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# PRELIMINARY INTERPRETATION OF RESISTIVITY AND SEISMIC REFRACTION DATA FROM THE SALTON SEA GEOTHERMAL FIELD

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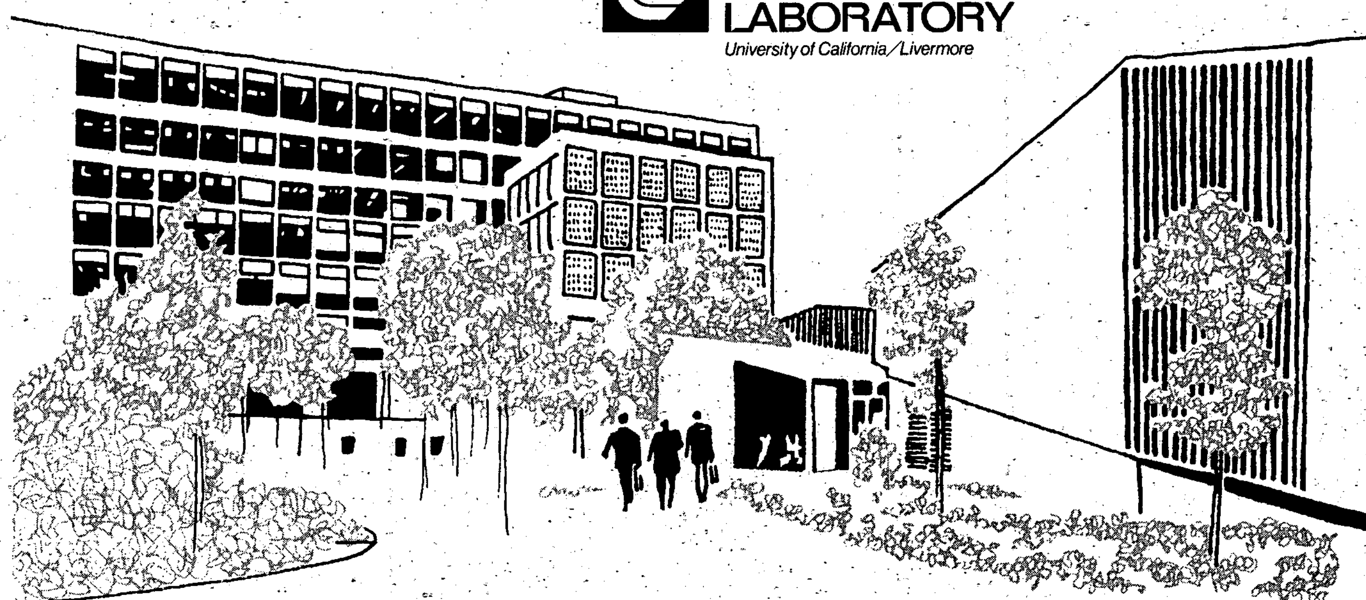

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## Abstract

Seismic refraction and electrical resistivity surveys have been conducted in the Salton Sea Geothermal Field. The resistivity data are used to infer the boundaries of a reservoir of saline fluid. One lateral boundary closely coincides with a fault that was located by seismic refraction.


## Introduction

Lawrence Livermore Laboratory has sponsored a large-scale seismic refraction and electrical resistivity survey of the Salton Sea Geothermal Field. The preliminary results presented here indicate that the natural flow patterns of hot brine are influenced by a large fault, the location of which was determined from seismic data. Upper and lower boundaries of what is believed to be a convecting hydrothermal system were mapped from surface resistivity measurements. Detailed interpretations of all these data will be presented in final reports by the various investigators involved in this study.

## Seismic Refraction Survey

The seismic refraction survey was performed by S. Biehler and associates and the experimental details of this work will be discussed in a future report.[1]

The locations of two reversed seismic refraction profiles are shown on the gravity anomaly map in Fig. 1. Each profile is at least 20 km long and has one end inside the drilled geothermal field, the area bounded by the 975-milligal gravity anomaly contour.

The seismic data presented in Fig. 2 were recorded along profile 1 and the shot point A was located near Obsidian Butte. A maximum of three arrivals are shown for recording stations up to 7000 m from the shot point. The quality of the data is excellent and three layers with distinct seismic velocities can be resolved. Also, data recorded farther from the shot point provide evidence for a fourth layer.

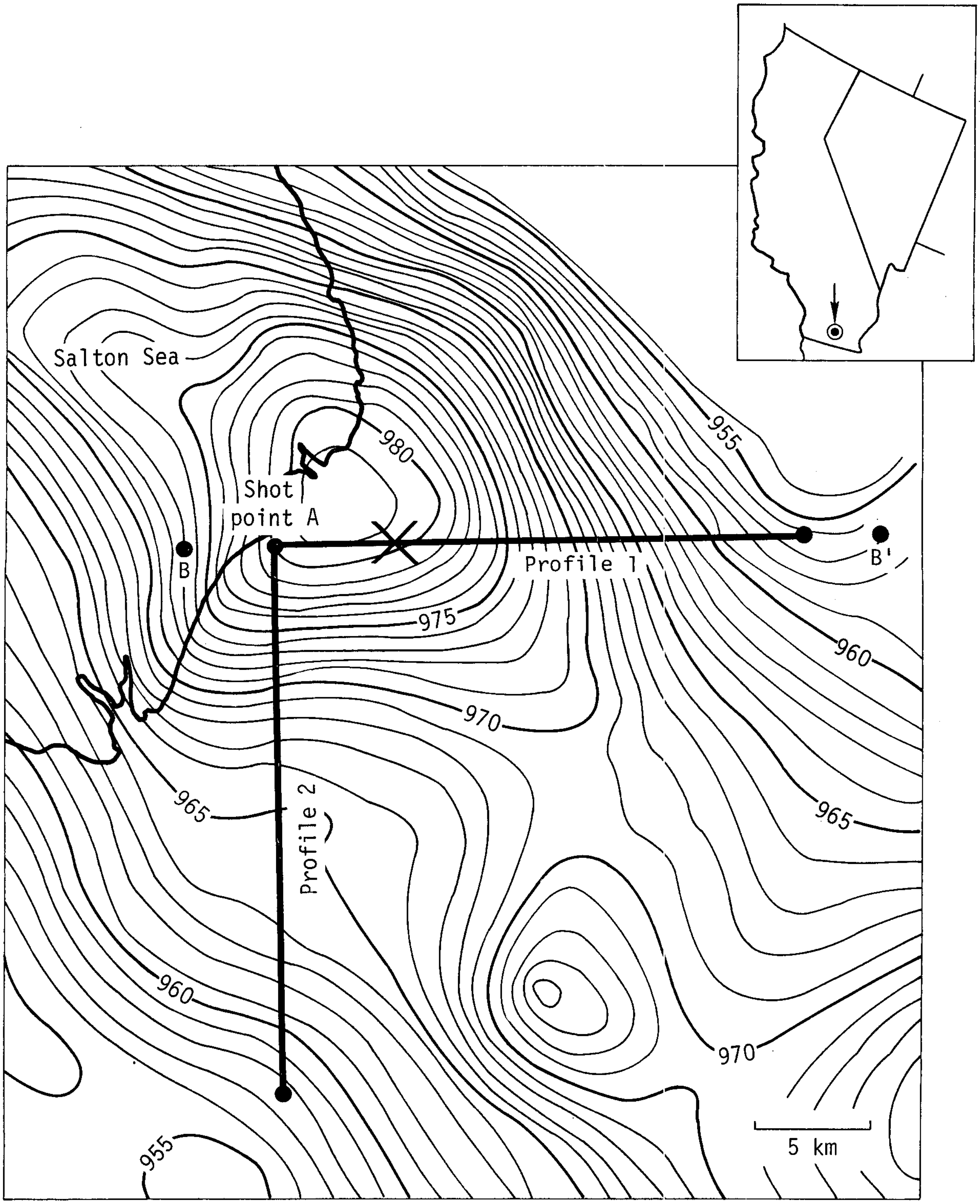


Fig. 1. Bouguer gravity anomaly map of the Niland-Brawley area.[7] Heavy solid lines show locations of two seismic refraction profiles; (X) represents location of the fault as determined from profile 1 (contours in milligals).

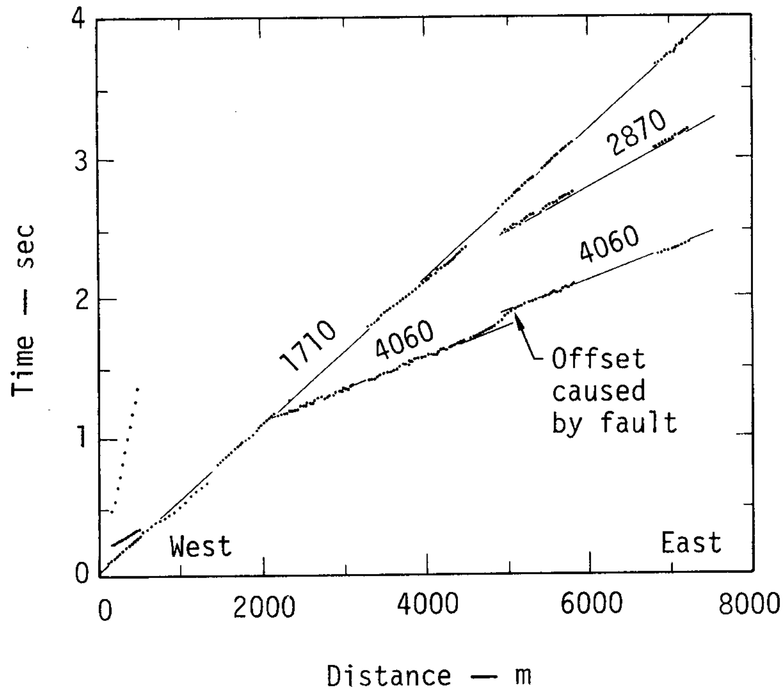


Fig. 2. Seismic refraction data along profile 1. Each dot represents an arrival time picked from the field record; velocities along refraction lines in meters per second.

The 4060 m/sec arrival is delayed by more than 0.1 sec at a distance of 5000 m from the shot point. An interpretation of this data[1] is shown in Fig. 3. The arrival-time delay is thought to result from a nearly vertical fault with an apparent vertical offset of 220 m. This is the simplest interpretation that fits the observations but other more complicated models involving hidden layers are possible.

Recent microearthquake studies[2] have indicated an active fault trending to the northwest through this region but have not accurately determined its location. Randall[3] has examined well logs and has postulated several faults running through the geothermal field with the same strike. The fault located by seismic refraction is assumed to also parallel the axis of the Imperial Valley.

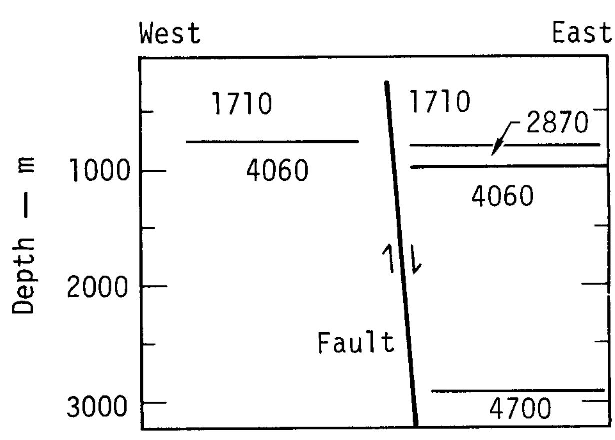


Fig. 3. Cross section along profile 1 showing fault interpretation and velocity layers (meters per second). Vertical exaggeration 2:1.

## Resistivity Survey

Approximately 60 electrical resistivity soundings have been taken by Geonomics, Inc., in the vicinity of the Salton Sea Geothermal Field. The soundings were made with a variety of electrode geometries and with effective penetration depths of up to 8000 m. (The details of the measuring technique are presented in a paper by Geonomics, Inc.[4])

### SIMPLE INTERPRETATION TECHNIQUES

For a given electrode spacing (AB), the apparent resistivity is defined as the resistivity of an imaginary uniform half-space which would produce the observed voltages. Because electric currents penetrate deeper for greater electrode spacings, the apparent resistivities determined for different spacing are averages over different depth ranges within the earth. If the actual resistivity in the earth changes with depth, then the apparent resistivity will change with spacing.

Field data from a single sounding are presented in Fig. 4 as a log-log plot of apparent resistivity vs the effective penetration depth in a uniform half-space (AB/2). In this figure, we see that the resistivity of the earth is high near the surface (greater than 5 ohm•m), decreasing to approximately 1.5 ohm•m at 1000 m, and then sharply increasing with depth to a value greater than 10 ohm•m.

Two methods[5] for rapid initial interpretation of sounding data were used and are discussed below.

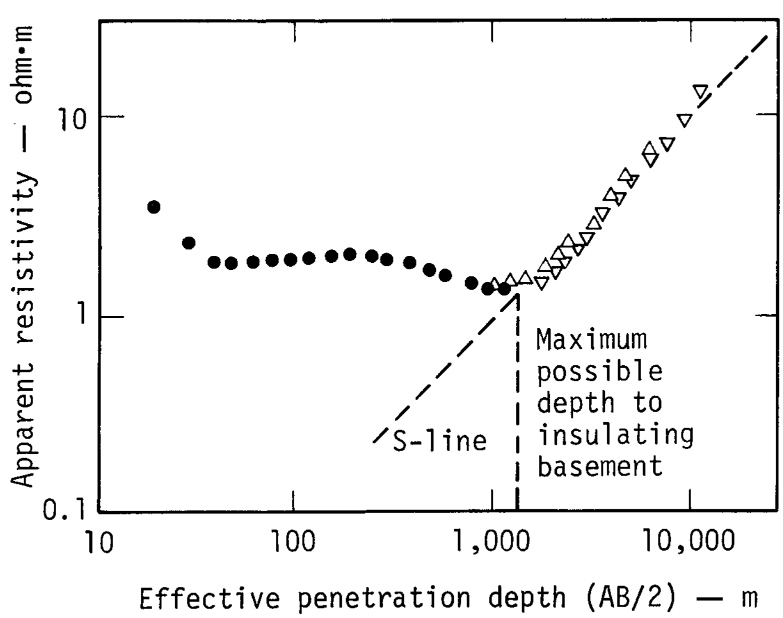


Fig. 4. Resistivity sounding curve. Dots and triangles represent different measurement geometries.

## The S-line

If a layer is much more resistive than the overlying layers, sounding curves will have the characteristic shape of a straight line with an upward slope of unity, increasing with depth. This sloping straight line is called the S-line and the ratio of effective penetration depth to apparent resistivity anywhere along this line is equal to the total conductance, S, of the overlying layers. (Layer conductance is defined as the ratio of thickness to resistivity and total conductance is the sum of these ratios.) Many of our sounding curves have such a slope, indicating an increase of resistivity below the geothermal system.

## Maximum Possible Depth to Resistive Layer

If the earth consists of a single layer over an insulating half-space, the resistivity and thickness of that layer is given by the point of intersection between the sounding curve and its S-line. If several layers of differing resistivity overlay the insulating basement, the total thickness of these layers must be less than or equal to the effective penetration depth at the intersection of the S-line and the sounding curve. When soundings encounter two resistive layers, the maximum possible depth to the top of each layer can be determined from the shape of the sounding curves.

## PRELIMINARY RESULTS OF RESISTIVITY SURVEY

The locations of soundings and the contours of conductance are shown in Fig. 5. High temperature or high salinity layers have low

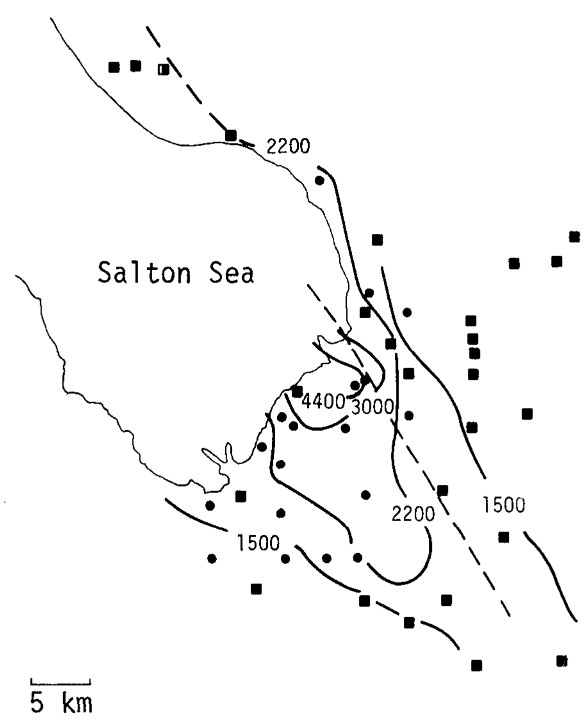


Fig. 5. Conductance map for surveyed area. Dots indicate location of soundings; broken line locates the fault; conductance in siemens. Some sounding curves do not continue to large enough spacings to show an S-line. For these, minimum values of conductance have been plotted ( ■ ).

resistivity and because conductance, S, is the layer thickness to resistivity ratio, high conductance values may indicate thick, hot, or salty regions such as a geothermal system. However, large amounts of clay can also have a high conductance and thus, high S values do not always indicate a geothermal field.

A high conductance anomaly is clearly associated with the drilled geothermal field enclosed by the 3000-siemen contour. The resistivity anomaly is much more elongated along the strike of the valley than is the gravity anomaly and appears to be bounded on the northeast side by the fault.

Soundings indicate that two resistive layers are present. Well logs from within the geothermal system are available and thus, we can relate these layers to known features of the geothermal system. Figure 6 presents data from electric and temperature logs from the Elmore No. 1 well.[6] A preliminary flat-layer interpretation of a single sounding near this well was made using the auxiliary curves from Keller and Frischknecht.[5] The resulting resistivity vs depth curve is shown by the broken line in Fig. 6.

A resistive region is seen in this figure between 550 and 860 m in the well log and in the sounding interpretation. This shallow resistive layer occurs where the temperature gradient begins to decrease and probably represents a feature associated with the top of a convecting system. The sandstone at this depth has high resistivity resulting either from low-salinity pore fluid or from reduced porosity due to circulation of fluids. This sounding, however, did not penetrate the deeper resistive layer indicated on the well log by the gradual increase in resistivity with depth.

The depth to the top of the shallow resistive layer is contoured in Fig. 7. The shallow layer does not appear on soundings outside the hatched area and seems to terminate at the fault. The soundings also suggest that the top of the system slopes down and away from the heat source. If this layer indicates the top of the convecting system, then the geothermal system must be much larger than the drilled field.

A contour plot of the depth to the top of the deeper resistive layer is given in Fig. 8 and a cross section of the area showing the shallow and deep resistive layers is presented in Fig. 9. Data from the well logs suggest that this region is characterized by a gradual increase in resistivity. This increase is probably a result of reduced porosity

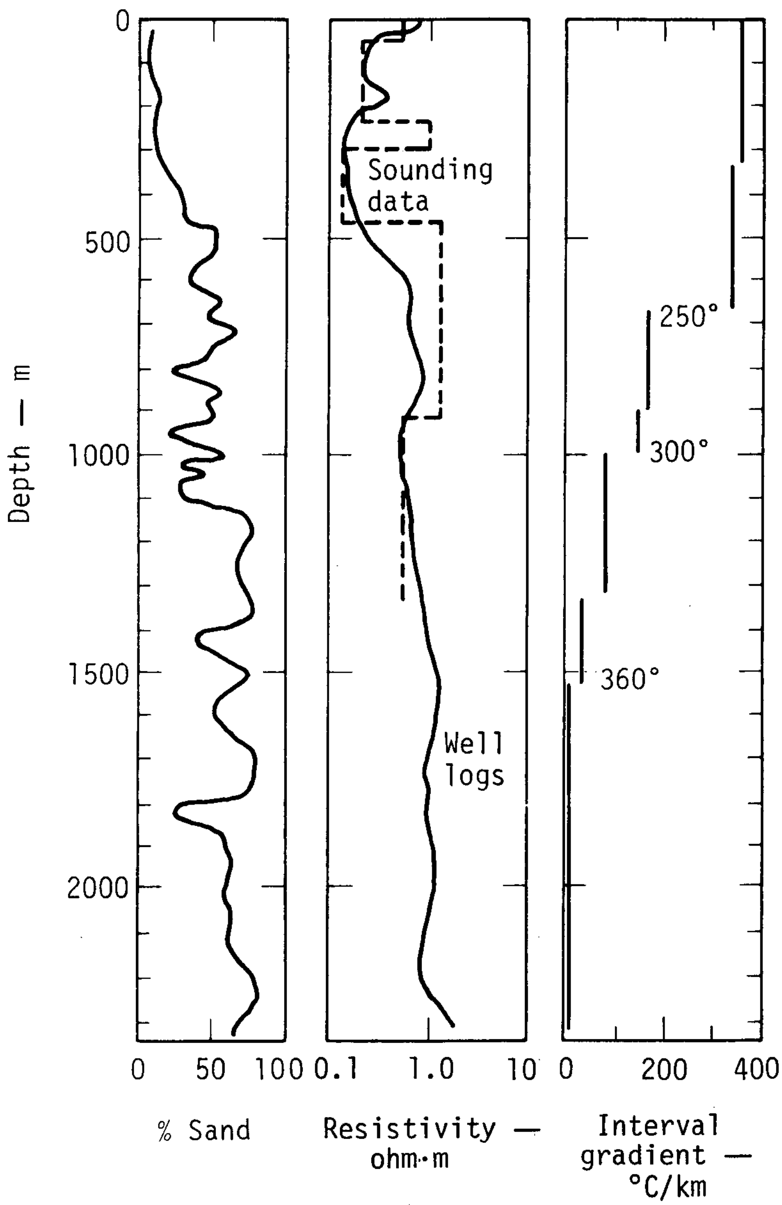


Fig. 6. Well log and sounding interpretation at the Elmore No. 1 well. Sand percentages were estimated every 30 m; induction log resistivity curve (solid line) has been smoothed.

because temperature and salinity are also expected to increase with depth. Reduced porosity, in turn, may be caused by pressure compressing the sedimentary rock and may indicate the bottom of the exploitable geothermal reservoir.

Thus, based on these preliminary interpretations, we draw the following conclusions. The gravity and resistivity anomalies are related to different components of the geothermal system. The gravity primarily reflects the source of heat and the resistivity indicates the location of the saline fluid. The fault acts as a barrier, excluding saline fluid from the area northeast of the fault.

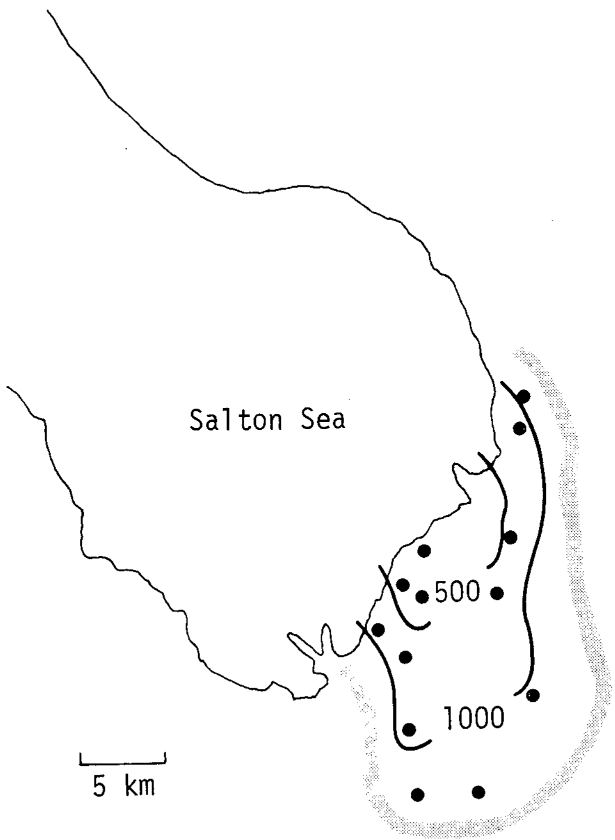


Fig. 7. Maximum possible depth (meters) to top of the shallow resistive layer. Dots indicate soundings where layer appears; the layer appears to end at the shaded region.

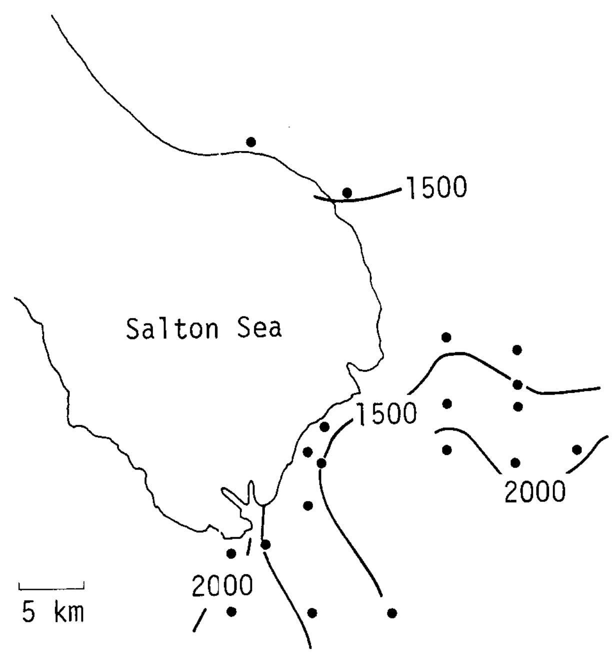


Fig. 8. Maximum possible depth (meters) to top of the deep resistive layer. Dots indicate soundings where layer appears.

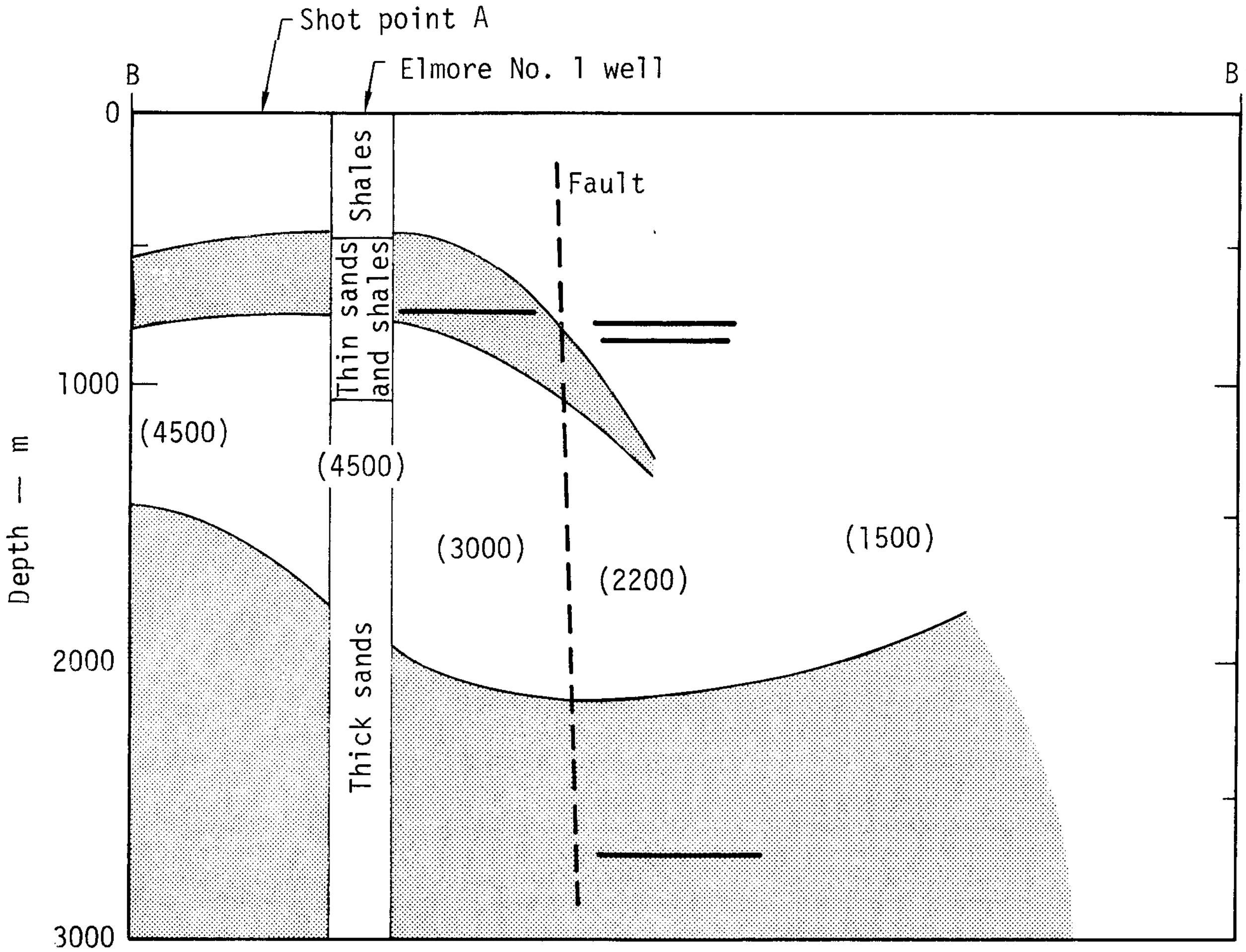


Fig. 9. Cross section along line B-B' of Fig. 1. Heavy solid and broken lines are respectively, the velocity layers and fault interpretation from Fig. 3. A simplified lithologic column based on the electric log from the Elmore No. 1 well is provided. Shaded regions represent the shallow and deep resistive layers as inferred from resistivity observations; total conductance (siemens) above the deep resistive zone is shown in parentheses. Vertical exaggeration 5:1.

## Acknowledgments

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The seismic refraction survey was performed by S. Biehler and associates at the University of California, Riverside. Geonomics, Inc., under the direction of T. Meidav, conducted the resistivity study.

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