182

Geothermics (1972) - Vol. 1, No. 1

Microearthquakes: Prospecting Tool and Possible Hazard in the Development of Geothermal Resources

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ABSTRACT

Microearthquakes have been observed near many major geothermal areas around the world. Where detailed data are available, there is a close spatial relationship between microearthquakes and geothermal activity. Earthquakes with magnitudes greater than about 4.5, however, are rarely observed in geothermal areas. Locations of microearthquakes can be used to locate active faults that may channel hot water toward the surface. Earthquakes provide some risk in the development of geothermal regions since during an earthquake the flow of thermal fluid can be enhanced or slowed and structures can be damaged. Modification of reservoir fluid pressure may influence the earthquake activity.

Introduction

Earthquakes occur near most major geothermal areas. Little attention has been given to these earthquakes, however, because they are rarely large enough to be located with data from the standard types of seismographs located throughout the world. The purpose of this paper is to show how common small earthquakes are in major geothermal areas and to discuss the advantages and problems of studying these earthquakes to determine the location of potential channels of hot water to reach the surface. Earthquake hazards are also discussed briefly because these need to be considered not only when building structures in geothermal areas but when determining the probable longevity of a geothermal field and when determining how geothermal fluids should be extracted and reinjected.

It is not surprising that earthquakes occur in major geothermal areas. « All the thermal areas being developed throughout the world are located in regions of Cenozoic volcanism » (McNitt 1965) and earthquakes are found near the majority of Cenozoic volcanoes (e.g. Isacks et al. 1968; Eaton and Murata 1960; Minakami 1960; Minakami et al. 1969; Goryachev 1962; Matumoto and Ward 1967). Furthermore, earthquakes are generated when slip takes place along faults and faults in many geothermal areas appear to provide zones of high permeability that allow convection of heat to the surface (e.g. Grindley 1966; McNitt 1965; Bodvarsson 1961). Finally, recent data suggest that the presence of water, which is found in abundance in geothermal areas, may have some role in determining where, when, and in what time sequence tectonic stress is relieved as seismic energy (Hubbert and Rubey 1959; Griggs 1967; Healy et al. 1968; Raleigh et al. 1971; Scholz 1968; Healy et al. 1970; Healy and Pakiser 1971).

Since earthquakes occur on faults, seismically active faults at depth beneath a geothermal region can be located by accurately locating the earthquakes. The best production wells might be drilled near these potentially permeable zones. Fault motion during earthquakes, however, may increase or decrease the flow of hot water from depth and thus could profoundly affect the longevity of a thermal area. Vibration during large earthquakes may damage equipment used to exploit geothermal power. The manner in which thermal fluid is withdrawn or reinjected may influence the occurrence of earthquakes. Thus, not only geologists and seismologists but reservoir engineers, production engineers, and investors have an interest in knowing where earthquakes occur in geothermal areas and what are the properties of these earthquakes.

Earthquakes with a magnitude (Richter 1958, p. 338) greater than 4 to 4.5 can generally be located with data from the standard types of seismographs situated around the world. Such an event occurring at a shallow depth might cause minor structural damage nearby. Major destructive earthquakes have magnitudes as large as 8.7 on this logarithmic scale. Earthquakes as small as magnitude —2 can be located with data from high-gain seismographs located within a few kilometers from the earthquake source (e.g. Asada 1957; Oliver et al. 1966; Brune and Allen 1967; Ward and Björnsson 1971). Such events with magnitudes generally from —2 to 4 are referred to here as microearthquakes. The main reason for studying these microearthquakes is that for each unit lower in magnitude, there are roughly 10 times as many events. Thus, as many as one million microearthquakes may occur in a region where only one event of magnitude 4 can be located during the same period of time. Several microearthquakes may occur each hour or day in a given region and data sufficient to locate faults can often be collected during a few weeks to a few months.

Microearthquakes should not be confused with microseisms; the former term refers to discrete small

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earthquakes whereas the latter term refers to the more or less continuous background noise recorded on seismometers and generated primarily by atmospheric storms, particularly at sea (e.g. Richter 1958, p. 375 ff). Other seismic waves that differ from microearthquakes and microseisms, as commonly defined, are found in geothermal areas. Nogoshi and Motoya (1962, 1963), Rinehart (1965, 1968a, 1968b) and Nicholls and Rinehart (1967) recorded ground noises generated near geysers and bubbling springs in Hokkaido, Japan; Beowawe, Nevada; Yellowstone, Wyoming; and northeastern and southwestern Iceland. Clacy (1968), Ward and Jacob (1970), Whiteford (1970), Goforth et al. (1971) and Iyer (1971) found that ground noise levels were higher near geothermal areas than in regions just outside of these areas. This noise may be related to underground thermal activity, blowing wells, or possibly even to amplification of microseisms in layers of low rigidity within the geothermal regions. These ground noises will not be considered further in this paper.

The emphasis in this paper is on small earthquakes in geothermal areas. Three questions will be considered: how common are such microearthquakes, how can they be used for prospecting, and what seismic hazards should be considered in the development of geothermal resources?

The major geothermal areas described in this paper are not simply warm or hot springs but are major zones of high temperature « characterized by a great number of steam holes, large areas of hot ground, and a very high degree of thermal metamorphism » (Bodvarsson 1961). Total heat output in such areas may be of the order of 10^9 cal/sec and temperatures greater than 200°C may be found at depths of a few hundred meters.

Occurrence of earthquakes in geothermal areas

Iceland. Small earthquakes have been felt near major geothermal areas in Iceland for centuries (Einarsson 1967). Tryggvason et al. (1958) questioned whether these small events are of tectonic nature.

The most detailed studies to date of microearthquakes in geothermal areas were carried out in Iceland. Ward et al. (1969) and Ward and Björnsson (1971) showed the following:

1. Most microearthquakes recorded throughout Iceland occurred within or very near major geothermal areas.
2. Geothermal areas that are structurally related to fissure systems generally had microearthquake activity whereas those areas that have few prominent fissures and seem only related to intrusions of silicic magma had little or no microearthquake activity.
3. Epicenters (1) of microearthquakes in two areas where detailed locations were possible were confined primarily to the region of thermal alteration observed at the surface. The greatest earthquake activity was often near the regions of greatest thermal activity observed at the surface (Figure 1).
4. Most well-located microearthquakes in Iceland occurred at depths of 2 to 6 km. Some events were as deep as 13 km (Figure 2).
5. Operation of a geothermal well, 0.3 km deep, did not significantly affect the occurrence of microearthquakes, which were located generally deeper than 2.0 km.
6. Earthquakes in geothermal areas in Iceland seem to occur primarily in swarm type sequences whereas earthquakes elsewhere in Iceland occur primarily as mainshock-aftershock sequences. The majority of the seismic energy in a mainshock-aftershock sequence is released during the mainshock. In a swarm sequence, however, the seismic energy is released over a period of as long as days or months during many shocks.
7. Earthquakes with magnitudes greater than 4.5 generally do not seem to be located within geothermal areas, although they may occur only ten or fifteen kilometers away.

United States and Mexico. Brune and Allen (1967) noted abnormally high microearthquake activity near geothermal areas south of the Salton Sea in southern California and concluded that « these earthquakes represent the same regional stress system as elsewhere, and are not solely the result of localized volcanic or thermal activity at depth ». Richter et al. (1967) and Allen et al. (1968), for example, show several earthquakes with magnitudes generally between 3 and 5 near geothermal areas in the Imperial Valley, California, and one event just to the south near Cerro Prieto, Mexico. Thatcher and Brune (1971) located four swarms of earthquakes since 1962 near Obsidian Buttes, a geothermal area just south of the Salton Sea. Lomnitz et al. (1970), however, in a preliminary study of records for two months from five fixed stations between the Gulf of California and the Salton Sea, did not locate any earthquakes near the Cerro Prieto geothermal field.

Lange and Westphal (1969) located nineteen microearthquakes « on the fault system associated with The Geysers steam zone in Sonoma County, California » and within the area of hydrothermal activity. Faults outside of the thermal area produced no measurable seismic activity during the period of observation. Hamilton and Muffler (1972) made a more detailed study of microearthquakes in The Geysers area and found 53 earthquakes in three weeks within 10 km of the thermal area. « Most of the epicenters lie in a zone about 4 km long and 1 km wide passing through the geothermal field along a principle fault zone. Focal depths are from near surface to about 4 km. A composite fault-plane solution indicates dextral strikeslip faulting on a NNW striking plane. » Bolt et al. (1968) give a strikeslip mechanism for an earthquake located just south of The Geysers. One nodal plane, also striking NNW, is parallel to the faults in the region and to the San Andreas fault. The motion is also right-lateral and of the same sense as motion on the San Andreas suggesting that this earthquake and most of the microearthquakes of Hamilton and Muffler (1972) are relieving regional stress.

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(1) An epicenter is the point on the surface of the earth directly above the hypocenter. The hypocenter is the point in the earth where an earthquake occurs as located with the times of the first seismic arrivals at a number of stations.

WESTPHAL and LANGE (1966) observed continuous microearthquake activity near hot springs in the Sawtooth Range, Idaho; Socorro Mountain, New Mexico; Bridgeport, California; and Dixie Valley, Nevada.

EL SALVADOR. WARD and JACOB (1971) located 17 microearthquakes in the Ahuachapan geothermal area. These events lie on or near a plane of activity that intersects fault breccia mapped in a well (Figure 3). The plane is nearly parallel to other faults in the region and is interpreted as a fault that allows hot water to circulate to the surface in this geothermal area.

NEW ZEALAND. Studies of microearthquakes in the geothermal areas of New Zealand are just being started by J. LATTER (Department of Scientific and Industrial

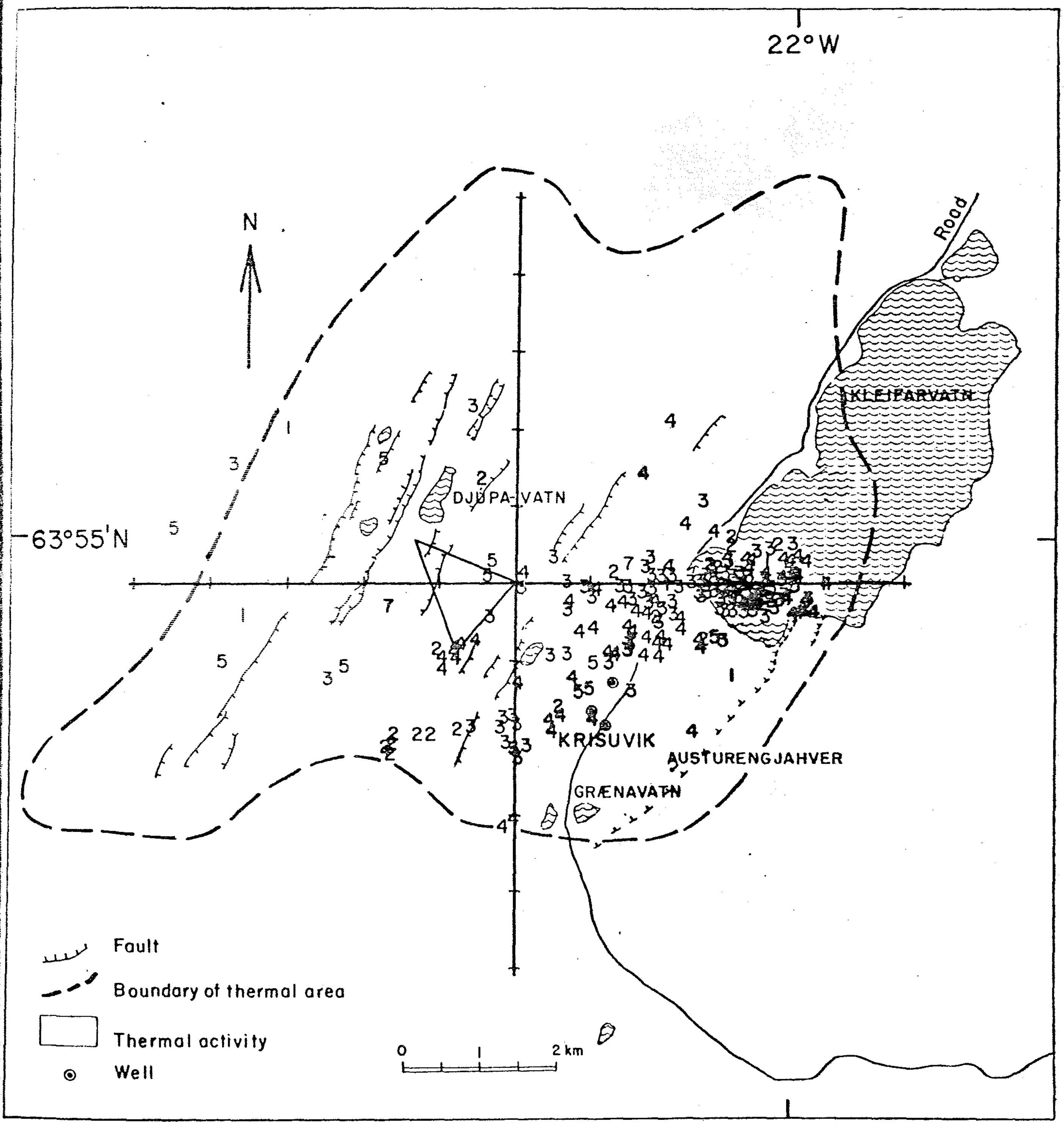


FIG. 1. — *Locations of earthquakes in the Krisuvik geothermal area, 25 km south-southwest of Reykjavik, Iceland. The numbers are hypocentral depths rounded to the nearest kilometer. The earthquakes were located using the tripartite area shown south of Djupavatn. The dashed line shows the horizontal extent of thermal alteration observed at the surface.*

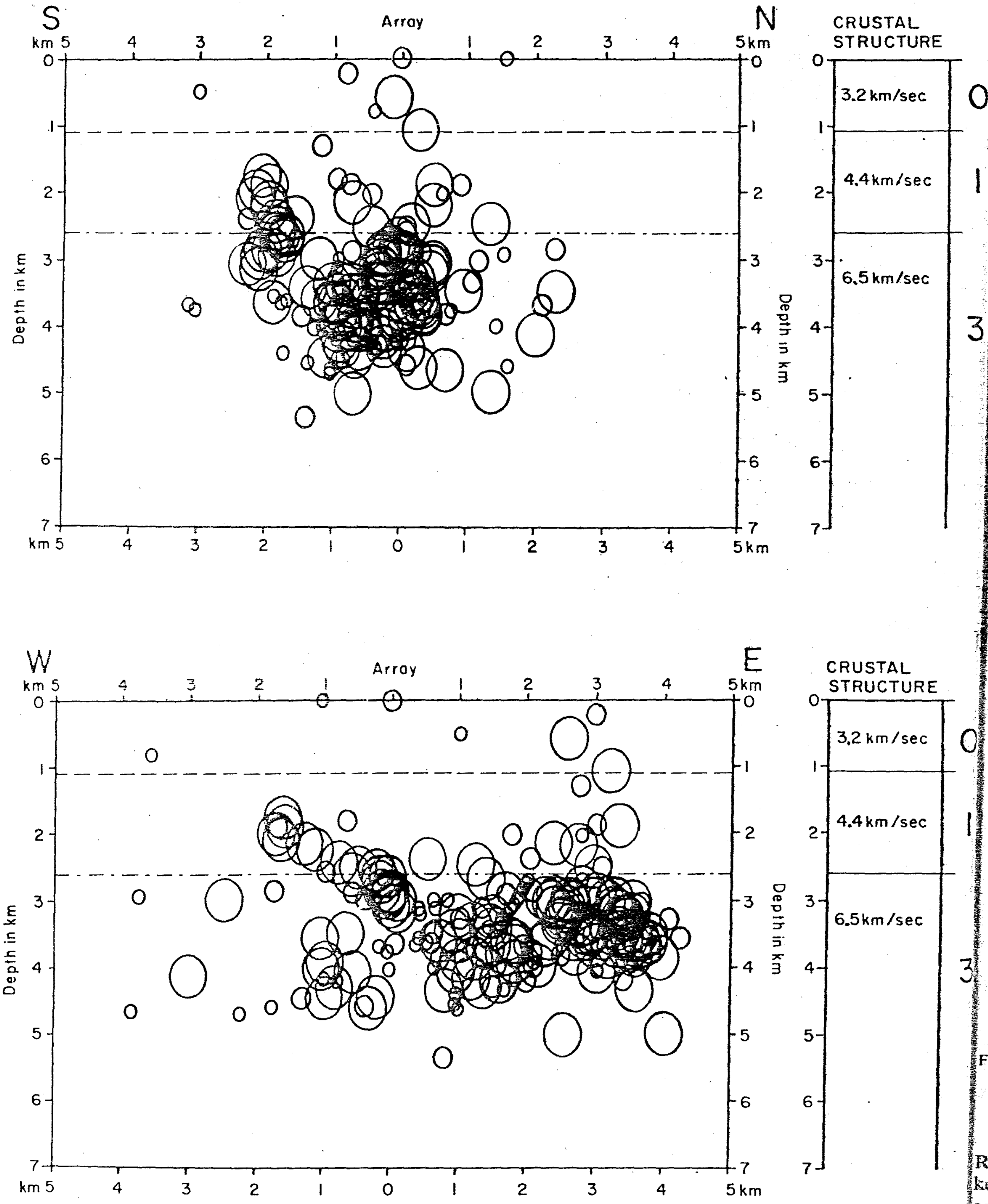
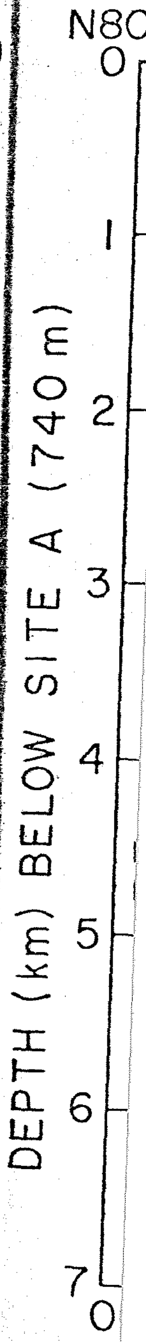


FIG. 2. — *Earthquake hypocenters in Krisuvik projected onto north south and east-west vertical cross-sections drawn along the ax in Figure 1. The crustal structure is from* PÁLMASON (1971).



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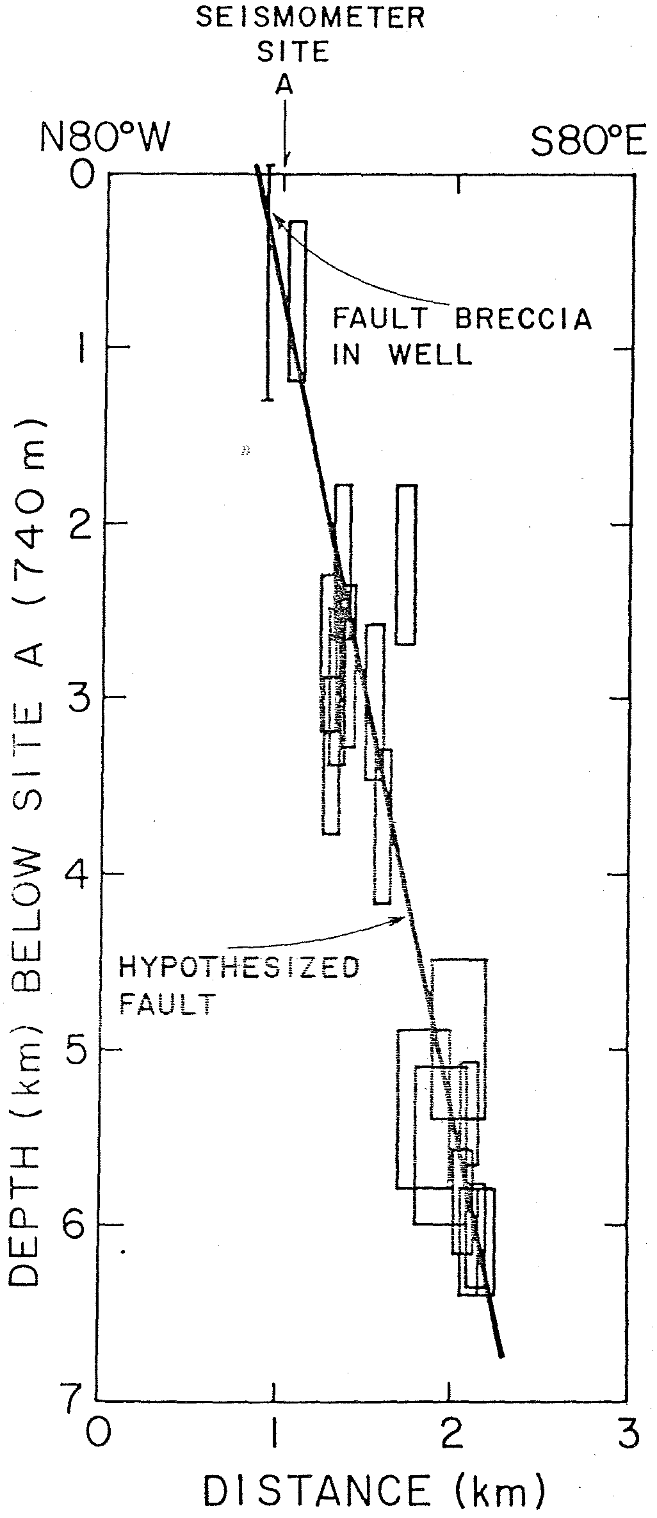

Fig. 3. — *Earthquake hypocenters projected on a vertical plane striking S80°E through the Ahuachapan geothermal area, 70 km west-northwest of San Salvador, El Salvador. Rectangles denote approximate precision in location.*

Research). A seismograph has been operated near Wairakei, however, for several years. G. A. Eiby (personal communication, 1971) counted earthquakes per month within 25 km of the seismograph and with magnitudes generally greater than 2.0. He generously provided the data in Table 1. The Wairakei seismometer has a gain of only about 300. Over 1000 times the events shown in Table 1 would have been recorded on instruments similar to those used by Ward and Björnsson (1971) in Iceland. Eiby (1966) describes several earthquake swarms occurring near the geothermal areas in the Wairakei-Rotorua-Taupo region.

Table 1. — *Earthquakes per month within 25 kilometers of the Wairakei seismograph station* (Eiby, *personal communications, 1971*).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1962											1	3
1963	2	5	3	2	3	8	1	2	2	0	6	3
1964	2	8	7	1	7	2	3	1	13	10	10	966
1965	117	11	4	3	1	8	7	8	9	25	55	33
1966	10	23	9	24	4	7	6	7	4	7	2	2
1967	5	1	6	3	3	2	1	12	4	1	1	1
1968	7	0	0	2	4	1	7	4	1	0	2	1
1969	2	5	2	2	16	1	5	7	10	7	3	1
1970	9	0	2	2	7	6	13	13	2	7	16	4
1971	0	0	3									

New Guinea. Fisher (in discussion after Eiby 1966) mentions earthquake swarms felt at E'sa-Ala on Normandy Island, off Eastern Papua, in the vicinity of well-developed geothermal areas and volcanoes.

Japan. Oki et al. (1968) and Oki and Hirano (1970) report earthquakes at depths of 0.5 to 5 km located primarily in a circle 1.5 km in diameter directly beneath a geothermal area on Hakone volcano (80 km southwest of Tokyo). Kasuga (1967) found that hot springs near Matsushiro had lower outflow and temperature right after periods of high seismic activity. These hot springs are located in the epicentral region of a swarm of over a million earthquakes that began in August 1965 and lasted for several years (Hagiwara and Iwata 1968).

West Indies. MacGregor (1938) and Sheperd et al. (1971) noted increases in heat flow at fumaroles on Montserrat that coincided with increases in earthquake activity and ground tilt.

Kenya. Tobin et al. (1969) observed microearthquake activity close to geothermal activity near Lake Naivasha and Lake Magadi. Molnar and Aggarwal (1971) found a few microearthquakes near geothermal areas around Lake Hannington and Lake Naivasha.

Italy. No microearthquake studies near these geothermal areas have been reported. Malaroda and Raimondi (1957) and Kárník (1969), however, show a few small earthquakes (magnitude 4) near Larderello and KÁRNÍK (1969) lists eight events within 0.5°, the minimum error in location of most of these events. DE PANFILIS (1959) reports one earthquake with the zone of damage centered about 15 km east of Larderello. Thus, there is a good probability that microearthquakes would be recorded near Larderello if studies with sensitive instruments were carried out.

Discussion

The data given above clearly show that microearthquakes occur in many geothermal areas. The regions discussed account for over 80% of the total geothermal electric power developed, under construction, or planned in the world (KOENIG 1971). Where microearthquake data are available, the better the data, the closer the observed spatial relationship between microearthquakes and geothermal areas.

Earthquakes with magnitudes greater than about 4.5, however, seem to be very rare in the crust under geothermal areas even though most geothermal areas occur near the major seismic belts around the world (BARAZANGI and DORMAN 1969). One of the largest shocks to occur near a geothermal area was the 1940 Imperial Valley earthquake, an event of magnitude 7.1 (RICHTER 1958, p. 487). Strike-slip faulting was observed extending most of the distance between the geothermal fields just south of the Salton Sea, California, and those near Cerro Prieto, Mexico. The faulting, however, did not extend into these thermal areas.

The observations that large numbers of microearthquakes are often found within but not outside of geothermal areas during short periods of field recording suggest that seismic activity within the geothermal areas may be a far more continuous process than seismic activity in most other areas, even though all the seismic activity may be along the same fault system and in response to the same regional stresses. The area of a fault surface that slips during an earthquake may be roughly on the order of 200 km^2 for an event of magnitude 5, 1.6 km^2 for an event of magnitude 3, and 1000 m^2 for an event of magnitude 0 (WYSS and BRUNE 1968). If deformation within a geothermal area is going on somewhat independently or at a different time sequence than deformation nearby, and since dimensions of most major geothermal areas are measured in terms of a few kilometers, then it is not surprising that events as large as magnitude 5 rarely if ever occur within geothermal regions.

In some regions the apparent difference in modes of earthquake activity under the geothermal areas and just outside may be easily explained. There is some suggestion in Iceland (WARD and BJÖRNSSON 1971) and considerably better evidence in the Imperial Valley (LOMITZ ET AL. 1970) that many of the major geothermal areas may occur on short segments of spreading mid-ocean ridge crests between longer segments of transform faults. If this is the case, then the occurrence of swarms of earthquakes in the geothermal areas would be consistent with the observations by SYKES (1970) that swarms of large earthquakes occur on mid-ocean ridge crests and not on transform faults and that normal faulting predominates on ridge crests whereas strike-slip faulting predominates on transform faults.

The few data available seem to support, but by no means prove, the following hypotheses that need to be critically tested:

1. Microearthquakes occur in most major geothermal areas.
2. Earthquakes in geothermal areas are primarily relieving regional tectonic stress along normal faults in grabens, strike-slip faults, etc. In a few yet unobserved cases, the earthquakes may be centered around an intrusive.
3. Stress release in geothermal areas is a far more continuous process than in most other regions. The crust in these areas may be weaker than crust nearby because of hydrothermal alteration of the rocks, the high temperature, the effects of fluids on fracturing, or possibly the presence of magma.
4. Active faulting is one important way of forming and keeping open permeable channels suitable for circulation of geothermal fluids. Active faulting of the chill zone around magma is a possible mechanism for maintaining the large heat fluxes (BANWELL 1963) observed in geothermal areas.

Microearthquakes as a prospecting tool

DEPTH OF EARTHQUAKES

Where earthquake locations have been determined accurately, few if any microearthquakes occur at depths of less than one or two kilometers (e.g. EATON ET AL. 1970a, b; HAMILTON and HEALY 1969; RALEIGH ET AL. 1970; WARD and BJÖRNSSON 1971). Apparently stress sufficient for an earthquake of magnitude greater than 0 or —1 cannot be accumulated at very shallow depths in most regions or there are systematic errors in location that have not yet been detected. Thus, by studying microearthquakes, it may be generally possible to locate faults only at depths of more than one kilometer. Such studies, however, provide the simplest method for finding active faults. The surface expression of a fault that has a simple geometry at depth may be quite complex. The location of deep faults that channel hot water to the surface is clearly of great importance for deciding how to develop a geothermal field.

ACCURACY OF EARTHQUAKE LOCATIONS

Earthquakes are located by measuring the arrival time of the seismic waves at various stations and calculating a location assuming some model for the crustal structure. The precision of earthquake locations can be determined by evaluating the errors in reading arrival times, locating the seismographs, etc. The precision is a measure of how well one earthquake is located relative to another that has been located by the same method. The accuracy of earthquake locations, which is a measure of how closely the calculated location approaches the actual location, is primarily affected by local inhomogeneities in the crust and by imperfect knowledge of the velocity structure. The accuracy can best be determined by locating explosions detonated as close to the earthquake hypocenter as possible.

The first arrival times of seismic waves at local stations can often be read to a few hundredths (EATON ET AL. 1970a) or even thousandths (WARD 1971) of seconds when accurate clocks or radio time are available and particularly when data from the different seismometers are transmitted by cable or radio telemetry to a central station and recorded on one magnetic tape recorder. In such cases the precision of epicentral and hypocentral locations is as good as plus or minus 100 or 200 meters.

The accuracy may be much poorer. HAMILTON and HEALY (1969), when locating a nuclear explosion, found errors as large as 700 meters in epicenter and 400 meters in depth even though they had 27 seismographs operating within a circle 32 km in radius and centered about the explosion. WESSON (1971) found that the better located earthquakes, at 1 to 4 km depth located with 15 stations spaced within a radius of about 10 km, may contain a systematic bias as large as 500 meters because of lateral variations in the seismic velocity. In both cases, seismic refraction data were available to give data on the crustal structure. Such observations show that although faults may in theory be located within a few hundred meters using microearthquake data, extreme care must be taken in the locating procedure and in evaluating the accuracy, particularly if drilling into a seismically active area is proposed. Locations in geothermal areas are especially difficult because the crust often contains large numbers of inhomogeneities such as grabens, horsts, dikes, and intrusives. Despite the inaccuracies, good locations of microearthquakes provide the most accurate data, except for drilling, on the position of faults at depths of one or two kilometers.

TYPICAL FIELD PROGRAMS

Small, high-gain, portable seismographs, which can be carried as luggage on an airplane, can be built or purchased for a few thousand dollars. One of these instruments, operated at a number of sites in and around a geothermal field for periods of from days to months, is sufficient to see if there is any local seismic activity. Three or more of these instruments can be used to crudely locate the earthquakes.

More precise and more accurate locations can be obtained using an array of seismometers with separate recorders but a common time signal or preferably with one recorder connected to many seismometers by wire or radio telemetry. Three seismometers located one or two kilometers apart are sufficient to obtain fairly precise earthquake locations. This so-called tripartite method is severely limited, however, because it depends not only on the first seismic arrival or P-wave, but also the arrival of the S-wave (WARD 1971). The S-wave may be highly attenuated in geothermal regions.

Perhaps the best locations, assuming there is a practical upper limit on the amount of equipment, can be determined using data from 6 to 13 seismometers located within and around the edges of the geothermal region and recorded on one 1/2 inch (7 channel) or 1 inch (14 channel) magnetic tape recorder. At least one seismometer should be located directly over the earthquake activity or at the epicenter and the other instruments should be within a radius of the epicenters approximately equivalent to the maximum expected hypocentral depth. Some seismometers might be placed to receive the first refracted waves from many of the earthquakes. The locations could be improved if one or more seismometers are located in boreholes near the hypocenters. In geothermal areas, however, the heat at shallow depth may be higher than the seismometer and cable can withstand. Equipment of a 13 component array complete with tape playback facilities might cost between US $ 50,000 and 100,000.

When good accuracy is desired the hypocentral locations should be calibrated by recording and locating artificial explosions detonated as near to the earthquake hypocenters as practical. An ideal location for such a calibration shot is at the base of a well.

The seismic equipment should be chosen carefully to allow maximum instrument gains of over one million in the 5 to 30 hertz range. This frequency band is set by the high microseismic level at periods of 3 to 20 seconds with the highest peak at around 6 to 8 seconds (BRUNE and OLIVER 1959), by the fact that microearthquakes are rich in frequencies of up to 20 or 30 hertz, and by the fact that high frequency seismic waves are attenuated far more rapidly in the earth than low frequency waves. Local noise sources such as blowing steam wells, rivers, and cultural noises should be avoided since they also often generate significant seismic energy in the frequency ranges of interest.

Earthquake risk

The possible hazards from earthquakes in geothermal areas are poorly understood. Earthquakes may change the intensity of geothermal activity, they may damage structures, and they may be affected by modification of fluid pressures within the geothermal field. There seems to be little need for excessive concern but these factors should be studied and more carefully evaluated.

EFFECT OF EARTHQUAKES ON GEOTHERMAL ACTIVITY

Flow from geothermal wells or springs may be modified during earthquakes either because fault slippage changes the permeability of feeder zones or because an increase or decrease of regional stresses changes the sizes of water filled cavities (BODVARSON 1970). RINEHART (1969) and RINEHART and MURPHY (1969) noted some effects on the eruptive cycle of Old Faithful Geysers in Yellowstone Park, Wyoming, from earthquakes less than 50 kilometers away and possibly even from a major earthquake in Alaska. MARLER (1964) describes effects of an earthquake less than 50 km away on hot springs in Yellowstone.

Pronounced changes have been noted in hot spring activity in Iceland after earthquakes within the thermal area. For example, in late 1967 a swarm of earthquakes in extreme southwestern Iceland was accompanied by surface fracturing in the Reykjanes thermal area and the formation of new geysers of brine up to 15 meters high, hot springs and fumaroles (WARD ET AL. 1969; TRYGGVASON 1970).

EFFECT OF EARTHQUAKES ON STRUCTURES

Structures in geothermal areas, particularly those handling superheated steam and water, should be designed to withstand local earthquakes. Since such design is often expensive, it is important to know just how large an earthquake is likely to occur in a given period of time and use that largest event for establishing design criteria. As discussed above, earthquakes greater than magnitude 4 to 5 appear to be rare in geothermal areas. If these preliminary observations turn out to be true throughout the world, only moderate attention needs to be paid to structural damage from earthquakes except where faulting may occur near the structure. Naturally the risk of large earthquakes near but outside of geothermal areas must also be considered by examining the historic record of activity and the regional seismo-tectonic setting. Many aspects of earthquake engineering are discussed in a book edited by WIEGEL (1970).

FLUID PRESSURE AND EARTHQUAKES

Considerable evidence suggests that thousands of earthquakes between 1962 and 1967, including one as large as magnitude 5.5, were triggered by the injection of millions of liters of fluid per month into a well 3671 meters deep near Denver, Colorado (EVANS 1966; HEALY ET AL. 1968). Detailed studies in Rangely, Colorado, similarly show that there is high seismic activity where fluid pressures due to injection exceed normal hydrostatic pressures and that modifying the fluid pressure seems to modify the occurrence of earthquakes (RALEIGH ET AL. 1970, 1971). Increases in seismic activity have also been suggested as resulting from the load of large reservoirs behind new dams (CARDER 1945; ROTHÉ 1970). If fluid pressures in geothermal fields are to be substantially modified by exploitation and reinjection, the possibility of modifying the mode of seismic energy release should be considered.

The most widely accepted mechanism for this effect of fluids on earthquakes involves pore pressure (HUBBARD and RUBEY 1959). If T is the shear stress on a fault plane, T_o is the intrinsic strength, S_n is the normal stress across the fault plane, P is the pore pressure, and u is the coefficient of friction (e.g. HEALY and PAKISER 1971), then

$$T = T_o + u\,(S_n - P)$$

The effect of increasing the pore pressure is thus to reduce the frictional resistance to slippage by decreasing the normal stress across the fault. In Denver, for example, the initial reservoir pressure was around 269 bars. By injection the down hole pressure was increased to about 389 bars when fracturing took place. After that time injection rates changed from being negligible at pressures of 362 bars to 114 liters per minute at pressures of 368 bars (HEALY ET AL. 1968). In Rangely, Colorado, pressure changes observed to influence earthquake activity are on the order of 60 bars (RALEIGH ET AL. 1971).

Thus the possibility of increasing seismic activity needs to be considered in geothermal regions where the permeability is low enough that fluid extraction or injection can raise the reservoir pressure, or pore pressure, above the local hydrostatic value. Even in these cases large earthquakes may not be triggered if large regional stresses do not exist or if the reservoir is at depths of less than one or two kilometers. In the latter case stress release may take place as aseismic faulting or creep (SCHOLZ ET AL. 1969). Reducing the reservoir pressure may decrease the number of microearthquakes but it may also mean that tectonic stress will be accumulated and released in a large earthquake at a later date.

No data is available but microearthquakes may be generated by the same principle when hydrofracturing is used to increase permeability around a borehole. If any events occur that are large enough for focal mechanisms to be compiled, the direction of the principle stresses could be determined. Hydrofracturing studies also give data on the amount of pore pressure needed, at a high strain rate at least, to induce fracturing.

Another effect of fluids on fracture is that of stress corrosion (SCHOLZ 1968). In this case « when a brittle material is stressed in a corrosive environment, the high tensile stresses at the tips of cracks accelerate the corrosion reaction there so that the cracks tend to lengthen ». GRIGGS (1967) discusses other types of water weakening.

Conclusions

Microearthquakes appear to be closely related spatially to major geothermal areas. Accurate locations of these earthquakes can provide new data on the locations of active faults that may be channeling hot water toward the surface. The earthquakes may damage structures or change the permeability of fault zones. Development of a geothermal field may in some cases increase or decrease occurrence of events. Thus the occurrence and nature of local microearthquakes should be evaluated in the development of a geothermal field.

Acknowledgements

I wish to especially thank G. A. EIBY, R. R. DIBBLE, L. WHITEFORD, A. L. LANGE, G. CLACY and G. R. ROBSON for providing data and comments when this paper was being compiled. JACK E. OLIVER, BRYAN ISACKS and ROBERT M. HAMILTON

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...cally read the manuscript. Parts of this work were carried ... under Grant GA-1534 from the National Science Foundation. Grant Number 8 from the Arthur L. Day Fund of the National Academy of Science and United Nations Purchase Order 9-20-11471.

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