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McPHAR GEOPHYSICS

NOTES ON GEOTHERMAL EXPLORATION USING THE RESISTIVITY METHOD

Many geophysical methods have been tried in the exploration for geothermally "hot" areas in the upper regions of the earth's crust. The only method that has been consistently found to be successful has been the resistivity technique. In this geophysical method, the specific resistivity (or its reciprocal, the specific conductivity) of the earth's subsurface is measured during traverses over the surface.

The principle of the technique is based on the fact that the resistivity of solution-saturated rocks will decrease as the salinity of the solutions is increased and/or the temperature of the system is increased (see Figure 1). Therefore, volumes of the earth's crust that contain abnormally hot and saline solutions can often be detected as regions of low resistivity.

The resistivity measurements are usually made using grounded current and potential electrodes, but some useful data can sometimes be obtained using electromagnetic techniques. The field data shown on plan maps in Figure 2 are from the Broadlands Area in New Zealand; in this area there are substantial flows of hot water and steam at the surface.

The results show resistivity lows measured with a Wenner Configuration Resistivity Survey and a loop-loop electromagnetic survey. The anomalous pattern is much the same in both cases and the regions of low resistivity correlate well with the areas of increased rock temperature.

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VARIATIONS OF SOLUTION RESISTIVITY
WITH TEMPERATURE AND SALINITY

FIG. 1

FIG. 2

If the rock volume saturated with hot solutions does not extend to the surface it will be necessary to use large electrode intervals to detect the resistivity lows. The resistivity data shown in "pseudo-section" form in Figure 3 is from Java. Along this line there are two deep regions of low resistivity detected for the larger electrode intervals used. Zone A is associated with surface manifestations of geothermal activity. The source of the resistivity low at Zone B is unknown.

If the abnormally hot region occurs in a sedimentary basin, the general resistivity level can be quite low, due to the high porosity in normal sediments. This is the case in the Imperial Valley of California. The resistivities shown in Figure 4 are from an area near El Centro, California. The largest electrode separation used was 12,000 feet.

The results show a two-layer geometry with the upper layer having a thickness of approximately one-half electrode interval (i. e. 1,000 feet). The resistivity in the upper layer is 3.0 ohm-meters; the resistivity of the lower layer is 1.5 ohm-meters. Due to the small resistivity contrast, additional measurements would be necessary to determine the possible geothermal importance of the lower resistivity layer at depth.

The results shown in Figure 4 are from a dipole-dipole electrode configuration survey. Our dipole-dipole data is plotted as a "pseudo-section" for several values of n ; the separation between the current electrodes and potential electrodes, as well as the location of the electrodes along the survey line, determine the position of the plotting point. The two-dimensional array of

APPARENT RESISTIVITY SURVEY, DENYO PLATEAU AREA, JAVA, INDONESIA

Pseudo Section Plotting Method Along Dang-Bater Road

FIG. 3

RESISTIVITY SURVEY, IMPERIAL VALLEY-CALIFORNIA.

LINE-"0", FREQUENCY-0.125 Hz.

24W 22W 20W 18W 16W 14W

(P)Ω-metres

FIG. 4

data is then contoured (see below). The contour plots are not sections of the

DIPOLE-DIPOLE PLOTTING METHOD

electrical properties of the earth; they are convenient graphical representations of the measurements made. However, with experience the contour patterns can be interpreted to give some information about the source of the anomaly.

If the contour patterns indicate very simple geometries, more quantitative interpretations can often be made. For instance, if the contours are horizontal for a lateral distance of four to six electrode intervals, a horizontally layered geometry is indicated. In this situation, theoretical type-curves for dipole-dipole measurements in a layered geometry can be used in "curve fitting" techniques to give the true resistivities and depths for the earth.

McPHAR GEOPHYSICS

REPORT ON THE

RECONNAISSANCE RESISTIVITY SURVEY

IN THE

EAST MESA AREA

IMPERIAL COUNTY, CALIFORNIA

FOR

U.S. DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

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1. INTRODUCTION

At the request of the U.S. Department of the Interior, Bureau of Reclamation, McPhar Geophysics has completed a Reconnaissance Dipole-Dipole Resistivity Survey in the East Mesa area, Imperial County, California. The survey area is located in T.15S., T.16S., T.17S. and R.16E., R.17E., R.18E. and R.19E.

The East Mesa area lies within the Imperial Valley trough which is filled with predominately nonmarine Tertiary and Quaternary sandstone and shales, to an estimated thickness of 20,000 feet. High heat flow measurements have been obtained throughout the area and abnormal amounts of dissolved salts are known to exist in the sediments. The East Mesa area has been designated a KGRA.

Intensive geological, geochemical and geophysical studies of the

East Mesa area have been conducted by the geological staff of the University of California at Riverside. Temperature gradient, gravity, magnetics and Schlumberger resistivity sounding surveys have previously outlined the East Mesa anomaly and the Bureau of Reclamation has drilled two deep wells and installed a pilot desalination plant.

The dipole-dipole resistivity technique simultaneously determines lateral and vertical variations in resistivity which assist the geological interpretation of the survey area. The purpose of the Reconnaissance Survey was to locate and delineate low-resistivity zones that might indicate areas of concentrated thermal activity. Measurements were made with 2000 foot dipoles at one-through-five dipole separations along reconnaissance lines spaced approximately one mile apart. A frequency of .125 Hz was used in order to minimize attenuation of the effective field due to eddy current dissipation of energy and at the same time avoid telluric noise.

2. PRESENTATION OF RESULTS

The resistivity survey results are shown on the following data plots in the manner described in the notes which accompany this report.

<u>Line</u>	<u>Electrode Intervals</u>	<u>Dwg. No.</u>
1	2000 feet	R 6131-1
2	2000 feet	R 6131-1
3	2000 feet	R 6131-1
4	2000 feet	R 6131-2
5	2000 feet	R 6131-2
6	2000 feet	R 6131-2

Also enclosed with this report is Dwg. No. RP 4950, at a scale of 1" = 2000'. The definite, probable and possible resistivity low anomalies are indicated by bars, in a manner shown in the legend, on this plan map as well as on the data plots. These bars represent the surface projection of the anomalous zones as interpreted from the location of the transmitter and receiver electrodes when the anomalous values were measured.

The generalized results from some of the previous geophysical surveys in this area have also been shown on the plan map.

3. DISCUSSION OF RESULTS

The detection of geothermal reservoirs within 5000 feet of the earth's surface by surface resistivity methods is normally quite simple. Many factors affect the resistivity level in a volume of rock, i. e. porosity, salinity, temperature. The presence of elevated temperatures in geothermally active areas almost always results in a decrease in the absolute resistivity level of the rocks. A temperature change of 100°C will cause a resistivity reduction in the order of 250% relative to the surrounding region. Universally, these reservoirs appear to exhibit a resistivity of less than 10 ohm feet and a ratio of 1:5 to 1:20 with the resistivity of the surrounding rock.

The East Mesa anomaly occurs in the southeast portion of the Imperial Valley, which is an alluvium-filled, northwest-trending basin with predominantly non-marine Tertiary and Quaternary sandstones and shales to a thickness of approximately 20,000 feet. Abundant (up to 20%) salts are contained in solution in the alluvium. This

abnormally high salt content produces an extremely low, uniform resistivity throughout the area and makes the detection of areas of high heat flow difficult.

McPhar Geophysics has conducted some theoretical resistivity model studies of possible geothermal sources. Case 1 and Case 2, attached, indicate that a source with a resistivity contrast of 1:20 and a depth of half to one dipole unit is easily recognized. When this source is covered by conductive overburden, half a unit thick, as in Case 3 and Case 4, the anomalous pattern is severely distorted and an anomalous response is only slightly evident.

The survey results of the East Mesa area indicate that the apparent resistivity in the west half of the area, west of station 360E, has a resistivity variation between approximately 2.5 ohm feet and 1.0 ohm feet.

With this level of resistivity, the measured apparent resistivity values will be distorted by inductive coupling effects; this is true even for the very low frequency of 0.125 Hz that was used for the survey. The values measured and recorded will be somewhat lower than would have been measured if d. c. had been used.

The following table shows the approximate magnitude of the reduction in apparent resistivity that would be expected for a uniform earth. Thus, for a uniform earth with a $\rho/2\pi$ value of 4.0, the value measured for $n = 5$ would be 3.6. For a uniform earth $\rho/2\pi$ equal to 1.0, the $n = 5$ value measured would be about 0.5.

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Theoretical Resistivity Studies
Scale Model Cases

CASE I

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Theoretical Resistivity Studies
Scale Model Cases

CASE 2

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Theoretical Resistivity Studies

Scale Model Cases

CASE 3

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Theoretical Resistivity Studies
Scale Model Cases

CASE 4

The effect of the inductive coupling can be seen in the results from Line 3, as an example. In the region from 320E to 460E, the reduction in resistivity from about 4.0 for $n = 1$ to about 3.5 for $n = 5$ can be explained by the inductive coupling effect. The much larger reductions in apparent resistivity with increased (n) in the interval from 20W to 100E can not be due to inductive coupling. In this region, the true resistivities are lower at depth.

Expected Decrease In Measured Apparent
Resistivities Due To Inductive Coupling Effects
Dipole-Dipole Electrode Configuration On Uniform Earth
at 0.125 Hz and X = 2000 feet

$\rho/2\pi = 4.0$	$n = 1$	0.5%
	$n = 2$	1.7%
	$n = 3$	3.5%
	$n = 4$	7.0%
	$n = 5$	10%

$\rho/2\pi = 2.0$	$n = 1$	1.2%
	$n = 2$	4.1%
	$n = 3$	9.0%
	$n = 4$	15%
	$n = 5$	24%

$\rho/2\pi = 1.0$	$n = 1$	3%
	$n = 2$	9%
	$n = 3$	19%
	$n = 4$	33%
	$n = 5$	48%

The survey results along each line are as follows:

Line 1

A definite resistivity low is present at 60E to 60W, decreasing gradually to the west. The decrease is classed as probable to 120W and open to the west, but apparently closing as indicated by increasing resistivities on $n = 3$ and 4. The definite zone is situated within a large, uniform low extending from 120W to 180E. A small, deep, probable low-resistivity anomaly is present at 140E to 180E at the eastern edge of the broad resistivity low.

The resistivities east of 180E are quite uniform. The dry dune sand is apparent as slightly higher resistivities on $n = 1$ throughout the length of the profile. Resistivities increase with depth and laterally, west of the canal in the irrigated fields, indicating an alluvium compositional change and/or a heat flow decrease.

A one-station, possible resistivity anomaly is present on $n = 4$ at 280E to 300E. Its significance is unknown.

Line 2

Line 2 was surveyed along a previously surveyed Test Line. The previous data are shown as attached Figure 6. Station 0 on Line 2 corresponds to 40E in Figure 6. The two sets of data show a relatively good match at the point where they overlap.

Keeping in mind that the data from Figure 6 have been corrected for inductive coupling, it can be seen that the region of low resistivity

EAST MESA GEOTHERMAL ANOMALY

IMPERIAL COUNTY, CALIFORNIA

TEST LINE 1

Frequency - 0.125 Hz.

Values corrected for inductive coupling

$$\rho/2\pi \text{ in ohm-feet} = (\rho \text{ in ohm-metres}) \times 0.52$$

to moderate. The anomaly here is much the same as on Line 2.

The resistivities are quite uniform from 260E to 400E. A relatively strong increase occurs east of station 400E, especially in the shallow data. Definite layering is present east of 400E. A very weak decrease in resistivity with depth occurs from 480E to 580E. The resistivity contrast is anomalous, but the magnitude of the resistivity is greater than the resistivities in the well-defined anomalous zones. This weak, deep, low-resistivity zone is a possible resistivity anomaly.

Line 5

Most of the $n = 5$ readings and some $n = 4$ readings were not obtained on this line. This was due to high contact resistance at the electrodes and is probably the result of a near-surface impermeable layer which prevented the water poured on the electrodes from penetrating to the water table.

The resistivity data obtained along this line indicate a gradual increase in resistivity to the east. The data from 320E to 480E indicate a uniform geology beneath this portion of the line. The eastern portion suggests a simple two-layered geometry.

The weak anomaly which was located on Line 4 between 480E and 580E has not been located on this line.

Line 6

The resistivity results along this line are essentially the same as

on the previous lines. Very low resistivity occurs on the west end of the line and there is a gradual increase in resistivity to the east.

A weak, possible anomaly exists between 20E and 220E. The resistivity between 220E and 500E is relatively uniform; from 500E to the end of the line there appears to be a gradual increase of near-surface, higher-resistivity material.

4. CONCLUSIONS AND RECOMMENDATIONS

The reconnaissance resistivity survey recently completed in the East Mesa Area for the Bureau of Reclamation has confirmed the previous work in the area. A broad zone of low resistivities at depth extends through the area in a NNW direction. The zone of low resistivities seems to be centred in the northwest corner of T16S, R17E.

The shallowest, most definite portion of the anomaly seems to be centred at 0+00 to 80E on Line 3. As shown on the plan map Dwg. RP 4950, this corresponds relatively well with the measurements of anomalous temperature gradient and seismic noise activity published by the University of California, Riverside.

The interpretation of the resistivity data and the location of the resistivity lows at depth is much less definite in the Imperial Valley than it is in other areas of geothermal exploration. This is due to the extremely low background level of resistivities. The low resistivities in the Imperial Valley are due to the high porosity of the sediments and the high salinity of the solutions contained within the rock. The expected decrease in resistivity due to elevated temperature is much more difficult to detect in this environment.

The eastern edge of the zone of low resistivities at East Mesa has been determined on all of the lines on which the anomaly was detected. The southern edge must lie between Line 4 and Line 5. The western edge of the zone is clearly outlined by the previous data from Line 2 (Test Line 1). Line 1 and Line 3 do not extend far enough to the west to completely delineate the zone of low resistivities.

It is possible that the zone of low resistivities continues to the north and west of the anomaly outlined on Line 1. The results available to date are not extensive enough to determine the edge of the zone in that direction.

Our information is that two deep test drill holes have been drilled approximately along Line 2. These would be located at approximately 30W and 70E. The eastern hole is nearer the centre of the resistivity low and has a considerably higher temperature at the bottom of the hole. If this correlation is valid, some additional detailed resistivity measurements would be warranted to attempt to better locate the centre of the resistivity low and its lateral extent so that additional drilling could be planned.

In any additional resistivity work at East Mesa it would be worthwhile to take the additional time necessary to use 0.05 Hz for the survey. The slower progress would increase the cost of the survey, but the lower frequency would further reduce distortions due to inductive coupling effects.

McPHAR GEOPHYSICS INCORPORATED

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Dated: January 21, 1974

McPHAR GEOPHYSICS

DWG. NO. - R - 6131-2

U.S. BUREAU OF RECLAMATION

EAST MESA GEOTHERMAL FIELD,
IMPERIAL COUNTY,
CALIFORNIA

LINE NO. - 4 (X=2000FT)
LINE NO. - 5 (X=2000FT)
LINE NO. - 6 (X=2000FT)

ELECTRODE CONFIGURATION

PLOTTING POINT

SURFACE PROJECTION OF ANOMALOUS ZONES

DEFINITE
PROBABLE
POSSIBLE

FREQUENCY: 0.125HZ

DATE SURVEYED: DEC 1979

APPROVED: [Signature]

DATE: 12/79

McPHAR GEOPHYSICS

RESISTIVITY SURVEY

NOTE: THIS PLOT WAS PRODUCED BY McPHAR COMPUTER DIVISION

NOTE: CONTOURS AT LOGARITHMIC INTERVALS 1.-1.5-2.-3.-5.-7.5-10