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SEISMICITY OF GEOTHERMAL AREAS

A Paper

Presented to the Graduate Faculty of the

New Mexico Institute of Mining and Technology

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science

in Geology

by

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December, 1971

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Two types of seismicity are observed in geothermal areas, (1) discrete microearthquakes, and (2) continuous noise. From less than one to 75 events per day have been recorded in thermal areas, with magnitudes as low as -0.7, and focal depths generally less than 8 km. Heat flow has been found to be from 4.5 to 100 x 10^{-6} cal/cm^2/sec. Steam is produced from faults in volcanic and sedimentary rocks and from contacts between units. Passive seismic surveys may be useful when employed in conjunction with other methods of prospecting for geothermal energy.

INTRODUCTION

The purpose of this paper is to review the published evidence relating seismic activity to geothermal areas and to investigate the possibility of using passive seismic exploration as a tool in the search for geothermal energy.

Two types of seismic activity are observed: (1) discrete microearthquakes produced by movement along faults, and (2) continuous seismic noise. The majority of published data concerns the former phenomenon.

The study consisted of a search of the literature for articles relating seismic activity to geothermal areas. Two volcanic areas, Alaska and Hawaii, were included in the study for comparison as they display seismic, but not geothermal, activity. These references exhibit considerable variations in the amount of detail given about the method in which the work was conducted. Descriptions of instrumentation, reduction of data, geologic conditions, heat flow, and conclusions varied so widely it was necessary in some cases to consult other references and to reduce the data to a standard form. The results are given in Tables 3 through 11. Values in brackets are calculated by myself from information given; all other values are cited as given by the original author. Minimum magnitudes for the Geysers in Sonoma County, California, and for Mt. Katmai, Alaska, were calculated using the formula from Brune and Allen (1967), p. 284:

Correction for attenuation:

$$M = \text{Log } A + \text{Log } (G_{wa}/G_{20}) - \text{Log } A_0 + \text{Log } A_{20},$$

where

A = Amplitude measured on record in millimeters.

G_{wa} = 2800 = Gain of Wood-Anderson torsion seismometer.

G_{20} = Gain of instrument with response peaked near 20 cps.

A_0 = Amplitude of magnitude zero event, in millimeters, recorded on Wood-Anderson torsion seismometer, as given by Richter (1958).

A_{20} = Amplitude-versus-distance correction for 20 cps seismic waves, determined empirically as follows: Log A_{20} = 0.55 at 5 km, 1.00 at 8 km, 1.50 at 15 km, 1.70 at 20 km, and and 1.80 at 24 km.

Where the minimum magnitudes considered did not equal zero, the number of observed events per day were normalized to M = 0 using the formula

$$\log N = A - bM$$

using values of 1.0 and 2.0 for b.

MICROEARTHQUAKES ASSOCIATED WITH THERMAL AREAS

Iceland

Ward and Bjornsson (1971) have studied the microearthquakes in Iceland. During the summers of 1967 and 1968 reconnaissance surveys were conducted using portable seismographs and some 2700 events were recorded. The activity was largely confined to 13 zones, with the areas generally having radii less than 5 km (Figure 1). Between 0.9 and 23 events per day were recorded in 9 of the 17 geothermal areas. The other 8 geothermal areas exhibited no seismic activity. The 600 microearthquakes that were reliably located were found to have occurred primarily at depths of 2 to 6 km, with a few being as deep as 13 km. The authors found that 9 of the 13 microearthquake areas were associated with geothermal activity, and a detailed study of two areas revealed that the epicenters were nearly confined to the zone of thermal alteration at the surface.

A total of 87 sites were occupied for periods of 8 to 25 hours of recording. The information on the major geothermal areas in Iceland is summarized in Table 1, while Table 2 shows the data on the areas with seismic activity. The locations of these areas is given in Figure 2. Further information is given in Table 3.

Although the authors admit that the number of events per day may vary by a factor of 3, and in one case, near the Krafla volcano, by a factor of 150, they believe the

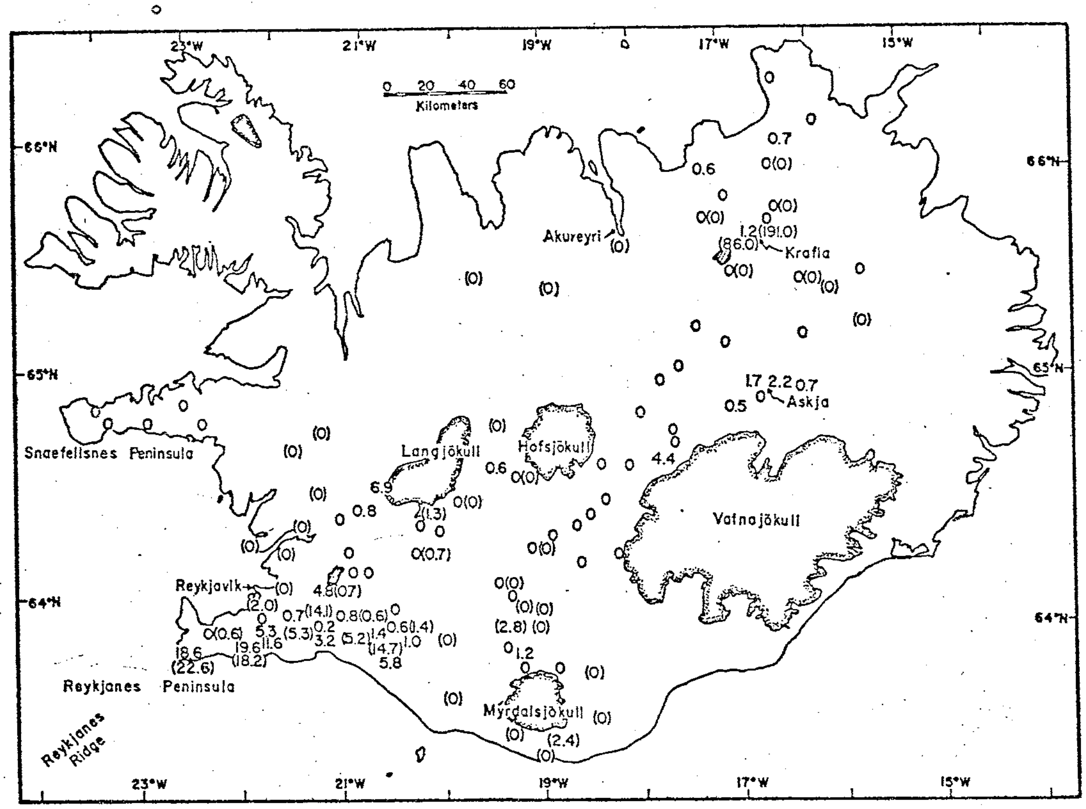

Figure 1. Average numbers of earthquakes per day in Iceland. From Ward and Bjornsson, 1971.

Table 1. Major Geothermal Areas in Iceland.

(From Ward and Bjornsson, 1971).

Area	Approx. Area, km²	Approx. Natural Heat Output, × 10^6 cal/sec	Elevation, meters	Dominating Structural Features			Explosion Craters	Acid Rocks at Surface	Approx. Fluorine Content of Water, ppm	Normalized No./Day	Quality of Observation	Distance, nearest km
				Fissures	Calderas	Shield Volcanoes						
1. Reykjanes	2	5–25	20	×				None	0.2–0.3	48	Good	1
2. Svartsengi	1	5–25	30	×				None	?	?	Poor	8
3. Krísuvík	50	25–125	160	×			×	None	0.3–0.4	60	Good	1
4. Brennisteinsfjöll	1	5–25	600	×				None	?	?	Poor	7
5. Hengill-Hveragerdi	90	25–125	30–400	×			×	Some	0.2–2.6	36	Good	1
6. Geysir	1	5–25	120					Some	9.5–12	0	Good	1
7. Hveravellir	1	5–25	600			×		Some	2–4	0	Good	1
8. Kerlingarfjöll	10	25–125	950					Major	1.5?	0	Fair	4
9. Katla	?	?	1100	?	?			Some	?	(30)	Poor	18
10. Torfajökull	150	125–750	600–1000	×	?		×	Major	?	3	Fair	7
11. Vonkarskard	10	5–25	1000	?				Some	0.3–27	4?	Poor	9
12. Grímsvötn	20?	125–750?	1340	?	×			?	?	?	Poor	45
13. Kverkfjöll	5	5–25	1700	×				?	?	40	Good	30
14. Askja	5?	5–25	1050	×	×		×	Some	?	8	Good	3
15. Fremrinámur	2	5–25	800	×		×		Some	?	?	Poor	24
16. Námafjall-Krafla	60	25–125	350–560	×		×	×	Some	0.5–1.5	1(191)	Good	1
17. Theistareykir	20	25–125	340	×		×		Some	?	0	Fair	1

* Locations are shown in Figure 1. Earthquake data in parantheses were collected in 1967; other data were collected in 1968.

Table 2. Seismic Areas in Iceland.

(From Ward and Bjornsson, 1971).

Earthquake Zone	Instrument Site	Daily Count	Average $S - P$ Time	Normalization Factor	Normalized Daily Count	Quality of Observation
Reykjanes	101	18.6	0.8	2.6	48	Good
Krísuvík	12	22.9	0.8	2.6	60	Good
Hengill-Hveragerdi	9	4.8	1.7	7.6	36	Good
Langjökull	110	6.9	0.7	2.2	15	Fair
SE of Hengill	125	1.4	0.6	1.1	2	Good
Surtsey	126	1.5	8.5	(172)	(258)	Fair
Katla	4†	2.4	2.0	12.6	30	Poor
N of Mýrdalsjökull	200	1.2	0.7	2.2	3	Fair
Vonarskard	143	4.4	0.4	0.8	4	Poor
Askja	158	2.2	1.0	3.8	8	Good
Kverkfjöll	165	0.9	4.0	(45)	(40)	Poor
In the ocean N of Mývatn	153	1.5	2.0	12.5	19	Fair
Krafla	54	1.2	0.4	1.0	1	Good

* Numbers in parentheses are less reliable because the daily counts are small and the distances are large.

† 1967.

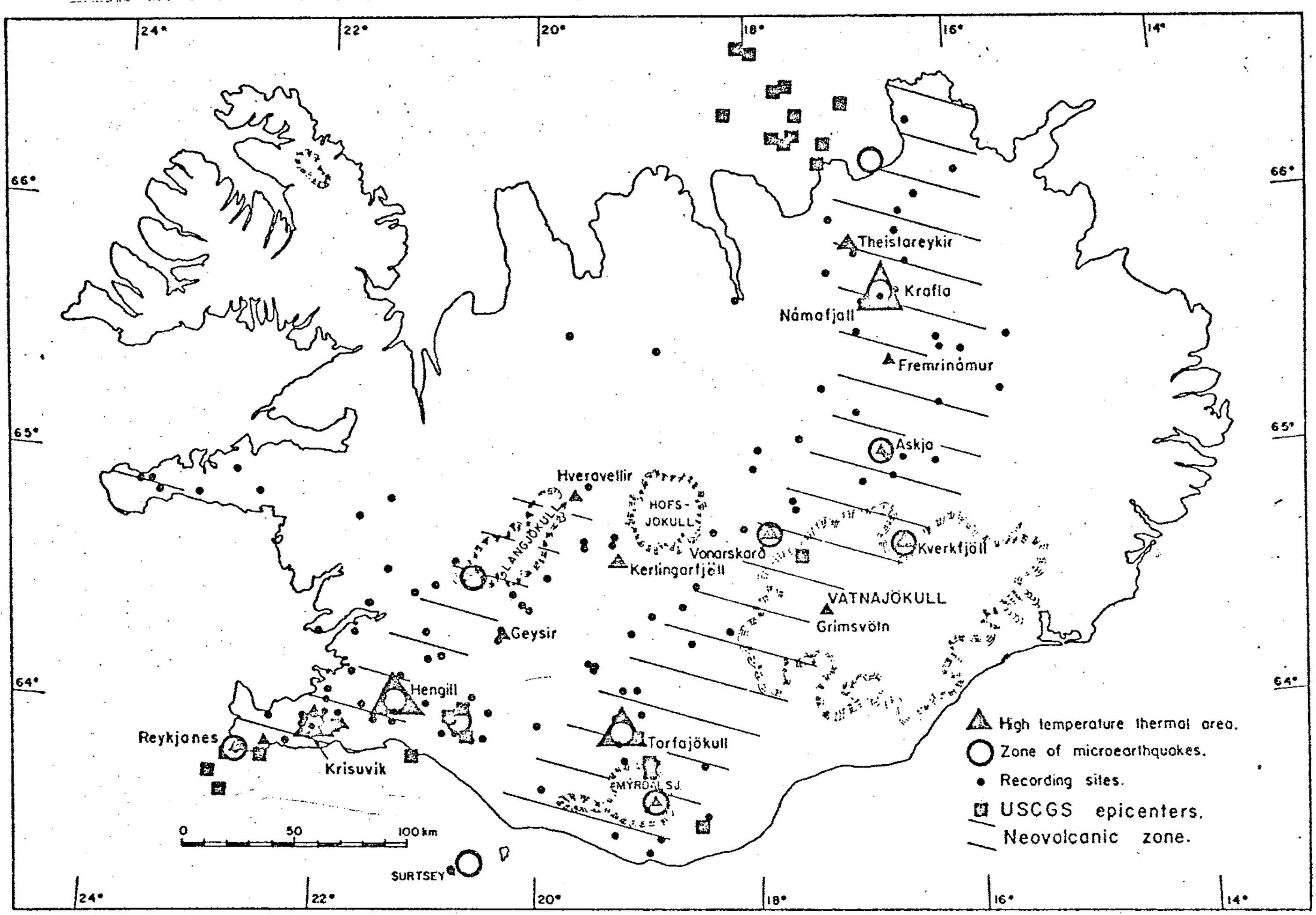

Figure 2. Microearthquake zones and thermal areas in Iceland. From Ward and Bjornsson, 1971.

Table 3. Summary of Data from Iceland

Microearthquakes per Day: 0.9 to 23 [1]

S-P Interval: ≤ 2.5 sec [1]

Minimum Magnitude: -0.7 [1]

Normalized Events per Day: 0.18 to 4.60 for b=1

0.03 to 0.92 for b=2

Heat Flow: 4.5×10^{-6} cal/cm^2/sec [2]

Temperature: 230°C at unspecified depth [3]

Geologic Conditions: The rocks consist of several kilometers in thickness of flood basalts. Steam is produced from contacts between lava flows as well as dikes and sills. The permeability of the basalt is due to (1) tubes and openings at the contact of lava beds, (2) columnar structure in and fissures along the walls of intrusive bodies, and (3) recent faults. This is an area of historic volcanism. A transform fault in southern Iceland is hypothesized. [4]

References: [1] Ward and Bjornsson, 1971.
[2] Lee and Clark, 1966.
[3] White, 1965.
[4] Bodvarsson, 1964.

fluctuations to be generally much less. On the basis of tripartite arrays operated continuously for 53 days, they obtained a frequency distribution of daily counts which they claim revealed that there is a 60% chance after one day of recording, a 65% chance after two days, and a 70% chance after three days, of their daily average being within 45% of the average based on two months of recording (Figure 3). The location of the arrays is given in Figure 4.

A possible explanation of why only nine of the thirteen major geothermal areas had significant microearthquake activity is that the geothermal areas that have no observed microearthquake activity might be dominated by acidic intrusions, whereas those areas with microearthquake activity are related to fissure systems trending parallel to the strike of the neovolcanic zone, according to the authors. Conversely, two seismic areas without geothermal activity were found to be in areas of submarine volcanism, while another was an aftershock zone.

The authors feel few data would have been recorded in the study if portable instruments had not been within 30 km of the active zone. They emphasize the need for placing high-gain, portable seismometers at many sites throughout the region to be studied. Airborne infrared surveys were found useful in identifying sources of heat at the surface on Iceland, and similar surveys in other areas are proposed as an adjunct to seismic surveys in prospecting for geothermal energy.

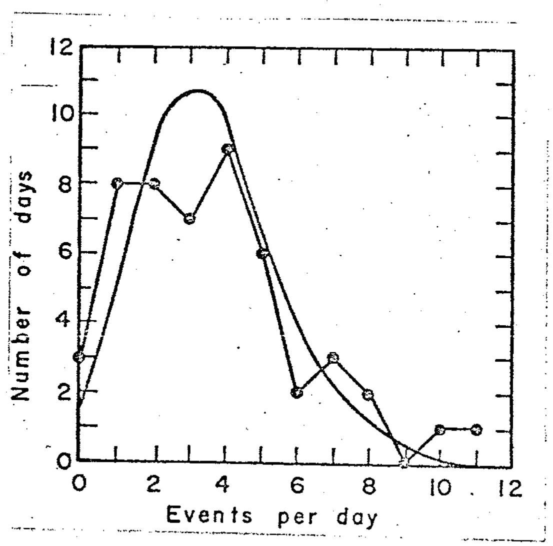

Figure 3. Events per day versus days observed in Iceland. From Ward and Bjornsson, 1971.

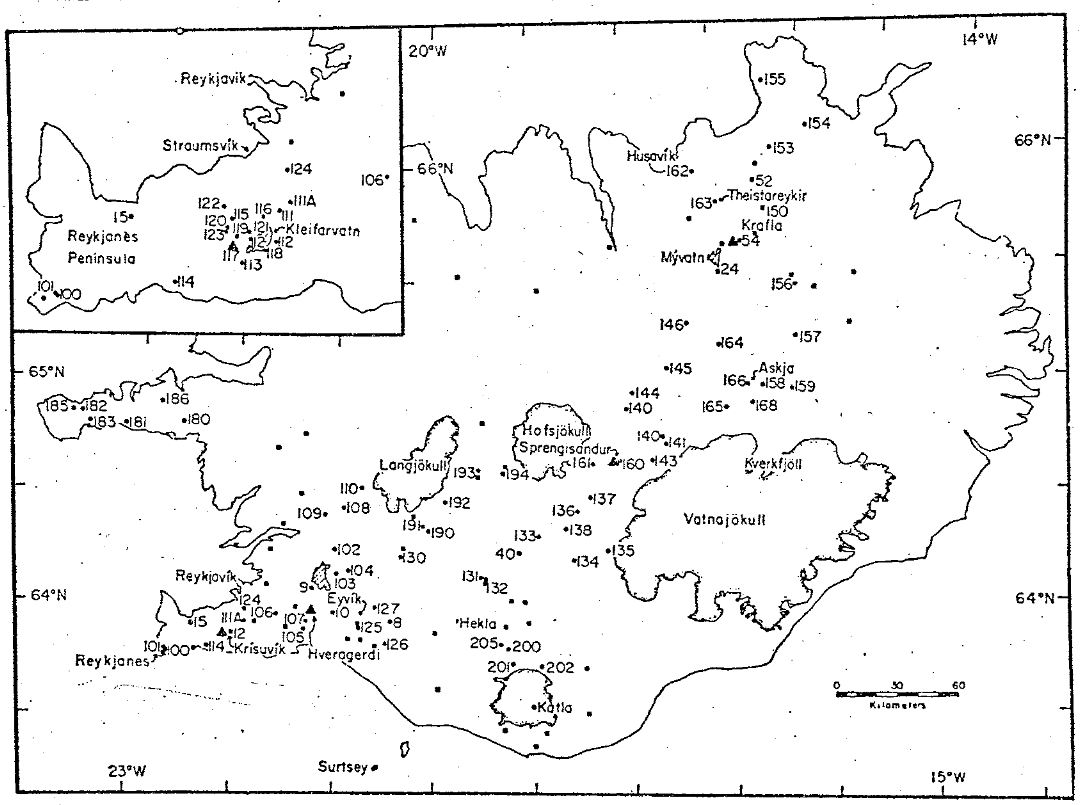

Figure 4. Location of tripartite arrays in Iceland (indicated by triangles). From Ward and Bjornsson, 1971.

El Salvador

Ward and Jacob (1971) have studied the microearthquakes in the Ahuachapon geothermal field in El Salvador, Central America, using three vertical-component seismometers operated 2 to 3 km apart and two horizontal-component seismometers at site A (Figure 5). About 500 earthquakes were recorded and analyzed during a 6 month period (Table 4). The authors report the events tended to occur in swarms of 10 to 20 events spaced days and weeks apart. Only 17 earthquakes could be accurately located. The epicenters lie on a vertical plate striking N 80°W through the geothermal region. Depths to epicenters are 2 to 6 km.

Concluding that the data from the study strongly suggests the existence of a seismically active fault directly beneath the best producing wells in the area, Ward and Jacob recommend that future production wells be drilled to intercept the fault. Furthermore, they feel that "simple microearthquake studies provide a powerful method of mapping active faults and can, therefore, be of considerable practical and economic importance in the location and utilization of geothermal heat sources."

The Geysers

Microearthquakes near The Geysers, Sonoma County, California, have been investigated by Lange and Westphal (1969). An array of six seismometers was operated for 120

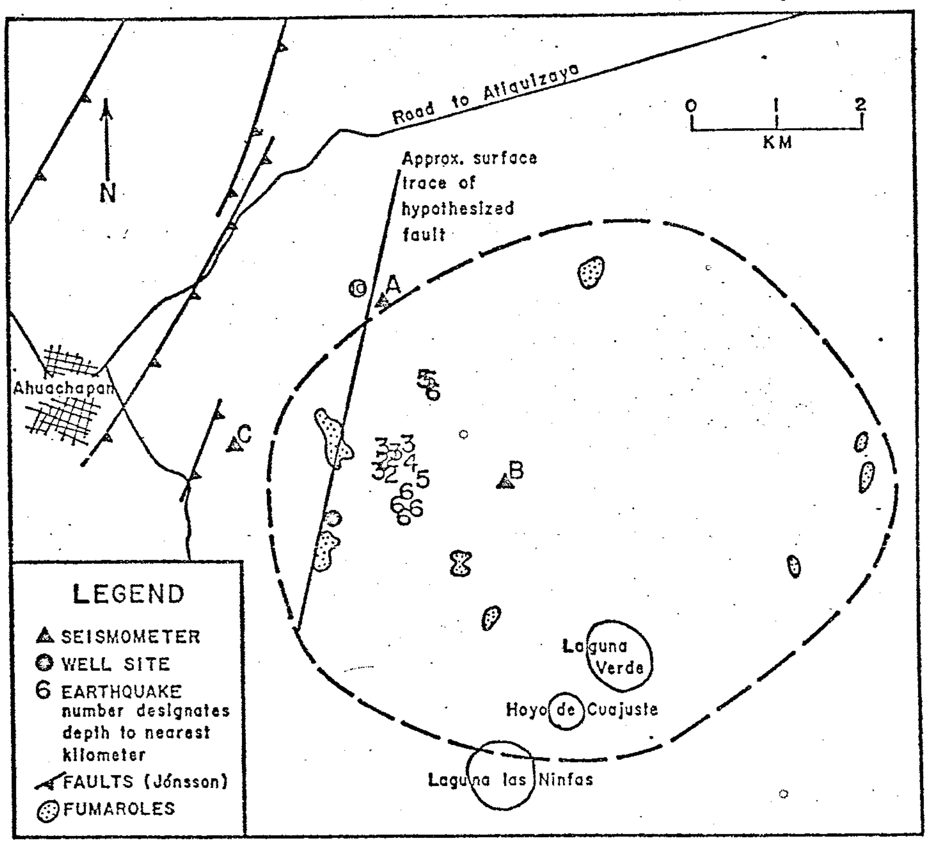

Figure 5. Map of the Ahuachapan geothermal area. From Ward and Jacob, 1971.

Table 4. Summary of Data from El Salvador

Microearthquakes per Day: 1.0 [5]

S-P Interval: < 8 sec [5]

Minimum Magnitude: 0 [5]

Normalized Events per Day: 1.0 for b=1, b=2

Heat Flow: 100×10^{-6} cal/cm^2/sec [6]

Temperature: 174°C at unspecified depth [7]

Geologic Conditions: Seismic epicenters lie on a fault zone within an eroded caldera. Steam emanates from fissure zones in two belts of Quaternary volcanic rocks covering a basement of Tertiary volcanic rocks. [7]

References: [5] Ward and Jacob, 1971.
[6] Durr, 1964.
[7] White, 1965.

hours 7.5 km southeast of the center of the Geysers steam field, recording 29 shocks, of which 19 were suitable for interpretation (Table 5). All of these 19 microearthquakes had epicenters apparently on the fault system adjacent to Big Sulphur Creek, shown in Figure 6. The other fault systems in the region produced no measurable seismic activity during the observation period. The authors state that the apparent genetic relationship between the hydrothermal activity and the fault zone "suggests that mapping of microearthquakes, as distinct from steam-generated seismic noise, could be used in the exploration for geothermal power. It may specifically define the active faults that maintain zones of high permeability that provide the steam reservoirs."

Imperial Valley

Brune and Allen (1967) found 75 microearthquakes per day at Obsidian Butte, with an average of 10 per day in the Imperial Valley of California (Table 6) and offer strain release by microearthquakes as an explanation of the absence of "truly great" earthquakes. Helgeson (1968) reports subsurface temperatures of 300°C at a depth of 3000 feet in the area.

Table 5. Summary of Data from the Geysers

Microearthquakes per Day: [3.8] [8]

S-P Interval: < 2.0 sec [8]

Minimum Magnitude: [0.4] [8]

Normalized Events per Day: 9.1 for b=1
22.9 for b=2

Heat Flow: [40×10^{-6} cal/cm^2/sec] [9]

Temperature: 208°C at 900 ft [10]

Geologic Conditions: Seismic epicenters lie along a fault zone and within an area of hydrothermal activity. Steam is produced from fractured and faulted medium to fine grained sandstone which has been hydrothermally altered and which has a porosity of less than 10%. [10]

References:
[8] Lange and Westphal, 1969.
[9] White, 1965.
[10] McNitt, 1964.

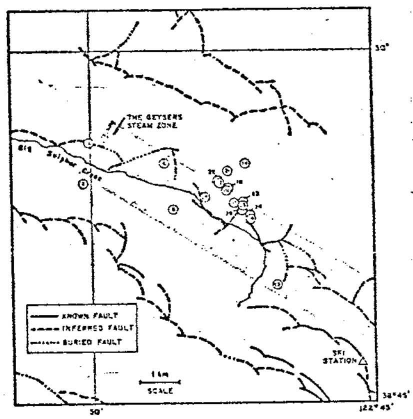

Figure 6. Earthquake epicenters in the Geysers steam zone. From Lange and Westphal, 1969.

Table 6. Summary of Data from the Imperial Valley

Microearthquakes per Day: Average = 10 [11]

S-P Interval: ≤ 3 sec [11]

Minimum Magnitude: 0 [11]

Normalized Events per Day: 10 for b=1, b=2

Heat Flow: 17×10^{-6} cal/cm^2/sec [12]

Temperature: 300°C at 3000 ft [12]

Geologic Conditions: The steam reservoir is a permeable sand, overlain by a circular cap of impervious argillaceous material with a radius of 3 mi., and underlain by similar material. At least two sets of fractures are encountered. [13]

References: [11] Brune and Allen, 1967.
[12] Helgeson, 1968.
[13] Goforth *et al.*, in press.

New Mexico

Sanford and Holmes (1962) recorded several hundred microearthquakes during the period from June 1960 to February 1962 (Table 7), using two high-magnification seismographs located in the mountains 3 miles west of Socorro, New Mexico. One recorded continuously, the other for several hours a day. They found that epicenters for most shocks were within a 36-km^2 area southwest of Socorro with focal depths of 2.7 to 6.3 km.

Sanford et al. (in press) report 400 microearthquakes per year with magnitudes greater than zero within 20 km of Socorro, mostly located to the west and southwest, but not associated with the fault separating Socorro Mountain from Socorro Basin.

Summers (1965) lists warm springs at Socorro flowing from lake beds of Tertiary age lying against lava hills. He gives their temperature as 90° to 92°F.

Africa

Microearthquakes in the rift valley of Kenya have been studied by Tobin and others (1969) using high-gain, high frequency, highly portable backpack seismographs. Figure 7 shows the location of the sites occupied and the average number of microearthquakes per day. A maximum of 47.1 events per day were recorded at the base of a 30 m scarp (Table 8). The second highest seismicity, 26.2 events per

Table 7. Summary of Data from New Mexico

Microearthquakes per Day: (0.47) to 3.55 [14] Sanford & Singh 208 177 203 161 165 5|914 183/365

S-P Interval: < 2.3 sec [14] 0.5/day

Minimum Magnitude: 0 [14] 0.5

$\log_{10} 0.5 = a - 0.5$

$0.70 - 1.00 = a - 0.5$ a = 0.2

Normalized Events per Day: 0.47 to 3.55 for b=1, b=2 MZO = 1.6

Heat Flow: 11.5×10^{-6} cal/cm^2/sec [15]

Temperature: 92°F at surface [16]

Geologic Conditions: Rift structure expressed by a number of elevated northward trending blocks, separated by structural depressions. The basins are filled with Late Tertiary clastic sediments and volcanic rocks, mainly basalts. The uplifted blocks display pre-Tertiary sediments and Early Tertiary volcanics and sediments. Structures include folding, and normal and reverse faulting. [17]

References: 14 Sanford, 1962.

15 Allan R. Sanford, personal communication.

16 Summers, 1965.

17 Sanford *et al.*, in press.

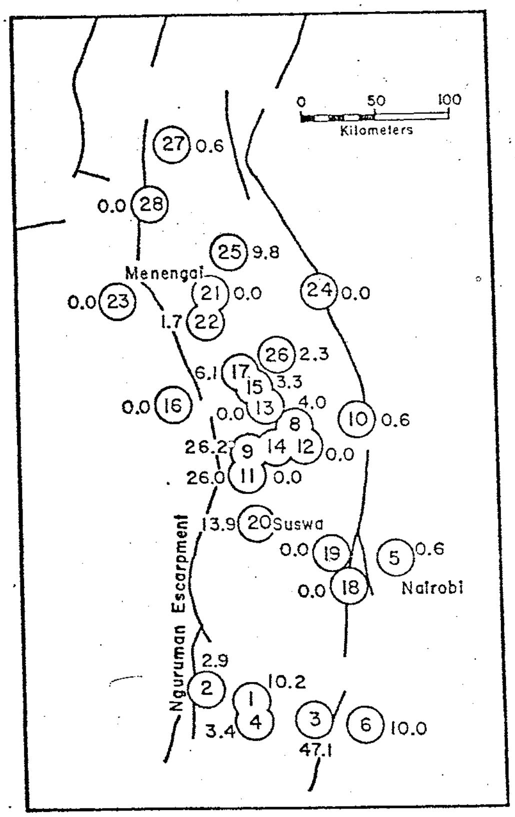

Figure 7. Map of recording sites in Kenya. Decimal numbers represent the average number of events per day. From Tobin et. al., 1969.

Table 8. Summary of Data from Africa

Microearthquakes per Day: 0 to 47.1 [18]

S-P Interval: ≤ 2.5 sec [18]

Minimum Magnitude: -0.7 [18]

Normalized Events per Day: 0 to 9.38 for b=1
0 to 1.88 for b=2

Heat Flow: Not given

Temperature: 177°C at 936 m [18]

Geologic Conditions: Earthquakes are confined to the center of the rift and are associated with grid faults, a geothermal area, and a recently dormant volcano. The faults cut Pliocene to Pleistocene lava flows in the rift. [18]

References: [18] Tobin _et al._, 1969.

day, was recorded at sites 9 and 11 near the numerous steam jets south of Lake Naivasha. Although this area was the one place in the region covered by the paper considered to have steam of commercial value, attempts at development failed. A temperature of 177°C was suddenly reached in a drill hole at 936 m depth. Sites 1 and 4, near the hot springs at Magadi, showed modest activity, as did site 15 near steam jets north of Lake Naivasha.

The authors report that the number of events per day was found to be generally characteristic of a site within a factor of 3 over a period of a few months, but admit the number may fluctuate by a greater amount from year to year. The focal depths are poorly known, but all events appeared to be shallow (less than 70 km).

Alaska

A study of microearthquakes at Mount Katmai in Alaska (Matumoto and Ward, 1967) conducted in 1965 recorded 1800 events in 39 days of nearly continuous recording, using a high-gain high frequency array of seismometers. The count ranged from 40 to 85 shocks per day (Table 9). The majority of events (60%) were found to be shallower than 10 km, although some were as deep as 150 km. The background noise in the area consisted of two sources, a ground noise with constant amplitude between 4 and 6 Hz, due mainly to a stream, and occasional wind noise which varied in amplitude from time to time over the frequency range of 20 to 70 Hz.

Table 9. Summary of Data for Alaska

Microearthquakes per Day: [0.62] [19]

S-P Interval: [≤ 3 sec] [19]

Minimum Magnitude: [0.6] [19]

Normalized Events per Day: 2.45 for b=1

9.75 for b=2

Heat Flow: Not given

Temperature: Not given

Geologic Conditions: Fifteen volcanic vents are in the Katmai area. Historic volcanic activity ranges from minor steaming to major explosive eruptions. [19]

References: [19] Matumoto and Ward, 1967.

During inclement weather, wind noise was high enough to obscure the smaller events. Regions of high seismicity were found to correlate with regions of recent volcanic activity (Figure 8).

Hawaii

Koyanagi (1964) recorded 840 events in a 15 month period on the lower east rift zone of Kilauea, Hawaii, volcano, ranging in magnitude from 0.5 to 4.0 on the Richter scale (Table 10). He reports 94% were less than magnitude 2.0, and frequencies ranging from 5 to 10 Hz. Depths to foci are given as mostly 3 to 8 km, with from 0 to 58 events per week. Fluctuations in activity are shown in Figure 9. Refilling of the shallow reservoir beneath the Kilauea summit is given as the cause of the seismicity.

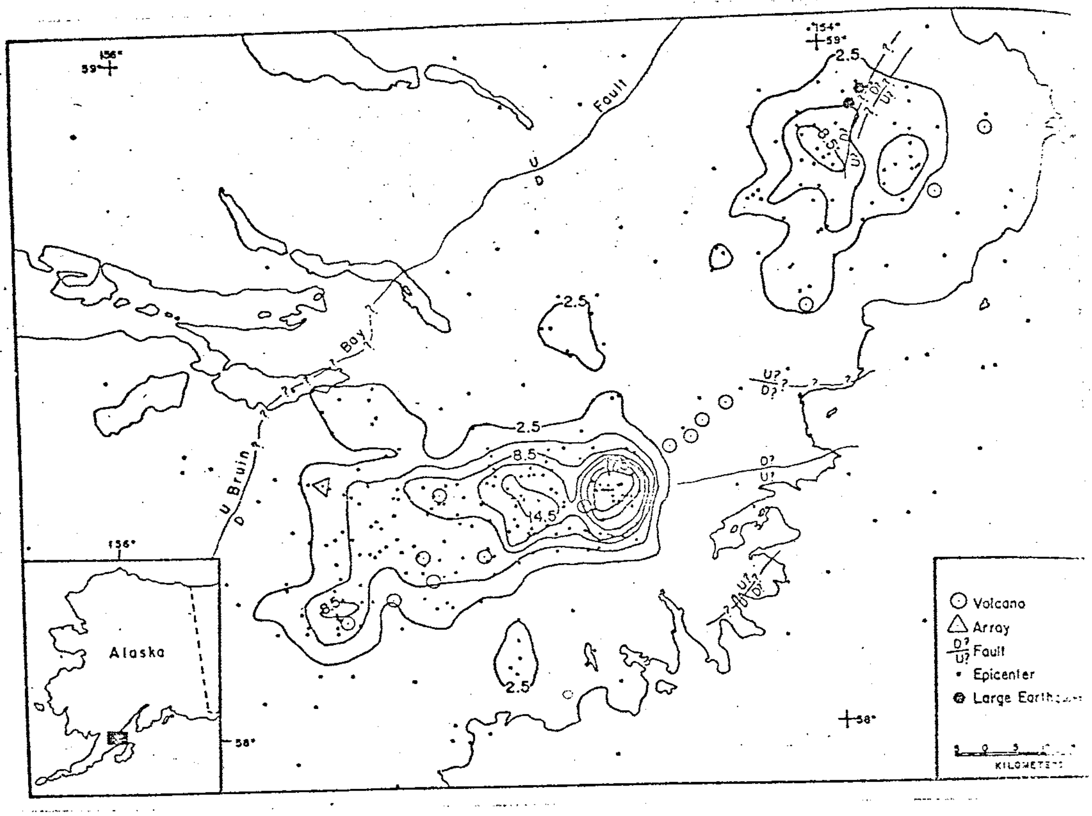

Figure 8. Seismicity map of the Katmai region. From Matumoto and Ward, 1967.

Table 10. Summary of Data for Hawaii

Microearthquakes per Day: 0 to 8.3 [20]

S-P Interval: Not given

Minimum Magnitude: 0.5 [20]

Normalized Events per Day: 0 to 26.2 for b=1
0 to 83 for b=2

Heat Flow: Not given

Temperature: Not given

Geologic Conditions: The seismicity is believed to be related to rapid refilling of a shallow reservoir beneath the Kilauea summit. Epicenters lie in a rift zone and are associated with volcanic cones, cracks, craters, and normal faults. [20]

References: [20] Koyanagi, 1964.

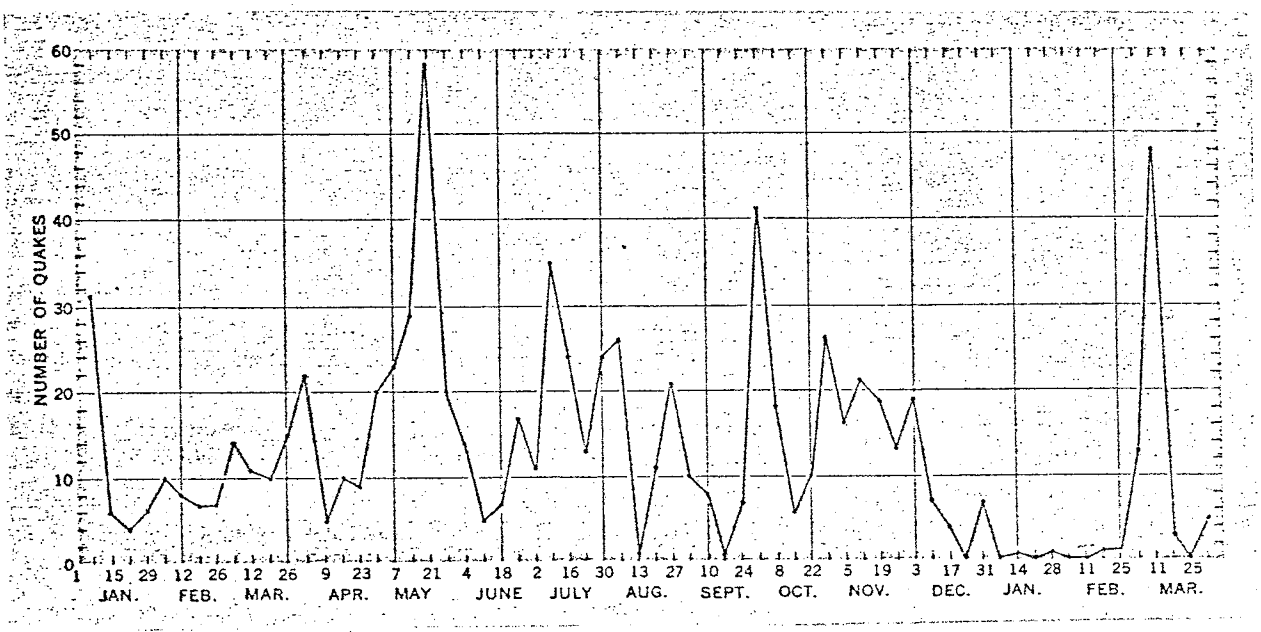

Figure 9. Weekly frequency of earthquakes at Kilauea, Hawaii. From Koyangi (1964).

CONTINUOUS SEISMIC NOISE IN THERMAL AREAS

New Zealand

The 400 square mile area near Lake Taupo, New Zealand, has been studied by Clacy (1968), using a continuous direct-recording tape seismograph and a Willmore seismometer (Table 11). He obtained noise highs in three geothermal areas by plotting contours of relative total ground-noise amplitude in the frequency band of 1 to 20 Hz. More detailed surveys in these three areas have local noise highs which did not necessarily correspond to zones of maximum surface geothermal activity. These highs had predominant frequencies of 1 to 3 Hz, whereas away from the areas the predominant frequencies were greater than 3 Hz. Cultural noise, winds, ocean microseisms, and other periodic surface noise was not included. Clay states "exclusion of noises is simple, because they are readily spotted during the frequency analysis process and because periods free of these spurious noises occur during the night." He concludes that "the seismic-noise pattern of a geothermal region is probably a useful method for determining an underground steam-producing aquifer because the water contact with heat appears to produce a useful seismic noise pattern that can be plotted to determine the possible extent of an aquifer."

Table 11. Summary of Data for New Zealand

Microearthquakes per Day: Not applicable-continuous noise

S-P Interval: Not applicable - continuous noise

Minimum Magnitude: Not given

Normalized Events per Day: Not applicable - continuous noise

Heat Flow: 40×10^{-6} cal/cm^2/sec [21]

Temperature: T = 266°C at unspecified depth [22]

Geologic Conditions: Volcanic rock predominates. A Cenozoic pumiceous breccia, 1500 to 3000 ft thick, is the aquifer from which steam is produced. It is covered by lacustrine mudstones 200 to 500 ft thick, which is in turn covered by 600 to 1000 ft of pumice breccia or lapilli tuff exposed at the surface. The sequence is traversed by sharply dipping fractures. High pressure steam comes from wells drilled into the active faults. [23]

References: [21] Lee and Clark, 1966.

[22] White, 1965.

[23] Grindley, 1964.

El Salvador

Ward and Jacob (1971) noted ground noise in several geothermal areas, so they operated a three component seismic system with frequency response peaked between 10 and 350 Hz near fumaroles and wells, and along profiles traversing the western part of the geothermal field. No systematic variation in the frequency or energy of the ground noise was observed except that the power of the high-frequency noise (10 to 50 Hz) generated by blowing geothermal wells, rivers, and fumaroles was attenuated at a rate of about 3 db per 50 m of distance in the area.

Imperial Valley

Goforth and others (in press) have investigated the correlation between seismic noise and geothermal activity in the Imperial Valley. They recorded primarily at night to avoid cultural noise, using four identical seismograph systems with velocity responses that were flat from 1 to 20 Hz. Each recording site was occupied for about 8 hours. A power density spectrum is shown in Figure 10. To further quantify the results, the total power in the frequency band 1 to 3 Hz was computed for each site by integrating the power density within this band. The values were plotted and contoured and are shown in Figure 11. Comparison with an isothermal contour map, obtained from wells, showing the depth to the 300°C isotherm (Figure 12) reveals the

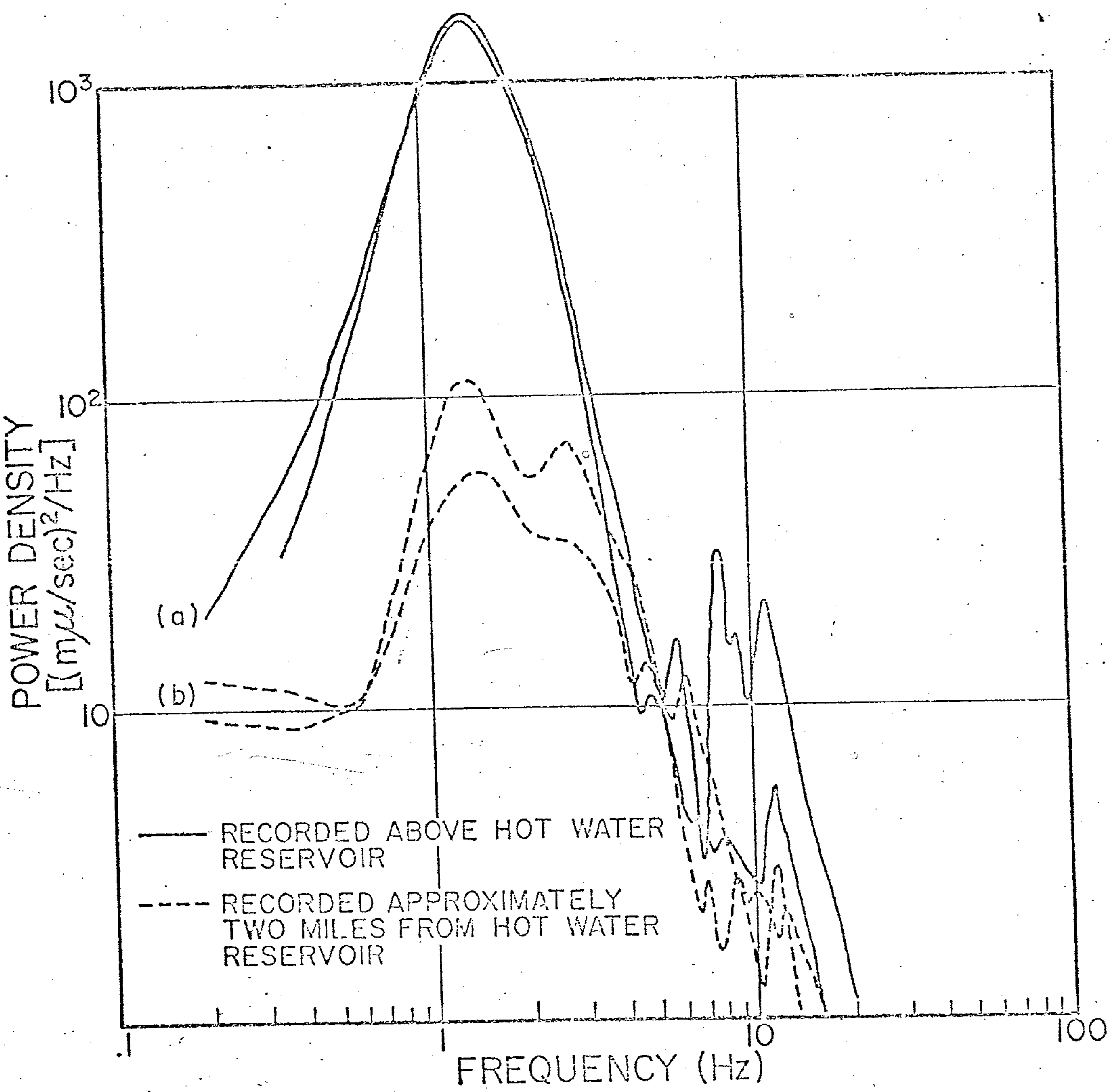

Figure 10. Power density spectrum in the Imperial Valley. From Goforth et. al., in press.

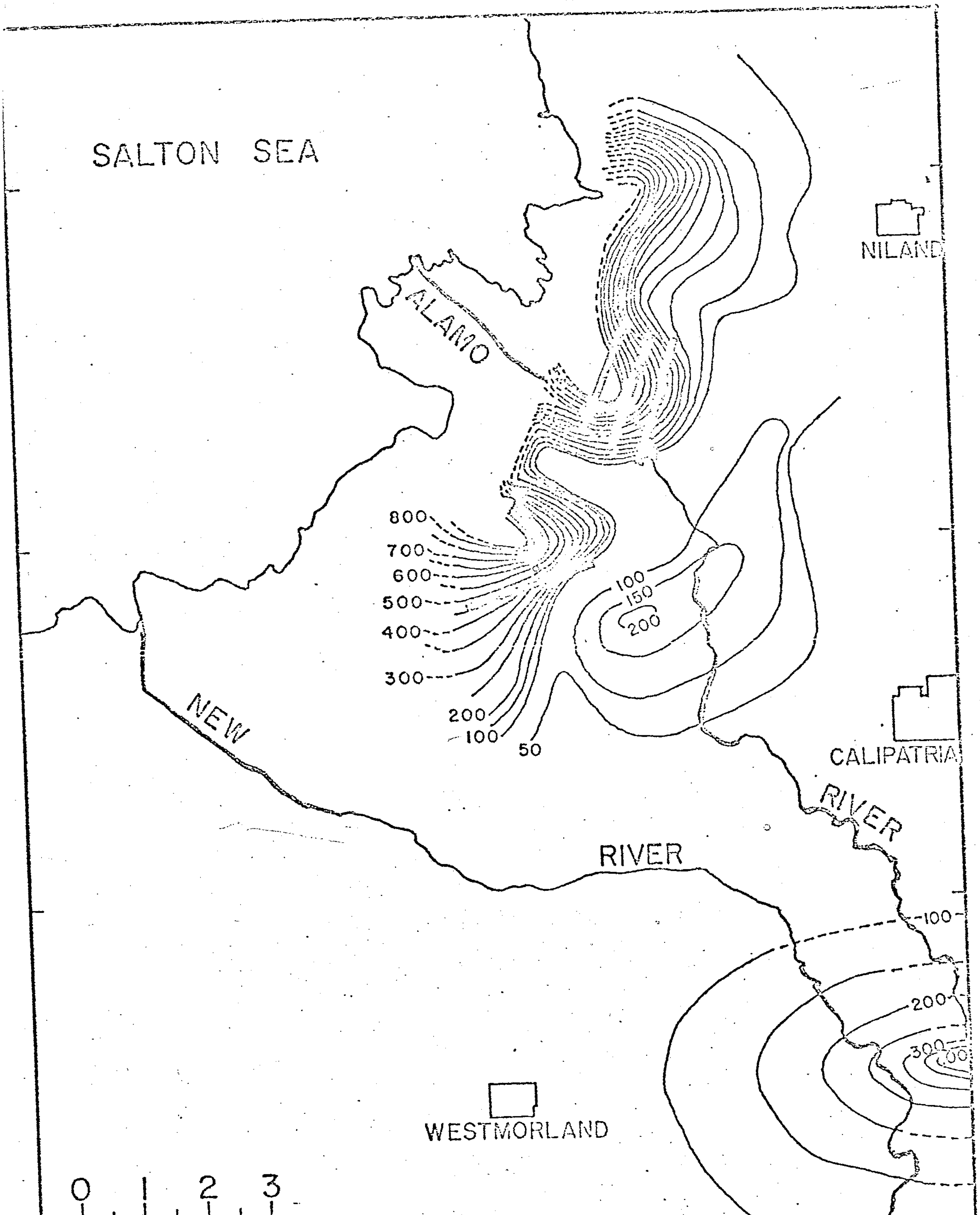

Figure 11. Ground noise amplitude in the Imperial Valley. From Goforth <u>et. al.</u>, in press.

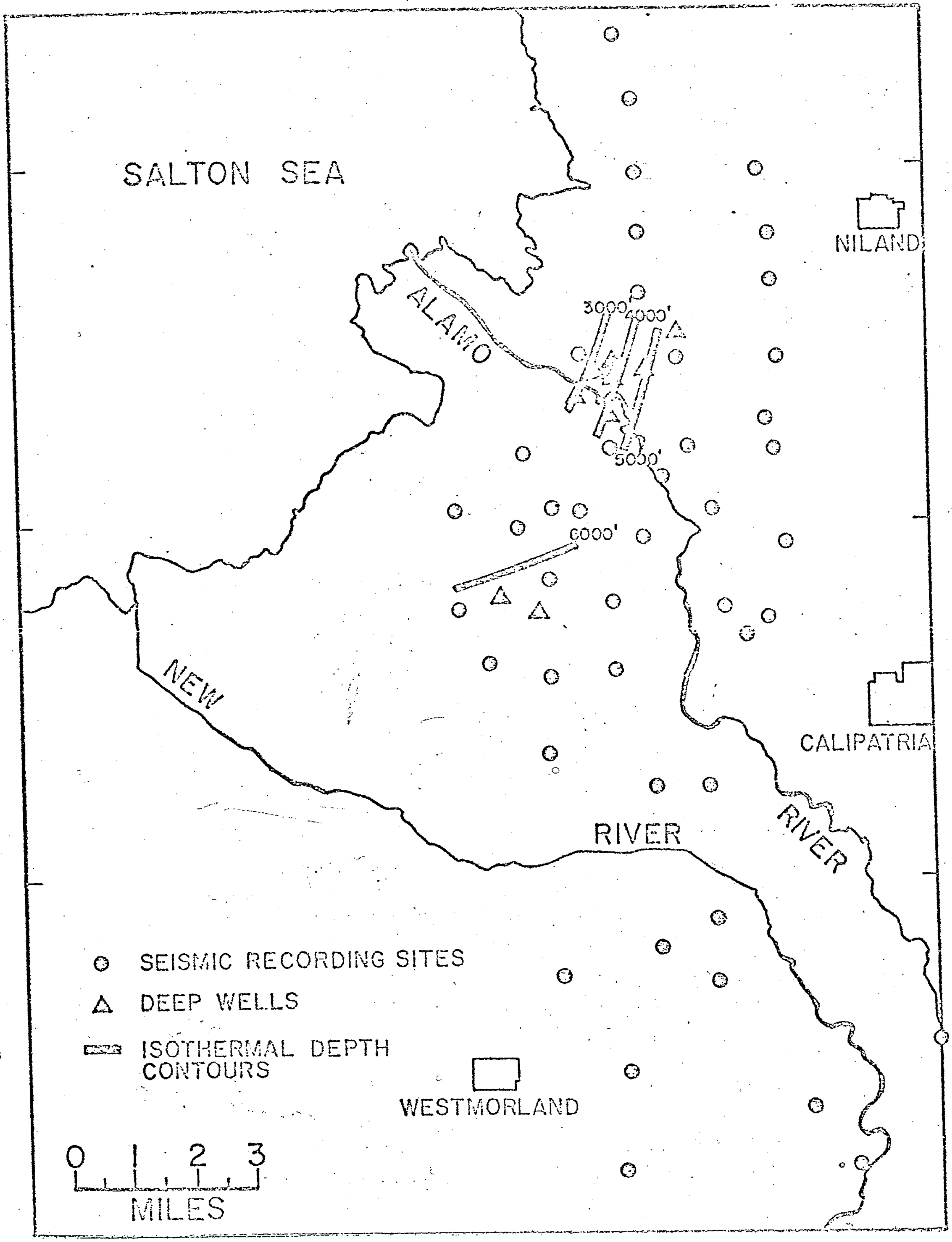

Figure 12. Isothermal contours in the Imperial Valley. Figures are depths in feet to the 300° C isotherm. From Goforth et. al., in press.

correlation between the temperature and seismic highs. Figure 13 shows the relationship between seismic noise and temperature gradient. The zone of anomalously high seismic noise is seen to correspond very closely to the center of the geothermal zone.

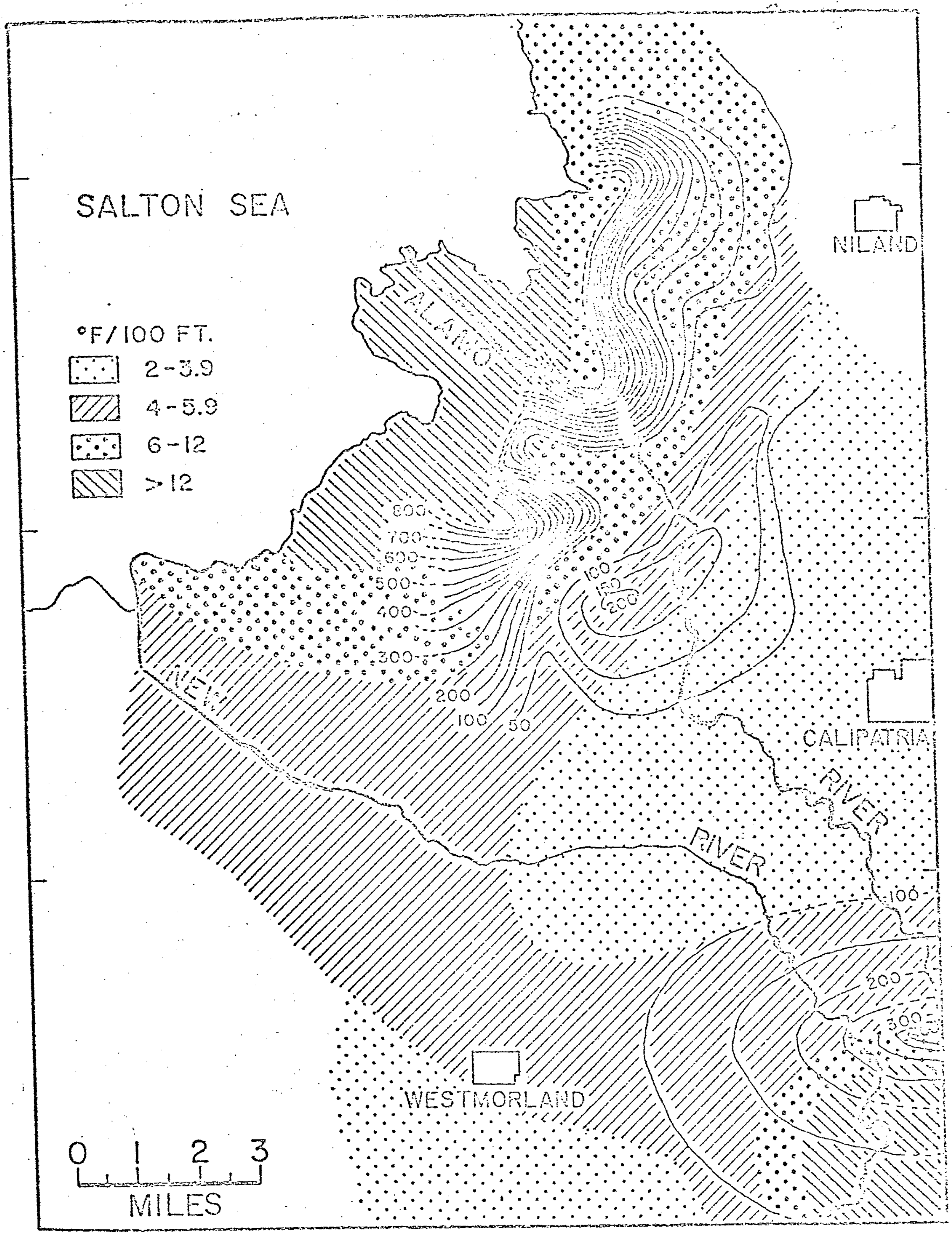

Figure 13. Noise amplitude versis temperature gradient. From Goforth et. al., in press.

POSSIBLE MECHANISMS FOR SEISMIC DISTURBANCES

Several possible explanations for microearthquake activity in geothermal areas are proposed by Ward and Bjornsson (1971). Fluid pressure is suggested as one possible mechanism, as Hubbert and Rubey (1959) have shown that slippage along fault planes can be triggered when the pore pressure is sufficient to reduce the normal force across a fracture below some critical level. Ward and Bjornsson concede that high fluid pressures may not necessarily exist in the geothermal areas of Iceland, however, since high pressures at the well head are generally due to superheated water flashing to steam in the well pipe. Thus some impermeable zone must exist that allows the fluid pressure to increase above the normal hydrostatic pressure in order to get high fluid pressures at depth, but such barriers may not exist in active fracture zones. The authors attempt to resolve the paradox on the basis of increased penetration of the pore fluid due to decreased viscosity, and suggest that in some regions only a very slight reduction in the normal force may be necessary to induce slippage. They also observe that geothermal waters have been observed at a depth of 2.2 km in Iceland and might be expected to circulate to the depths of the observed microearthquakes.

Another possible mechanism suggested is stress corrosion, where corrosion reactions produced by water occur preferentially at points of high tensile stress. Being exponentially dependent on temperature, it may be of importance in geothermal areas although of minor importance at room temperature. Silica, for example, could be leached out from irregularities in the fault surface by circulating fluids. This leaching weakens the irregularities and could thus decrease the coefficient of static friction, allowing slippage to occur.

SUMMARY

Two types of seismic activity are observed in geothermal areas, (1) discrete microearthquakes produced by movement along faults, and (2) continuous noise. The discrete microearthquakes are apparently triggered by circulation of fluids along fault planes, causing a decrease in the normal force across the fault, or due to stress corrosion. The causes of the continuous noise are less certain, although in New Zealand steam generation at depth is hypothesized. In the case of the microearthquakes, from less than 1 to 75 events per day have been recorded with magnitudes as low as -0.7 and at focal depths generally less than 8 km. Heat flow has been found to be from 4.5 to 100 x 10^{-6} cal/cm^2/sec. Steam is produced from faults in volcanic and sedimentary rocks and from contacts between units.

The existence of seismic areas without geothermal activity but displaying seismic characteristics similar to areas with thermal activity indicate passive seismic surveys are only a useful tool to be used in conjunction with other methods in exploration for geothermal energy. Conversely, thermal areas without seismicity were also noted. Further study in other areas is needed.

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