The Detection of Subsurface Stream Channels in Carbonate Rocks by Geoelectrical Methods

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ABSTRACT

The distinction of partially dissolved from compact carbonate rocks and from the alluvial overburden is a major problem in geological engineering and water resources. Geoelectrical depth soundings after Schlumberger were applied over karst terraines in three locations of the Ozarks in Missouri. The zone of dissolved carbonate rock shows intermediate resistivities between low values for the overburden and extremely high values for the compact rock.

The main part of the investigation was directed towards solving the underground flow and disappearance of Logan Creek near Ellington, Missouri. Combined geoelectrical and gravity surveys under consideration of some near surface seismic refractions indicate zones of increased depth and degree of dissolution at the Ellington Fault. A detailed gravity profile across the fault shows a negative anomaly with a minimum of -2.0 mgal, which extends over approximately 3 miles with large lateral gradients. A theoretical model can explain the anomaly if the depth of the cavernous limestone has a maximum of 350 feet and if the bulk volume of fissures and stream channels amounts to 15%.

The coincidence between the fault and the negative anomaly suggests that ruptures along fault planes weakened the rock so that chemical dissolution from surface waters had a greater penetration.

Keywords: Karst terranes, stream channels in carbonate rocks, resistivity method, gravity method.

The Detection of Subsurface Stream Channels in Carbonate Rocks

1. Introduction

Surface weathering of carbonate rocks causes landforms known as "karst topography." Precipitation water becomes slightly acidic when it penetrates through the organic top soil. Any part of the carbonate rock, which is contacted by this water, is subject to chemical dissolution forming cavities, sinkholes and buried stream channels. The distribution, size and number of these karst phenomena appears to be irregular and unpredictable.

The construction of buildings, dams and water reservoirs in such a geological environment is riskful. Foundation sites must be carefully selected to avoid damage from collapsing caves and sinkholes and also to prevent the formation of new solution channels.

The hydrogeology of karst terrains offers many interesting aspects. The widely distributed stream channels present an aquifer system of large capacity. Karst springs supply an abundance of water. Unfortunately karst water undergoes little if any filtration during its underground flow. If pollutants somewhere enter into underground water passages, they hardly will be absorbed and most likely reappear in a karst spring.

The variety of landforms, caves and picturesque springs offers recreational facilities and attracts the attention of scientists and conservationists from the aesthetic point of view.

Conventional prospection techniques for the detection of cavities and underground stream channels have a comparatively low rate of success because of the irregularities of karst features. Remote sensing techniques are very promising in depicting areas with sinkhole structures (W.M. Warren et al., 1973) and in mapping surfaces of anomalous streamflow patterns (E.J. Harvey and J. Skelton, 1970). These methods have hardly any depth penetration so that other geophysical techniques are used to explore the depth continuation of karst features. Dusan Arandjelovic (1966) reports about geoelectrical resistivity methods for the determination of the "depth of karstification" in the Dinaric Karst.

The major part of the Ozarks in southern Missouri and northeastern Arkansas is covered with Paleocoic limestone-dolomite. The area is characterized by karst springs, caves and sinkhole structures. Geoelectrical and gravity investigations were conducted in several parts to obtain quantitative data related to subterranean water transport.

2. The Measuring Problem Over Carbonate Rocks

Karst structures present in their simplest form a three-layer case as shown in Fig. 1

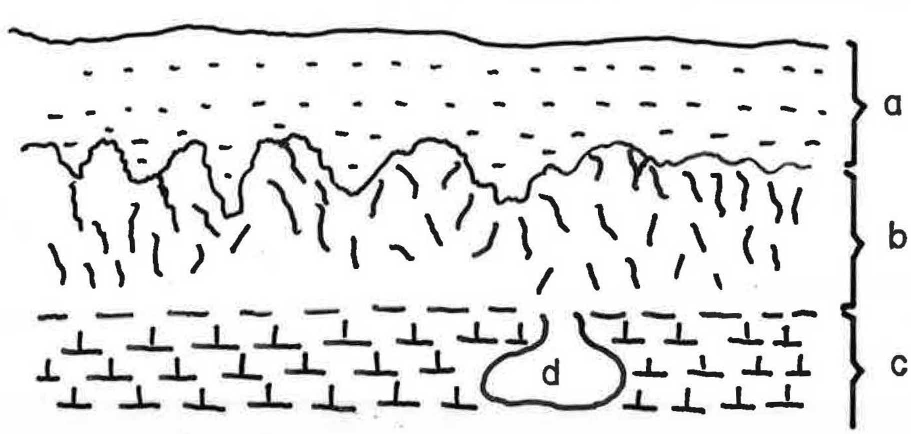

Fig.1: Weathering structures in carbonate rocks

The overburden, a, partially fills the cavities of the highly dissolved limestone b, which at greater depth becomes compact, c. Of particular interest is layer b, which simply by it's origin cannot be expected to have uniform physical parameters. Moreover, significant lateral changes within this layer are of great interest. These, however, will further complicate the geophysical detectability. Caves (d) in the more or less compact limestone, c, may be very important for the geologist. Their diameter related to the depth, in most cases, prohibits detectability because of diagnostic limitations such as seismic wavelength and distance relations.

Finally the lack of distinctive discontinuities of the zone b explains the difficulty to interpret geophysical measuring results.

Presently there does not exist a useful specific method, which is superior to other techniques in detecting solution cavities. Therefore it is believed that combined methods such as geoelectrics, gravity and refraction seismic can be most helpful in determining the subterranean environment of carbonate rocks.

Geoelectrical depth sounding methods are expected to be applicable if the solution channels are filled with water or clay. This would reduce the resistivity of the cavernous limestone.

The seismic refraction technique can also be helpful in distinguishing velocities between compact and karstified limestone. Significant lateral changes, however, may obscure the refraction pattern.

The gravity method responds to density contrasts between compact and karstified limestone. The effect may be very small so that accurate observations with a close net are necessary.

3. The Scope of the Field Investigations

Geophysical measurements were conducted in the southeastern part of Missouri as shown in Fig. 2. Geoelectrical depth soundings were conducted at Lane Spring (location I) and near St. Genevieve (location II). A combined gravity and geoelectrical survey was conducted in the area of Logan Creek (location III). The investigations at locations I and II were test studies for the geoelectrical depth sounding method. Combined investigations at location III were initiated to understand subsurface water flow of a disappearing river.

The geoelectrical depth sounding method can predict subsurface conditions from measurements at the surface on account of the rock resistivity. An electrical current is fed into the ground via two electrodes. Symmetrically to the center of both current electrodes the voltage is measured across a pair of closely spaced electrodes. The current, voltage, and electrode configuration determine an "apparent resistivity," which is a function of the geometry and true resistivities of the subsurface materials. There are many electrode configurations in use; most have in common a base line on which all four electrodes are located. In the context of this investigation the Schlumberger arrangement was applied, in which the spacing of the potential electrodes is kept very short. With an increase of the current electrodes, L, for successive measurements, one obtains a set of apparent resistivities, which are related to an increasing depth of penetration. Results are presented by plotting the

Fig.2: Location of geophysical investigations in southeastern Missouri. I Lane Spring. II St. Genevieve. III Logan Creek

apparent resistivity, ρa, versus the half of the spacing between the current electrodes, L/2 on transparent bilogarithmic paper. Data plotted in this fashion can be interpreted with theoretical master curves by curve matching.

The gravity method responds to small differences of the gravitational attraction of the earth. They are caused by lateral density contrasts. The conventional application of this method is the detection of large tectonic structures such as folds, faults, salt dome structures, and igneous intrusions. The high precision and accuracy of modern gravimeters allow the detection of very small density contrasts, caused by near surface changes of the bedrock depth. In this context the method is used to distinguish cavernous from compact limestone.

4. Geoelectrical Investigations at Lane Springs (Frohlich, 1972)

Lane Spring (Location I, Fig. 2) is a small alluviated spring in the valley of the Little Piney River some 20 miles south of Rolla. Fig. 3 shows the geographical location of the spring and the orientation of the geoelectrical depth soundings. For the first 250 m the spring flows southwest, from where it has been artificially forced to reverse its direction to the north. Several hundred meters further downstream it joins the Little Piney River. The underground flow of the water resurging from this spring is a suitable study object for the geoelectrical depth sounding method. Geological and topographical conditions are favorable for geophysical field experiments. The underground water most likely flows from the east and northeast underneath the valley to feed the spring. Since, on the other hand, the yield of the spring is small, one can only expect a small decrease of the limestone resistivity from the water content in the fissures and joints. This investigation, therefore, is a test study for the accuracy and diagnostic power of the resistivity method. In the valley the limestone bedrock is uniformly covered with an alluvial overburden of clay and chert with an average thickness of 5 m.

The depth soundings D.S. 1 to 8 present typical two-layer cases shown in Figs. 4 to 6. Maximum electrode separations were L = 200 m. The resistivities of the overburden range between 80 and 240 Ωm. Two characteristic curve types, shown in Fig. 4, can be distinguished from each other. The first, D.S. 6, shows linear slope angles of 45^{o} at the right hand side of the graph. The other type, D.S. 2, does not approach a straight line at the right hand branch and linear

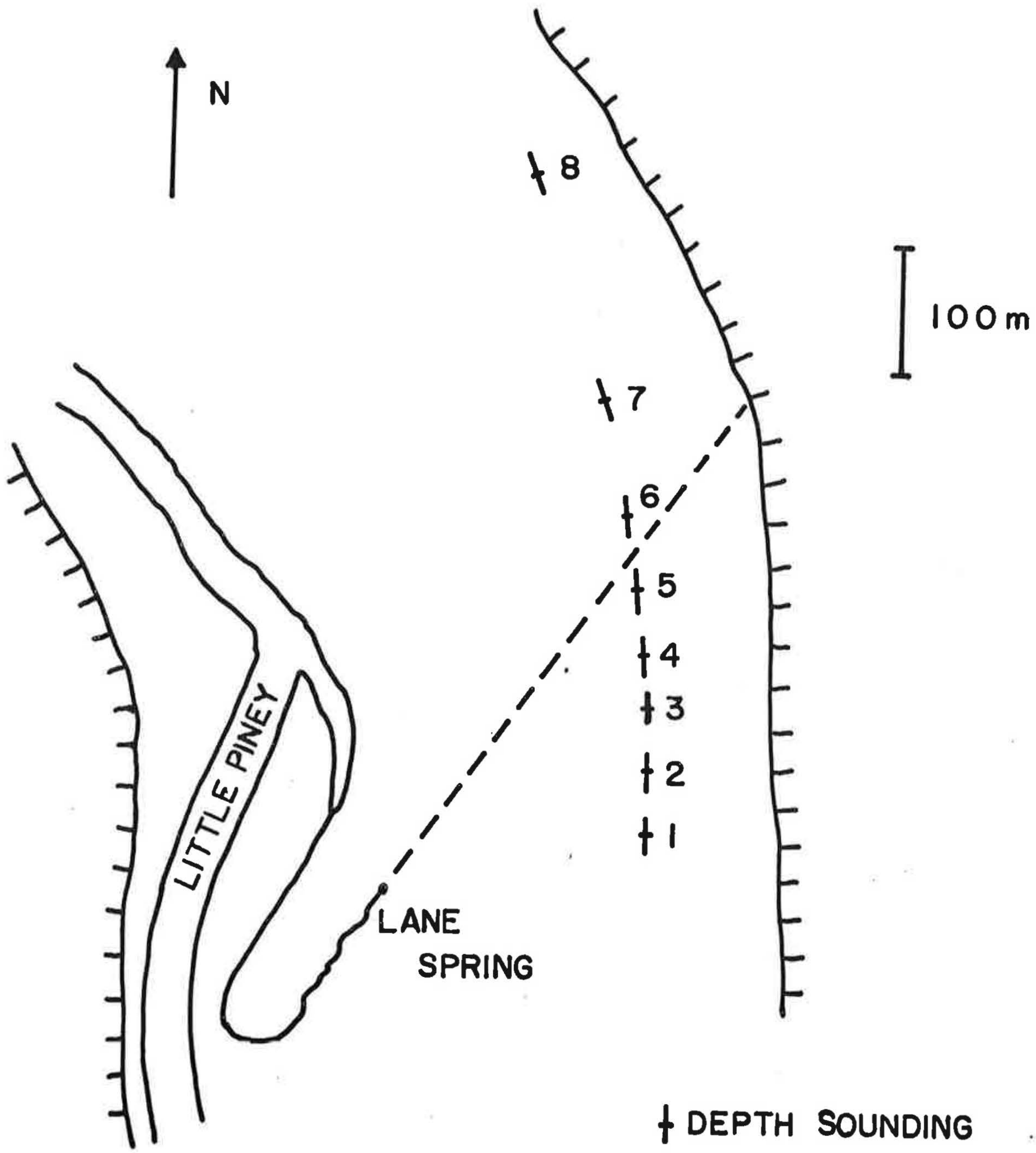

Fig.3: Location of geoelectrical depth soundings at Lane Spring

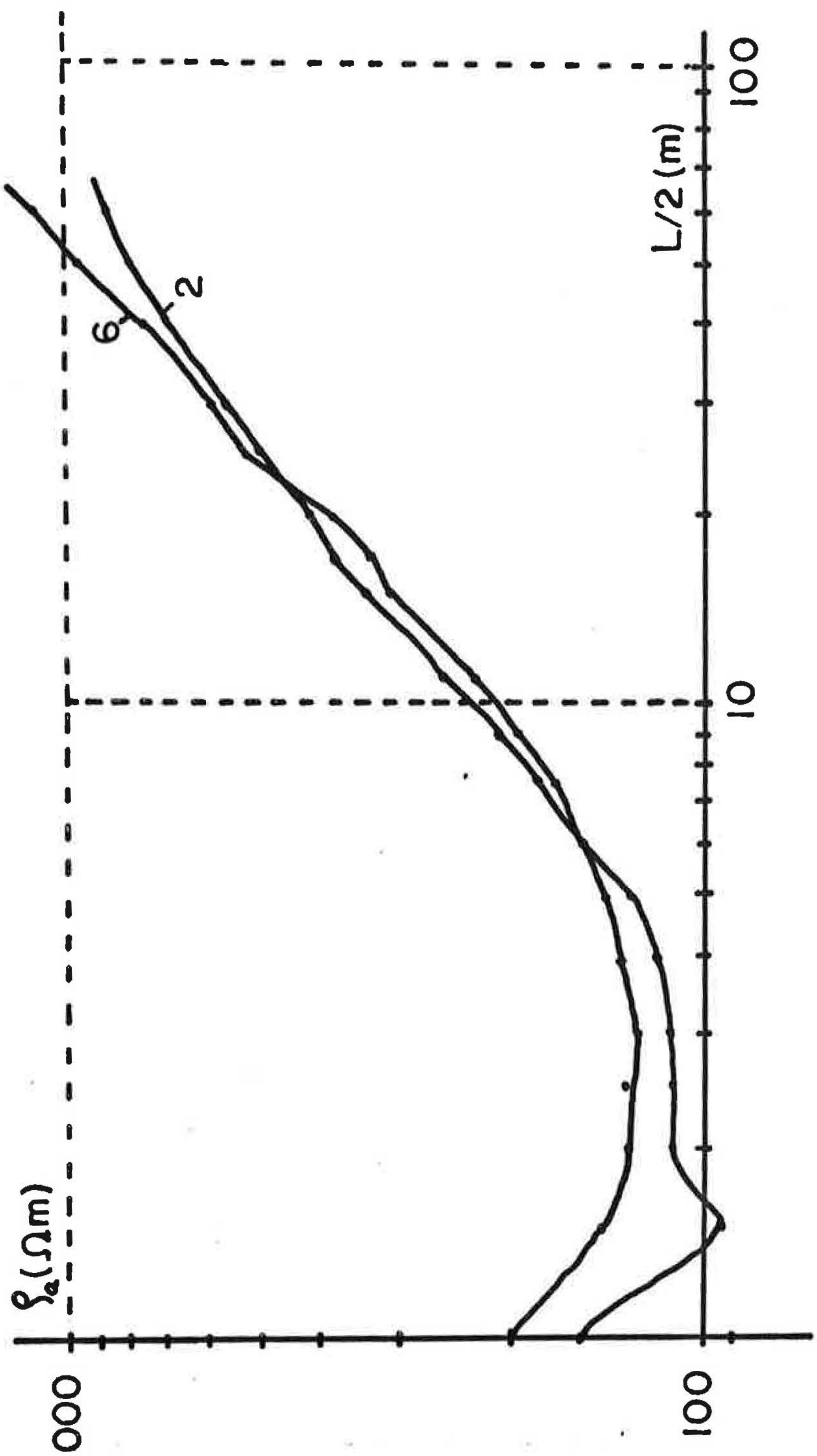

Fig.4: Two-layer field curves at Lane Spring

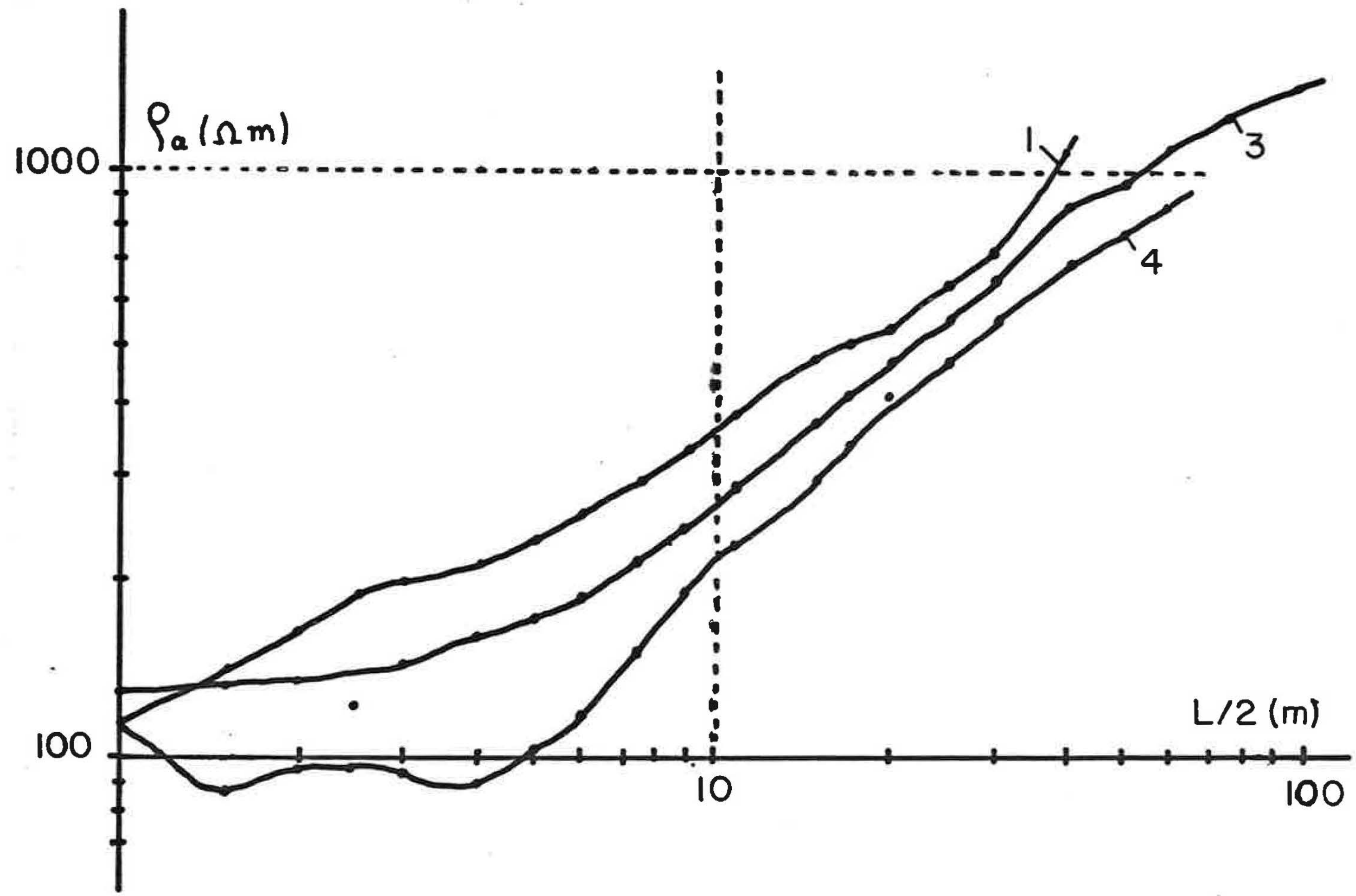

Fig.5: Two-layer field curves at Lane Spring

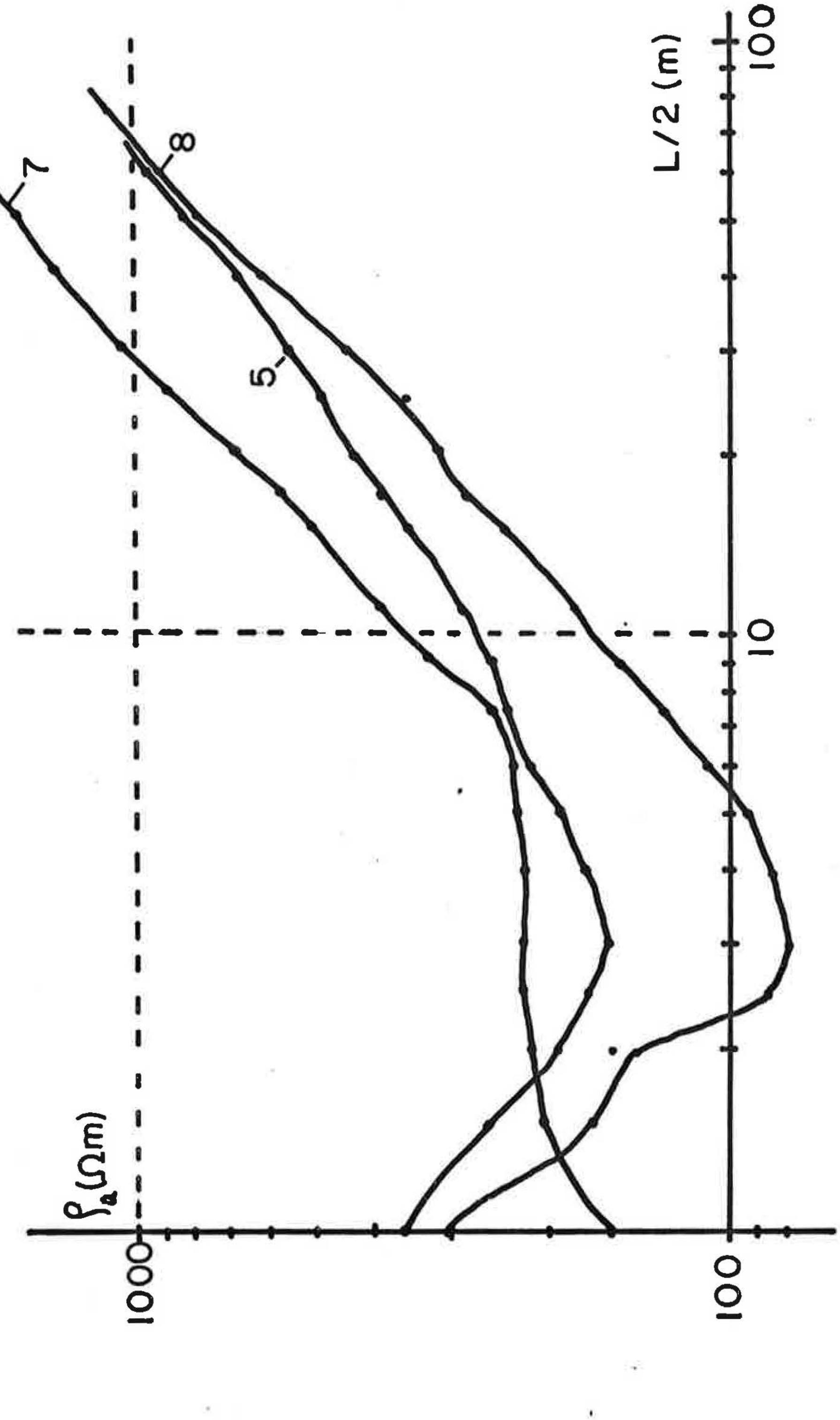

Fig.6: Two-layer field curves at Lane Spring

approximations always result in a slope angle, which is smaller than 45^{0}. Theoretical calculations show that a two-layer curve approaching a slope angle of 45^{0} is caused by an infinitely high bedrock-resistivity. For smaller slope angles the theory predicts a finite bedrock resistivity.

If we project the first 250 m of Lane Spring backwards across the valley (see Fig. 3), this line separates depth soundings 1 to 5 from 6 to 8. It happens that the latter soundings (D.S. 6 - 8) show an infinitely high bedrock resistivity, whereas they range between 1000 and 2100Ω m south of this dividing line. Though such resistivities are rather high, it is believed that they account for the small water transport through fissures, joints and possible stream channels towards Lane Spring. This interpretation implies that north and northwest of this line no or negligible water flows through the bedrock accounting for the infinitely high bedrock resistivity.

Fig. 7a presents the resistivity depth profile compiled from all depth soundings. The resistivities were obtained from curve matching with theoretical master curves. Though these are simple two-layer cases, the examples show that, in spite of the shallow overburden, long electrode separations are necessary to distinguish high bedrock resistivities from one case to another.

Approximation of the right hand side of the depth soundings with a straight line results in slope angles, which are presented in Fig. 7b. This presentation allows a reliable distinction of the conductive from the nonconductive bedrocks.

A conventional method for the investigation of lateral changes

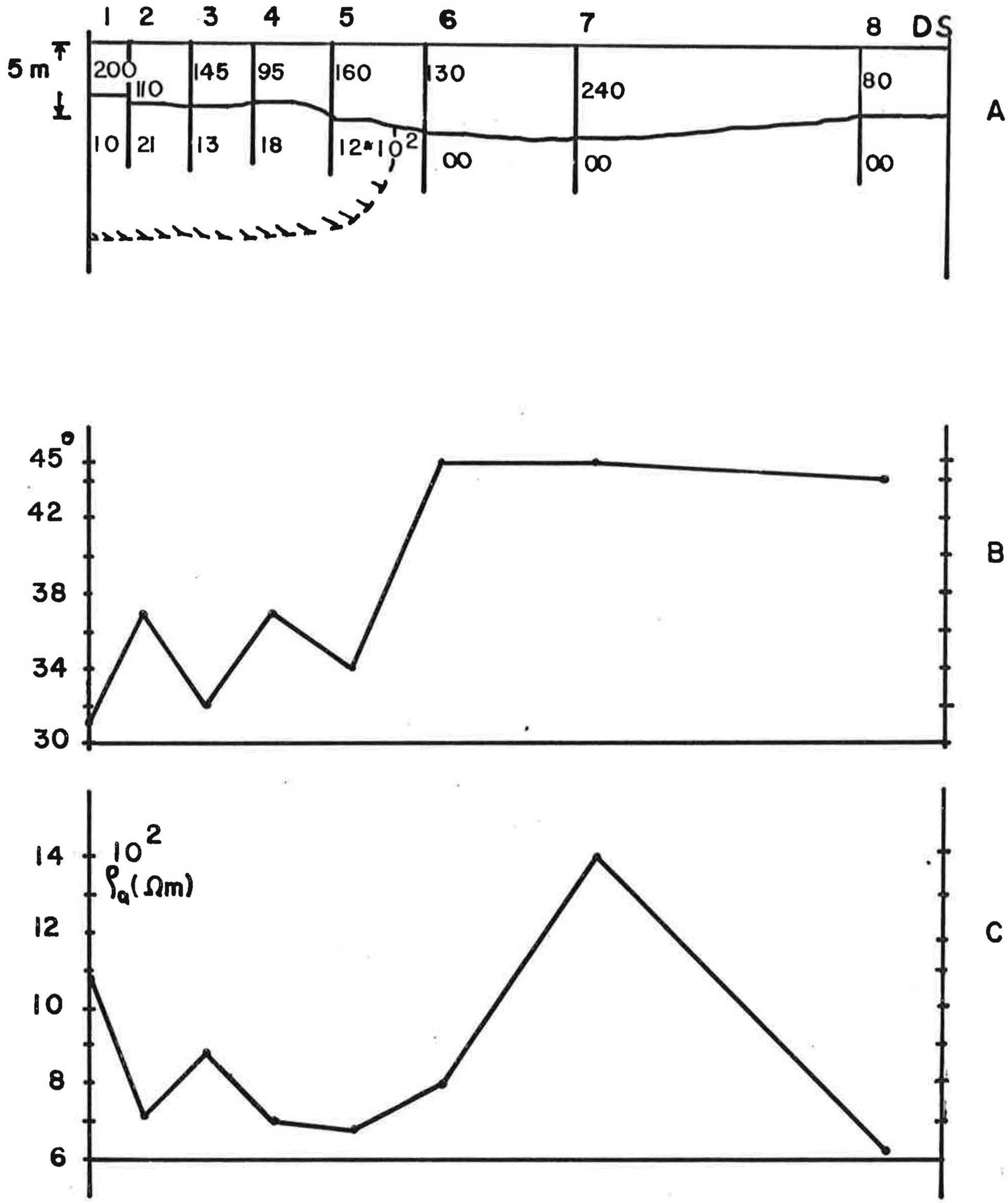

Fig.7: Geoelectrical profile obtained from depth soundings. A: Resistivity depth profile. The left part of the limestone contains stream channels. B: Slope angles of the right hand branch of the sounding curves. C: Geoelectrical profile of apparent resistivity with an electrode separation of L= 80 m.

of resistivity is known as electrical profiling. With a constant electrode separation the array is moved along a profile for successive measurements. Fig. 7c shows the results of geoelectrical profiling, which one would have obtained for an electrode separation of L = 80 m. The values were taken from the depth soundings. The result shows that except for the value obtained from D.S. 7 there is no indication of a nonconductive zone. Geoelectrical profiling can only be useful if subsurface conditions are very simple, which in this field study certainly is not the case.

5. Geoelectrical Investigations Near St. Genevieve

An area near St. Genevieve, Missouri, Fig. 2, location II, was selected for geoelectrical depth soundings, where the dissolution of limestone has further progressed compared with Lane Spring.

Underneath an overburden of 8 to 10 m the cavernous limestone is partially filled with clay to an average depth of 15 m. Four depth soundings are shown in Figs. 8 to 11. If the first three measuring points to the left are ignored the curves present three-layer cases with $\rho_1 < \rho_2 < \rho_3$ corresponding to A-type master curves. The intermediate layer of resistivity ρ_2, described as zone b in Fig. 1, is relatively small. The field curves can therefore mistakenly be identified as two-layer cases.

D.S. 3 of Fig. 10 shows the strongest influence of this intermediate layer on the field curve. A step-wise interpretation with two-layer master curves demonstrates the influence of various layers on the depth sounding. Again, the curve approaches to the far right a linear slope with an angle of 45°. The thin curve shows the match of a two-layer master curve ($\rho_2/\rho_1 = \infty$) with the linear rise at the far righthand side. Interpretation 1 at the bottom, obtained from this match, results with an overburden of $40 \Omega m$ of a thickness of 12.5 m. Layer depths interpreted from geoelectrical soundings are plotted parallel to the abscissa using the scale for L/2 also for the depth. This first step of the interpretation ignores the intermediate layer, which causes the field curve to deviate significantly from the master curve ($\rho_2/\rho_1 = \infty$) between L/2 = 5 and 40 m. In the next step, within this interval, a match

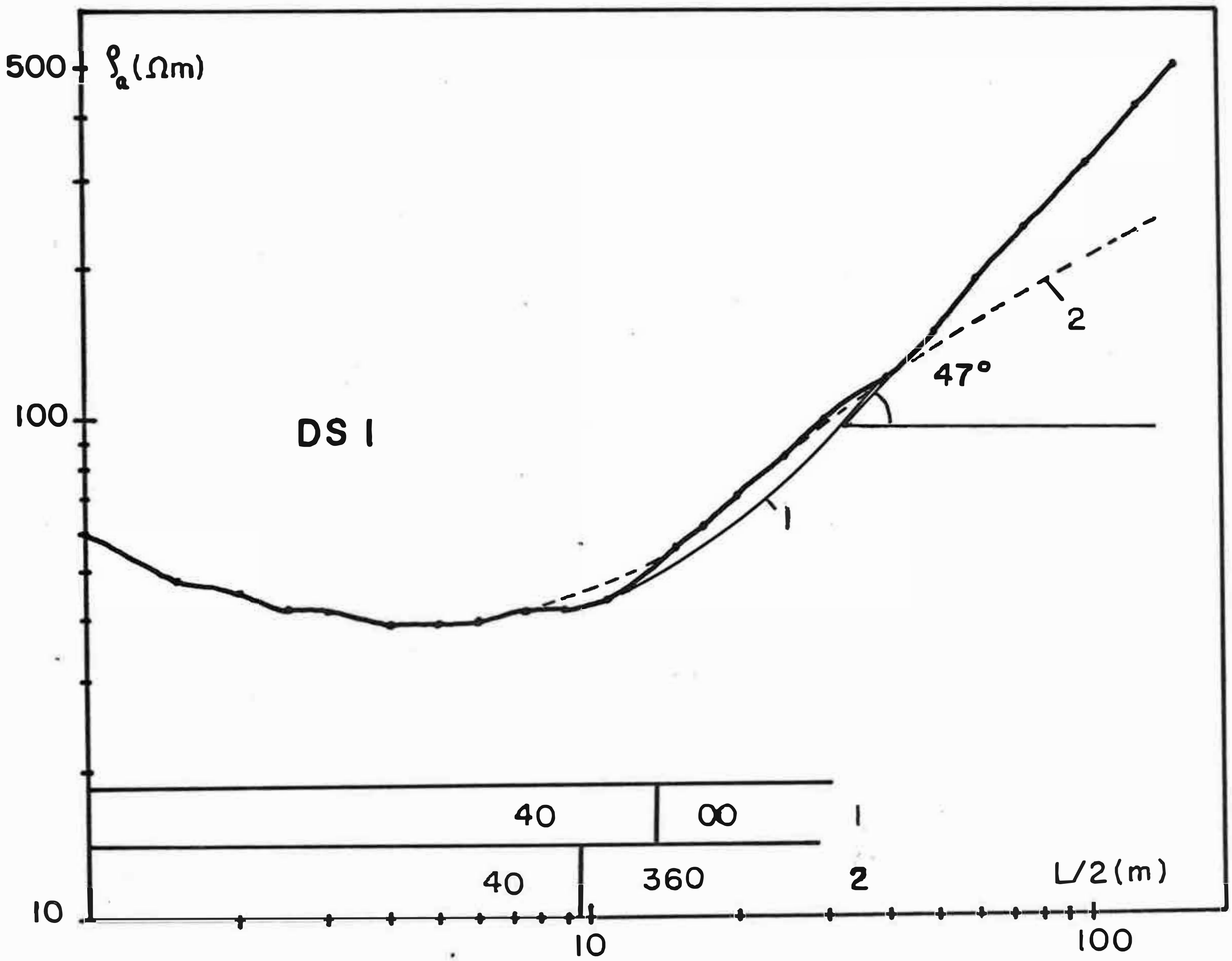

Fig.8: Geoelectrical depth soundings near St.Genevieve

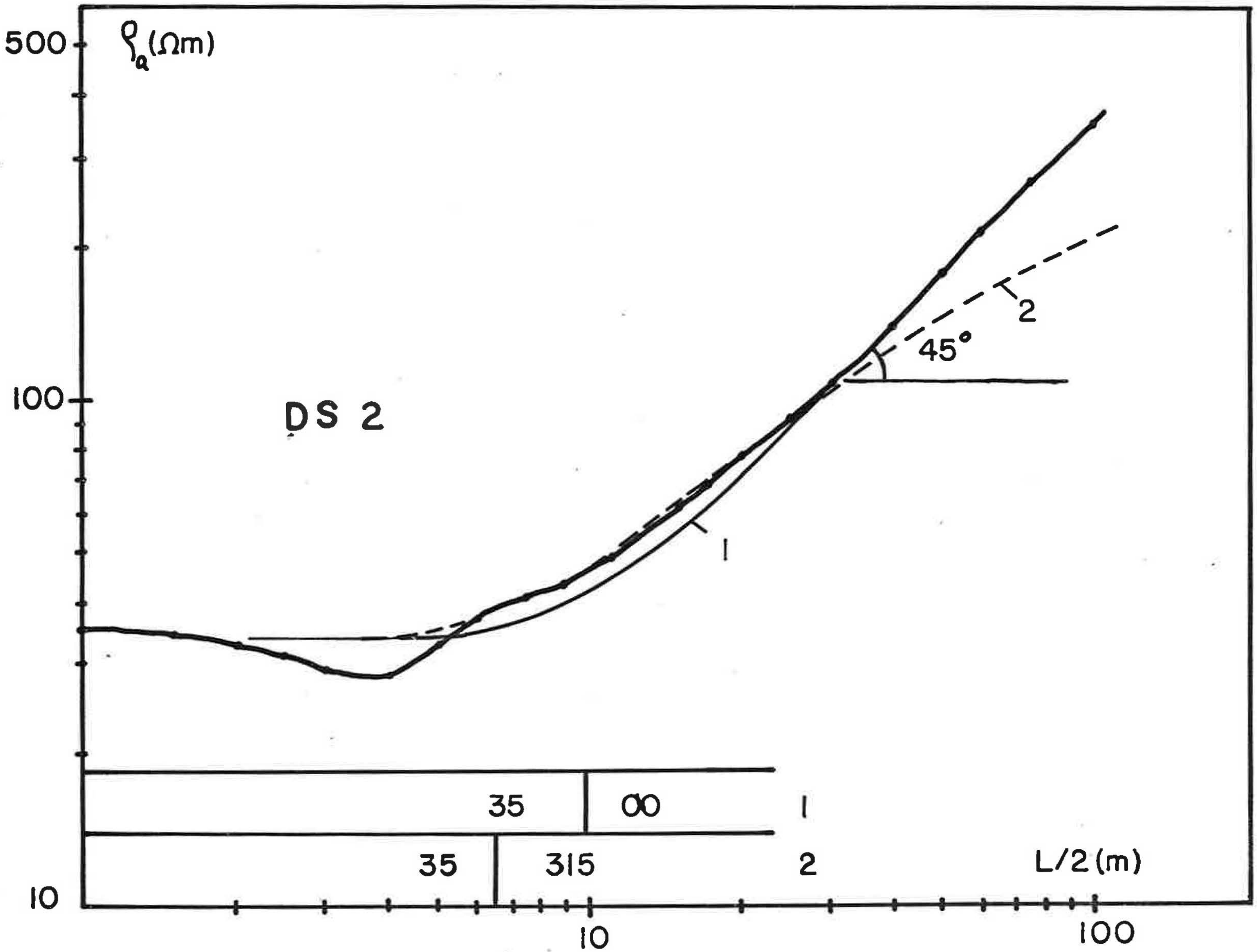

Fig.9: Geoelectrical depth sounding near St.Genevieve

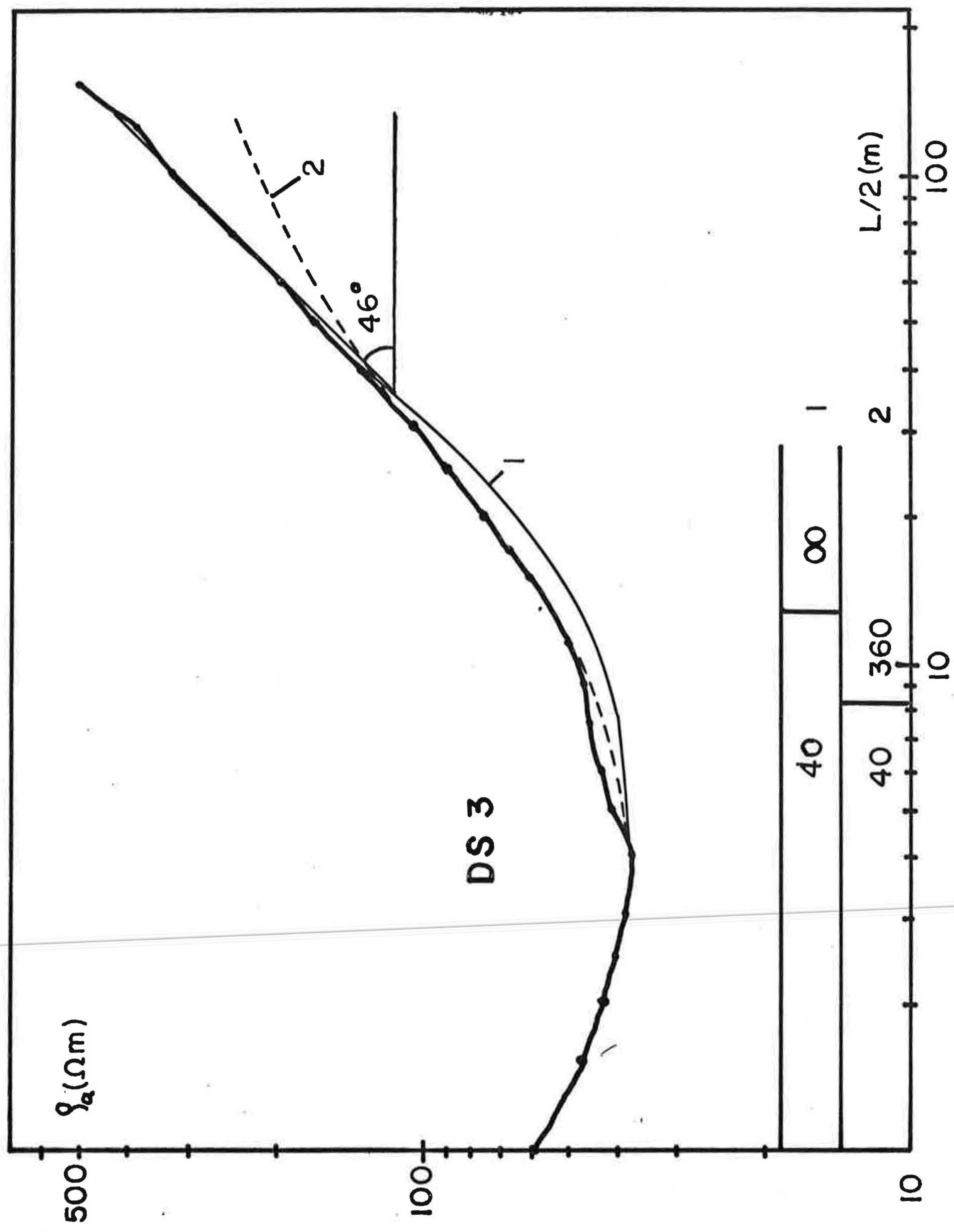

Fig. 10: see Fig.8

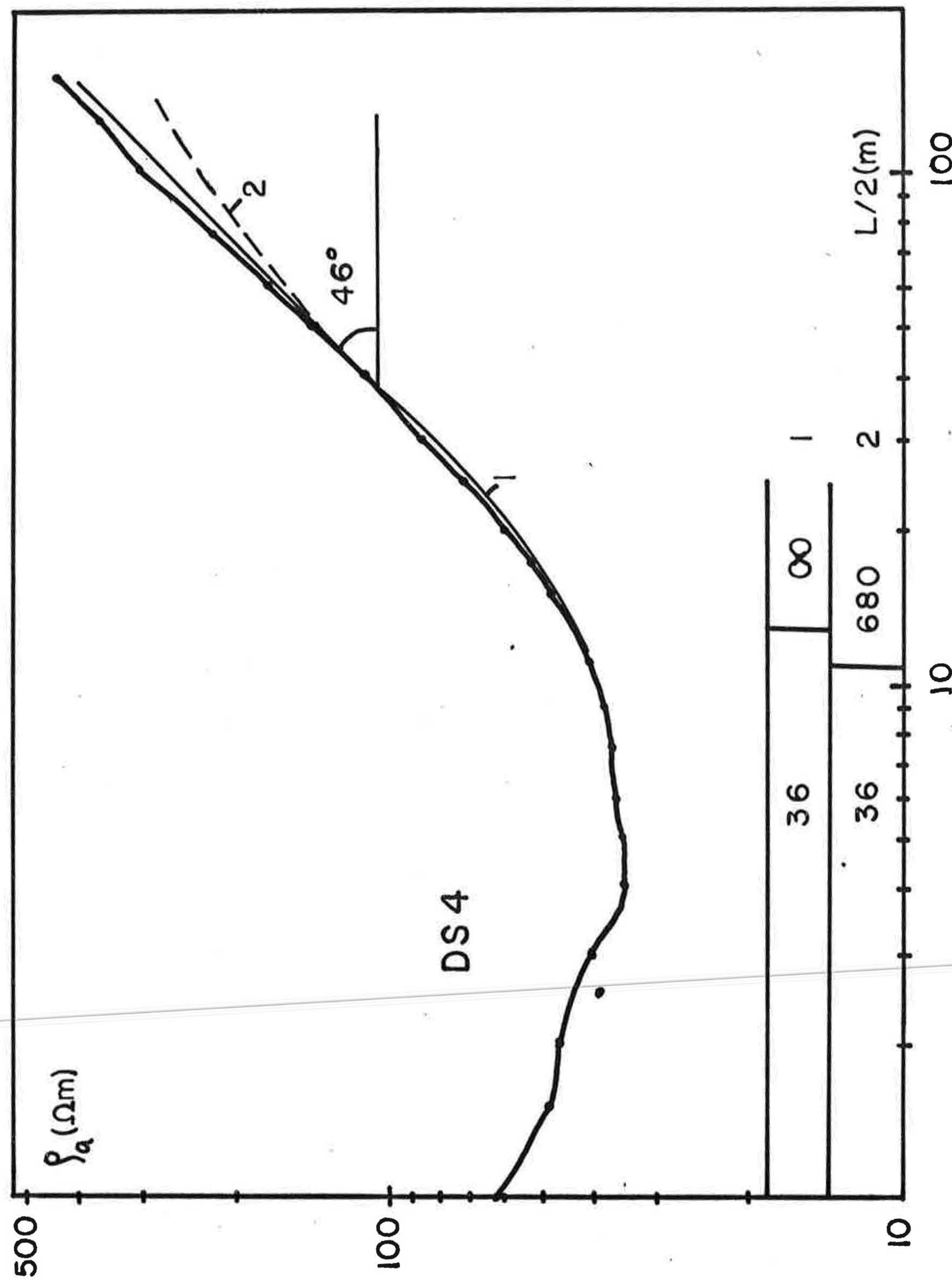

Fig.11: see Fig.8

is obtained with another two-layer master curve, presented by the dashed curve. This part of the interpretation ignores the non-conducting bedrock and is shown in solution 2. Both interpretations are summarized in solution 3, which presents resistivities and thicknesses for a three-layer case with $\rho_1 = 40\Omega m$, $\rho_2 = 360\Omega m$, $\rho_3 = \infty$.

This interpretation has the advantage that the effect and detectability of the intermediate layer can be shown graphically. The larger the area between the field and master curve ($\rho_2/\rho_1 = \infty$), the larger is the effect of the intermediate layer on the field curve. This layer is characterized by solution channels in the limestone and the relatively low resistivity of $360\Omega m$ strongly suggests that the cavities are filled with clay. D.S. 4 in Fig. 11, on the other hand, is almost a two-layer case, since the intermediate layer has hardly any effect on the field curve.

6. Combined Geoelectrical and Gravity Investigations in the Logan Creek Area

6.1 Introduction

Logan Creek, in the southeastern part of Missouri (location III, Fig.1), is known for an impressive karst phenomenon - the disappearance of a stream. Throughout the area the water level is low during dry seasons. Geologically it is at the southern flank of the Ozark Dome. The bedrock is of limestone-dolomite with chert and is of Ordovician age. The disappearance of the river is believed to be related to the Ellington Fault, which intersects the north-south direction of the upper part of Logan Creek Valley, see Fig. 12.
Geoelectrical depth soundings were conducted to investigate the depth of the alluvial river deposits and the thickness and degree of rock dissolution, particularly at places, where the surface stream disappears.
A gravity profile across Ellington Fault along the Logan Creek Valley was expected to indicate details, whether it is a single fault or rather a fault zone. Also the density contrast between dissolved and compact carbonate rock can give a small but recognizeable gravity effect.
Finally some near seismic refraction measurements were considered. The survey was conducted by the Missouri Geological Survey and Water Resources Division to obtain the depth of the overburden layers.

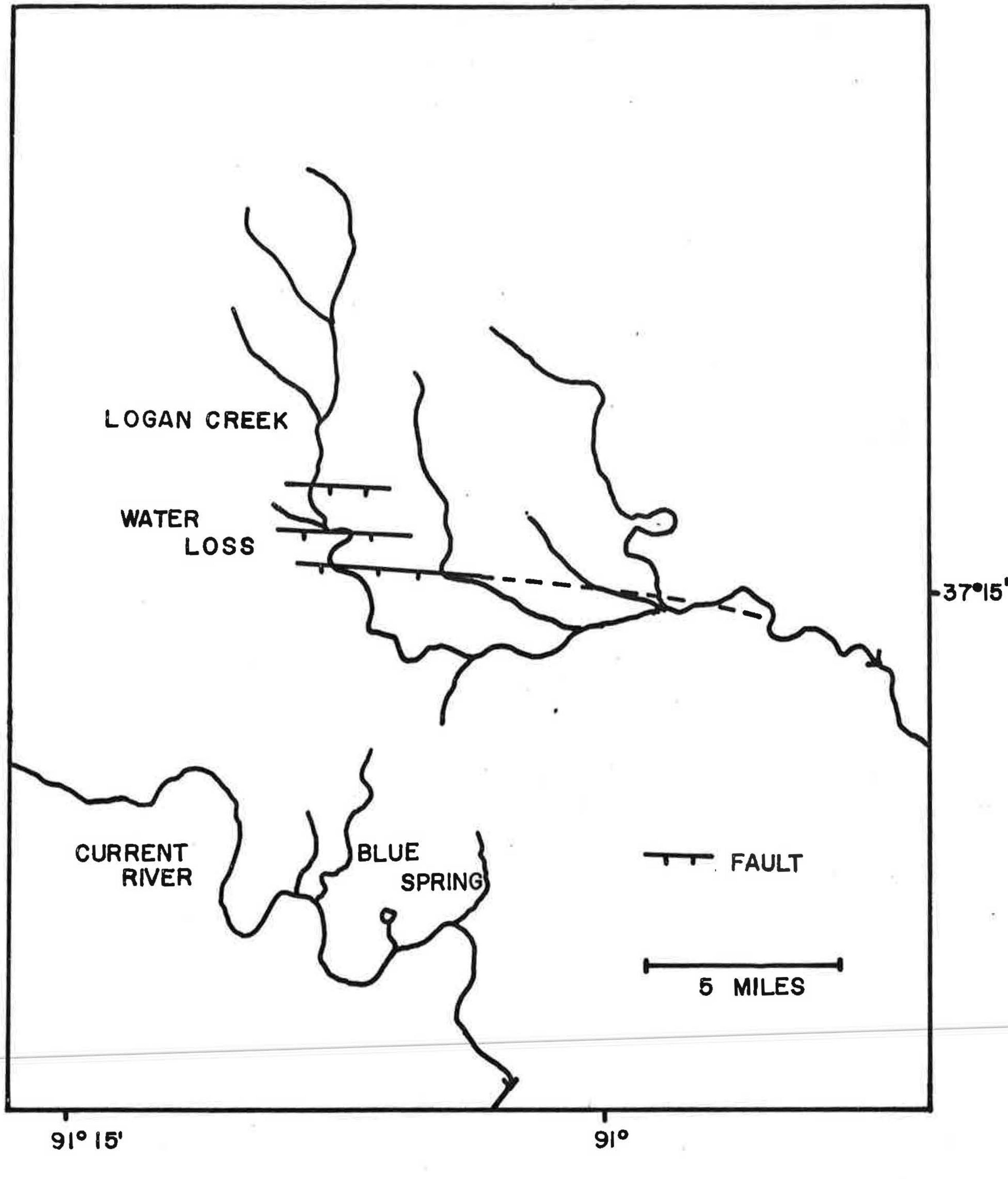

Fig.12: Elligton Fault System at the upper part of Logan Creek

6.2 Results from Seismic Investigations

Seismic refraction profiles were conducted by Mr. Dean Thomas of the Missouri Geological Survey in the Logan Creek Area. He assigned velocities between 1.83 and 2.44 km/sec to very badly weathered bedrock or cemented sandstone, water saturated sandstone or dense clay. At depths between 24 and 30 m seismic velocities exceeded 3.0 km/sec. This velocity was interpreted as being indicative of a bedrock condition. However, irregularities in the high velocity portion of the travel time curve were observed. The maximum velocity for bedrock was found at 3.97 km/sec.

Velocities for compact limestone are known to be much higher. L.D. Leet and F. Birch (1942, p. 97) published a value of 5.09 km/sec for Ordovician limestone near the surface. T.V. McEvilly and W. Stauder (1965) found an average shear velocity of the sedimentary layers in the Ozarks of 2.5 km/sec. This value was found from the analysis of surface wave dispersion. With a Poisson's ratio of 0.25 this accounts for a compressional wave velocity of 4.3 km/sec.

Velocities between 3.0 and 3.97 km/sec, which were found in the Logan Creek Area by Thomas, consequently cannot be assigned to compact limestone but rather indicate still a high degree of alteration due to solution channels and cavities.

6.3 Geoelectrical Depth Soundings

Five depth soundings with the Schlumberger electrode configuration were conducted in the Logan Creek Valley. The depth to a nonconductive compact limestone was obtained and the measurements were conclusive in respect to the nature of the boundary between compact and karstified limestone. Fig.13 shows the location of the depth soundings. Figs. 14-18 show the field curves.

All depth soundings except D.S. III show a linear rise of the right hand branch at a slope angle of 45^0, which is indicative of an infinitely high resistivity. Like at Lane Spring this condition reflects compact limestone. Depth soundings were extended to a maximum value of L/2 = 200m. Most readings of the apparent resistivity align themselves on a steady curve for small and intermediate values of L/2. In spite of very careful measurements for long electrode separations, readings are scattered around the linearly ascending branch. This scatter can be explained by the irregular nature of the boundary between karstified and compact limestone.

Fig.15 with D.S. II shows a representative example for which the procedure of the interpretation with two- and three-layer curves is shown. From left to right the curve shows a maximum followed by a minimum until finally readings scatter along the linear rise of 45^0. In the successive steps of interpretation the influence of the very first small layer is ignored. According to the nomenclature of layer types (after E. Orellana and H.M. Mooney, 1966) D.S. II appears to be a three-layer case of type H ($\rho_1 > \rho_2 < \rho_3$). The two-layer master curves, which gave a best fit with the upper portion of the descending branch, are the dashed curves with resistivity ratios 1:0.2 and 1:0.142, both originating from Point A. The comparison shows that a complete match of the descending branch cannot be achieved with two-layer master curves. A better match is possible with a three-layer master curve with resistivity ratios 1:0.2:0.066, also originating from point A. The

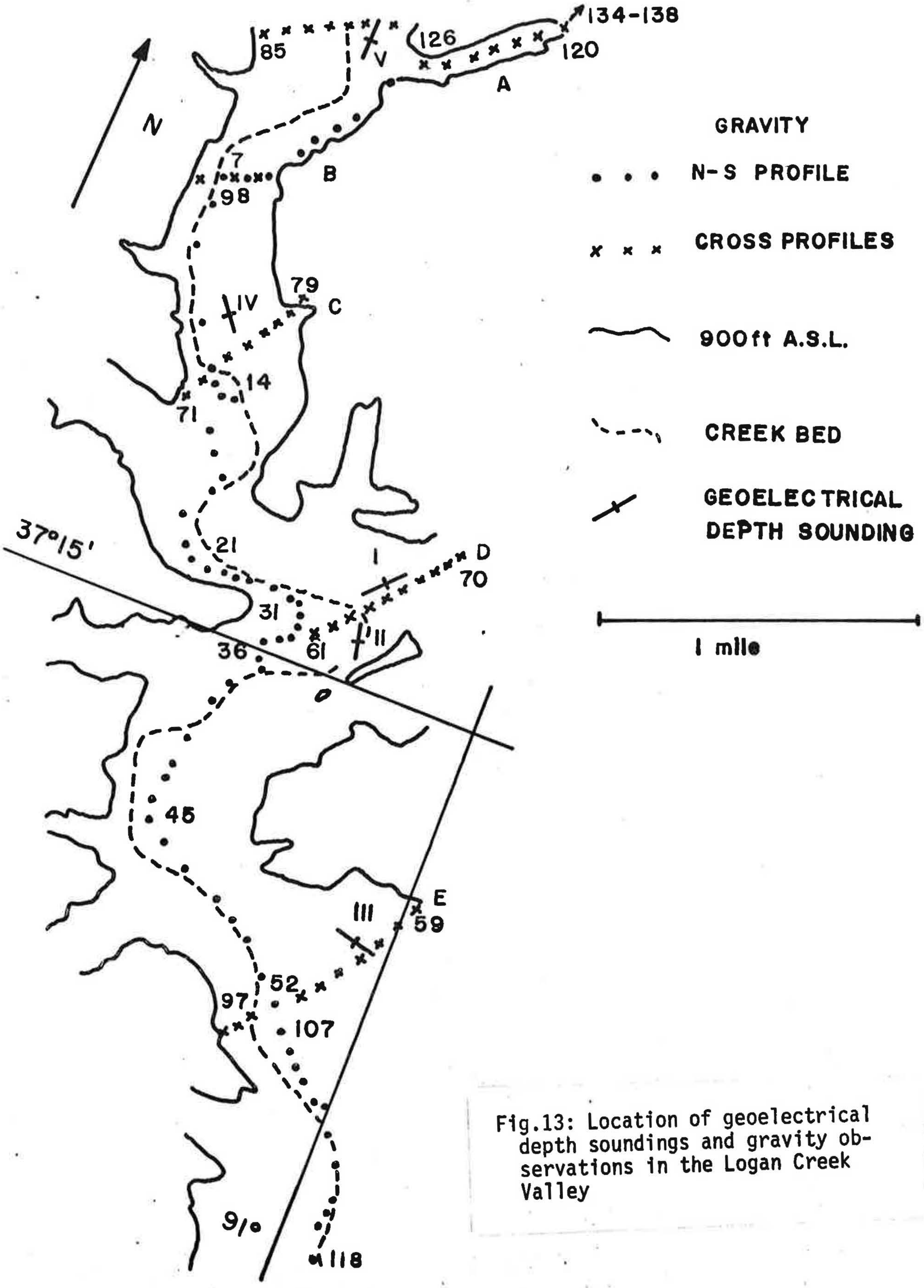

Fig.13: Location of geoelectrical depth soundings and gravity observations in the Logan Creek Valley

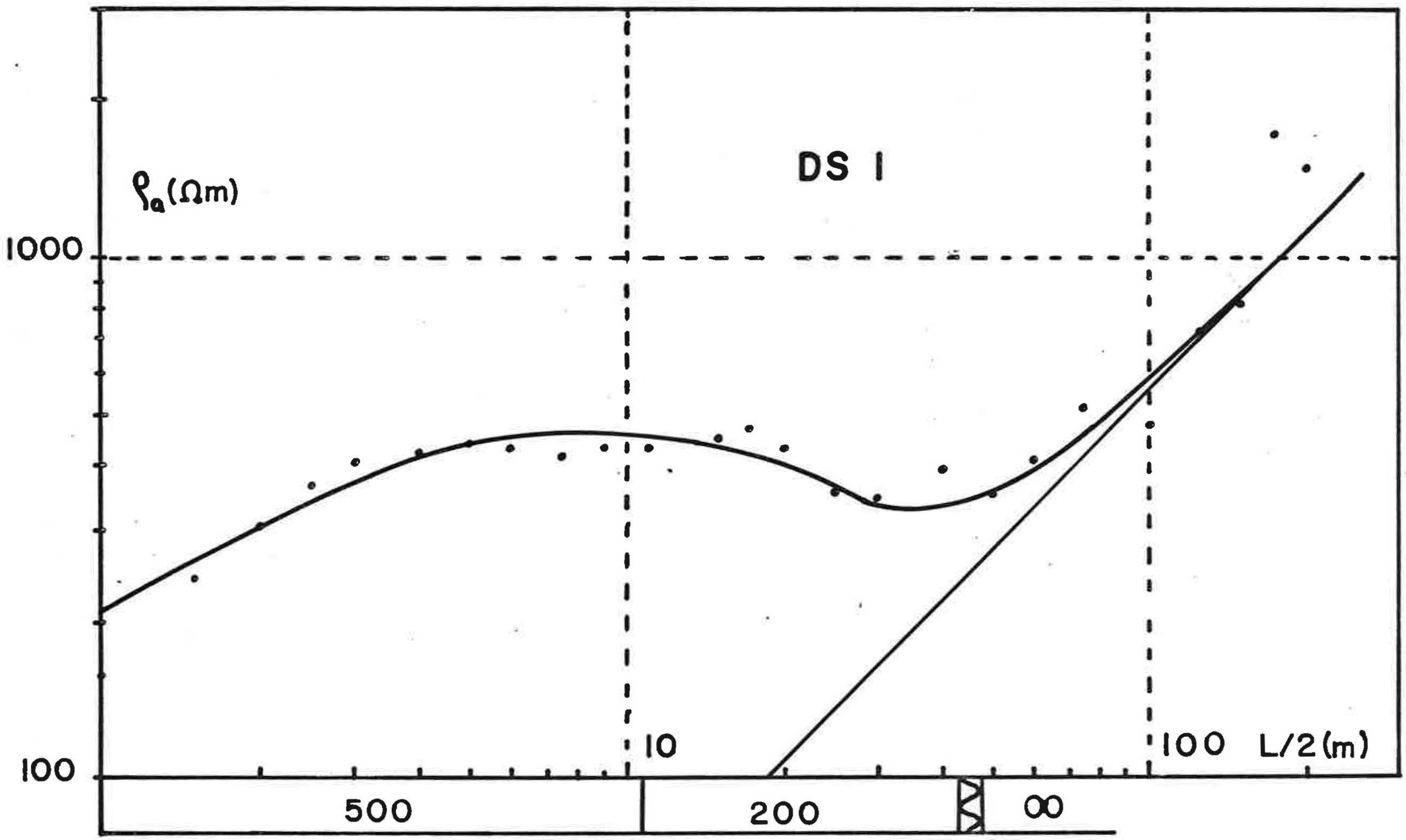

Fig.14: Geoelectrical depth sounding in the Logan Creek Valley

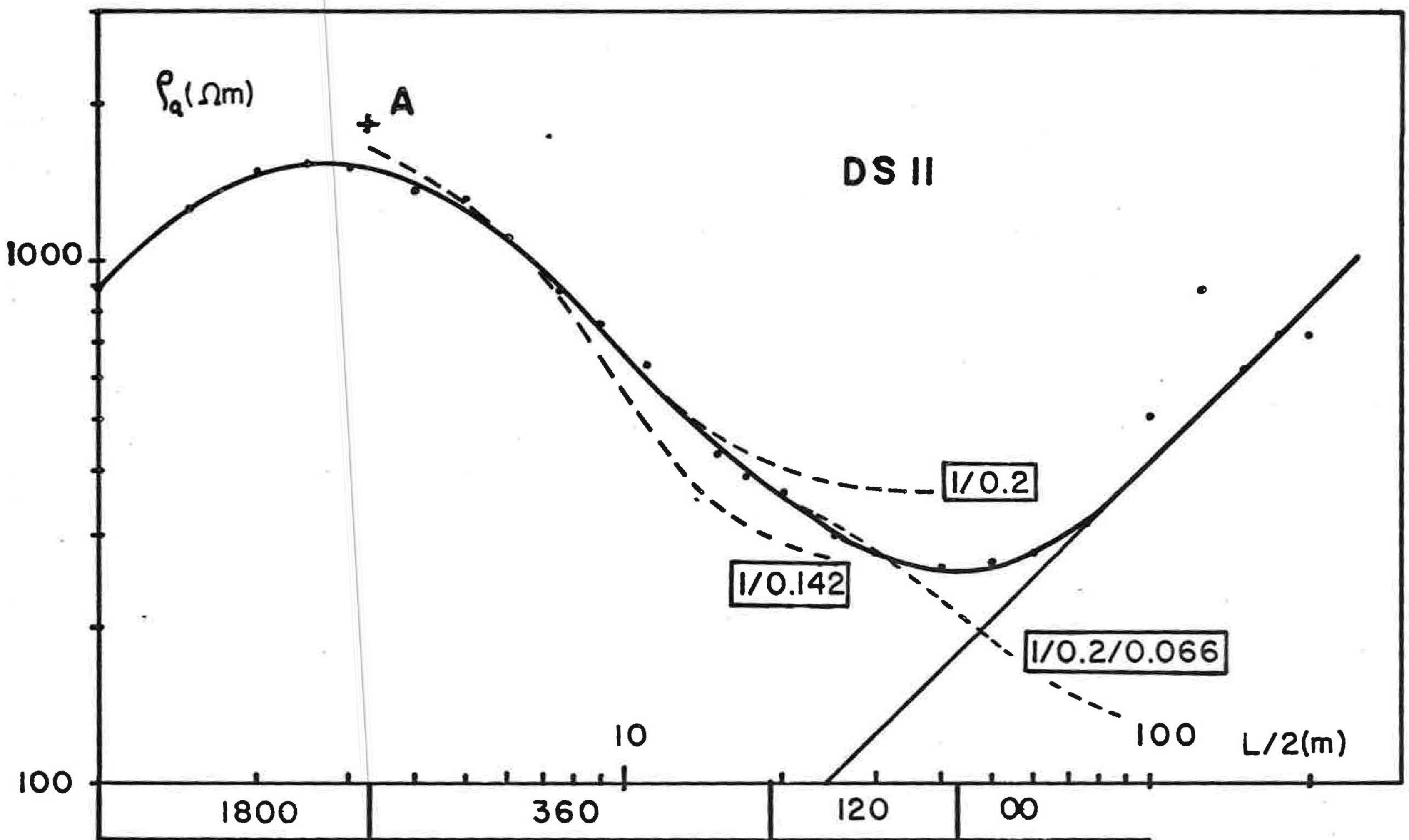

Fig.15: Geoelectrical depth sounding in the Logan Creek Valley

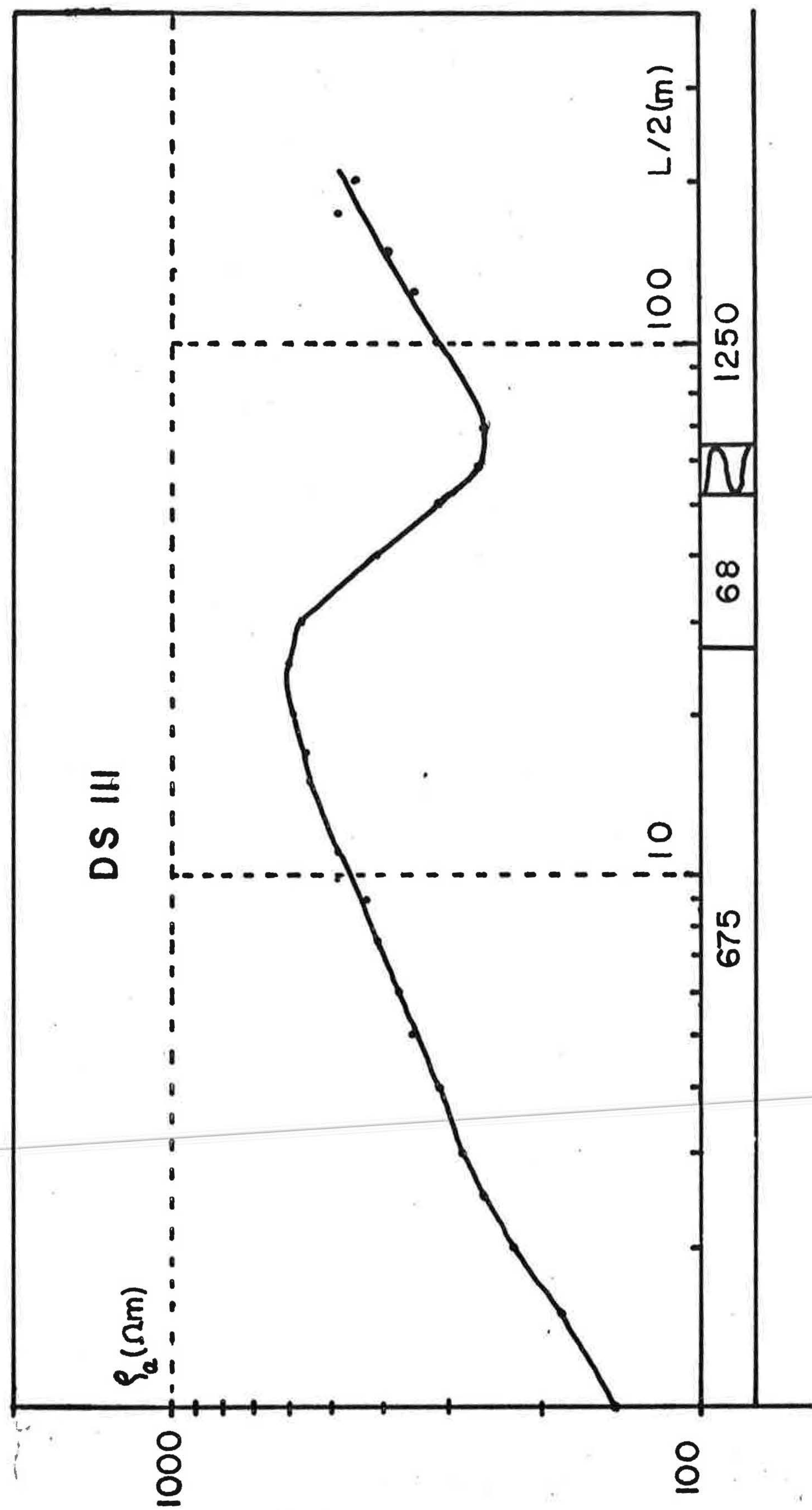

Fig.16: Geoelectrical depth sounding in the Logan Creek Valley

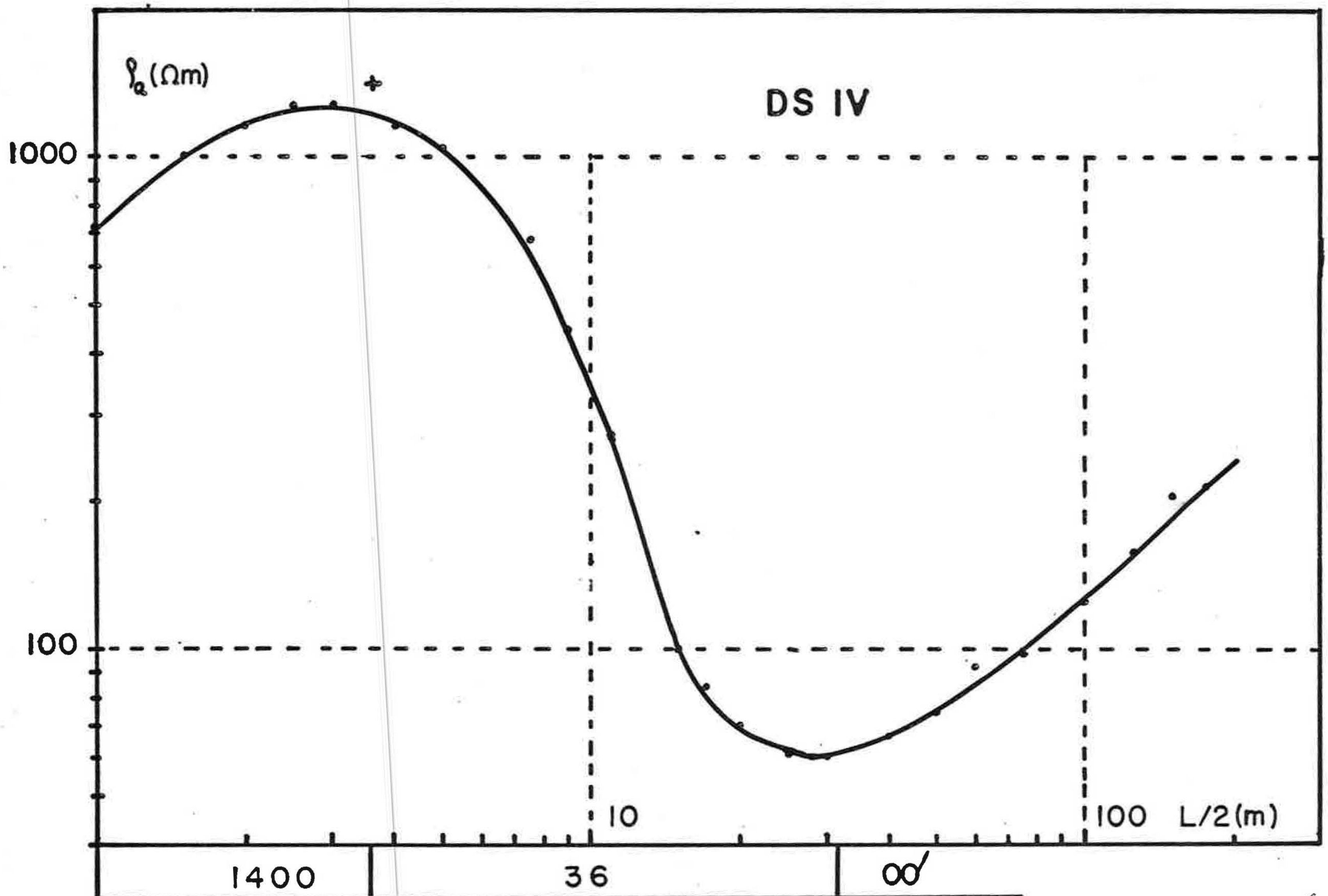

Fig.17: Geoelectrical depth sounding in the Logan Creek Valley

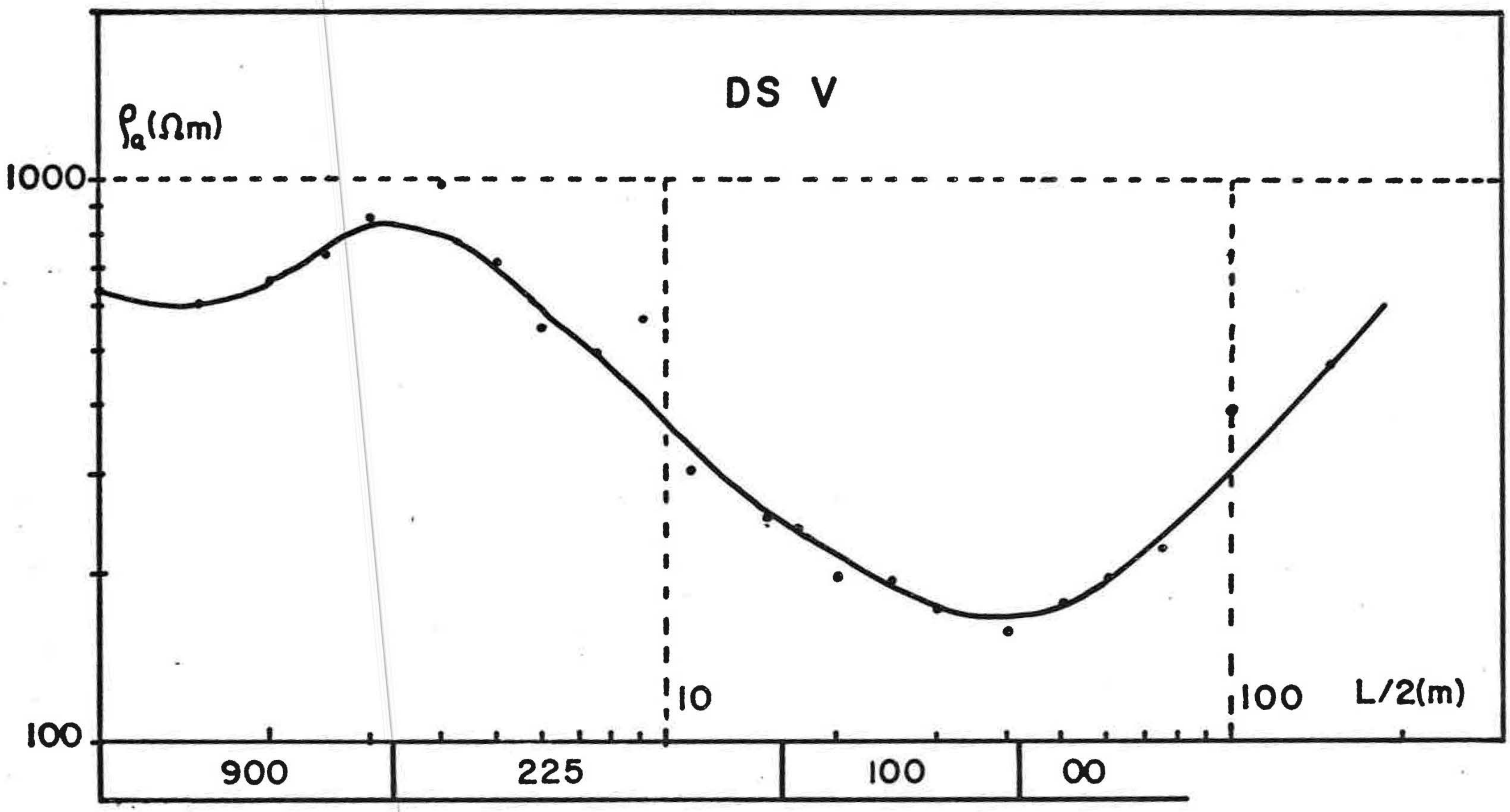

Fig.18: Geoelectrical depth sounding in the Logan Creek Valley

minimum of the field curve, therefore, is caused by two layers with a successive decrease of resistivity. D.S. II consequently presents a four-layer case of QH-type with $\rho_1 > \rho_2 > \rho_3 < \rho_4$, again the first layer of the field curve being neglected.

The depth to the compact limestone was determined by combined matching with three-layer master curves and the calculation of the total longitudinal conductance S. The electrical current is confined to flow between the surface and the nonconductive basement. S can be determined from the field curve by extending the straight line of slope angle of 45^{0} backwards (P.K. Bhattacharya and H. Patra, 1968). The intersection with the abscissa through ρ_a = 1.0 gives S. In Fig. 15 for D.S. II this value is S = 0.24. The definition of S gives us the relationship:

$$S = \frac{H}{\rho_l} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} \qquad (1)$$

where H is the total thickness of the conductive layers and ρ_l is the longitudinal resistivity of the range H. From curve matching we obtain:

$h_1 = 3.3$ m $\quad h_2 = 15.7$ m $\quad h_3$ unknown

$\rho_1 = 1800\,\Omega$ m $\quad \rho_2 = 360\,\Omega$m $\quad \rho_3 = 120\,\Omega$m $\rho_4 = \infty$

This leaves h_3 to be calculated by solving (1) for h_3.

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3}$$

$$0.24 = \frac{3.3}{1800} + \frac{15.7}{360} + \frac{h_3}{120}$$

$$0.24 = 0.00183 + 0.0436 + \frac{h_3}{120}$$

solved for h_3:

$$h_3 = 120 \cdot 0.195 = 23.4 \text{ m}$$

or d_3 = 42.4 m depth of the compact limestone below surface. This numerical example demonstrates the error, which is involved in this interpretation. The term $^{h_3}/\rho_3$ of the third layer contributes more than 80% to the total conductance S. Errors in ρ_3, adopted from the curve matching, will significantly influence the depth to the compact limestone. Within certain limits the principle of equivalence allows h_3 and ρ_3 to be altered as long as $^{h_3}/\rho_3$ remains constant.

The other depth soundings were interpreted similarly and the results are shown in Table 1. D.S. IV presents a three-layer case and the layer with intermediate resistivity, ρ_2, seems to be absent. D.S. III indicates a larger depth range between 52 and 65 m to a poorly conducting basement which, however, has a finite resistivity of 1250Ωm.

The assignment of infinitely high resistivity to compact limestone shall not exclude the existence of substantial stream channels in this portion of the limestone. In the contrary, hydrogeological observations strongly suggest that the disappearing stream water flows through lower parts of the limestone. A more conservative conclusion from the geoelectrical investigations cannot be specific in respect to water transport through the compact limestone. The nature of the solution channels changes at a depth range between 42 and 48 m. This, for instance, can be caused by the disappearance of clay with depth or by a confinement or rearrangement of solution channels to a different pattern. Seismic refractions and geoelectrical depth soundings indicated two boundaries, which both are most likely within the karstified limestone. The first indicated a depth range between

24 and 30 m, while the second method refers to a range between 42 and 48 m. This shows the complexity of this intermediate horizon.

	layer	1	2	3	4
D.S. V	ρ_i (Ω m)	900	225	100	∞
S = 0.32	di (m)	3.3	16	42	
D.S. IV	ρ_i	1400	36	∞	
S = 0.77	di	3.6	31.6		
D.S. I	ρ_i	190	500	200	∞
S = 0.18	di	0.6	10.6	43-47	
D.S. II	ρ_i	1800	360	120	∞
S = 0.24	di	3.3	19	42.4	
D.S. III	ρ_i	135	675	68	1250
0.37 S 0.56	di	. 1.0	27	52-65	

Table 1: Result of geoelectrical depth sounding in the Logan Creek Area .
d_i = depth below surface.

6.4 Hydrogeology of the Logan Creek Area

While information of drillhole data is scarce, some data on water level fluctuations are available from Logan Creek. The following list of water level observations during periods of water loss was kindly supplied by Mr. E. Harvey of the U.S. Geological Survey, Water Resources Division, Rolla, Missouri (see Table 2). Water levels were observed to be either close to the surface or at an average depth of 69 m below the surface. The average elevation of the deep water levels is at 186 m A.S.L. This is an interesting figure since the maximum depth to the compact limestone under D.S. III was 65 m. This shows that in dry seasons the water disappears through solution channels and is stored in confined solution channels in the lower portion of the limestone, which was found to be electrically nonconductive.

The water of Logan Creek is believed to be in connection with Blue Spring, a major spring in the Ozarks discharging some 16 miles southwest into the Current River. E.J. Harvey and J. Skelton (1970) reported on communication with Messr. Feder and Barks that dye tests confirmed hydraulic connection between Logan Creek and Blue Spring. The elevation difference between Logan Creek (D.S. V to D.S. III) and Blue Spring ranges approximately between 95 and 120 m. Therefore it is reasonable to assume that an extensive network of stream channels has developed underneath the Logan Creek Area to a depth of at least 100 m. This network not only allows a free water flow but must also be capable to store sufficient water to maintain continuity between consumption from Logan Creek and discharge from Blue Spring. Where this deep aquifer is cut by the surface topography, such as by the CurrentRiver Valley, the aquifer discharges at a hydraulic pressure due to the level of the water column.

Date of Observation	Latitude °	'	"	Longitude °	'	"	Elevation (ft. A.S.L.)	Water Level (ft. A.S.L.)	Water Level below surface (ft)
5/20/71	37°	19'	36"	91°	07'	21"	935	927	8
5/19/71	37	16	18	91	06	42	910	652	258
5/27/71	37	15	53	91	07	06	835	628	208
5/27/71	37	16	48	91	07	18	915	602	314
5/28/71	37	15	32	91	06	02	830	580	250
5/28/71	37	15	24	91	10	04	830	730	119
7/30/71	37	13	49	91	03	21	770	605	165
7/29/71	37	13	34	91	02	13	780	722	58
7/21/71	37	14	29	91	05	50	820	534	286
7/21/71	37	13	33	91	05	05	780	576	204
10/6/71	37	14	30	92		20	680	673	7
7/22/71	37	18	12	91	07	34	886	860	26
5/26/71	37	17	44	91	07	43	875	852	23

Table: 2 : Water Level Observations in Logan Creek.

6.5 The Gravity Measurements

A total of 131 gravity stations were observed with a Worden gravimeter. The location of the stations are shown in Fig.13. Elevations were determined with an overall accuracy of 0.2 feet. All gravity observations are related to point # 7. No provisions were made to tie the observations into benchmarks or gravity observations of the U.S. Geological Survey, since this survey was geographically limited. Since only a small gravity effect was expected, the instrumental and tidal drift was controlled at half hour intervals by repeated station readings. The gravity anomaly pertaining to the distribution of subsurface masses is known as the "Bouguer Anomaly". It is obtained from the measured observations by means of the following reductions:

$$\Delta g_B = \Delta g_M + \Delta g_{FA} + \Delta g_{BR} + \Delta g_{TOP} + \Delta \gamma_o \qquad (2)$$

The single terms are :

Δg_B : Bouguer Anomaly, related to base point 7

Δg_M : Measured gravity difference related to point 7

Δg_{FA}: Free Air Reduction from the elevation of the observation to a common base level.

Δg_{BR}: Bouguer Reduction ; this term considers the gravitational effect of the horizontal slab between the point of observation and the base level.

Δg_{TOP} : Topographic Reduction ; this term considers the gravity effect of the topography. Nomograms of S. Hammer (1939) were used.

$\Delta \gamma_0$: Lattitude Reduction ; this term was derived from the International Gravity formula and has a value of 1.26 mgal/mile at the medium lattitude of 37^o.

For the reduction of Δg_{BR} and Δg_{TOP} a proper knowledge of the surface density is necessary. Both reductions were calculated for two surface densities, $\sigma_1 = 2.7$ and $\sigma_2 = 2.5$ gr/cm^3 . The elevations in the valley were steadily declining from north to south along the profile and the Bouguer Anomaly calculated with σ_1 showed an overall gradient from north to south. The anomaly calculated with $\sigma_2 = 2.5$ did not show the gradient and therefore this density was adopted for the surface density. The Bouguer Anomaly and the reductions for all observation points are shown in the appendix.

The main part of the gravity survey is the north-south profile which crosses Ellington Fault at almost right angles. It shows (see Fig.19) a negative anomaly of about 3 miles of extension. This broad negative anomaly is interrupted by small positive peaks. The northern part of the anomaly can be correlated with the Ellington Fault and with sections in the creek where the stream disappears. Extreme values amount to - 2.0 mgals. The large gradient suggests that the anomaly is caused by nearsurface mass deficits of possibly two origins: