U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Ground-water Exploration in the South Kohala District, Hawai'i County, Hawai'i Using Vertical Electrical Sounding

by

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ABSTRACT

Ten deep electrical resistivity soundings were completed across the island of Hawai'i near the town of Waimea in an effort to locate high-level, dike-impounded water. The resistivity data did not support the existence of a high-level water occurrence. Instead, the data show that a thick basal fresh-water lens underlies the area.

INTRODUCTION

The purpose of this investigation was to locate high-level ground-water occurrences in the vicinity of Waimea on the island of Hawai'i, that could be tapped by wells drilled no deeper than 600 m. The work was requested by the Division of Water and Land Development (DOWALD), State of Hawai'i because the present water supply system, which is based on surface runoff, has proved to be inadequate during periods of low rainfall. If found and developed, the target ground-water sources would be used to supplement existing water supplies during drought times.

Ground-water can be expected beneath most areas of the islands of Hawai'i, occurring in a basal mode. That is, rain water percolating downward through the island mass, comes to rest and floats on sea water which has saturated the island below sea level. The more fresh water there is, the deeper the top of the salt water is depressed and the higher the fresh water surface is elevated relative to sea level. Under static equilibrium conditions, there is 40 times as much fresh water below sea level as above. Constant lateral flow towards the coast and into the ocean causes the body of fresh water to be thinner near the coast than farther inland; in cross section, the upper and lower surfaces of the fresh water are shaped similar tO those of an optical lens. If it contains a sufficient amount of fresh water, a basal lens (as the body is called) can be a very good water supply; however, to be developed, wells would have to be drilled to within a few meters of sea level. This is financially impractical in Waimea owing to the high elevations (1000-1300 m) and the high cost of drilling in Hawai'i, hence the effort towards locating high-level water where fresh water levels may be several hundred meters above sea level.

Classically, high-level water is located within the compartments of a dike complex making up a volcanic rift zone. This type of water body can be differentiated from basal water hydrologically by its significantly higher water levels. The levels remain high because lateral flow is prevented by impermeable, vertical structures, usually dikes. The elevated water levels imply that high-level water probably does not float on salt water as does a basal lens. Using a mean water level for dike-impounded water on O'ahu of at least 100 m (Takasaki, 1981), the base of the fresh water would have to be at a depth of 4 km below sea level if it was floating on salt water. Rocks at that depth are not believed to be permeable; therefore, high-level water is probably supported at a shallower depth by denser impermeable, possibly intrusive rock (Macdonald and Abbott, 1970).

Based on geology, the most likely location for high-level water in the Waimea area is within the southeast rift zone of Kohala volcano. Most of this structure is buried beneath later Mauna Kea lavas; however, a gravity survey (Kinoshita and others, 1963) shows that its axis continues southeast from the Kohala summit out under the saddle between Kohala and Mauna Kea.

Prior to any exploratory drilling, geophysical methods were proposed for the task of distinguishing basal from high-level water. One of the earliest applications of geophysics to Hawaiian hydrology was the use of vertical electrical-resistivity sounding (VES) for just this purpose (Swartz, 1937). The success of this approach is based on the fact that sea water saturated rock has a much lower resistivity than rock that is dry or saturated with fresh water, and that the VES technique can detect such low resistivities at great depths. Where low resistivities, which can be associated with sea water saturation, are found less than a few hundred meters below sea level, ground-water is probably basal. Where low resistivities are not found within several hundred meters below sea level, ground-water is probably high-level.

To cover the area as fully as possible, ten VES were completed between Oct. 12-25, 1981 along a profile from Puako on the west coast to Kukuihaele on the east coast, and passing to the south of Waimea (fig. 1). The soundings were approximately 5 km apart and most of them were expanded to about 4 km between each current electrode and the VES center allowing good resolution of the hydrology-controlled resistivity structure below sea level. VES were not conducted north of Waimea because the area is a State watershed and the process of obtaining access, even for one day, would have required more time than was available.

THE VES METHOD

The variation of electrical resistivity with depth can be determined with the aid of a resistivity sounding or VES. Any of several electrode arrangements may be used, although the most common is the Schlumberger array used in this study. Four electrodes are placed in line (fig. 2) - the outer two are for electric current injection, the inner two are for measuring a voltage produced by that current. For sounding, the array is expanded outward from its center (i.e., the current electrodes are moved farther apart) to achieve deeper penetration. The voltage and current values, as well as the electrode array dimensions, are used to calculate an apparent resistivity which is then plotted versus half the separation of the current electrodes. More details may be found in Zohdy(1974).

The produced data plot can be visually inspected to estimate some of the parameters of the subsurface resistivity structure; however, it is more informative to use one of the available computer-assisted interpretation programs. We used two different programs in sequence: an automatic interpretation program (Zohdy, 1973 and 1975) which smoothed the data and gave a detailed sequence of resistivities which fit the data, followed by a Marquardt inversion program (Anderson, 1979) which found the simplest, horizontally-layered earth model that also fit the data. The first computer program prepared the data for interpretation and gave a good estimate of the resistivity sequence encountered, whereas the second program simplified the resistivity sequence obtained from the first program and estimated the resolution of the various resistivities and layer thicknesses. The resulting interpretations for each of the ten VES from Waimea are listed in the appendix along with the smoothed data. The interpretations are also summarized graphically in fig. 3.

Each of the VES interpretations shows a basement with a resistivity much lower than the shallower parts of the section. It is so low that the Marquardt program repeatedly tried to set that resistivity to zero, which then caused computer errors. To avoid these errors and the subsequent program abortion, the basement resistivity value was assumed to be constant at 5 ohm-m for most of the VES. One solution (VES 7) did resolve a basement value of about 36 ohm-m. Although technically unresolvable, the basement resistivity must be less than 50 ohm-m. Resistivity values for the shallower layers range from a few hundred to a few thousand ohm-m.

For this ground-water investigation, we are primarily interested in the existence of a deep, low resistivity basement and the depth to it; however, estimation of the entire sequence of resistivities is necessary for accurate determination of its whole thickness. During interpretation, several problems can arise, of which the most common is that of 'equivalence'. This occurs when one or more of the layers is not thick enough to allow resolution of its resistivity. Equivalent solutions to layering are common because the thicknesses required for good resistivity resolution can be several times the depth to that layer and are determined by the resistivity contrast between that layer and the overlying as well as underlying layers. All that can normally be resolved accurately for a given layer is some combination of the layer resistivity and thickness (Zohdy, 1974). Nonunique resolution of a layer's resistivity automatically means nonunique resolution of its thickness. Because the depth to low-resistivity basement is the sum of all overlying layer thicknesses, and one or more of these thicknesses may be nonunique, the depth may also be nonunique; however, in most cases, permissible values of resistivity for these layers can be determined from adjacent soundings, or other criteria, thereby determining the layer thicknesses more closely. Situations where a severe equivalence problem has appeared in the Waimea VES are noted in the appendix either explicitly or as a fixed layer resistivity (no associated error).

The two interpretation programs used for this data respond to equivalent layers in distinctly different ways. The Zohdy program appears to minimize resistivity differences between adjacent layers, thereby maximizing the thickness of an equivalent layer. The Marquardt program appears to maximize resistivity differences between adjacent layers, thereby minimizing the thickness of an equivalent layer. A bonus of the Marquardt program is that an equivalent layer can be theoretically distinguished from one that is genuinely thin by the parameter error estimates for that layer. When these estimates are small, the associated parameter is well resolved, therefore a genuinely thin layer that is well resolved would have a small error estimate for that layer's thickness. On the other hand, an equivalent layer would have large parameter error estimates for both its resistivity and thickness and the two parameters would be highly correlated (a variation in one would be indistinguishable from a variation in the other one). The interpreted layering sequence for each VES listed in the appendix has several equivalent layers which are probably made artificially thin by the Marquardt program (the equivalence is recognized by the parameter error estimates and correlations). No attempt has been made at this stage to make these thicknesses more realistic for two reasons -- 1) external information (i.e. electric logs) is not available with which to limit the possible resistivities in any given solution, and 2) variations in shallow layer thicknesses due to equivalent layering are unimportant relative to the total section thickness. Therefore, the interpretations are listed in the appendix exactly as determined by the Marquardt program. Modification of these interpretations using adjacent sounding results will be outlined later in the discussion.

The possibility remains that our assumption of horizontal homogeneity (i.e., resistivities vary only vertically within the earth volume sensed by each sounding) is not completely valid and that some VES may have detected a conductor that is laterally displaced from rather than vertically under the sounding site. For example, this might be the case for VES8 in which the conductor is much deeper than in the two surrounding VES. Work by Lee (1972, 1981) suggests that VES conducted along a profile but expanded perpendicular to that profile can be used to determine undulations of a layer's surface beneath the profile. He does this essentially by interpreting the VES data initially as we have done above but then using the depths as the radii of cylinders superposed along the VES expansion line to which the sought surface is assumed tangential.

When we applied these ideas to the Waimea VES data with particular emphasis on the deep low-resistivity layer, none of the hypothetical cylinders intersected, which means nothing more than the profile spacing was inadequate for using this approach and we have insufficient data to evaluate whether the low-resistivity basement is sensed vertically or laterally.

One final problem to consider is the effect of metallic pipes on the VES, because of the unusually large number of pipes in this area. Extensive theoretical calculations by one of us (JK) show that a well-grounded (i.e., buried) metallic pipe at a lateral distance, d, from a VES and making an angle of less than 45o to the VES could be confused with a low-resistivity layer at a depth, d, beneath the sounding site. After reexamining the VES locations, we found only one site where a pipe was known to be at a distance similar to the depth interpreted for the conductive basement. That sounding was VES9; the pipe was about 800 m from the VES center and made an angle of about 30o to the VES expansion. The suspicion of VES distortion by this pipe heightens when we note that the depth to conductive basement in VES9 is less than half what it is in the adjacent soundings VES8 and VES10. Ultimately proving or disproving the effect of pipes is not practical but we note that distortion by pipe is a qualitatively acceptable model for VES9.

The theoretical calculations also show that when a pipe is actually crossed by a current electrode in a VES expansion, a cusp should be seen at that point in the data. Several pipes were crossed during this study and several cusps were noted in the data; however, the two were rarely noticed at the same place. Again, proving the effects of pipes is really not practical because many pipes cannot be seen and even if they are seen, they may not be grounded well enough to affect a sounding.

DISCUSSION

The low-resistivity basement is the zone that presumably represents basalt saturated with salt water. When the interpretations are compiled and viewed together (as in fig. 3), the interpreted depths to salt water saturated rock appear extremely variable throughout the whole profile. They are generally smaller on the west side, but can vary between soundings by as much as 1000 m along the rest of the profile. This is contrary to the impression one gets when viewing the VES data plotted together as in fig. 4. A transition can be seen from VES1 to 3, VES4 through 8 are nearly identical for AB/2 values greater than 1000 m, and VES9 and 10 are again a transitional pair in a manner similar to VES1 to 3. These observations suggest that the profiled section is more uniform than might be thought from interpreting each VES individually with program MARQDCLAG, and that the VES need to be interpreted together to emphasize common portions of the section.

The largest portion of each sounding interpretation is the layer just above electrical basement, which has been assigned resistivity values ranging from 350 to 1650 ohm-m (see Appendix). The data values for VES4 through VES8 at AB/2 values greater than 1000 m (fig. 4) suggest that the layer just above the basement should actually have a resistivity of about 700 ohm-m. To bring the soundings more into line, VES 2, 3, 5, 6, 8, and 9 were reinterpreted making every effort to limit the resistivity of the layer just above basement to about 700 ohm-m. Within certain limits, artificially adjusting the resistivity of this layer is permissible as long as its thickness is also adjusted so that the new layer is electrically equivalent to the layer determined by program MARQDCLAG, as discussed above. In this case, the layering is equivalent if the product of resistivity and layer thickness is the same. The real measure of permissibility is the "standard error of fit" calculated by program MARQDCLAG. If this error is not significantly changed by the adjustments, then those adjustments did not significantly alter the fit of the calculated to the observed data. The results and the new standard error of fits are shown in fig. 5 (the data fits in the appendix are not changed significantly). In general, limiting that layer's resistivity to about 700 ohm-m also required a basement resistivity higher than 5 ohm-m; therefore, a new, constrained value of 36 ohm-m was adopted from the original VES7 solution.

The depths to basement are much more uniform in the reinterpreted profile and range between 400 m and 500 m below sea level for VES 4 through 9. The uniformity of these depths produced by smoothing out the variations in resistivities between soundings substantiates the hypothesis that the variations were due mainly to the extremization tendency exhibited by program MARQDCLAG when an equivalent layer problem is encountered. The reinterpretations have somewhat larger error-of-fits (listed at bottom of figs. 3 and 5) than those in the appendix, but they are still acceptable because their values are still less than or about equal to the estimated measurement error of 10-15 percent.

VES 1, 2, 3, and 10 require different interpretations. At an elevation of 65 m, VES 1 shows the low-resistivity basement at a depth of 54 m ± about 8 m. At first glance, one might think that this result indicates salt water at 11 m above sea level; however, the indicated resolution (a standard error of 8 m) suggests that a basement depth of 65 m (with a similarly adjusted resistivity) would fit the data almost as well. In any case, there is no appreciable lens beneath VES 1. Numerous equipment and field problems were encountered during both the VES 2 and VES 10 expansions, so that, although they are interpreted here, their validity is suspect and they will not be discussed further.

Finally, VES 3 was interpreted with a depth to basement of about 100 m below sea level. If we apply the Ghyben-Herzberg ratio of 40:1 (depth to salt water below sea level to elevation of water table above sea level), VES 3 would suggest a water table elevation of about 2.5 m. Just a few hundred meters away is a well operated by Waikoloa village with a water level of either 5.5 m or 2.4 m (the level is disputed). The results of VES 3 appear to substantiate the lower water level claim.

CONCLUSIONS

The VES results show that there is a low-resistivity basement at a depth of 400-500 m below sea level beneath the central portion of the profile. Assuming that the low resistivity is the result of salt water saturating the rocks at those depths, these soundings indicate the presence of a thick basal groundwater lens under the profile, including the presumed continuation of Kohala's southeast rift zone. Based on these VES results, we must conclude that high-level water is not present beneath the profile.

If exploratory drilling is planned, then a site within the southeast rift zone of Kohala volcano would still be the most favorable location based on geology; however, our VES results indicate that high-level water probably does not exist south of Highway 10. Further exploration should concentrate on the 12 km section of the rift north of Highway 10.

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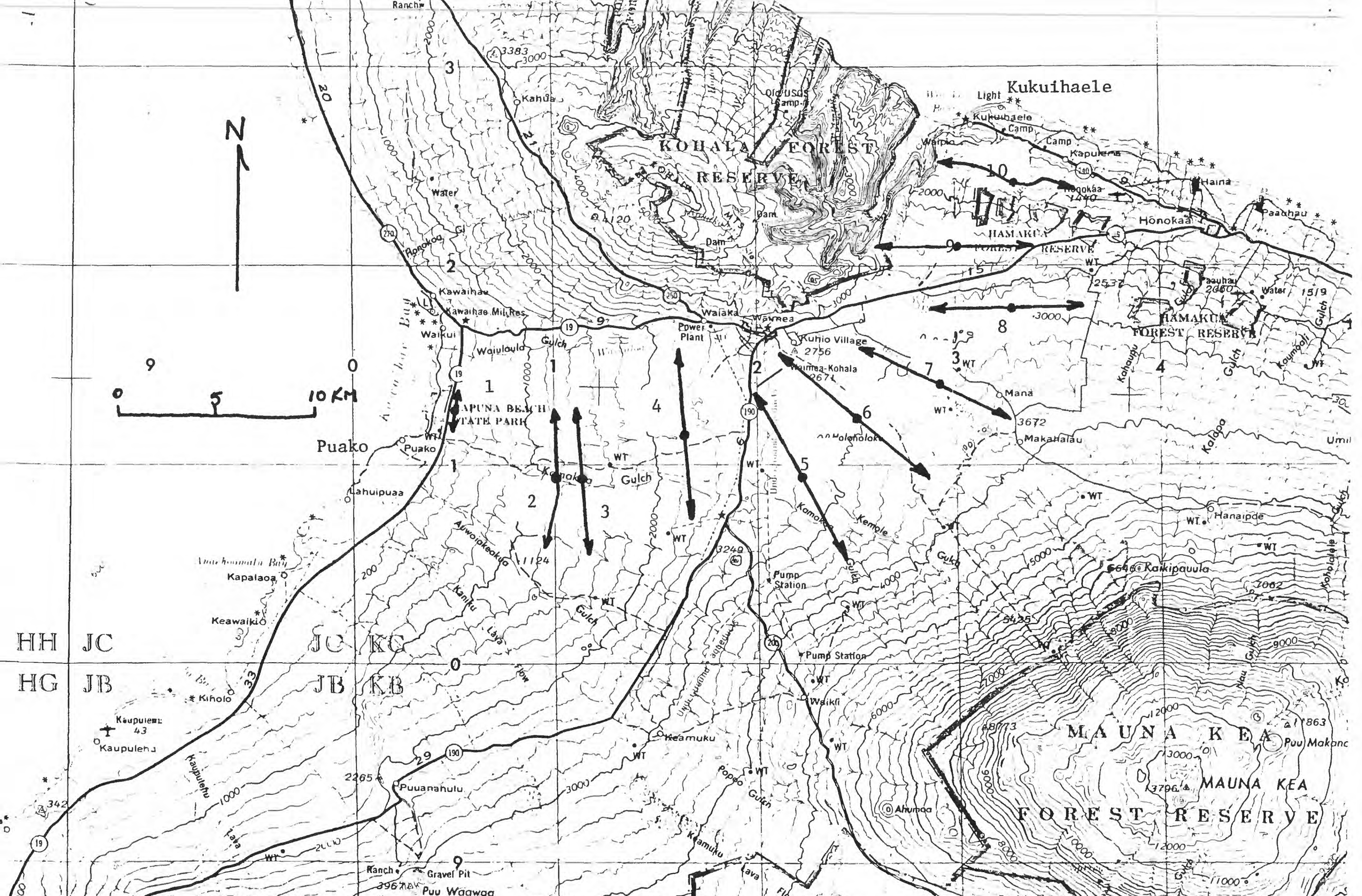
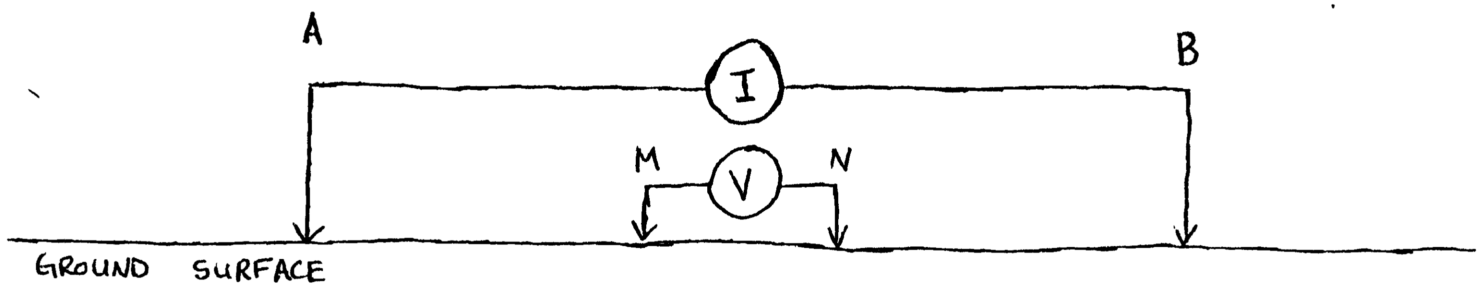
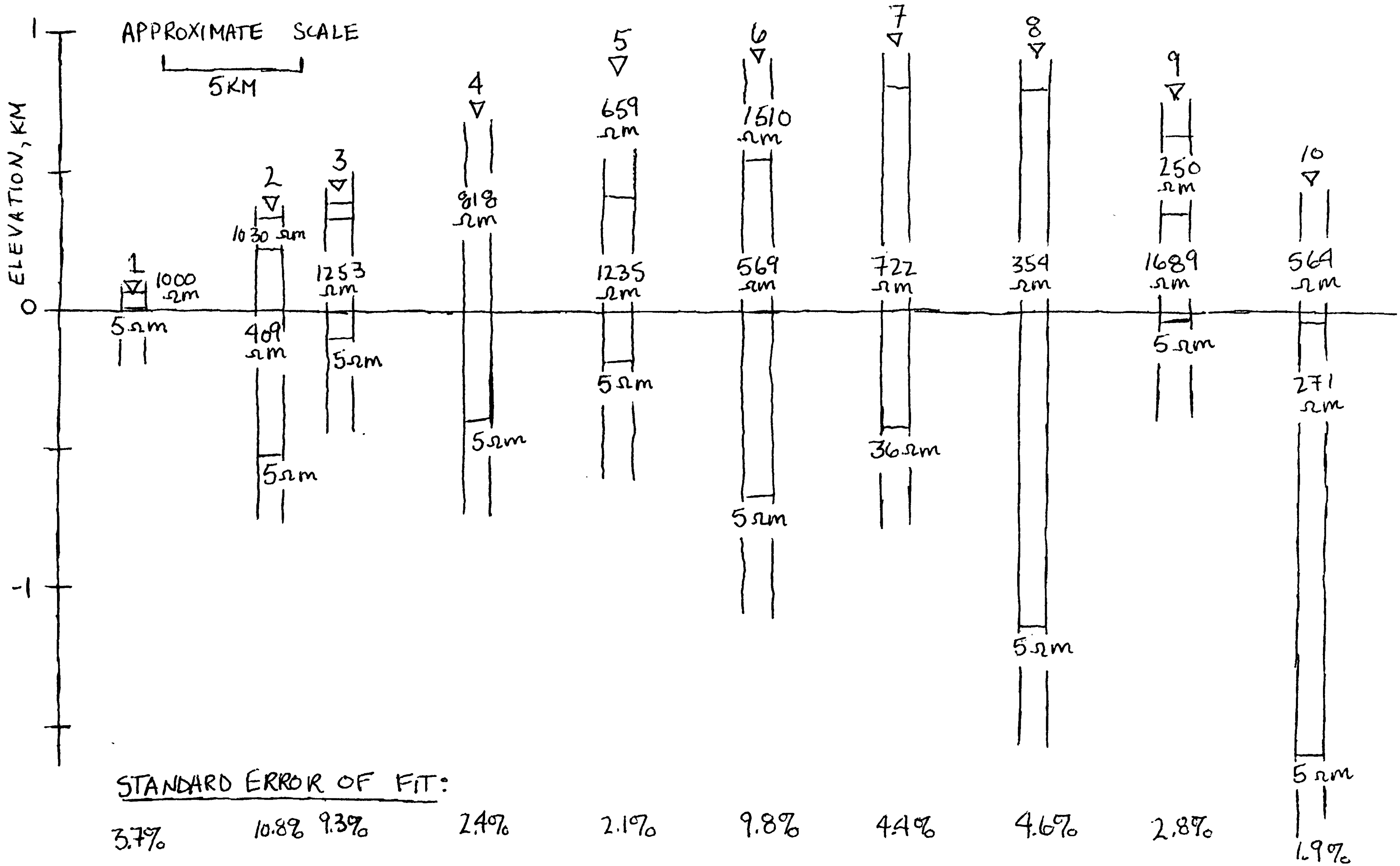


Figure 1. Schlumberger sounding locations between Puako and Kukuihaele.

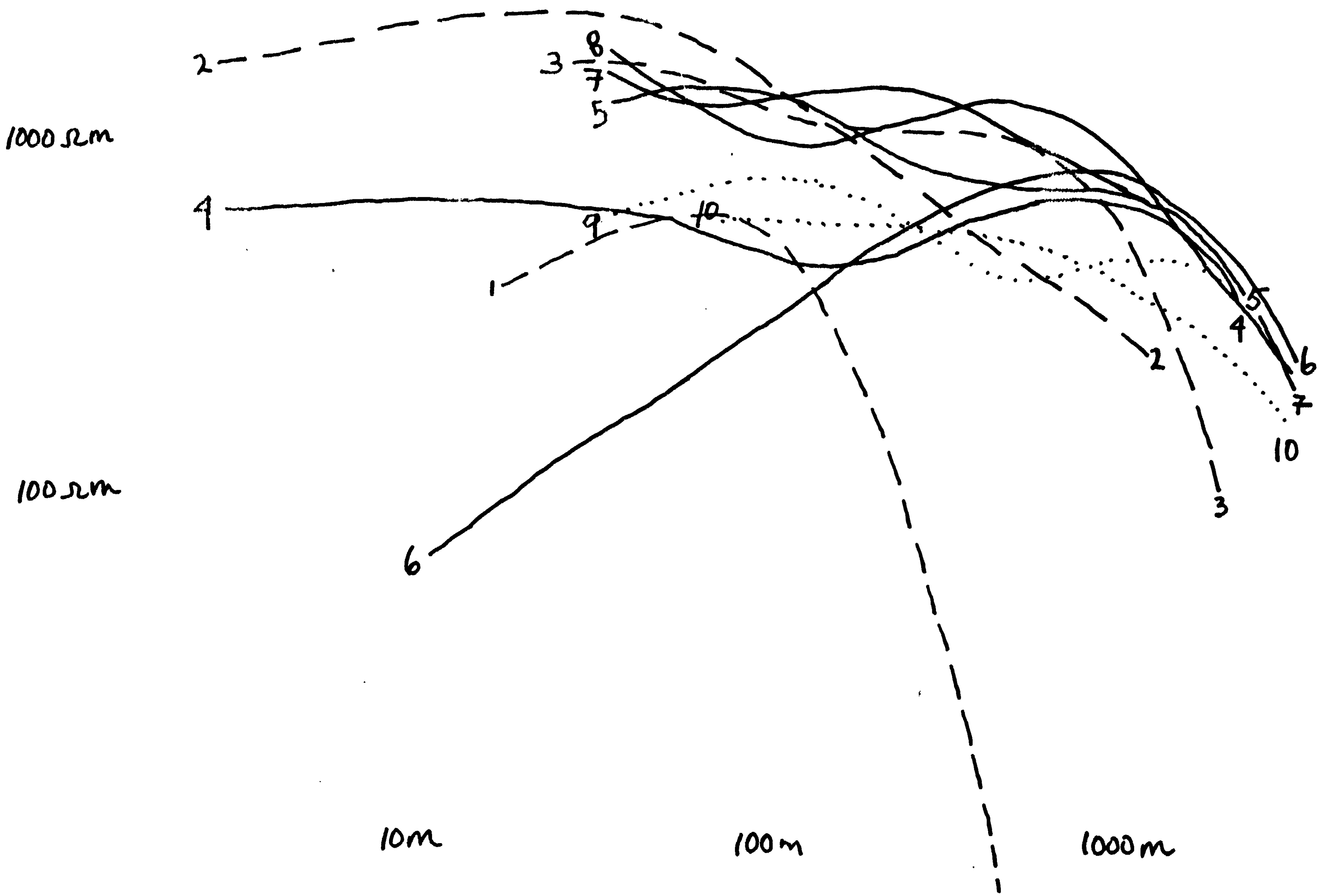


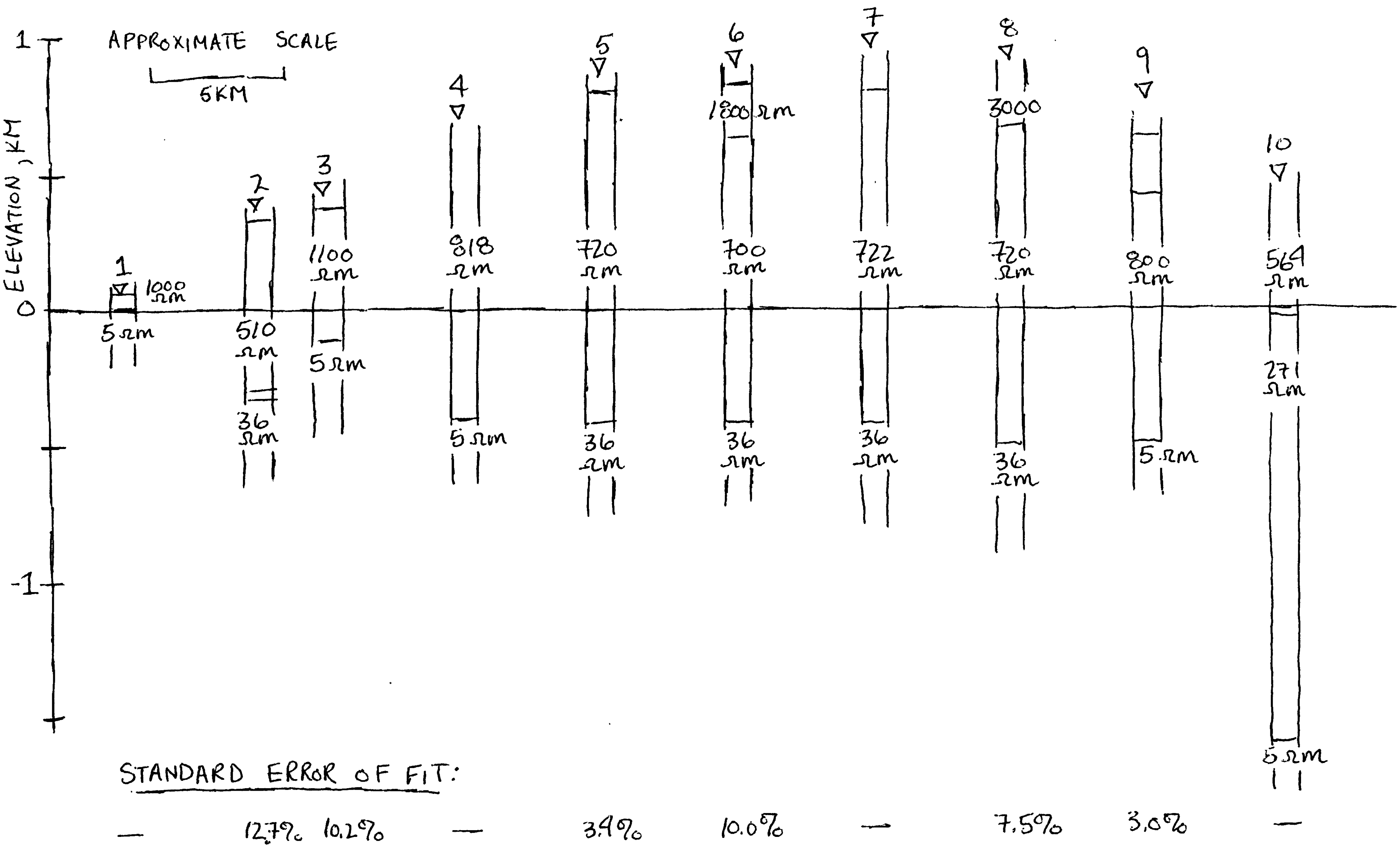
2 Diagram showing electrode positions and labels for the Schlumberger electrode array.



3 Graphical compilation of the VES interpretations detailed in the appendix as initially produced by computer program MARQDCLAG.

4 Composite plot of the data from all ten VES. VES 4 through 8 have solid lines, 1 through 3 are dashed, and 9 and 10 are dotted. VES 4-8 are emphasized because they represent the central, uniform part of the profile.



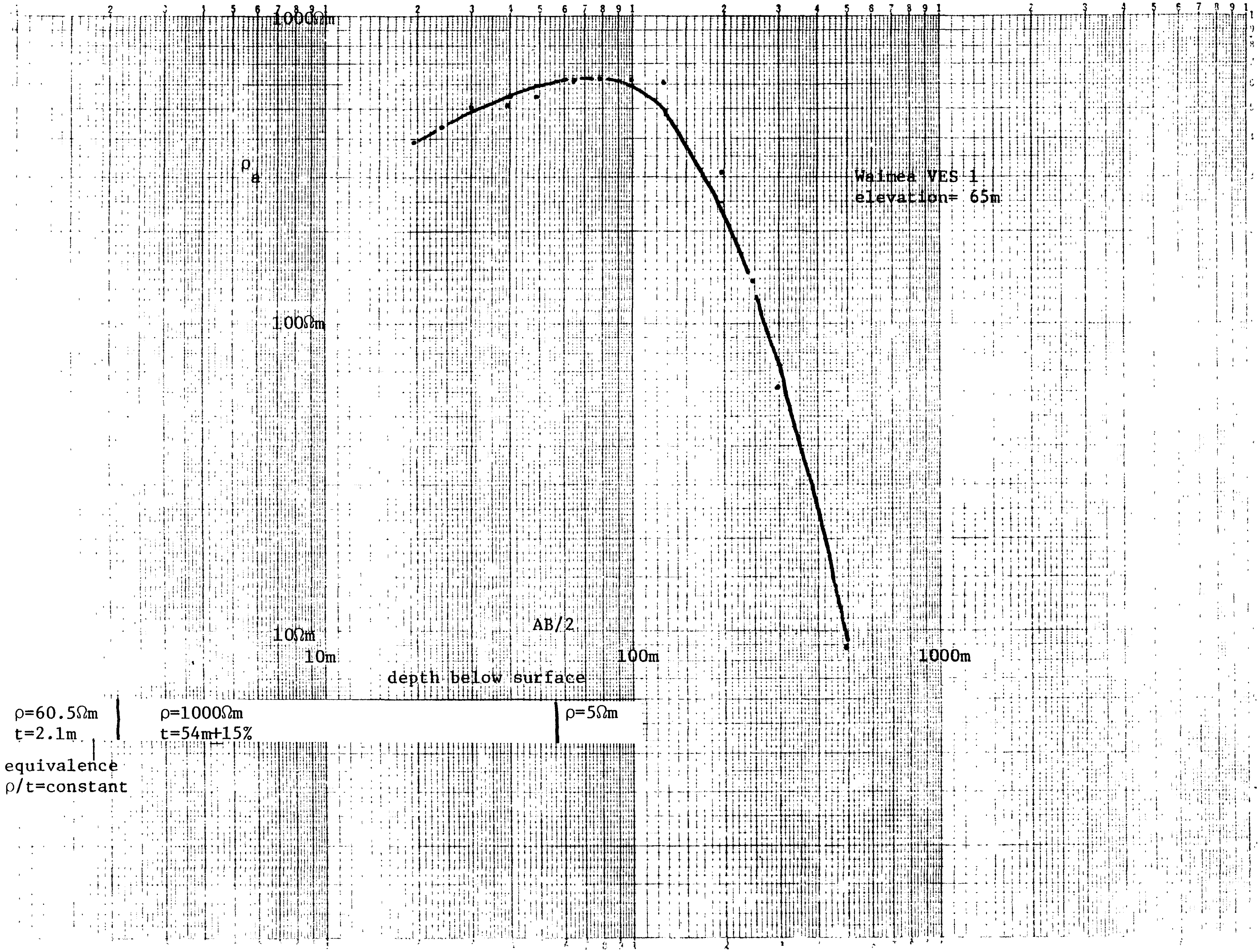


5 Graphical compilation of the interpretations for the Waimea VES adjusting the layer above the basement conductor to be as close as possible to 700 ohm-m.

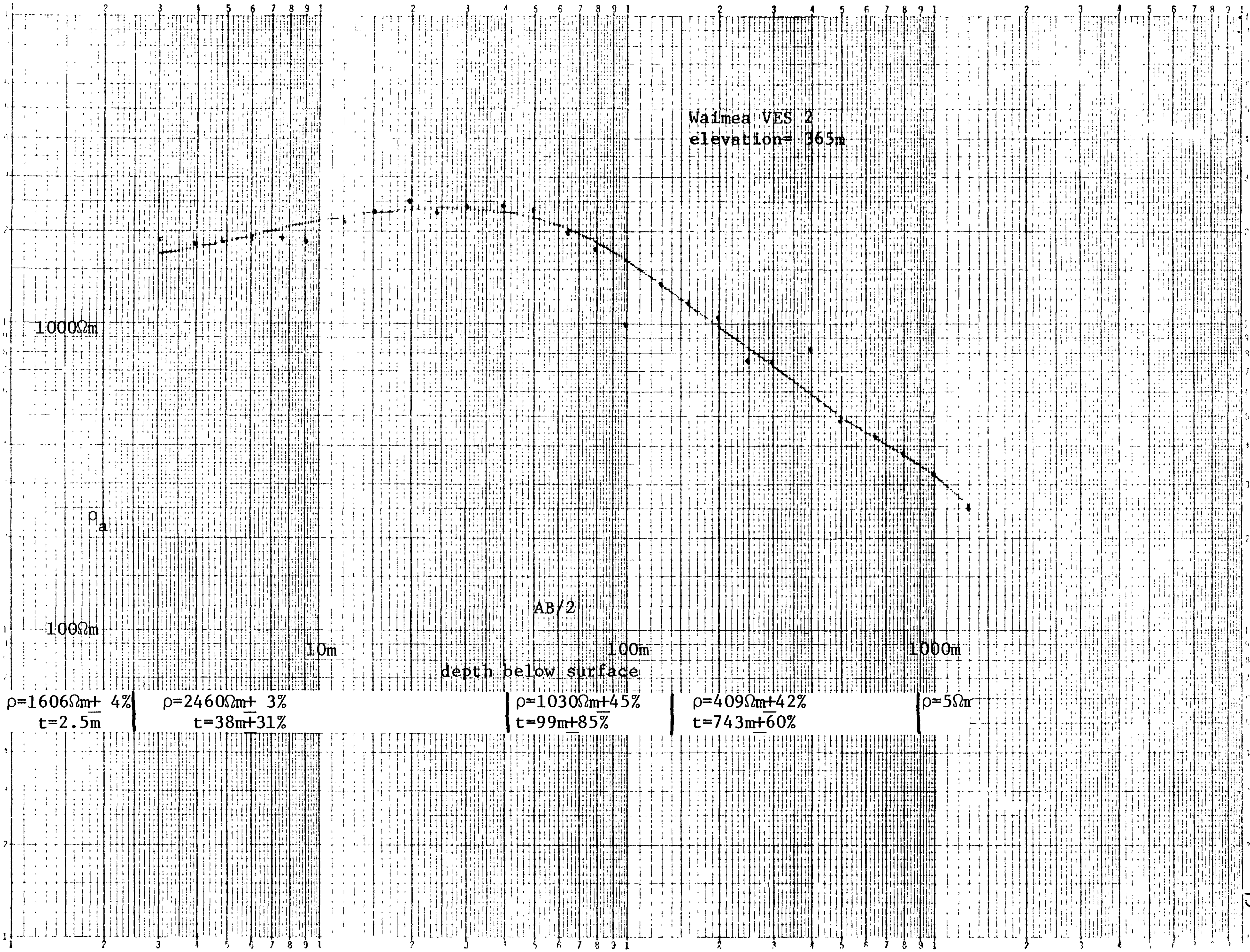
APPENDIX

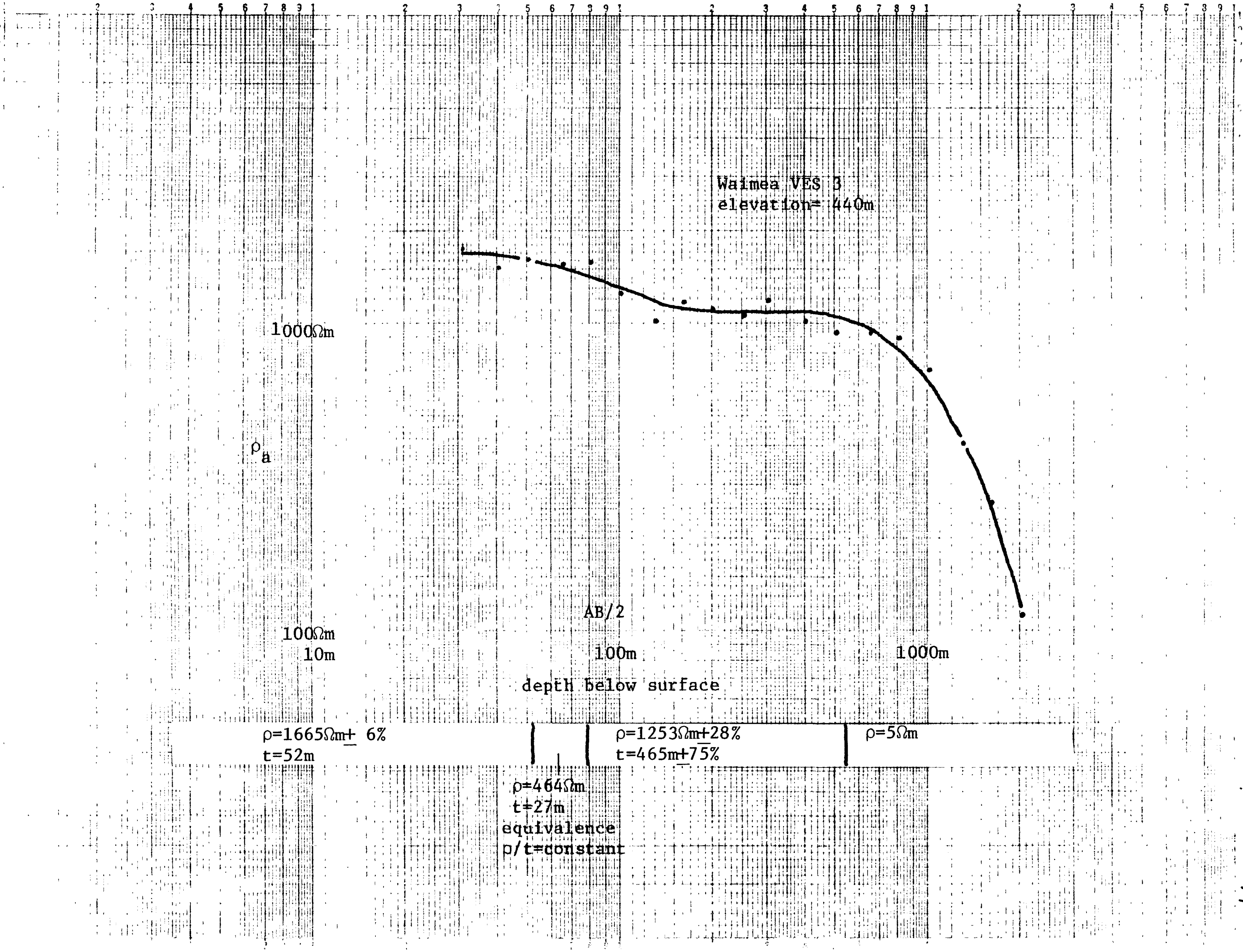
explanation of the symbols used:

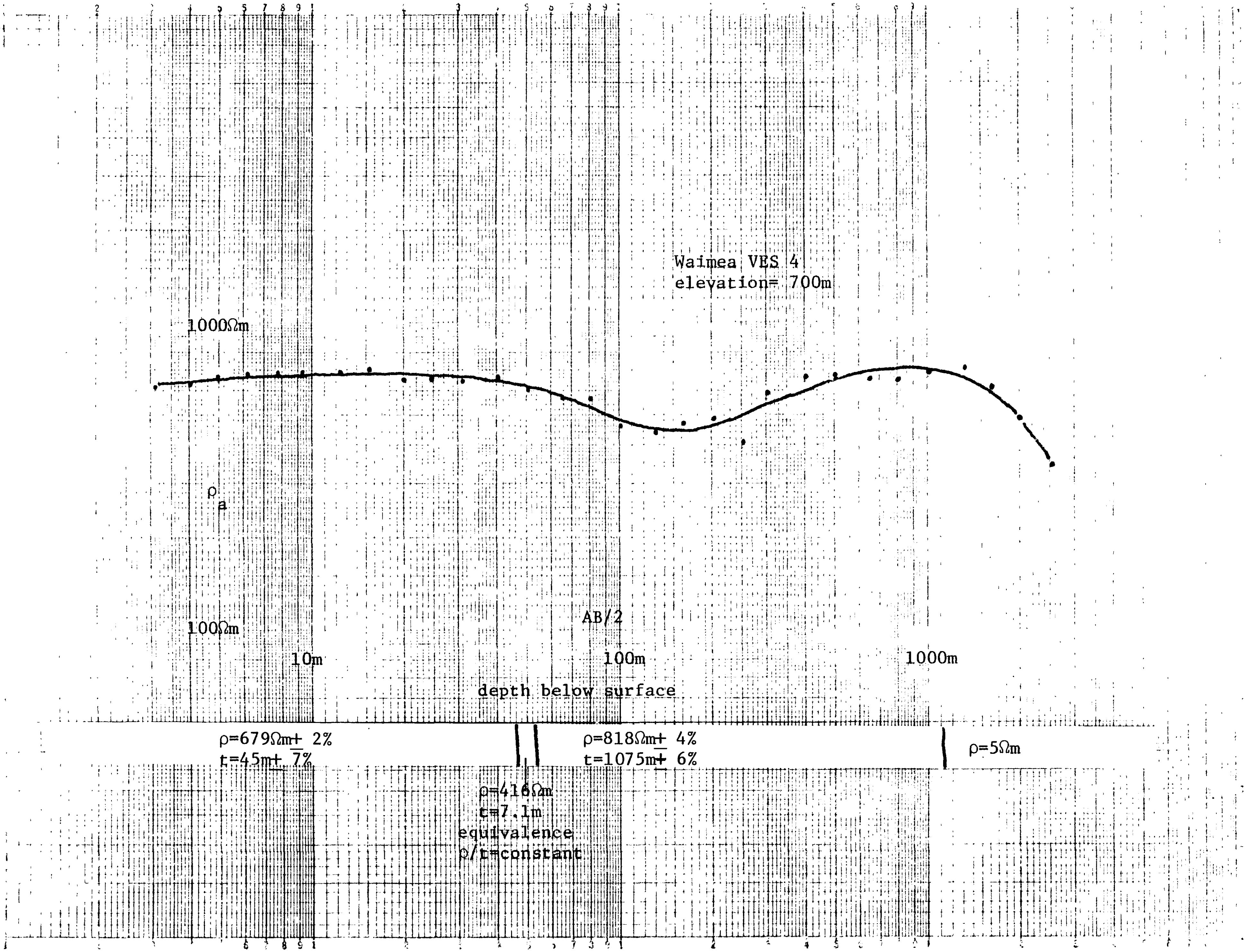
Dots represent the smoothed data points and the solid, curved line represents the values calculated for the model found by computer program MARQDCLAG. The model itself is listed below the horizontal axis of the plot as a resistivity and thickness for each of a number of horizontal layers. The depth of each interface may be read directly from the horizontal axis. The estimated errors for each of the model parameters are also listed as plus-and-minus percentages accompanying the parameter values. Parameters with correlated errors are noted with the word "equivalence" and a formula demonstrating the type of correlation. Parameters with no listed or correlated errors were not allowed to vary during computer interpretation.



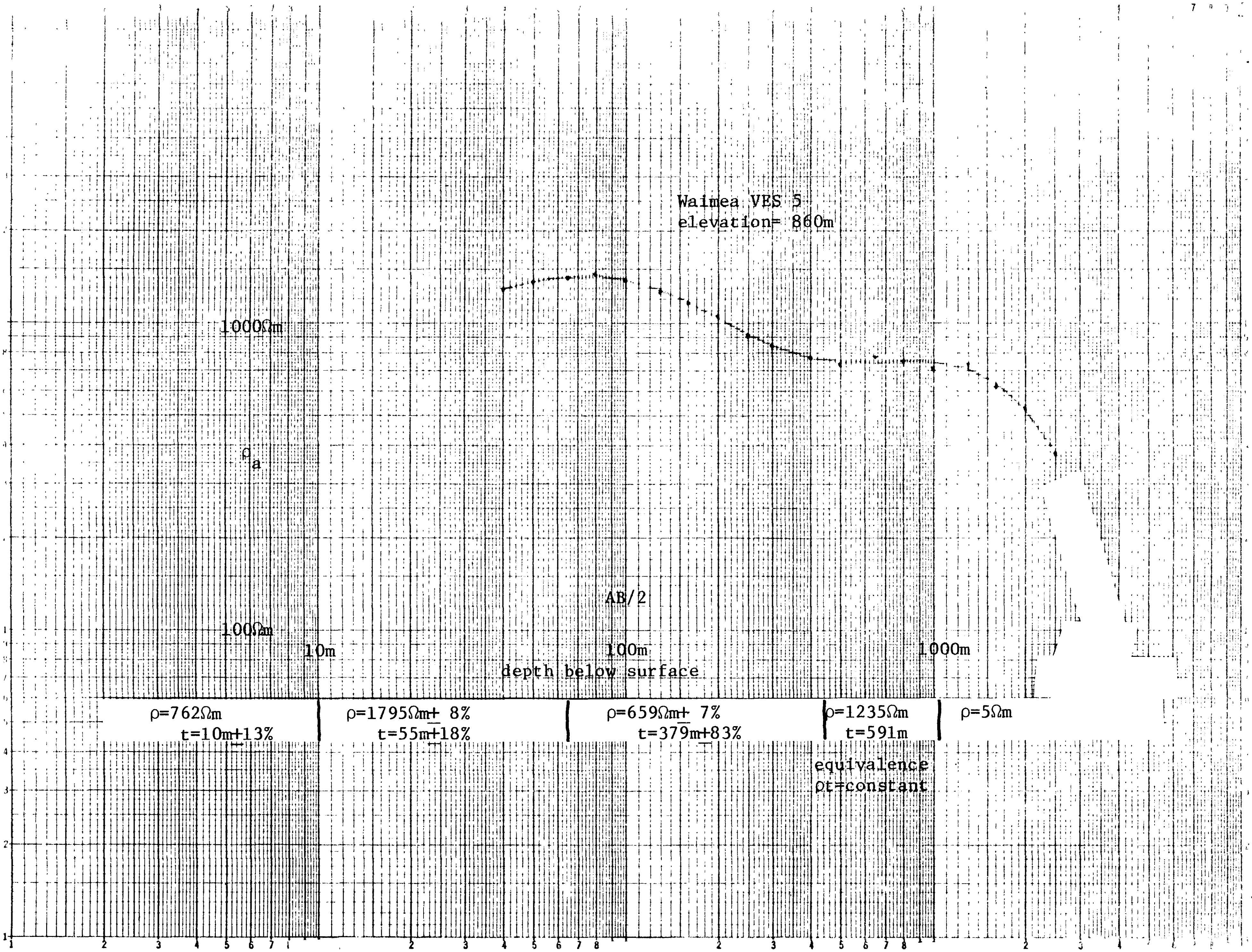
Waimea VES 1
elevation= 65m
ρ
a
1000Ωm
100Ωm
10Ωm
10m
100m
1000m
AB/2
depth below surface
ρ=60.5Ωm
t=2.1m
ρ=1000Ωm
t=54m+15%
ρ=5Ωm
equivalence
ρ/t=constant


Waimea VES 2
elevation= 365m
1000Ωm
100Ωm
ρa
AB/2
10m
100m
1000m
depth below surface
ρ=1606Ωm± 4%
t=2.5m
ρ=2460Ωm± 3%
t=38m±31%
ρ=1030Ωm±45%
t=99m±85%
ρ=409Ωm±42%
t=743m±60%
ρ=5Ωm

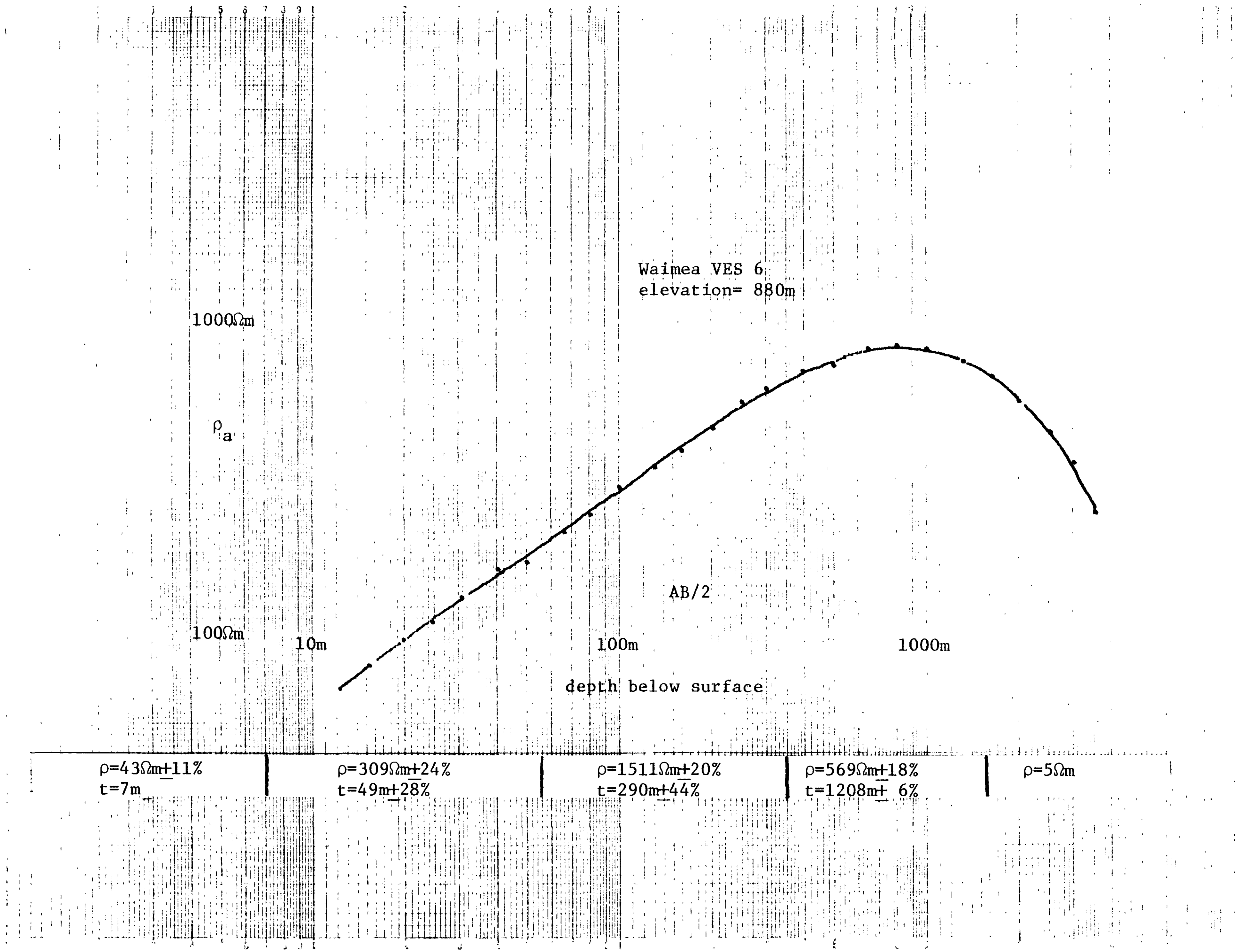

Waimea VES 3
elevation= 440m
1000Ωm
ρa
100Ωm
10m
AB/2
100m
1000m
depth below surface
ρ=1665Ωm+ 6%
t=52m
ρ=1253Ωm+28%
t=465m+75%
ρ=5Ωm
ρ=464Ωm
t=27m
equivalence
ρ/t=constant

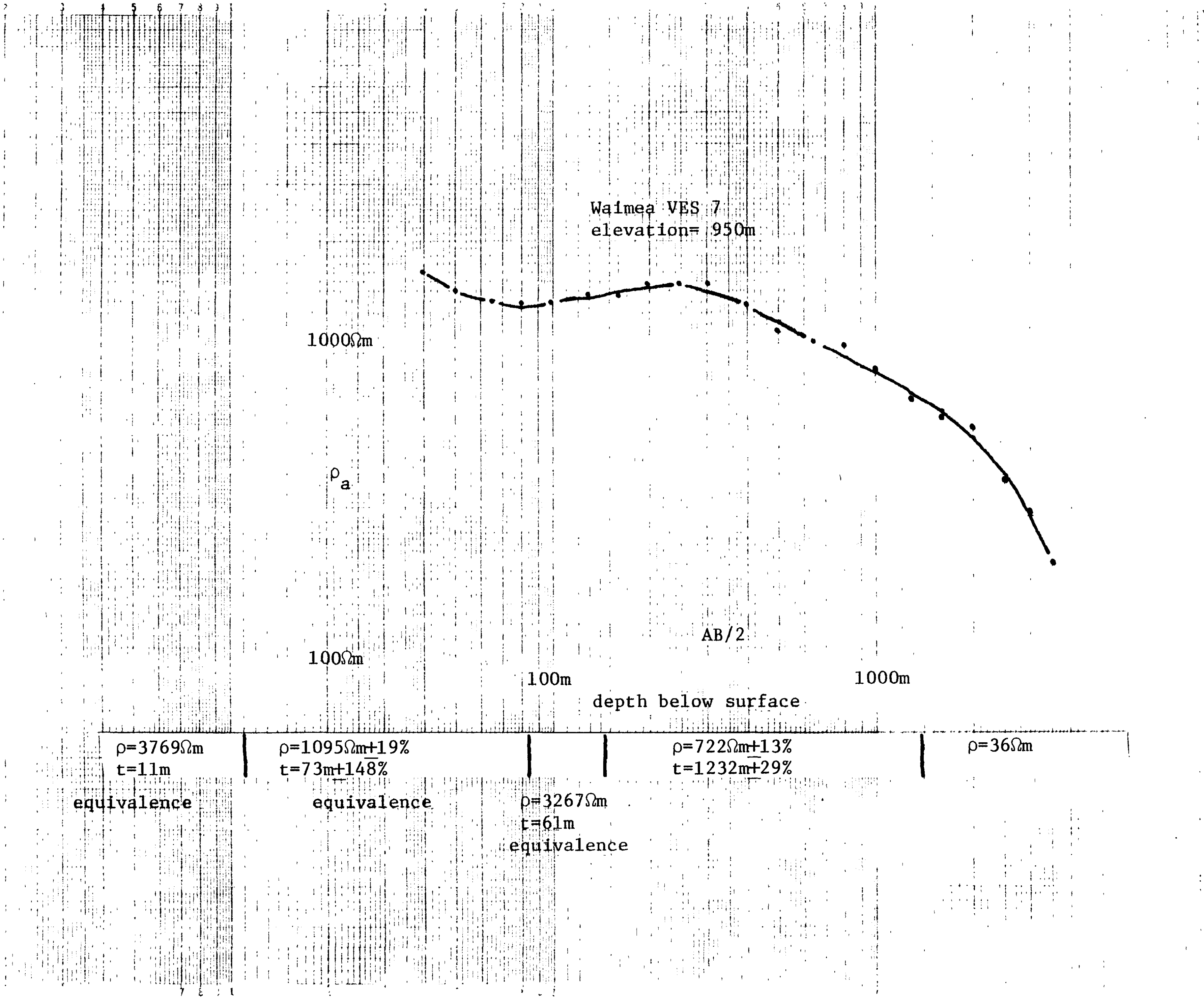


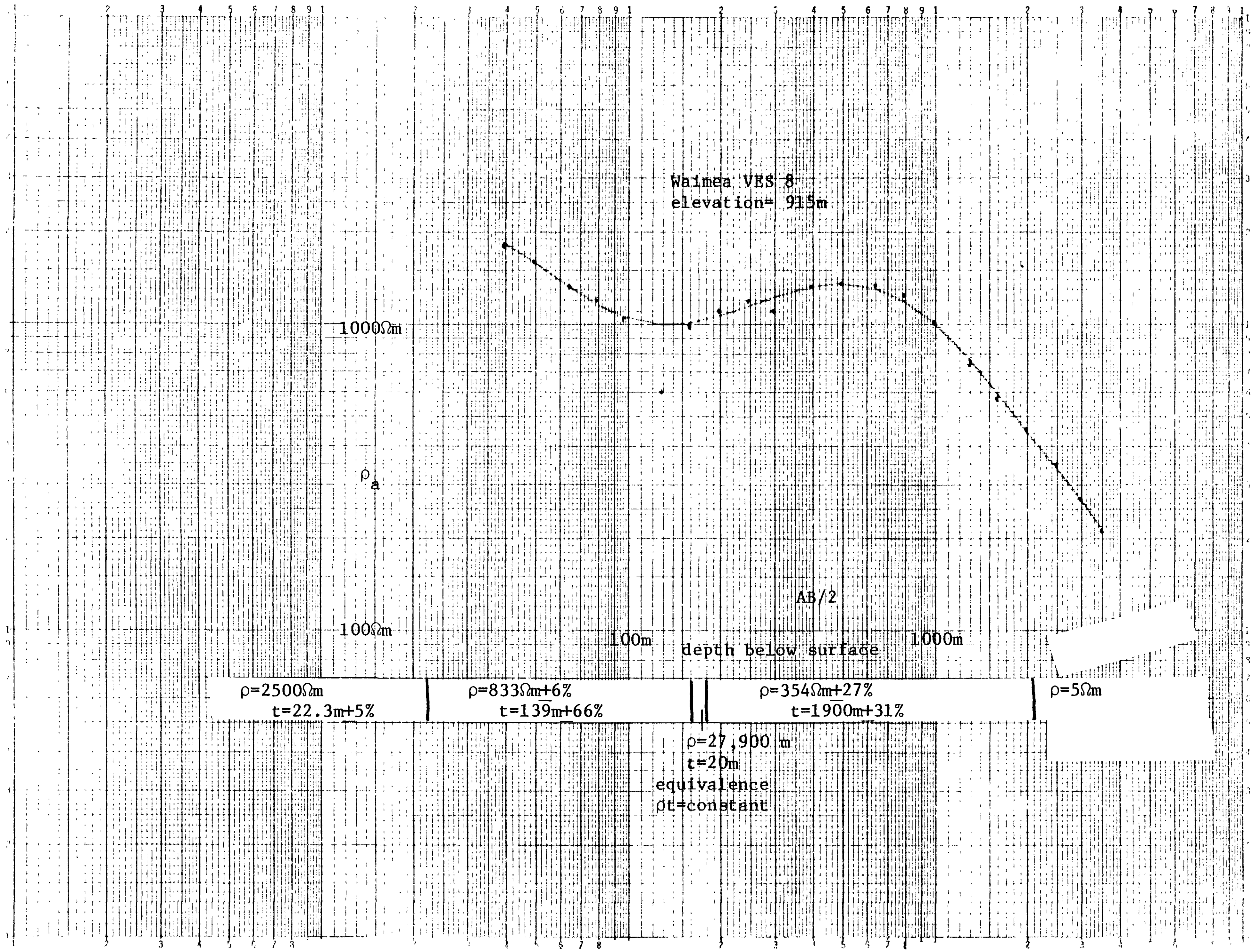
Waimea VES 4
elevation= 700m
1000Ωm
100Ωm
ρ a
AB/2
10m
100m
1000m
depth below surface
ρ=679Ωm± 2%
t=45m± 7%
ρ=416Ωm
t=7.1m
equivalence
ρ/t=constant
ρ=818Ωm± 4%
t=1075m± 6%
ρ=5Ωm



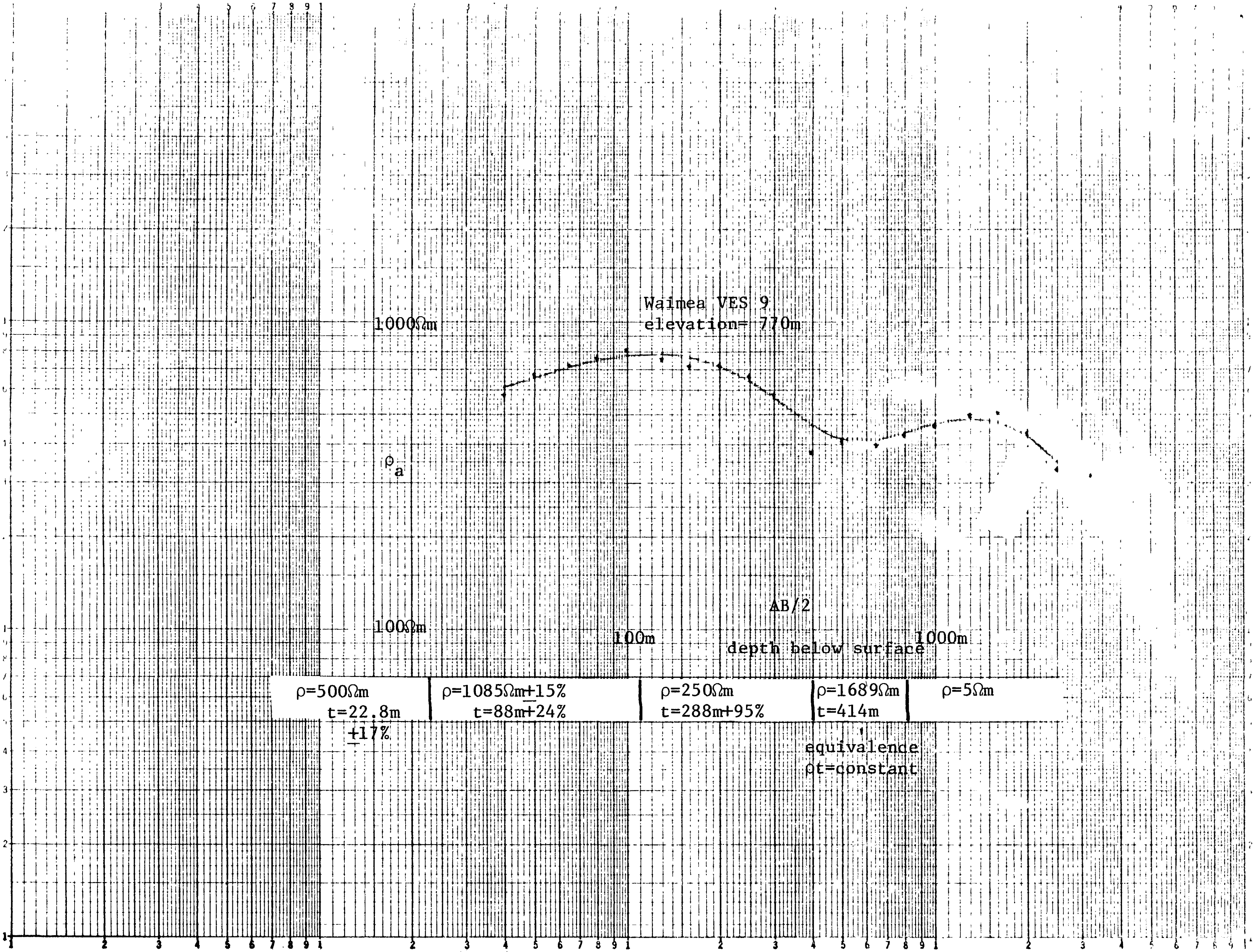
Waimea VES 5
elevation= 860m
1000Ωm
ρa
100Ωm
AB/2
10m
100m
1000m
depth below surface
ρ=762Ωm t=10m±13%
ρ=1795Ωm± 8% t=55m±18%
ρ=659Ωm± 7% t=379m±83%
ρ=1235Ωm t=591m
ρ=5Ωm
equivalence
ρt=constant

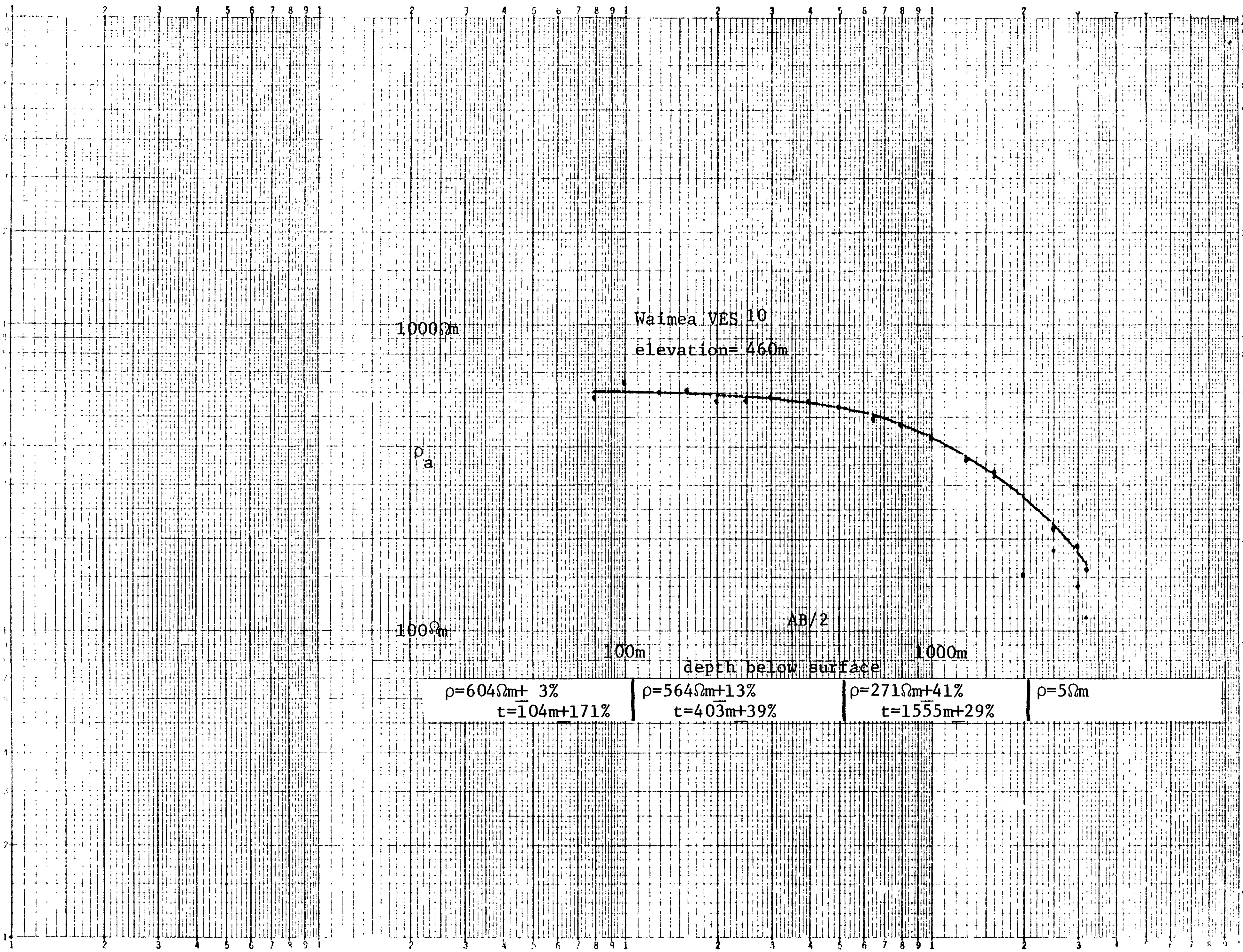

Waimea VES 6
elevation= 880m
1000Ωm
ρa
100Ωm
10m
100m
1000m
AB/2
depth below surface
ρ=43Ωm±11%
t=7m
ρ=309Ωm±24%
t=49m±28%
ρ=1511Ωm±20%
t=290m±44%
ρ=569Ωm±18%
t=1208m± 6%
ρ=5Ωm


Waimea VES 7
elevation= 950m
1000Ωm
ρa
100Ωm
AB/2
100m
1000m
depth below surface
ρ=3769Ωm
t=11m
equivalence
ρ=1095Ωm+19%
t=73m+148%
equivalence
ρ=3267Ωm
t=61m
equivalence
ρ=722Ωm+13%
t=1232m+29%
ρ=36Ωm



Waimea VES 8
elevation= 915m
1000Ωm
ρa
100Ωm
AB/2
100m
1000m
depth below surface
ρ=2500Ωm
t=22.3m+5%
ρ=833Ωm+6%
t=139m+66%
ρ=354Ωm+27%
t=1900m+31%
ρ=5Ωm
ρ=27,900 m
t=20m
equivalence
ρt=constant


Waimea VES 9
elevation= 770m
1000Ωm
100Ωm
ρ_a
AB/2
100m
1000m
depth below surface
ρ=500Ωm
t=22.8m
±17%
ρ=1085Ωm±15%
t=88m±24%
ρ=250Ωm
t=288m±95%
ρ=1689Ωm
t=414m
ρ=5Ωm
equivalence
ρt=constant


Waimea VES 10
elevation= 460m
1000Ωm
ρa
100Ωm
AB/2
100m
1000m
depth below surface
ρ=604Ωm+ 3%
t=104m+171%
ρ=564Ωm+13%
t=403m+39%
ρ=271Ωm+41%
t=1555m+29%
ρ=5Ωm