Electrical Resistivity Surveys in Salt Mines

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ABSTRACT

Electrical resistivity surveys, utilizing the Gish-Rooney type equipment and the Wenner electrode configuration were initiated in an experimental manner in salt mines in Texas, Louisiana and Michigan. These surveys were made to obtain the variations in the apparent electrical resistivities of the various salt beds and to locate areas of abnormal moisture content in the salt beds. Results indicate a large variation in the measured apparent resistivities of dry salt, i.e., from a high of 2 -- 4 x 10 log 5 ohm cms. to a low of 6 -- 10 x 10 log 3 ohm cms. Where an abnormal moisture content is present in the salt the apparent resistivities are less than 10 x 10 log 2 ohm cms. It has been demonstrated that the electrical resistivity of the salt beds in the mines is a potentially useful method for testing salt since it is very sensitive to brine content and structure.

INTRODUCTION

Geophysical investigations using the normal electrical resistivity method were undertaken in the underground mining areas of the Grand Saline Salt Dome, Grand Saline, Texas, and in the bedded deposits of the International Salt Mine at Detroit. In these areas not only underground mining is taking place, but also in relatively close proximity to such mining the brining technique of salt extraction is employed. The detection of the encroachment of the brining areas on the mining areas obviously is most desirable.

It was believed that the electrical resistivity method would be a rather ideal approach to the problem since salt in a dry state has measured apparent electrical resistivities ranging from 3×10^3 to 3×10^5 ohm-cms., while in a wet state the measured apparent resistivities may approach 1 to 10 ohm-cms. This being the case, the problem was to measure the apparent resistivities of the rock salt at various intervals and penetrations in the wall and floors of the mine areas and to determine whether or not changes in the measured apparent resistivities of the order stated above could be related directly to high moisture content or actual brine areas situated in the influence of the induced electrical system. The interpretation of the resultant data, however, could be rather difficult because of the complexity of the mine features, i.e., the presence of pillars, rooms, ceilings, floors, walls, and brine pits.

ELECTRICAL RESISTIVITY METHOD

Fundamentally, the earth resistivity method is a field application of Ohm's Law, which states that when a direct current flows in an electrical circuit, the resistance, R, in ohms, equals the voltage, V, divided by the current, I, in amperes. Wenner (1915) followed Ohm's basic law

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and found that a current could be passed through the ground between two current electrodes and the potential difference measured between two other electrodes. From the results of this procedure, it was possible to calculate the "apparent resistivity" of the earth from the equation:

$$\rho = 2\pi a\, E/I$$

where ρ is equal to the apparent resistivity and "a" is the approximate depth to which this apparent resistivity has been determined. For the proper functioning of the system, the electrodes must be placed in a straight line and be equi-distant as shown in Figure 1.

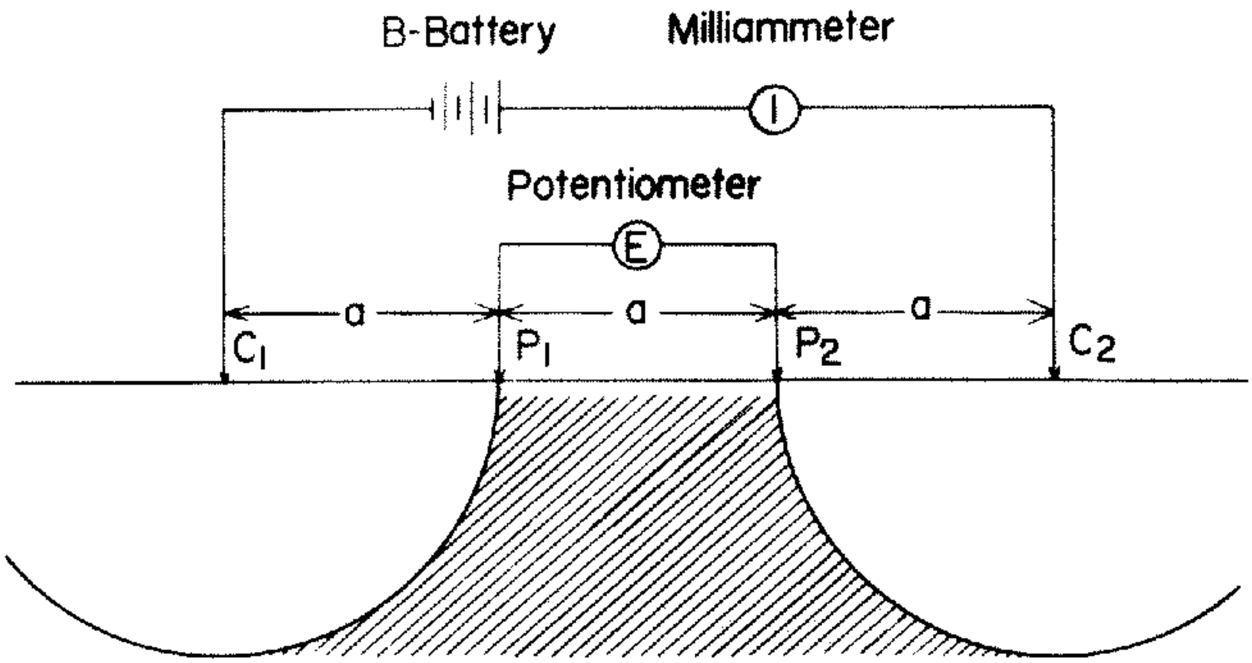


Figure 1. Electrical Resistivity Schematic Showing Wenner Electrode Configuration.

FIELD PROCEDURE

Equipment used in measuring the apparent resistivities in these investigations was that as designed by the Houston Technical Laboratories of Houston, Texas, and as described in their Bulletin No. E-401. Electrodes employed were 1/4" round, 1/2" square cold steel bar stock, 1/4" black iron pipe and 1/2" round bronze rods.

Variations in electrode and salt contacts were used. In the Grand Saline mine one inch holes to a depth of 14" were drilled in the floor about six feet from the wall and spaced ten feet apart. The electrodes were set in these holes and the hole then filled with water and salt to form a thick brine. At the International mine in Detroit the same electrode spacing procedure was used; however, stake holes were drilled only around the shaft pillar. For the remainder of the survey insulated bronze rods with brine soaked sponges tied to them were held against the wall by hand and the necessary measurements made.

QUALITATIVE EFFECTS OF BODIES IN THE ELECTRICAL SYSTEM

To develop the theory of the electrical resistivity configuration, it must be assumed that a homogeneous isotropic earth of resistivity " ρ " is being dealt with. This is relatively easy mathematically, as demonstrated by Wenner (1915), and makes interpretation relatively easy as compared to conditions where steeply dipping or vertical bodies of differing electrical properties are placed in the area of measurements. (Lee, et al., 1946)

For instance, in Figure 2, block "A" shows the distribution in plan view of the current lines as they flow between electrodes C_1 and C_2 in a homogeneous medium. But now place a steeply dipping bed of material of a different resistivity between these two current electrodes and it may be shown that the current flow will be distorted from its original pattern of simplicity as in "A."

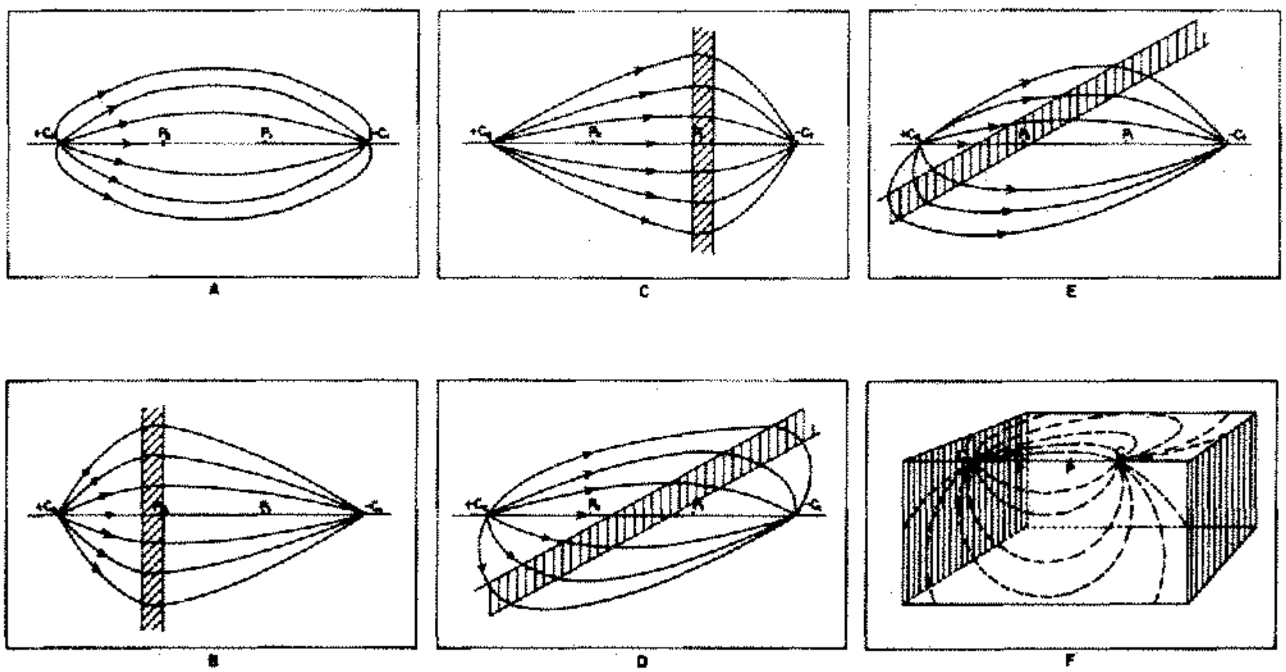


Figure 2. Forms of Current Fields in Isotropic Medium and as Modified by a Conducting Body.

In the cases of "B" and "C," the body is placed at right angles to the line of electrode configuration, in one instance near C_1 (Block "B") and in the other near C_2 (Block "C").

In the cases of Blocks "D" and "E," the inserted body is crossing the line of electrode configuration at some oblique angle. Once again the current lines and their paths are greatly distorted as a result of the current field as it is made to penetrate this anisotropic medium.

If the current lines are distorted as a result of these energized anisotropic media in the influence of the current flow, then the potential bowls, which are created as a result of the potential electrodes, P_1 and P_2 being in the circuit, are also greatly distorted. Picture, therefore, the placing of any shaped anisotropic media in the influence of these current paths and especially somewhere between C_1 and C_2 and crossing the line of measurement. The blocks "B" through "E" show only the plan view or surface expression of the distortion produced. Block "F" shows the distribution in two dimensions as the current lines pass through a homogeneous isotropic medium. To show this distortion in an isometric illustration is even more complex, yet it is this latter condition which is always dealt with in the electrical resistivity application to earth measurements.

This distortion of the current paths of the induced electrical flow and hence the current bowls becomes a rather important and bothersome factor in the application of the electrical resistivity method in underground operations such as salt mines. The influence of mine pillars, mine rooms with their walls, floors and ceilings have a profound distortion effect on the distribution of electrical currents in the method. The open rooms may be considered as a medium of different electrical resistivity than the salt and hence could produce extreme distortions that would influence the final interpretation of the electrical data. Not only the mine features are effective, but also the presence of brine ponds which are so often present in the salt mines.

Geological features obtaining in the mines are also considered as factors which make interpretation of the data difficult. In the salt domes the salt is usually free of brine inclusion, thus giving a rather high electrical resistivity. At the same time, however, rather complex flow structures and associated seams of anhydrite are present that naturally have an end effect on the apparent resistivity. Bedded deposits usually contain brine inclusions. These inclusions are normally elongated which affect the measured resistivities. The resistivities vary not only because of the size of the brine inclusions, but also in what direction the resistivities are measured, i. e., parallel or at right angles to the long axis of the inclusions. Another characteristic of bedded deposits is the fact that the various beds may be separated by seams of dolomite, anhydrite and/or shale, each of which individually or collectively have an effect on the measured apparent resistivities in the salt mines.

Again, however, it is restated that no matter how complex the geologic situation in the salt mines may be, the resistivities' differences between dry salt and wet salt are so great that the method was still believed applicable in seeking the solution of the problem.

SALT DEPOSITS

The rock salt deposits in the areas of investigation present entirely two different geological environments. At Grand Saline, Texas, the rock salt is in the form of a dome, exhibiting rather complex structures, while in the Detroit area the rock salt is in layers or beds, serving as part of the normal stratigraphic sequence.

Grand Saline Salt Dome

Underground observations reveal that layers of salt and anhydrite are always present and visible. In that portion of the mine where geophysical measurements were made, the salt and anhydrite layers form rather intricate systems of folds, the axes of which plunge nearly vertically. The limbs of the folds are also very steep. Superposed on the limbs of the larger folds are countless smaller structures which have been described as shear folds.

Both anhydrite and halite are characterized by a linear alignment. Aggregates of anhydrite and halite are always visibly elongated in nearly perpendicular orientation. This direction of elongation is parallel with the axes of the folds.

The Grand Saline salt dome is characterized by the absence of fractures, faults, cross-cutting salt layers, inclusions, and brine. This would indicate a gradual flowage of the salt mass into its present position. The salt may, under these conditions, represent a certain amount of recrystallization, and certainly a straining of the normal crystal growth.

Straining of the crystal form (elongation along a certain crystal axis) and recrystallization would produce an inhomogeneous anisotropic medium within each crystal. In addition, the structural features and interfingering of anhydrite and salt would also produce such a medium. A medium of this nature would naturally have varying electrical resistivities in different directions of measurement.

Salina Salt Beds, Detroit Area

In the Detroit area the evaporite salt-bearing beds occur in the Salina formation. The formation contains dolomite, anhydrite, gypsum, and salt with occasional shale beds. The entire formation is approximately 800 feet thick.

Of prime importance is the varying thicknesses of the individual salt beds and the interbedding of foreign materials such as dolomite, anhydrite, and sales. Four salt beds are present which fall into two sequences. The 'Upper Salt' includes, above, a bed from 10-20 feet thick, generally encountered between 950-980 feet depth. Fifty to sixty-five feet below, separated by dolomite and anhydrite, is a second salt bed which ranges from 80-110 feet in thickness. The 'Lower Salt' occurs from 250-300 feet below the 'Upper' and is generally logged by the driller as consisting of two benches separated by an intervening bed of limestone or dolomite. The aggregate thickness of these beds is in the neighborhood of 200 feet.

No data were available at the time the geophysical measurements were made on the physical properties of the salt in this area, but it was reasonable to assume that the salt crystallization in its occurrence is unlike that of the Grand Saline salt dome. It is possible that this salt has a higher moisture content and that it is less deformed, if at all, in its crystal growth. Such structural features would present a more homogeneous and isotropic medium in which to measure apparent electrical resistivities. Further, the possible higher moisture content of this salt most likely would account for lower apparent resistivities than for salt at the Grand Saline salt dome.

GRAND SALINE SALT DOME RESULTS

The Grand Saline Salt Dome is one in which both mining and brining are simultaneously being performed. In the cross section view of Figure 3 these two features are shown. Mining is at a

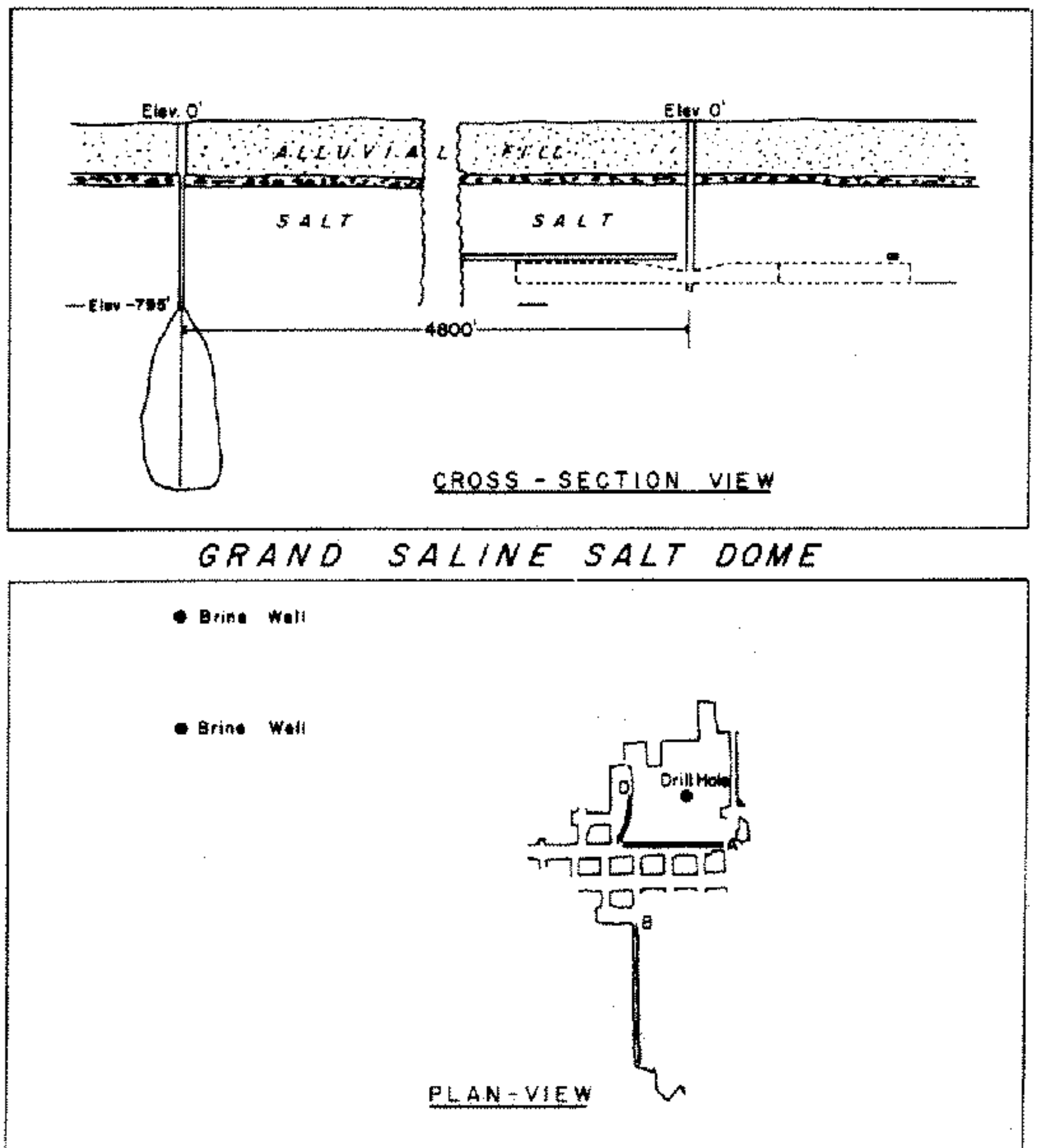


Figure 3. Vertical and Plan Views of the Grand Saline Salt Dome Showing Locations of Electrical Tests.

depth of approximately 600 feet, while brining, the center of which is 4800 feet from the mine shaft, is at a depth of 800 feet. Actual altitude of the mining area is obtained by transit surveying; however, no method has been found whereby the brining cavity can be adequately defined. Hence the necessity of attempting to control mining as a function of brining through a geophysical technique within the mine area. In plan view Figure 3 shows not only the position of part of the mine workings with its pillar and wall system, but also the position of the brine wells with respect to this mining area.

Although considerable geophysical work was performed in the mine area, only the results along Traverses A, B and D are presented.

Wall "A"

Electrical resistivity measurements were made over a distance of 600 feet at the base of wall A. Apparent resistivities were determined for depths varying from 10 to 170 feet at 10 foot intervals along this traverse.

Results of the vertical distribution of the electrical resistivities are shown in the isometric illustration of Figure 4. Here the data have been contoured as isokilo-ohm-cm lines with any

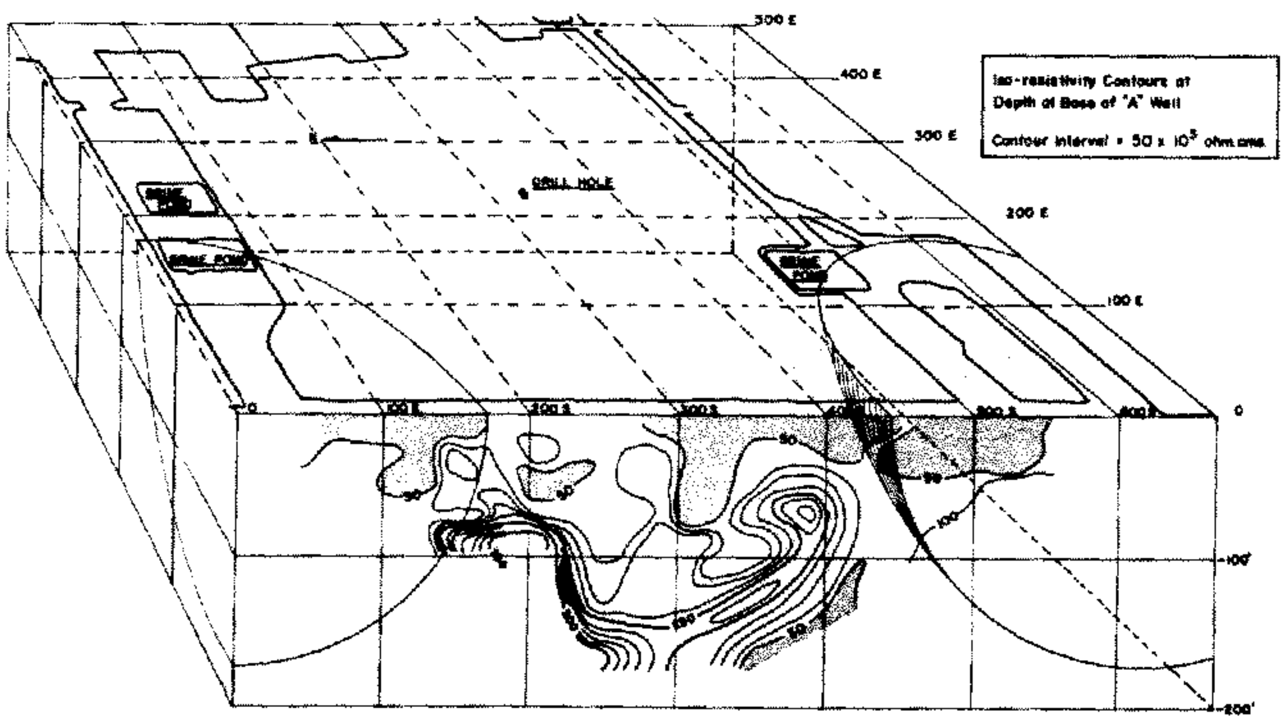


Figure 4. Isometric Drawing Showing Electrical Resistivity Results at Wall "A," Grand Saline Salt Dome.

area less than 50 kilo-ohm-cm shaded. Two distinct low resistivity low zones are noted on the vertical plan. One is centered around 100S and penetrates to a depth of 50 feet. Another is confined to a zone from 300S to 550S with a maximum depth of penetration of 10 feet near 300S. In the depth penetration of these lows, the pattern is quite irregular. It is quite possible that a penetration of moisture has taken place along the axes of shear folds, or in contacts between anhydrite and salt layers which in the mine appear to be nearly vertical. The irregular pattern of high resistivities may reflect a distribution of massive salt in which anhydrite is at a minimum and certainly areas in which moisture or brine is absent. The resistivity distributions bear out the geophysical features of the Grand Saline Salt Dome, i.e., that it is not a homogeneous isotropic media. The only time such would be the case in the salt dome would be when the salt has become highly moisted or saturated with water.

In the same isometric drawing (Figure 4) the outlines of the current bowls at their maximum size have also been traced. At this maximum size, when the radii were 170 feet, it is shown that both cut the brine ponds situation at coordinates 50S-150E and 500S-125E. At this interval the current lines may be sufficiently distorted to produce the abnormally low resistivity situated from 350S-425S at depths of 170 to 100 feet respectively. It is believed that the maximum effects of brine ponds will be when they are coincident to the line of measurement and not offset as in this case. This effect is best illustrated in the results along floor "D."

Floor "D"

To adequately demonstrate the effect the brine ponds in or adjacent to the line of measurement, a series of apparent electrical resistivity determinations were made on the floor adjacent to the "D" wall. The location of this line of observations is shown on the plan view of Figure 3 while the results of the measurements are presented in the isometric diagram of Figure 5.

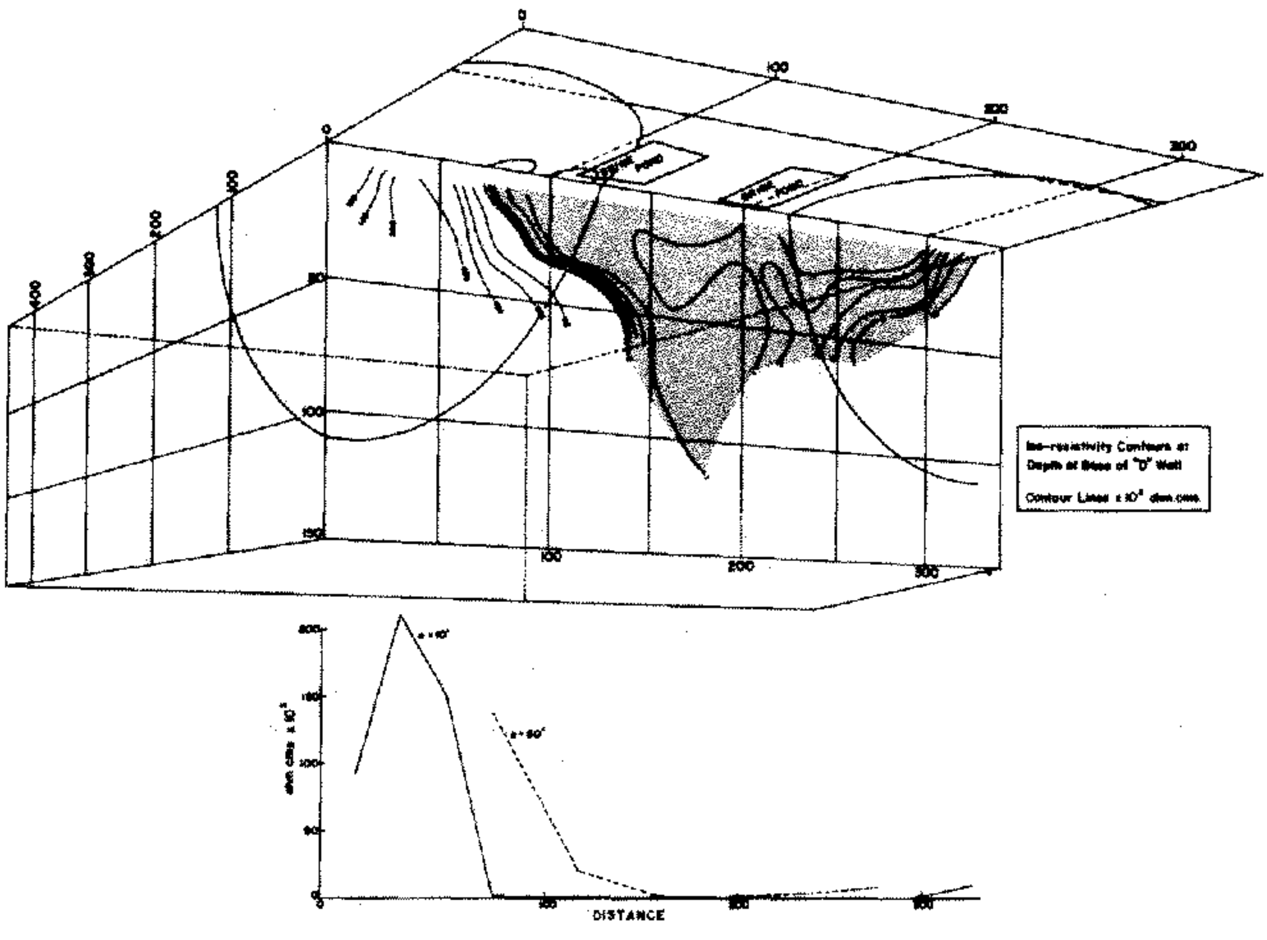


Figure 5. Isometric Drawing and Resistivity Profiles Showing Electrical Resistivity Results at Wall "D," Grand Saline Salt Dome.

Measurements along this floor ranged from a minimum depth of 10 feet from traverse intervals 10 to 320 feet and a maximum depth of 110 feet at 180 feet on the traverse. Electrical results along this traverse are presented as iso-kilo-ohm-cm contours. Maximum resistivities of better than 200,000 ohm cms. are present. These high resistivities drop off rapidly near 100 feet on the traverse to as low as 80 ohm-cms.

It is noted that the line of measurements on the D floor was made in the vicinity of two water ponds. These ponds were filled with water in 1951 and 1956 respectively. At one pond water undermined the pillar and as a result was pumped out. The pond was then filled with loose salt. The other pond, before water was added, was entirely coated with gunite and then covered with a heavy coat of tar.

From the nature of the electrical resistivity results over this traverse, it is interpreted that considerable moisture is still present in the surrounding salt and that this moisture, as well as the water ponds themselves, have had a profound effect on the distribution of the current lines. On Figure 5 are also shown the minimum and maximum outlines of the current bowls produced throughout the measuring system. As soon as the minimum bowls neared the brine pond, the resistivities dropped rapidly, and remained extremely low, as shown by the shaded area (less than 5000 ohm-cms.). For clarity, two horizontal electrical resistivity profiles along this traverse are shown on Figure 5, one for data at a depth of 50 feet. The extremely sharp drop-off in the apparent resistivities can be attributed to the presence of the brine ponds along the line of traverse and clearly demonstrates the effect of brine on the electrical characteristics of the salt.

Wall "B"

A third taverse, over which electrical resistivities were determined at 10 foot intervals to depths ranging from 10 to 130 feet, was occupied in an area of the mine where no moisture was evident at the surfaces and brine ponds non existent. The location of this traverse was in the extreme west side of the mine and along the "B" wall (see Figure 3).

On this traverse the electrical resistivities were determined for the Wenner electrode configuration by using the Carpenter and Habberjans Tri-Potential Method (1956). This method of determining resistivities was designed to evaluate any lateral changes of resistivity in depth exploration. Usually three sets of readings are taken by the manipulation of the configuration as shown on Figure 6. These sets of readings have been referred to as positions 1, 2 and 3 with position 1 being the normal Wenner configuration. If the resistivities as measured are a function of depth only the three sets of data should depict the same general trends and values. If any divergence or convergence of the three sets of data then surface effects are indicated as influencing the resultant electrical resistivities.

The electrical resistivity results on this traverse are presented as three vertical sections showing the distribution of the apparent resistivities as isokilo-ohm-cms contours. Any area of electrical resistivity values less than 50,000 ohm-cms has been shaded. However, unlike results at either Wall "A" or Floor "D," the shaded areas in these results never measured less than 20,000 ohm-cms. The results of the three-vertical sections indicate some divergence, however, in general, the results show the same high and low areas and similar trends. These variations most likely reflect the flow structure of the salt and anhydrite seams present. One thing they do reflect and which is of prime importance, is the complete lack of moisture content in the salt within the measuring system. This leads to the conclusion that for a maximum depth of 130 feet along this traverse the salt is very dry.

INTERNATIONAL SALT MINES RESULTS

Some electrical resistivity measurements were made in the International Salt Mines at Detroit, Michigan. These measurements were made around the shaft pillar, close to a brine well (Traverse A), along a 600 foot corridor facing dry salt, about a large pillar surrounding a very small cavity (Traverse E) and at various wet places in the mine.

Electrical resistivity results in this mine are presented as vertical isokilo-ohm-cms. Sections for Traverse A and Traverse E are shown with their locations in Figure 7. The results on face "A" indicate resistivities ranging from 1000 to 5000 ohm-cms, with a small area of less than 1000 ohm-cms (lowest value measured was 450 ohm-cms) from 105 to 120 feet on the traverse. This low continues downward to the maximum depth measured (50 feet), however its value increases to between 1000 and 2000 ohm-cms. This is to be expected because the resistivities are

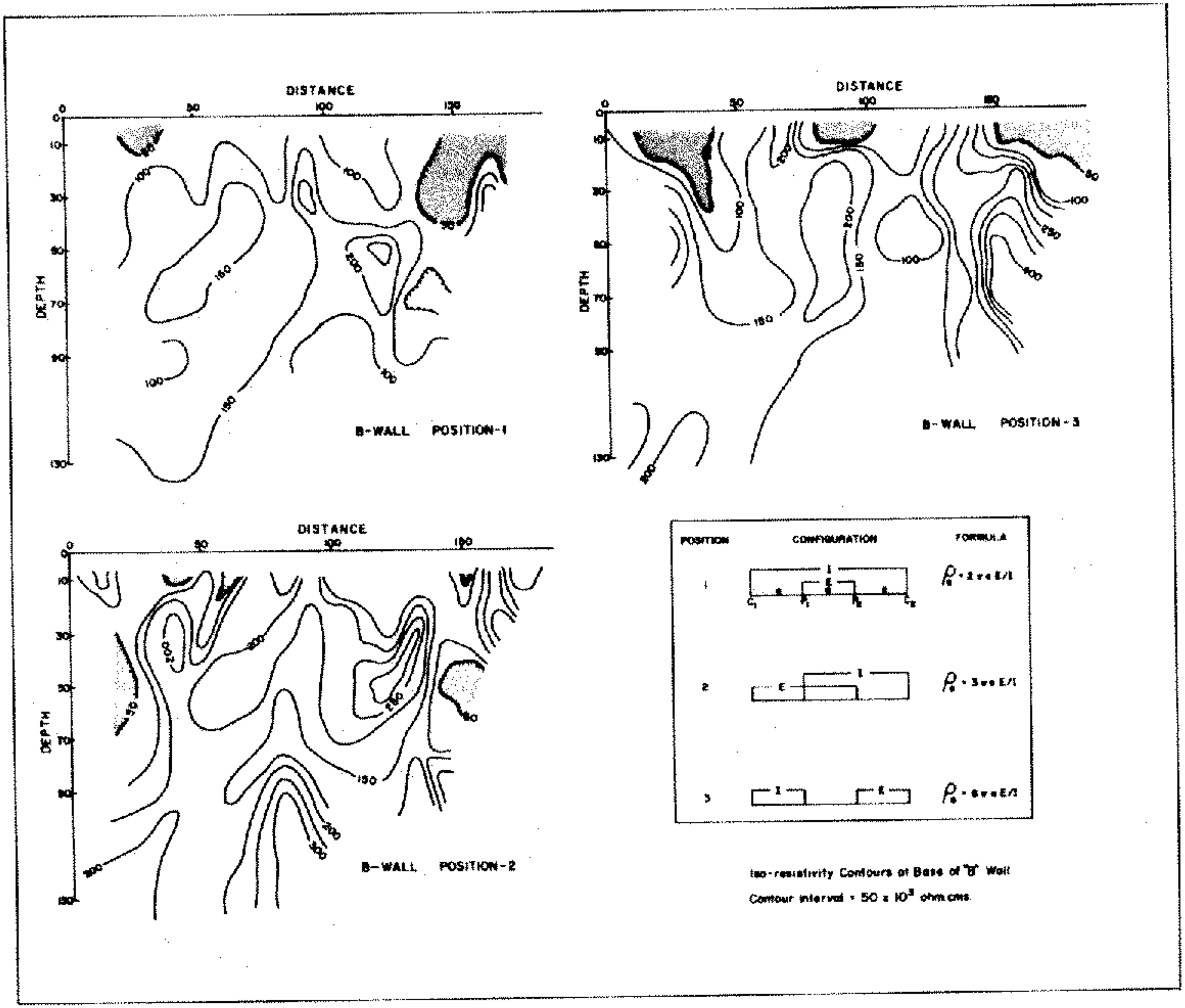
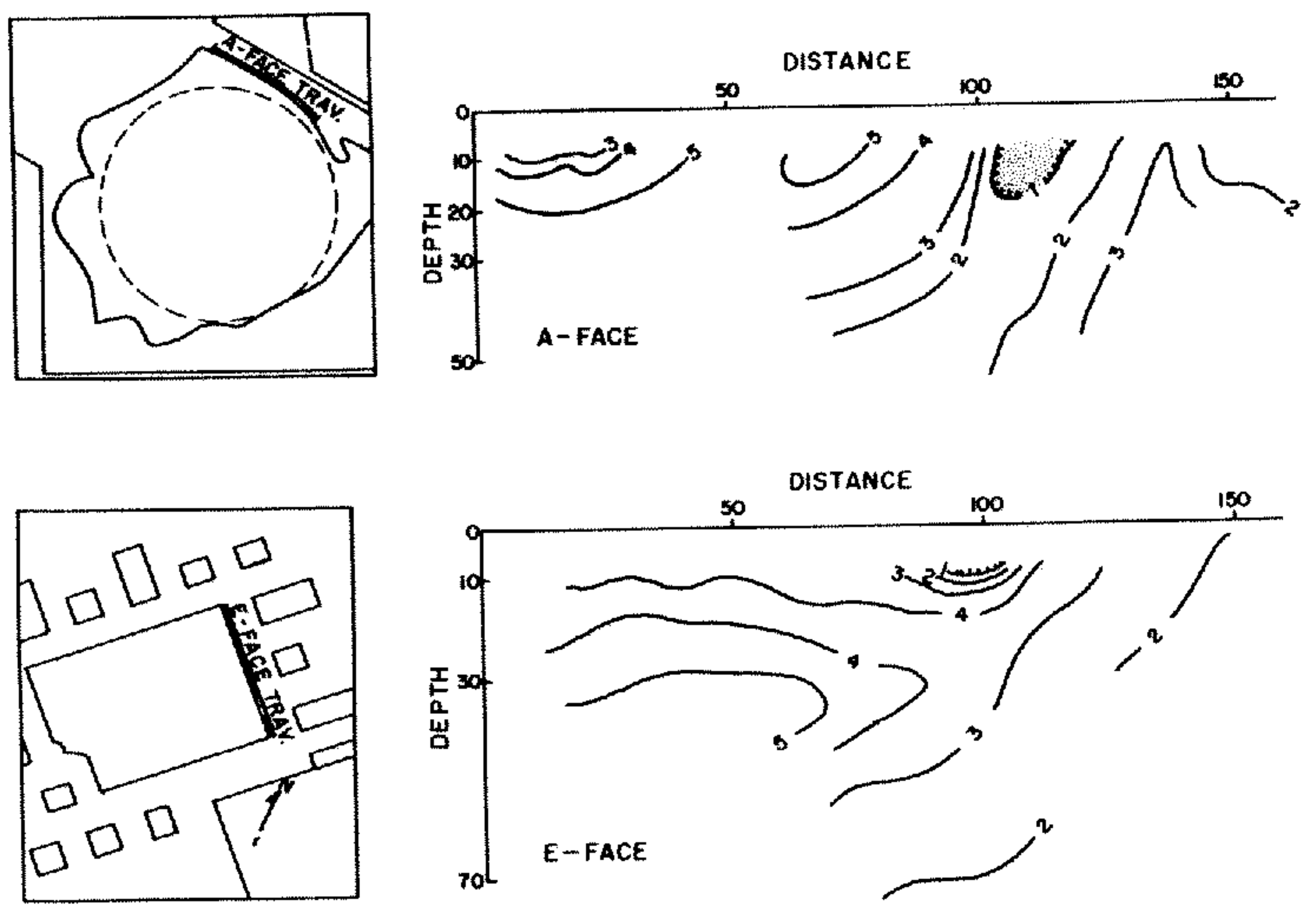


Figure 6. Tri-Potential Electrical Resistivity Results at Wall "B," Grand Saline Salt Dome.



Iso-resistivity Contours at Base of "A" and "E" Faces, International Detroit Salt Mines.

Contour Interval = 1×10^3 ohm cms

Figure 7. Plan View Showing Locations of Electrical Surveys with Vertical Iso-Resistivity Sections. International Salt Mines, Detroit.

only apparent and should increase slightly with depth. Resistivity results along the "E" face also indicate resistivities ranging from 1000 to 5000 ohm-cms. At a distance of 100 feet on this traverse a low of less than 1000 ohm-cms is indicated at a depth of 10 feet. Both this low and that on the Traverse at face "A" reflect moisture spots in the salt; however that on "E" is interpreted as being only surficial while on the "A" face it penetrates to a depth of at least 50 feet.

The apparent electrical resistivity results in the bedded salt deposits at Detroit indicate a lower apparent resistivity for this salt than for that in the salt dome. This lower apparent resistivity is believed to reflect possible brine cavities in bedded salt while such cavities are possibly at a minimum or not present in salt in dome structures.

CONCLUSIONS

It is concluded that the electrical resistivity method is a potentially useful method for testing salt for moisture content since it is very sensitive to brine content and structure.

There is no doubt that the electrical method can indicate these moisture or brine areas in a salt horizon within a mine; however difficulty arises in trying to pin-point the actual outline of moisture and/or brine with respect to the point of field observation.

Apparent resistivities of salt vary considerably; i. e., from 100,000 to 800,000 ohm-cms in salt dome structures to 1000 to 6000 ohm-cms in bedded salt deposits.

ACKNOWLEDGEMENTS

It is the desire of the author to acknowledge with sincere thanks and appreciation the help and assistance of Mr. Horace Diamond of the Morton Salt Company, Mr. Don Richner of Diamond Alkali Company, the International Salt Company and Mr. Jack Veasaw of Texas Instruments Company.

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