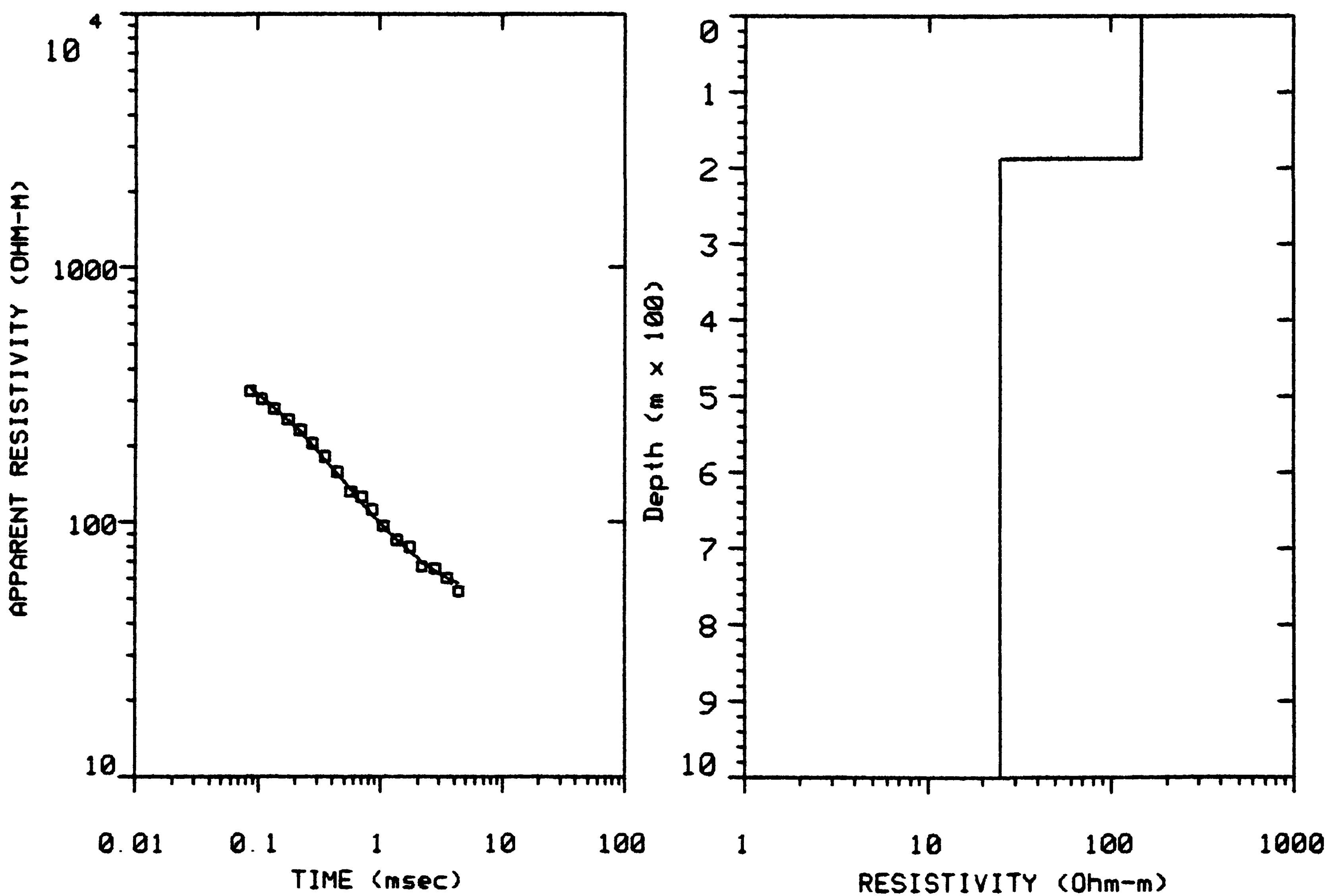


Fig 12b.--Two-layer equivalent models for TCW12. All models adequately fit the data shown on Fig 12a.

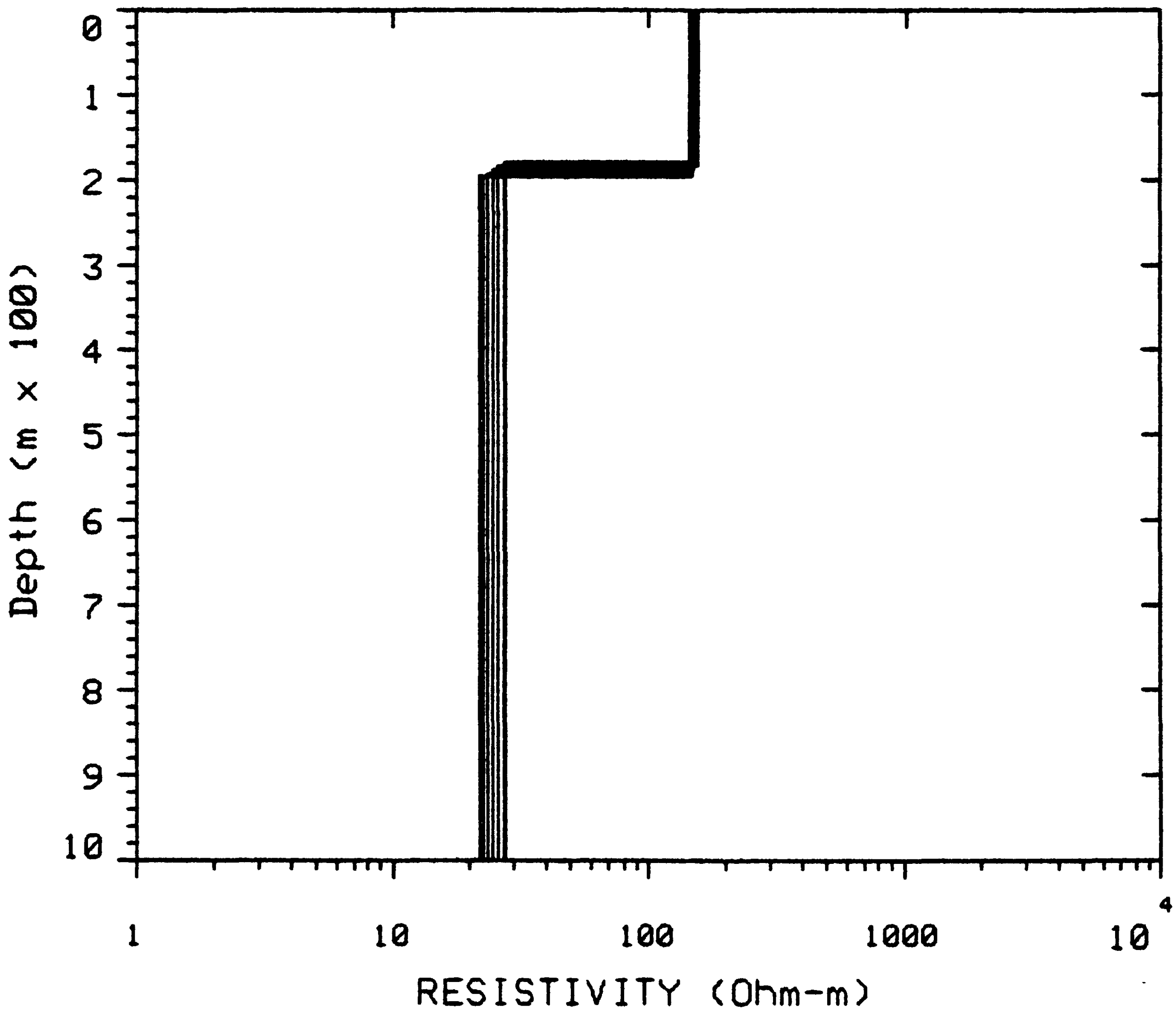


Fig 12c.--Three-layer equivalent models for TCW12. This plot helps indicate constraints or lack of them on the two-layer solution shown in Fig 12b. Note depth scale change from Fig 12b.

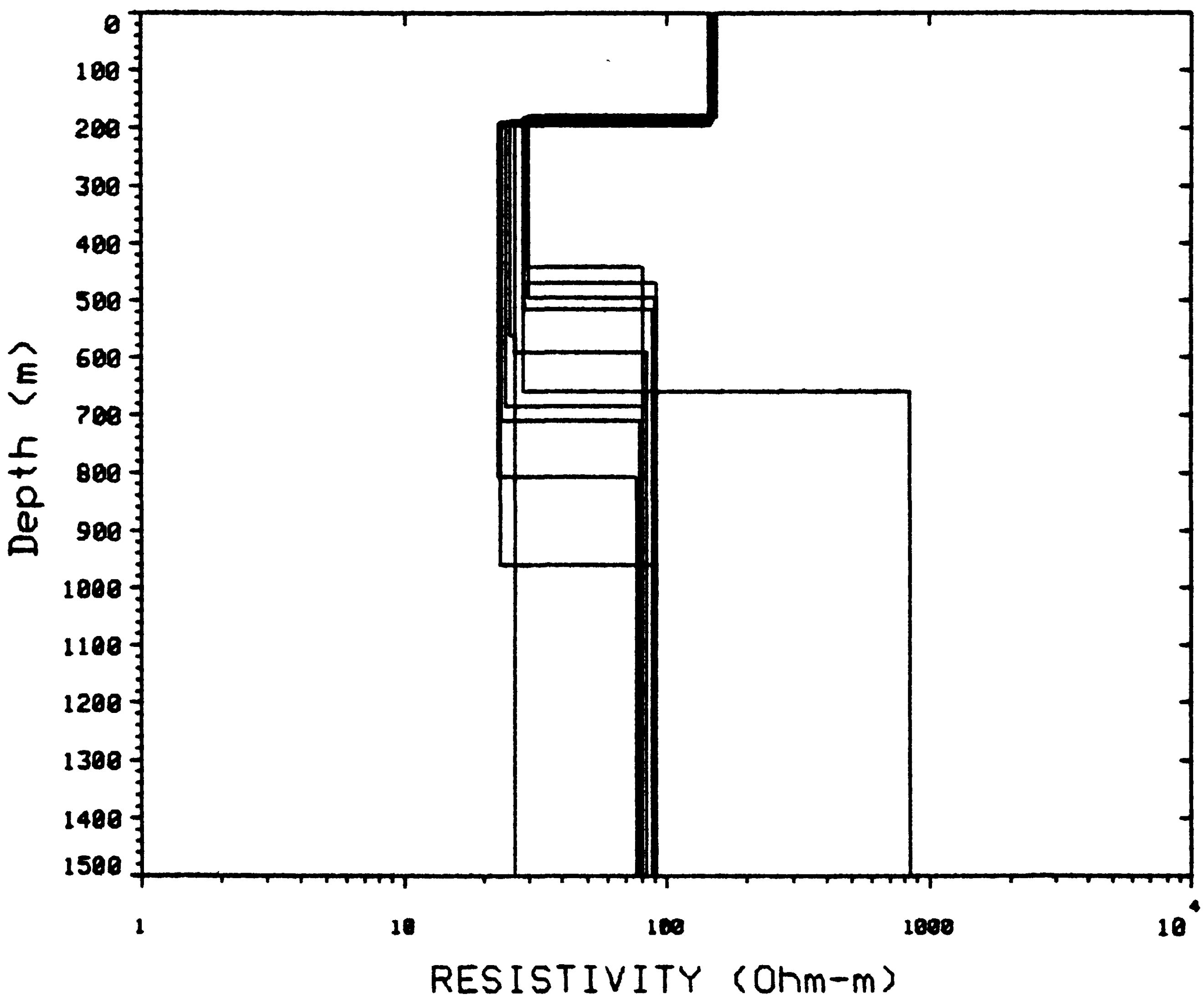


Fig 13a.--TCW13 best fit model. Left panel shows observed (squares) and calculated (solid line) sounding data. Right panel shows interpreted distribution of resistivity with depth.

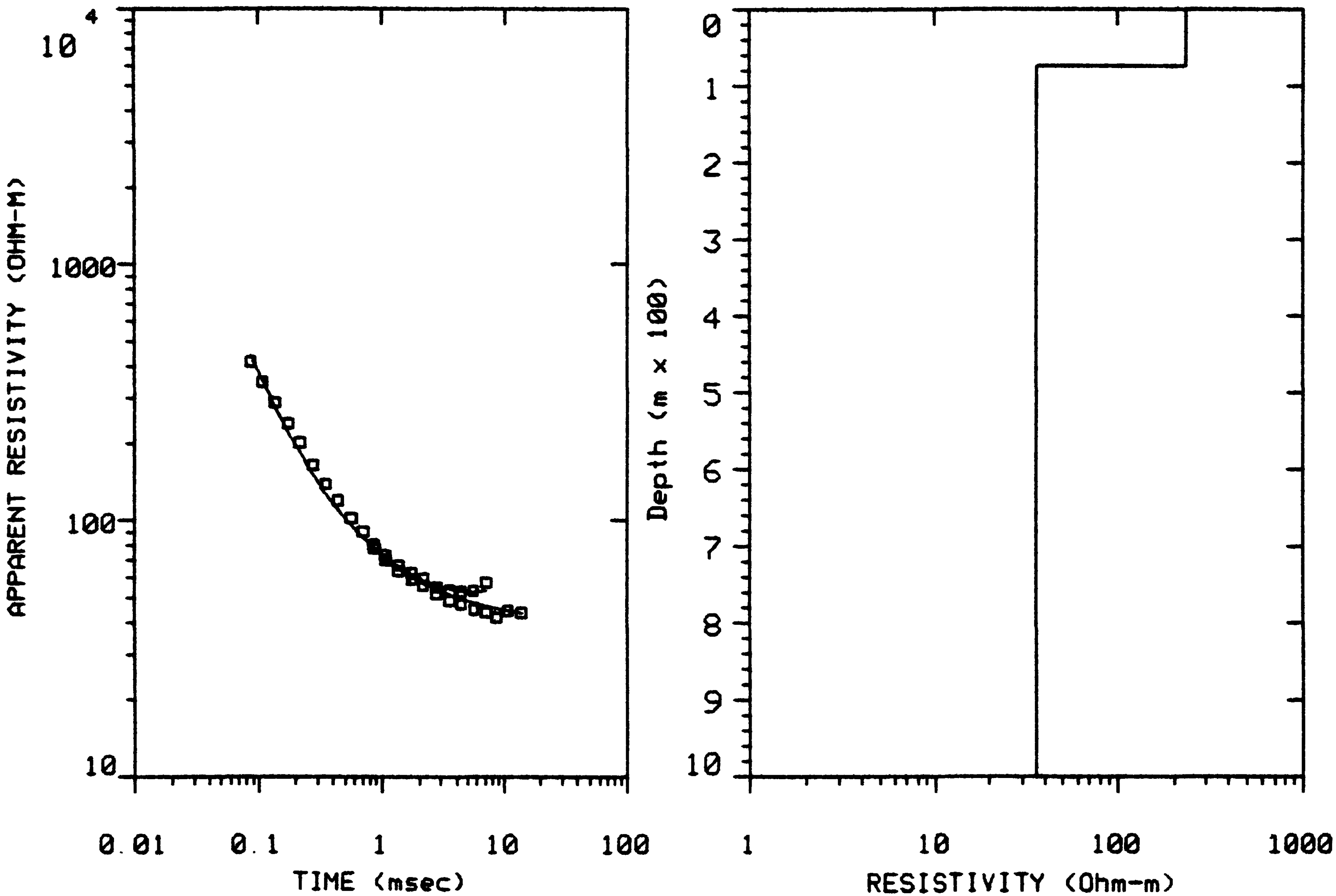


Fig 13b.--Two-layer equivalent models for TCW13. All models adequately fit the data shown on Fig 13a.

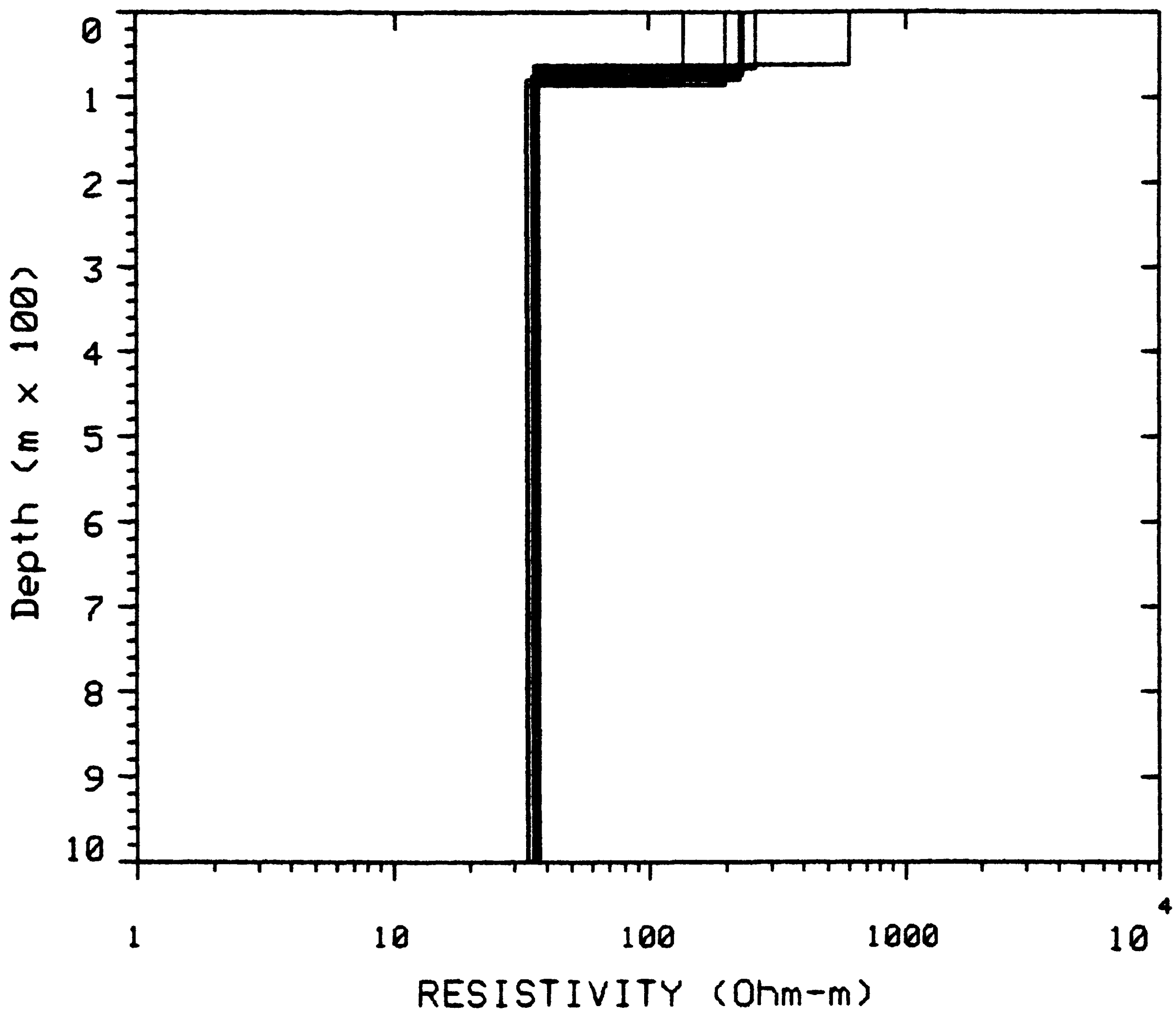
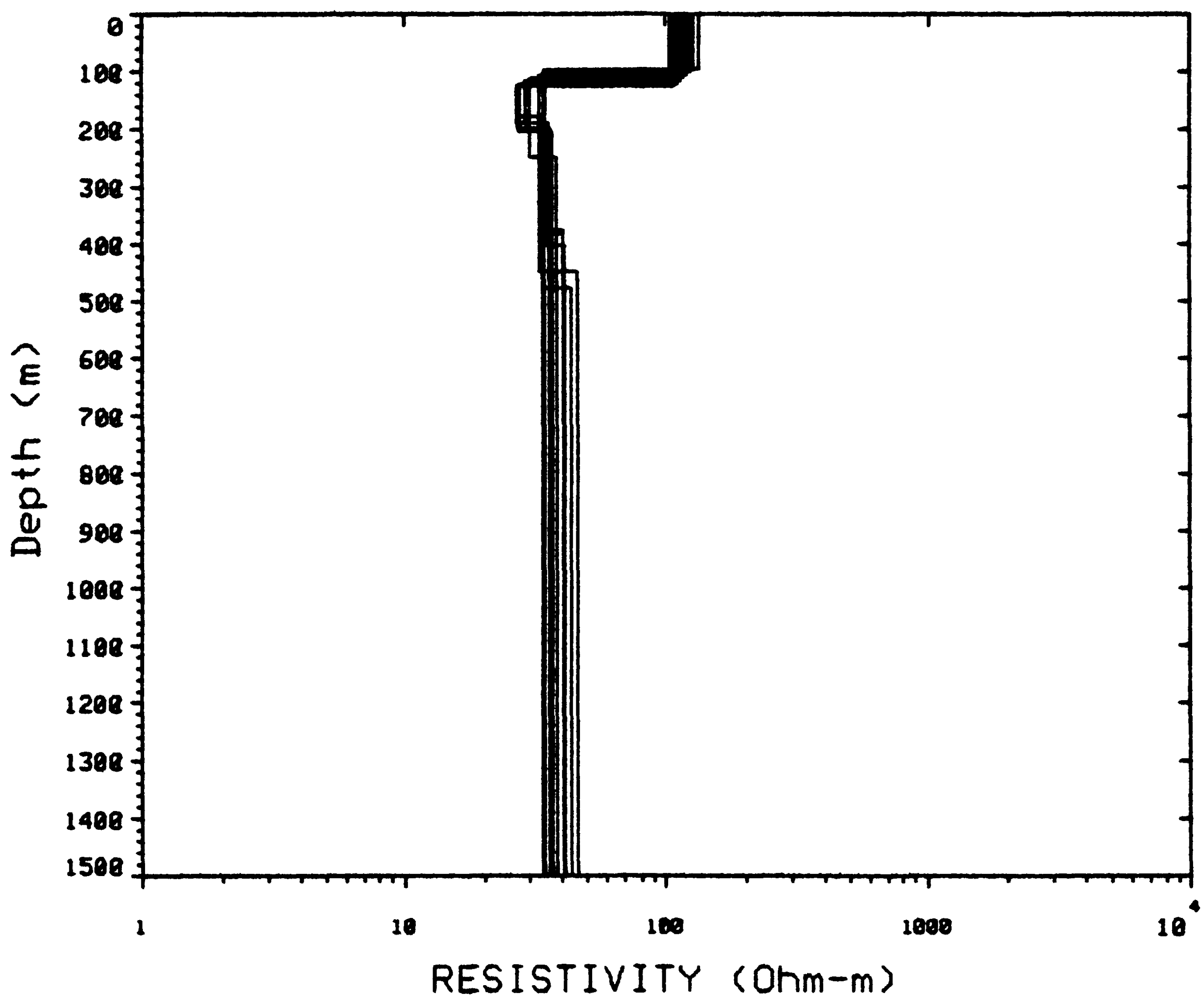
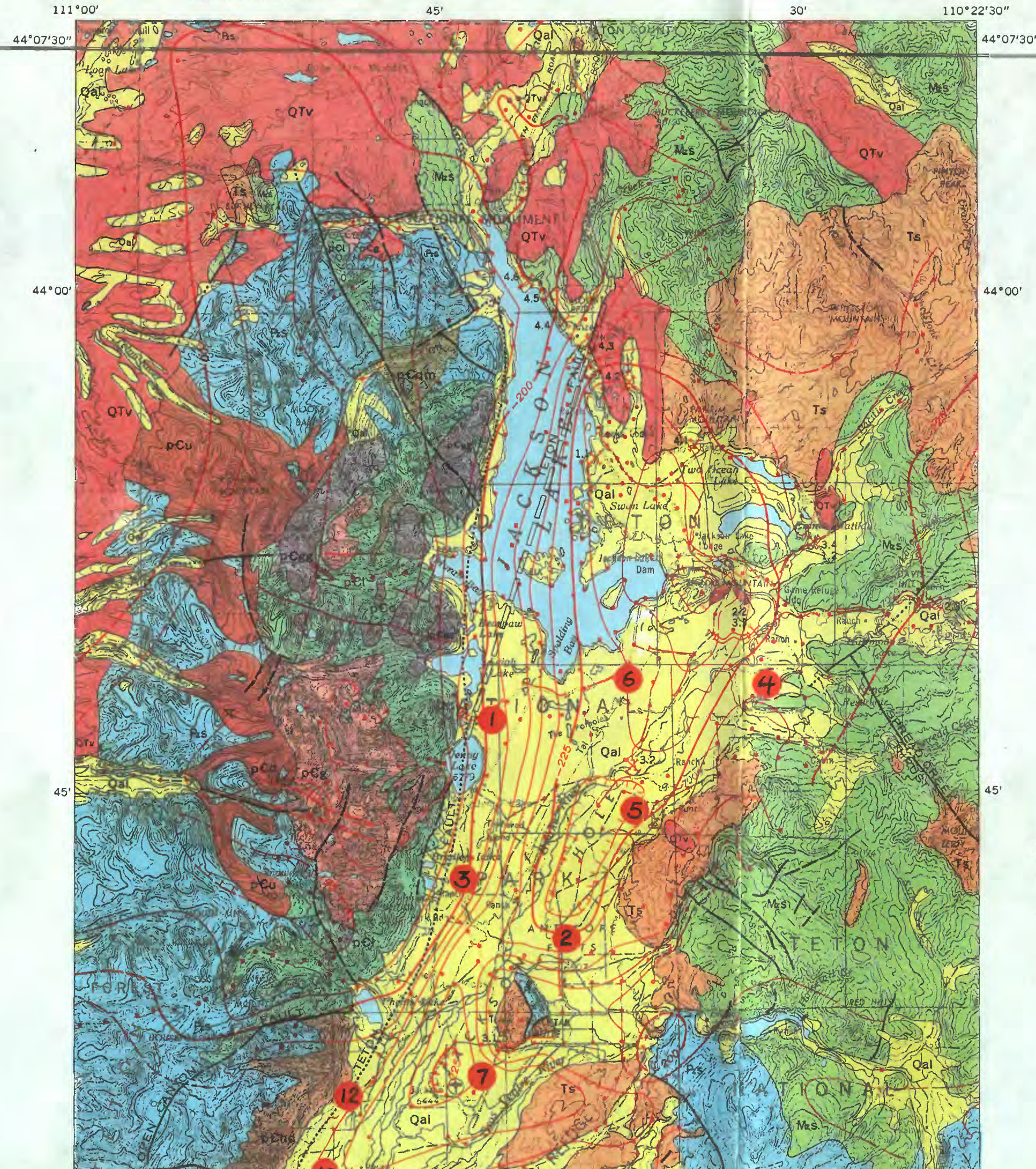


Fig 13c.--Three-layer equivalent models for TCW13. This plot helps indicate constraints or lack of them on the two-layer solution shown in Fig 13b. Note depth scale change from Fig 13b.





EXPLANATION

Qal — Quaternary sediments, alluvium, and glacial deposits

QTv — Quaternary and Tertiary volcanic rocks

Ts — Tertiary sedimentary rocks

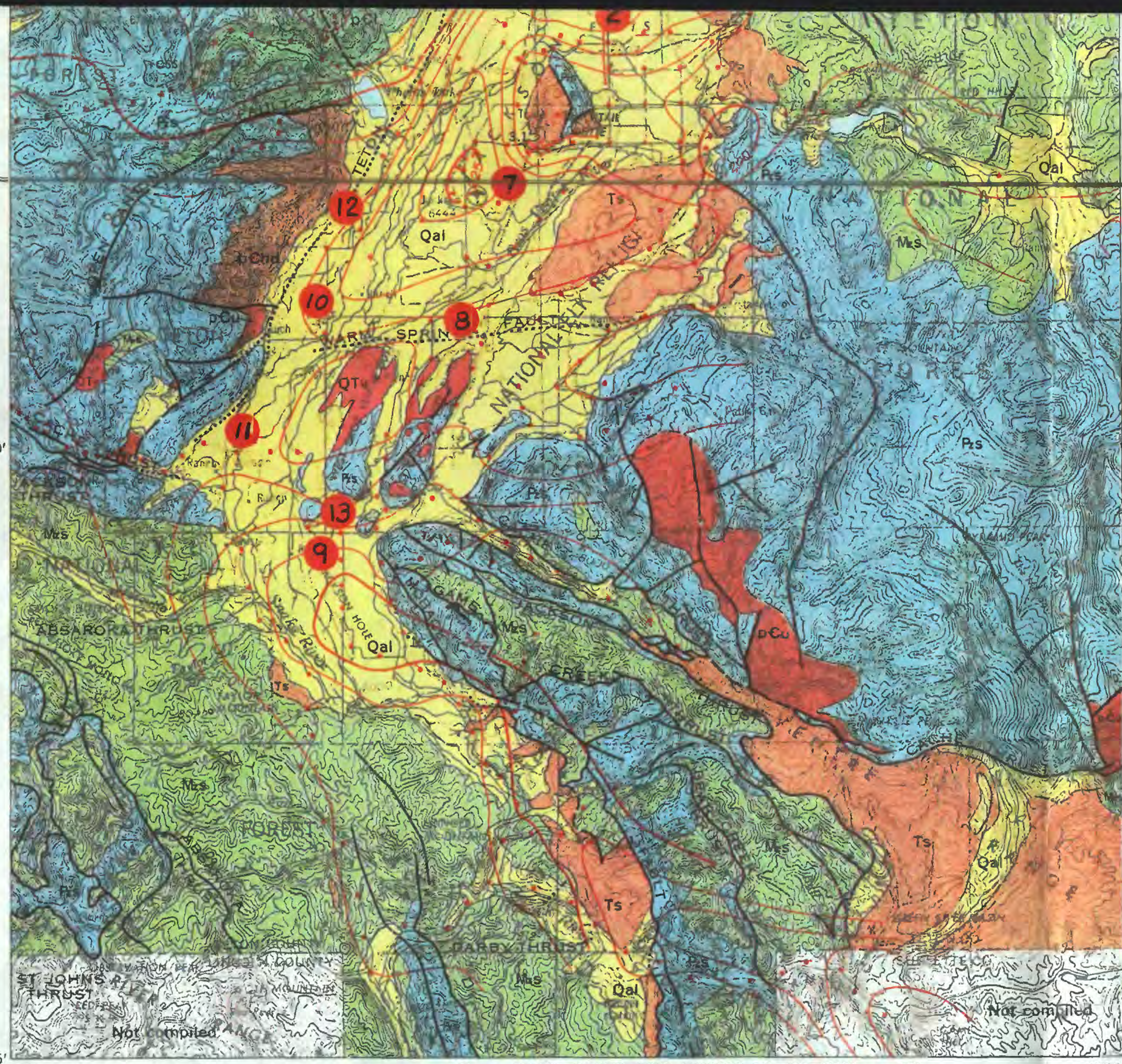
Mzs — Mesozoic sedimentary rocks

Pzs — Paleozoic sedimentary rocks

Precambrian rocks undivided (p€u):

- p€d — Diabase
- p€g — Granodiorite and pegmatite
- p€qm — Hornblende-quartz monzonite gneiss
- p€gg — Biotite granodiorite gneiss
- p€hd — Hornblende-plagioclase gneiss
- p€l — Layered gneiss

Contact
Dashed where approximately located



Layered gneiss

Contact
Dashed where approximately located

Fault
Dashed where approximately located; dotted where concealed

Fault inferred from geophysical data

200
Gravity contours
Dashed where approximately located. Interval 5 milligals. Hachures indicate closed area of low gravity

Gravity station

4.5
Seismic shotpoint and number

Geophone array

Base from U.S. Geological Survey
Driggs, 1955–62, and Ashton, 1955

Geology generalized by J. C. Behrendt
from Love (1956) and data for Precambrian
geology supplied by J. C. Reed, Jr., 1965

BOUGUER ANOMALY AND GENERALIZED GEOLOGIC MAP OF GRAND TETON NATIONAL PARK AND VICINITY, WYOMING

TRUE NORTH
MAGNETIC NORTH
17°
APPROXIMATE MEAN DECLINATION, 1968

SCALE 1:250 000

5 0 5 10 MILES

5 0 5 10 KILOMETERS

CONTOUR INTERVAL 200 FEET
DATUM IS MEAN SEA LEVEL

~~Fig~~ Plate 1.--TDEM sites in Jackson Hole (red dots). Numbers on dots indicate sounding number. Base map from USGS Professional Paper 516-E.