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GEOTHERMAL GROUND-NOISE SURVEYS†

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In recent years there has been increasing interest in the role of geothermal steam as a source of energy. Only recently has geophysical exploration begun to play a major role in the exploration for geothermal resources; heat flow, gravity, and resistivity measurements have been the techniques most used. One recent development is the discovery that high surface-noise levels are associated with the presence of geothermal reservoirs below the surface. Field surveys using short-period seismographs have been conducted in the Imperial Valley of California in areas where heat-flow measurements or drilling have indicated the presence of a geothermal deposit. In all three surveys abnormally high noise levels were found above the reservoir in the frequency range of 0.5 to 5.0 hz. The ground-noise anomalies show a more complex pattern than the associated heat flow and gravity measurements. A theoretical model has been developed in which small, random pressure variations in a convecting geothermal reservoir are suggested as the source of the noise. Using this model, the noise level above one of the anomalies was duplicated, using a reasonably sized reservoir with pressure variations of less than 1 millibar.

INTRODUCTION

Geothermal power plants operating in Italy, New Zealand, and the United States have proven the practical value of using natural steam and hot water as a relatively pollution-free source of energy. The success of these projects has stimulated exploration for this valuable natural resource; at the present time, geothermal development has, in general, concentrated on areas of surface activities such as hot springs. Geologic and geophysical exploration techniques have only recently begun to play a major role in the identification and location of geothermal resources.

In this paper we discuss experimental evidence that indicates that geothermal reservoirs are a source of short-period seismic energy that can be detected using modern instrumentation and data-analysis techniques. For historical reasons, the technique is usually referred to as the ground-noise method of geothermal exploration. The original study on the method was done in the New Zealand Rotorua, Taupo volcanic region and was published by Clacy (1968).

The results discussed in this paper were obtained from research conducted in the Imperial Valley of California. The Imperial Valley was chosen because of the known presence of geothermal reservoirs and the numerous heat-flow and gravity measurements that are available for comparison with the results of the ground-noise surveys.

Basically, the method is very simple. It consists of measuring the power spectrum of the vertical background noise in the survey area; the presence of a geothermal reservoir is indicated by a sharp increase in the noise level. To date, the experimental evidence indicates that the noise is most prominent in the frequency band of 0.5 to 5.0 hz. The problems associated with the method are mainly the recognition and elimination of interfering energy from other sources, such as lakes, traffic, wind, earthquakes, etc. This aspect of the problem is as much an art as a science; noise samples free from interfering noise sources almost always can be found if the interpreter of the data is experienced in background-noise

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analysis. A considerable amount of published material is available in this field (e.g., Douze, 1967). Another problem associated with the method is the well-known changes in noise level caused by variations in acoustic impedances of the near-surface material at the recording site. In sedimentary basins such as the Imperial Valley, this problem is not severe because of the general homogeneity of the sediments.

If the background-noise method is to be accepted as an exploration tool, the source of the noise must be understood. Later in this paper, we present a simple model based on pressure variations in the reservoir as a possible explanation of the high noise levels found above several known geothermal reservoirs.

Three noise surveys have been conducted in the Imperial Valley. The first one was on the southeastern edge of the Salton Sea (see Figure 1) where a geothermal reservoir is known to exist from wells drilled into it; these wells are not being produced. The results of this survey are being published (Goforth et al, 1972) and the survey will be discussed only briefly. The second was a small survey in the Heber area where a sharp noise high was found; only a few stations were occupied, and the extent of the anomaly is not determined at this time. The third and largest survey was in the Mesa area (see Figure 1) where heat flow and gravity measurements are available for comparison with the ground-noise survey.

The method of computing the spectra of the noise is straightforward. The original analog data are digitized at 40 samples/sec. Power spectra of selected samples of the noise are computed using the method described by Welch (1967). The time series is divided into N segments of M data points. Each segment is transformed into the frequency domain using the fast Fourier transform. The result is multiplied by its complex conjugate, and the average over the number of segments used is taken to obtain the spectrum. Usually, approximately 30 blocks of data, each 512 data-points long, were used in the computation of the spectra. The statistical confidence limits of the spectra presently being computed are ±1.6 db at the 90 percent level. This number assumes time stationarity which is only approximately true. A number of spectra (usually 10) are averaged to reduce nonstationarity effects. At sites close to cultural activity, the recordings used were from nighttime samples when these activities are at a minimum.

The total power in the bandwidth where the largest amplitudes are found is computed and contoured, sometimes on a db scale.

The seismograph system used consisted of a short-period seismometer with its associated electronics and an FM tape recorder. The system has a flat velocity response from 1 to 20 hz. The systems are calibrated in the field, thus absolute values of ground-particle velocity are obtained.

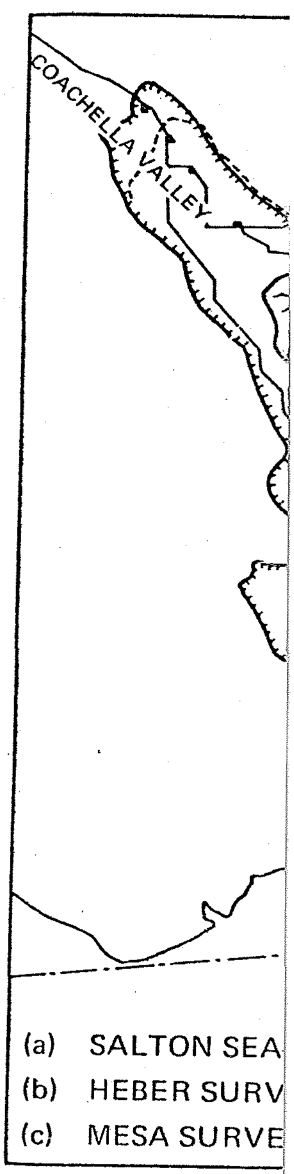
FIELD EXPERIMENTS IN THE IMPERIAL VALLEY

Beginning in the summer of 1970, a limited number of experimental noise surveys were carried out in the Imperial Valley over known geothermal features. Previously it has been thought that the dominant frequency was of diagnostic value (Clacy, 1968). The dominant frequency could not be interpreted in any of these surveys. Therefore, only the average power, in appropriate frequency bands, was used.

The first survey was on the edge of the Salton Sea where a geothermal reservoir is known to exist (see Figure 1 for exact location). The reservoir is a permeable sandstone about 1-km deep and approximately 600-m thick. The reservoir appears to have a cap of altered argillaceous material. The discovery wells are not operational because of the high salinity of the water. Hence, they contribute nothing to the observed noise field.

Figure 2 shows the location of the recording sites used in the noise survey and the wells drilled into the reservoir. Figure 2 also shows the results of the ground-noise survey and the heat-flow measurements obtained from results published by Rex (1970). It should be noted that the heat flow is based on a limited number of observations, and the contouring can be changed appreciably in a number of areas. Power spectra of the noise recorded in the area where the reservoir is present and well outside the limits of the reservoir are shown in Figure 3; there is significantly higher power in the spectra above the anomaly with most of the power concentrated in the band of 1.0 to 3.0 hz. Therefore, the power in this band was computed and plotted in Figure 2.

The zone of anomalously high seismic noise corresponds closely to the outline of the geothermal reservoir as it is known on the east side. Toward the west it was not possible to occupy



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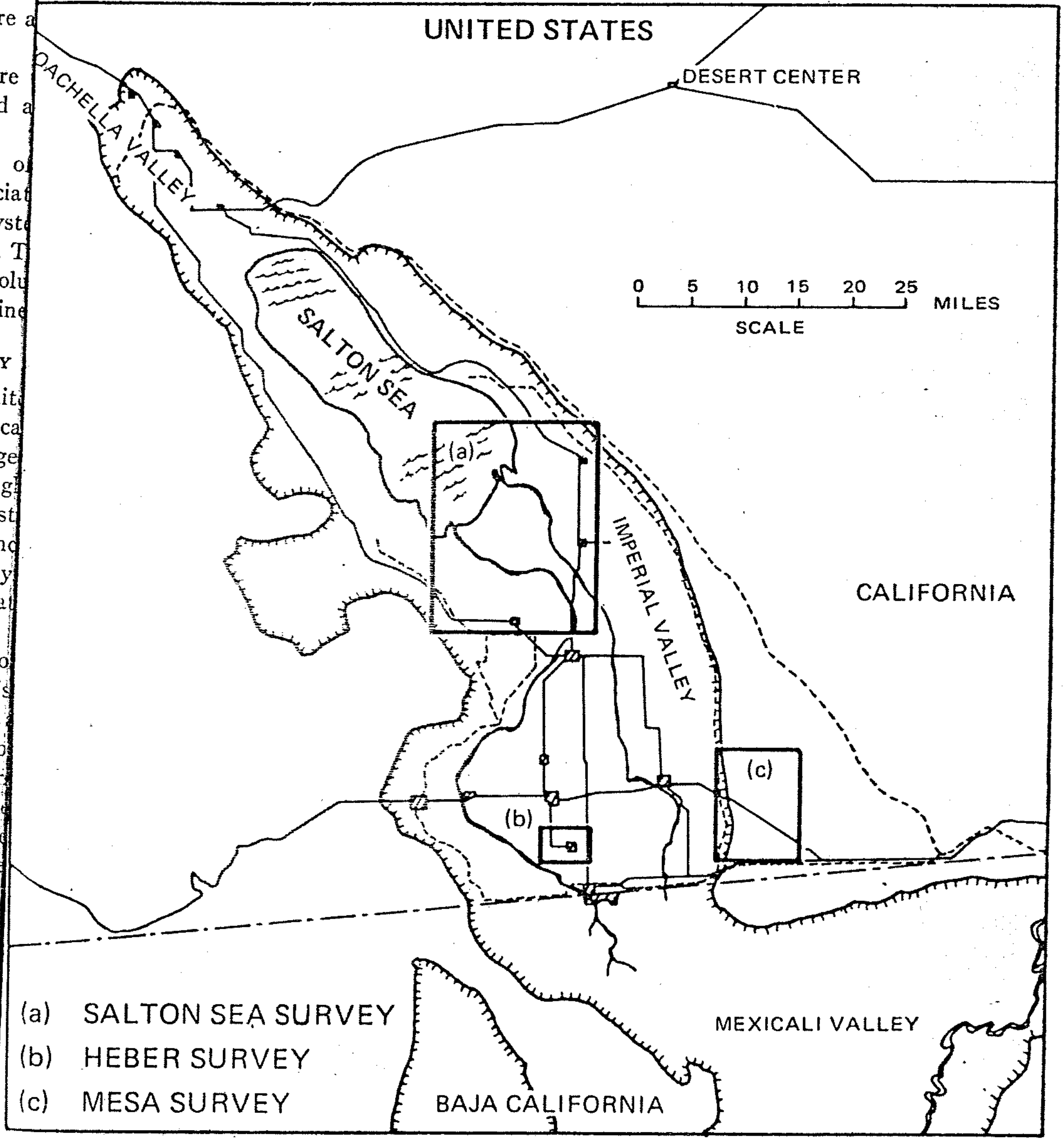


FIG. 1. Map of Imperial Valley, California showing locations of the geothermal ground-noise surveys.

ground-noise stations because of a marsh; hence the extent of the anomaly on the lake side is not known. At first there was some concern that the noise might be caused by wave action in the Salton Sea. A careful study of weather conditions, especially wind velocity, indicates that the power levels observed could not be attributed to lake-generated noise.

At the time of the original survey the heat-flow map was not available. Thus, the high noise level at the southeast corner of the survey area was unexpected. The heat-flow measurements confirmed the presence of an anomaly in this area. For the principal anomaly the ground-noise and heat-flow anomaly agree well. At the secondary anomaly the two are offset from each other; the possible reasons for this behavior are discussed later in the paper.

A small survey was conducted at the Heber anomaly; the results are shown in Figure 4. The

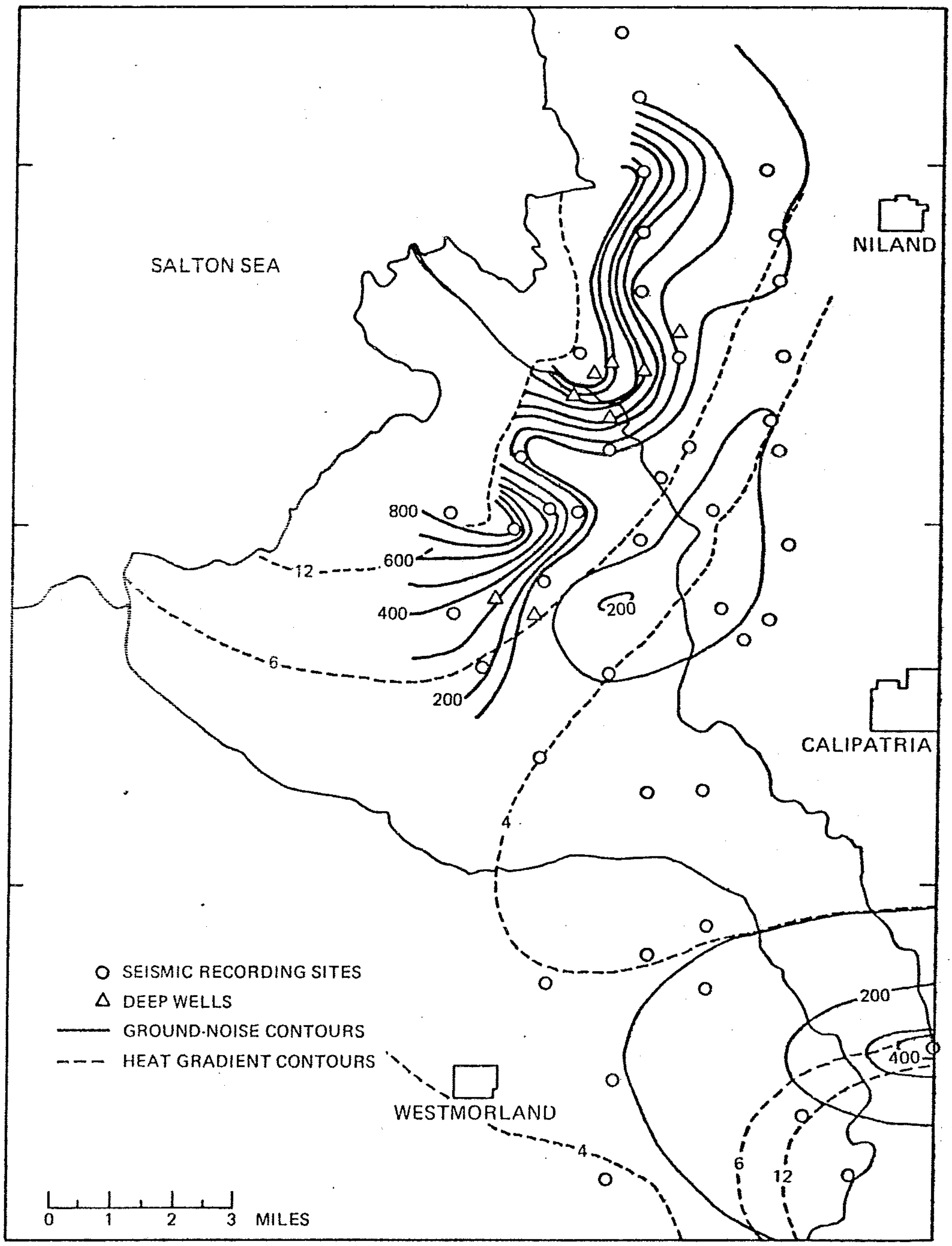
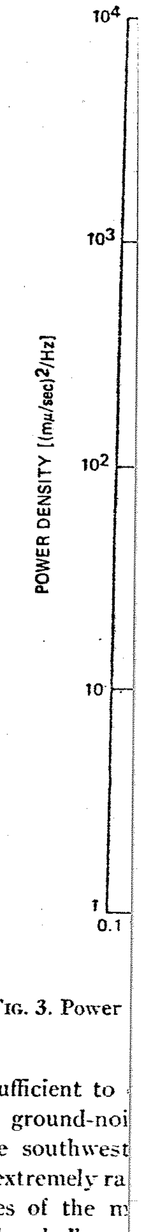


FIG. 2. Salton Sea survey showing the ground-noise and heat-flow anomalies. Heat flow after Rex (1970). Ground-noise contours: power 1.0–3.0 hz band. Heat-gradient contours: °F per 100 ft.



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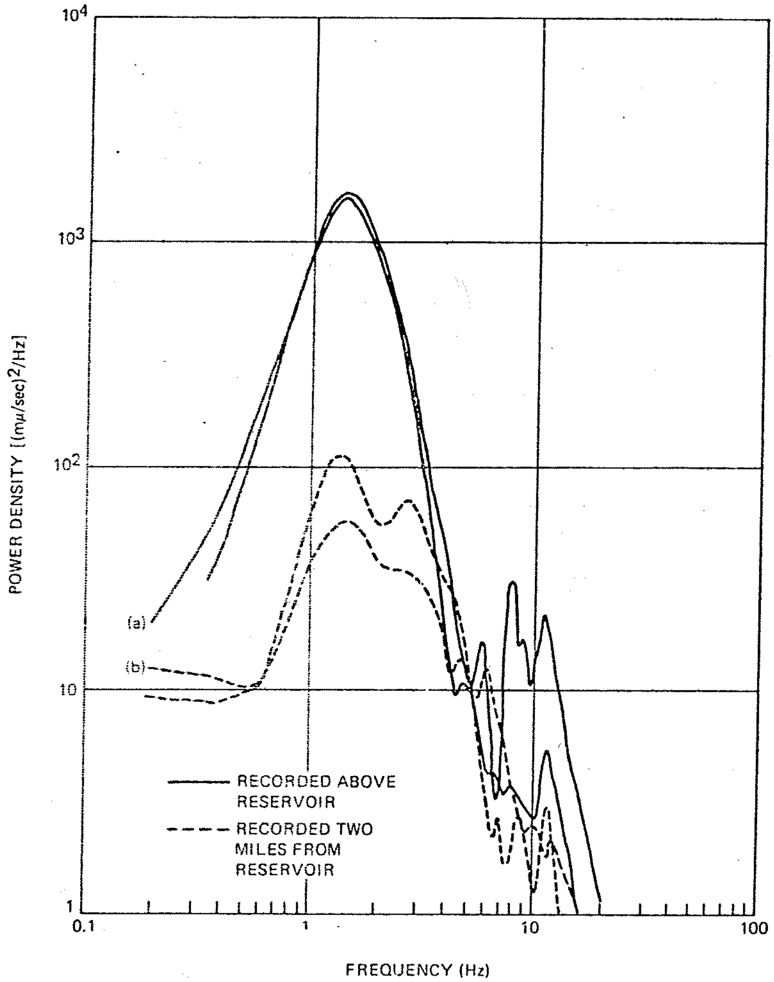

FIG. 3. Power density spectra of the noise inside and outside the ground-noise anomaly.

data are insufficient to outline the entire anomaly, but the ground-noise high appears to continue to the southwest. The most interesting result is the extremely rapid change in power level on both sides of the maximum; this implies a comparatively shallow source, as is discussed later. A heat-flow anomaly in this area has been established (Rex, 1970), however, this anomaly is larger and approximately circular. More recent unpublished results (personal communication, Dr. J. Combs of the University of California at Riverside) indicate that measurements made at greater depths show a more linear feature than the original data. At this time we cannot make detailed comparisons between the different methods.

Most of the later field experiments were conducted at the Mesa geothermal anomaly (see Figure 1 for location). At this site both heat-flow and gravity data were made available to us for comparison with the ground-noise surveys. The heat-flow survey was conducted by Dr. J. Combs and the gravity survey by Dr. S. Biehler, both from the University of California at Riverside.

Figure 5 shows the Bouguer gravity anomaly found at the Mesa geothermal anomaly, together with the results from the ground-noise survey. The regional effects have been removed. The gravity high of 5 mgal is almost certainly caused by the hydrothermal alteration of reservoir rocks and possibly the formation of a hydrothermally altered caprock. Hochstein (personal communica-

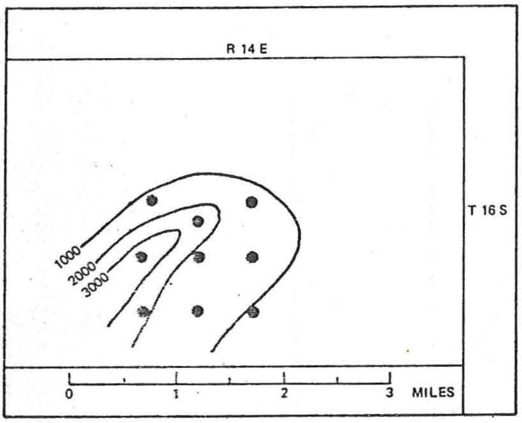

FIG. 4. Contour map of the Heber anomaly, total power in the 1.0–3.0 hz band.

tion) has shown that there is a density contrast of .3 to .4 gm/cm^3 between hydrothermally altered and unaltered rock in the same geologic unit.

The gravity high is a simple, almost circular, anomaly while the ground-noise survey results are considerably more complex. The highest gravity value falls on the edge of the northern part of the main ground-noise anomaly.

Figure 6 shows the results of heat-flow measurements and the ground-noise survey. The contours are lines of equal gradient in degrees Fahrenheit per 100 ft (30.5 m). Geothermal temperature measurements made at depths of 61, 122, and 183 m indicate that the patterns change with depth, suggesting that groundwater flow is affecting the results at shallow depth (Bureau of Reclamation, 1971).

In the western half of the survey area, the agreement between the two methods is very good except that the ground-noise high continues to the south. However, it should be noted that there are no drill holes in this region, and the closure of the heat-flow contour cannot be verified. In the eastern half of the survey area both surveys indicate the lack of high heat flow or high noise in the northeastern corner. The ground-noise method detected a region of high noise in the southeastern corner that appears to continue outside the explored area. While the heat-flow values are not as high as in the center, the heat-flow pattern shows a distinct extension in this direction, suggesting there may be another geothermal reservoir to the southeast. In conclusion, considering the completely different method of exploration, the agreement is as good as can be expected.

Examination of the recordings made at the center of the Mesa anomaly reveals clearly that the noise does not have the same characteristics as background noise at sites, even noisy sites, outside of geothermal areas. The noise is characterized by frequent bursts and in sufficient number such that, for the time average used in spectral computations, the noise is approximately time stationary. These noise bursts do not resemble microearthquakes. At no time do they exhibit impulsive starts. They increase and decrease gradually. The noise level changes very rapidly from normal background levels outside of the anomaly to extremely large values on the anomaly. A few very preliminary measurements made with seismographs only a few hundred meters apart show that the visual coherence decreases rapidly with distance, much more rapidly than cultural noise which often has been examined in recordings from seismological observatories.

In general, the agreement between the different methods is good; however, appreciable differences occur in the detail of the structure of the contours. The ground-noise method indicates a considerably more complex situation with the reservoir continuing toward the southwest and another area of high noise level in the southeast corner of the survey.

These differences could be caused by the fact that the three techniques measure different parameters. For example, geothermal reservoirs are usually considered to be transient phenomena when measured on a geologic time scale. Hydrothermal alteration and the formation of a caprock must take some time to develop; thus, the center of the gravity anomaly could be associated with the older part of a reservoir that is changing its location in space. On the other hand, to generate the noise recorded at the surface, short-time variations of some parameter, such as pressure or temperature, must be taking place. Thus one might speculate that the ground-noise method is detecting present activity. The differences between the ground-noise and heat-flow methods could be caused by the well-known fact that the size and shape of heat-flow anomalies can be distorted by ground-water flow, and it is known that this phenomenon is taking place in the Imperial Valley. These ideas cannot be verified at this time, and a

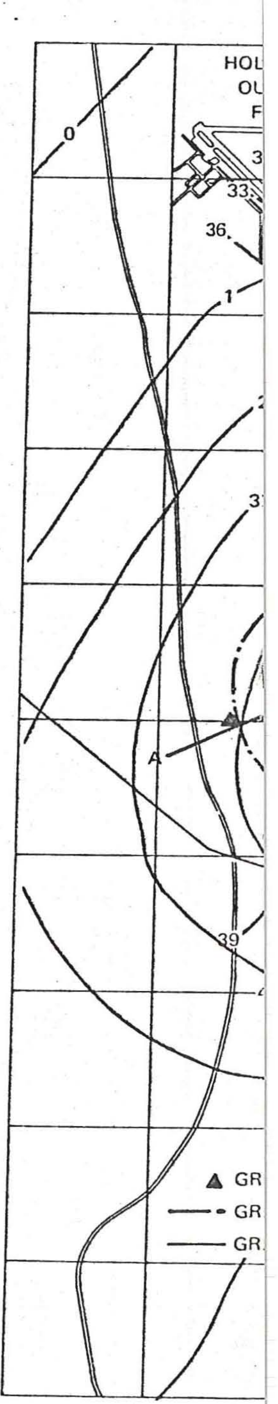

FIG. 5. Mesa area showing the
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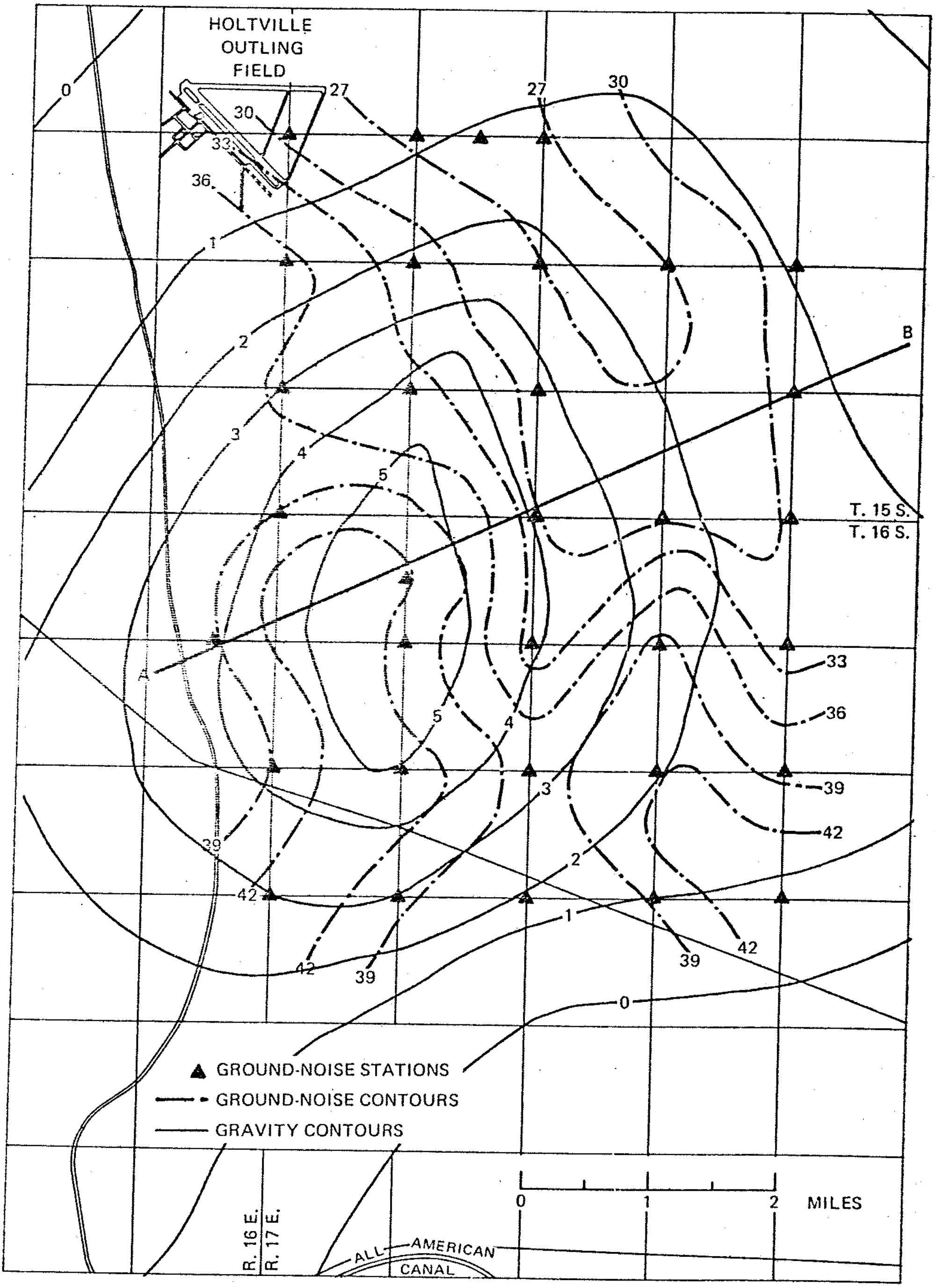

FIG. 5. Mesa area showing the results of the ground-noise survey (power in the 3.0 to 5.0 hz band in db) and the Bouguer gravity after the regional has been subtracted. Gravity from Bureau of Reclamation, 1971. Contour interval: 1 mgal.

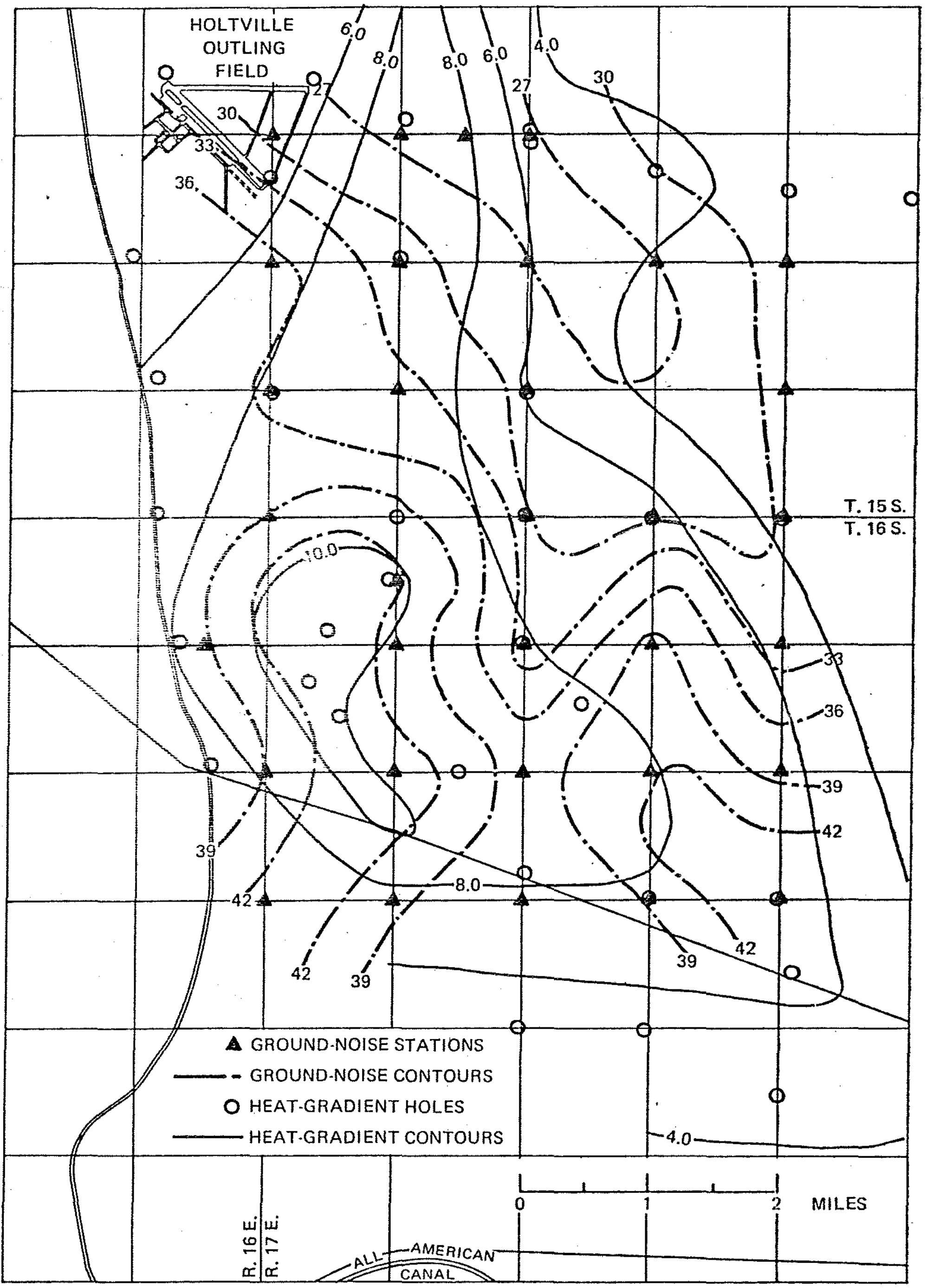

FIG. 6. Mesa area showing the results of the ground-noise and heat-flow surveys (°F per 100 ft). Heat gradient from Bureau of Reclamation, 1971.

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where

α = compressional-wave
$\tau = t-(R-a)/\alpha$,
θ = phase angle, and
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observation.

considerably larger amount of information on geothermal reservoirs will be needed to evaluate them.

A PROPOSED THEORETICAL MODEL

In the previous section, the experimental results of three geothermal surveys conducted in the Imperial Valley were discussed. The correspondence between the heat-flow anomalies of geothermal reservoirs and the high noise levels found during the ground-noise surveys indicates that the method is capable of locating geothermal resources, at least under favorable conditions.

At this point it is necessary to attempt to explain the high noise levels with some reasonable physical model. There appears to be general agreement that the high temperatures in a geothermal reservoir cannot be explained solely on the basis of heat flow, but that heat transport by circulating water must be involved. It also has been suggested that the water as it cools will deposit some of the minerals in solution, thus decreasing the permeability. Based on these assumptions we suggest the following model: zones of time-varying pressure will exist from place to place in the pressure field that forces the hot water through the rocks. A simple mathematical model has been constructed to determine if small pressure variations acting throughout a reservoir of reasonable size can account for the high noise levels recorded at the surface.

We start with the displacements that are obtained from sinusoidal pressure variations in one cavity and then generalize the results for a large number of small cavities representing the reservoir.

The radial particle velocity at distance R obtained from a sinusoidal pressure variation

$$P(t) = P_0 e^{-i\omega t}$$

in a cavity of radius a in the infinite medium of rigidity μ, has been derived by Blake, 1952.

$$U = \frac{Pa^3}{4\mu}\left[\frac{\omega}{R^2} + i\frac{\omega^2}{R\alpha}\right] e^{-i(\omega\tau-\theta)}, \qquad (1)$$

where

α = compressional-wave velocity,
$\tau = t-(R-a)/\alpha$,
θ = phase angle, and
R = distance from center of cavity to point of observation.

Because of the nature of the source, no shear waves are generated; λ and μ (Lame's constants) are assumed to be equal, and higher powers in wavenumber of the solution given by Blake (1952) are neglected. The cavity is assumed to be small compared to the depth of burial, thus the formula is assumed to be valid for a halfspace. At the free surface, conversion of P to S waves will take place: if this conversion is neglected, the vertical component of motion at the free surface becomes

$$U_z = \frac{Pa^3C}{2\mu}\left[\frac{\omega}{R^3} + i\frac{\omega^2}{R^2\alpha}\right] e^{-i(\omega\tau-\theta)}, \qquad (2)$$

where C = depth to center of cavity.

The first term predominates at close distances and is similar to the deformation computed from static theory of elasticity (Mindlin and Cheng, 1950). At large distances the second term predominates. Some preliminary computations indicate that, for the depths under consideration in geothermal prospecting, the first term is two orders of magnitude less than the second, and can, therefore, be omitted from the analysis.

The conversion of P- to S-wave energy can be taken into account if it is assumed that the source is sufficiently deep so that plane-wave theory is applicable. The vertical amplitude at the free surface from an incident P wave can be obtained from the reflection coefficients. Using the formulation given by Bullen (1963) the vertical particle velocity is

$$\frac{U_z}{U} = \frac{3}{2}\,\frac{\sin e \sec^2 e\,(1 + 3\tan^2 e)}{\tan e \tan f + (1 + 3\tan^2 e)^2}\cdot \qquad (3)$$

where e is the angle of incidence of the P wave and f is the angle of reflection of the S wave as measured from the horizontal.

Equation (3) can be rewritten as

$$U_z = \left[\frac{i3Pa^3\omega^2}{8\mu R\alpha}\cdot\frac{\sin e \sec^2 e(1 + 3\tan^2 e)}{\tan e \tan f + (1 + 3\tan^2 e)^2}\right] e^{-i(\omega\tau-\theta)}.$$

The vertical displacement at the free surface depends on the cavity radius to the third power; furthermore it is apparent that the same results will be obtained for a number of small cavities as for one large cavity, as long as the dimensions are kept very small compared to the wavelength.

Then the formula can be rewritten as

$$U_z = \frac{i9P\omega^2 V}{32\pi\mu R} \cdot \left\{ \frac{\sin e \sec^2 e(1 + 3\tan^2 e)}{\tan e \tan f + (1 + 3\tan^2 e)^2} \right\} \cdot e^{-i(\omega\tau - \theta)}, \tag{4}$$

where V is the volume of space filled with hot water (analogous to porosity).

Equation (4) can be considered as the transfer function between the pressure variations at depth and the particle velocities measured at the surface. The experimental measurements are in terms of power spectra. The transfer function $H(\omega)$ between the spectrum of the pressure variation (ϕ_u) and the spectrum of the velocities at the surface (ϕ_p) is

$$\phi_u = \phi_p \cdot \mid H(\omega) \mid^2$$

and

$$\mid H(\omega) \mid^2 = \left\{ \frac{9P\omega^2 V}{32\pi\mu R\alpha} \cdot \left[\frac{\sin e \sec e\,(1 + 3\tan^2 e)}{\tan e \tan f + (1 + 3\tan^2 e)^2} \right] \right\}^2. \tag{5}$$

If the pressure variations in one element of volume are independent from that in adjacent elements of volume, and assuming equal pressure variations, the power spectra at a point x_0, y_0 at the surface from an arbitrary geothermal reservoir can be expressed as (noting that the power from independent sources is additive):

$$\phi(x_0, y_0, \omega_0) = \int_x \int_y \int_c \phi_u(x, y, c, \omega_0)\,dxdydc. \tag{6}$$

Numerical integration of formula (6) was used to obtain estimates of the pressure variations that would be required to exist in a geothermal reservoir to explain the noise being recorded at the surface. We have assumed that pressure variations exist because of circulating hot waters, but it is possible to construct a similar model assuming random temperature variations caused by the circulating water. Goodier (1937) has shown that the elastic effect of a nonuniform temperature (T) distribution is the same as that of a distribution of centers of dilatation of strength $-\beta/4\pi$, where

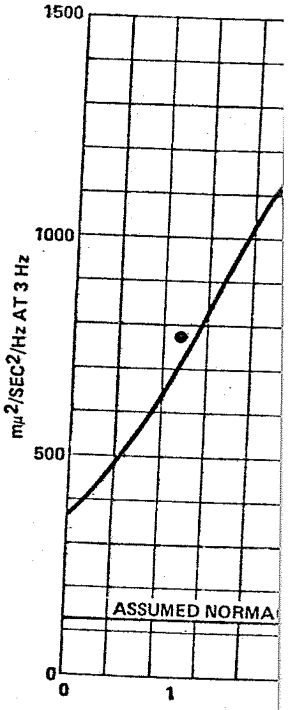
$$\beta = \alpha T(1 + \nu)/(1 - \nu), \quad \text{and}$$

α and ν are the coefficients of linear thermal expansion and Poisson's ratio. Although the authors are inclined to believe that pressure variations are a more likely explanation for the recorded noise, the possibility of random temperature variations cannot be ruled out at this time.

As an example of the results that are obtained with a model using pressure variation, an attempt was made to duplicate the main anomaly at Mesa. The results are shown in Figure 7 in terms of a cross-section along line A-B (see Figure 5). The line was chosen to avoid interference with the high in the southeast corner of the map. The model has the following parameters: It is 300-m thick, 500-m wide, 3000-m long, and the top is at 1500-m depth. Its porosity is 20 percent, the rigidity is 5×10^{10} dynes/cm^2, and the P-wave velocity is 2700 m/sec. The theoretical and experimental values are measured at 3.0 hz. The cross-section is assumed to be at the north edge of a slab which extends in a southerly direction. One of the more significant assumptions that must be made is the volume over which the pressure variations are coherent. The model used here assumes that the pressure variations in each cube of 10m×10m ×10m act as a unit and are totally unrelated to those in adjacent volumes. Because there is no data point in the middle of the anomaly at the line A-B, the data point from the site below it was taken and may be somewhat too high.

To obtain the particle velocities recorded at the surface, root-mean-square pressure variations of 0.65 millibar at 3.0 hz would have to take place in the model. As shown in Figure 7 the agreement between experiment and theory is excellent.

The pressure variations in the reservoir necessary to produce the noise recorded at the surface do not appear to be unreasonably large. Water at 250°C has a vapor pressure of 40 bars. The variations required are less than one-tenth of one percent of this pressure. One interesting aspect of the model is the relatively narrow width necessary to duplicate the experimental results. The authors are aware that the model is not unique; other models with different parameters could be used to fit the data in an acceptable manner. For example, the theoretical anomaly could be made sharper by adding a realistic attenuation factor. At this point of our general knowledge of the



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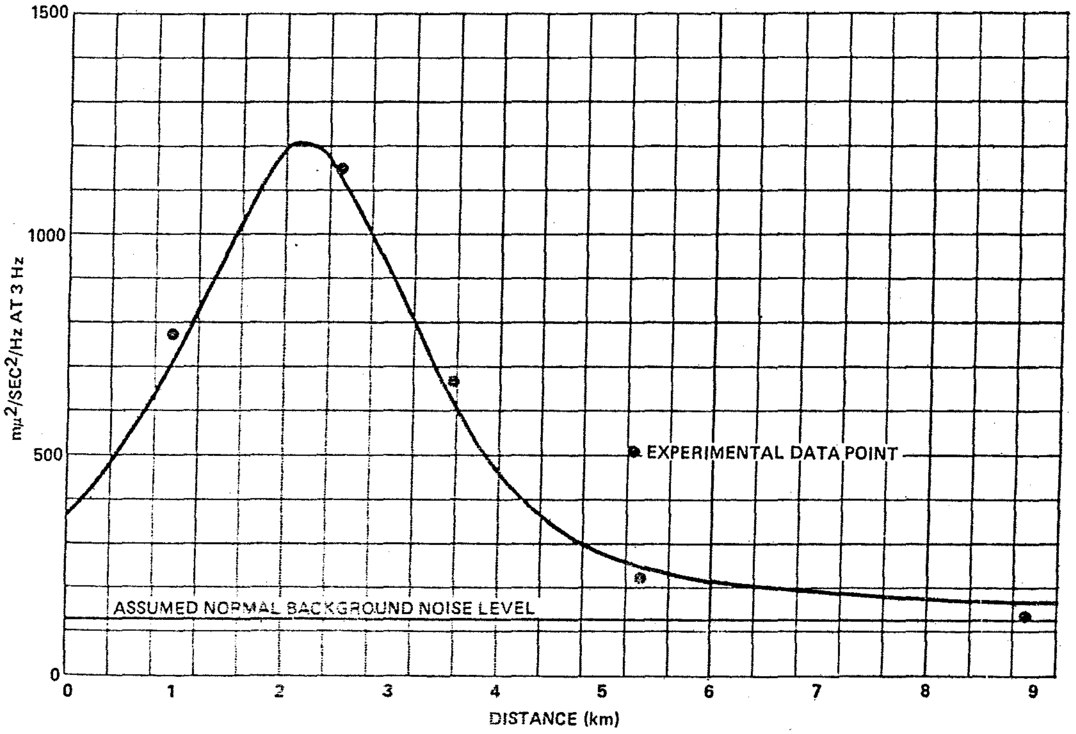

FIG. 7. Experimental and theoretical results for the Mesa anomaly along line A-B on Figure 5. Rms pressure variations of .65 millibars at 3.0 hz.

activity inside geothermal reservoirs, we only wish to show that reasonable pressure variations can account for the noise levels that are being recorded.

CONCLUSIONS

Three experimental ground-noise surveys conducted in the Imperial Valley of California have shown anomalously high background-noise levels over known heat-flow anomalies. In one case, the Salton Sea anomaly, the survey was conducted over a known geothermal reservoir. In the other two cases, heat-flow anomalies of sufficient magnitude to indicate the presence of a reservoir are present, but the results have not been tested by drilling. In general, the high noise levels appear to be concentrated in the frequency band of 0.5 to 5.0 hz. Lower frequencies were not analyzed in detail because of the well-known large amplitudes of the 6-sec microseisms. Variations in the frequency at which the maximum power was found varied from survey to survey and, in a lesser degree, from site to site; no pattern was found that could be correlated in a convincing manner with the reservoir or the heat-flow anomalies.

The empirical evidence presented in this paper strongly indicates that geothermal resources can be found with the ground-noise surveying method. The Imperial Valley, in one way, is an ideal test area because of the simple geologic structure and lack of lateral velocity variations. On the other hand, because of the presence of cultural activity, it is an area where differentiating between different noise sources presents some problems.

A theoretical model has been developed that appears to explain the anomalously high noise levels that are recorded at the surface. Small rapid pressure variations on the order of a millibar in a reservoir with an areal extent of a few square kilometers can explain the noise levels. The model is very simple, and numerous simplifications are used, such as no wave attenuation and no variations in velocities. However, it is clear that the use of more sophisticated models will only change the shape and level of the theoretical results in a relatively minor fashion. Until better information on the physical processes inside a geothermal reservoir is available, the theoretical model cannot be proven to be correct and must be considered as a first attempt to explain the experimental results.

ACKNOWLEDGMENTS

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