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DEPARTMENT OF BUSINESS,
ECONOMIC DEVELOPMENT & TOURISM

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DIV. OF WATER & LAND DEVELOPMENT

July 30, 1993

MEMORANDUM

TO: Manabu Tagomori, Manager and Chief Engineer
Division of Water and Land Development

FROM: Dean A. Nakano

SUBJECT: Request for Review and Comment on Two Draft Reports Prepared by GeothermEx, Inc. for the Department of Business, Economic Development and Tourism

The Geothermal Project Office respectfully requests your assistance in reviewing and providing comments on the following revised draft reports prepared by GeothermEx, Inc:

1) "Volcanic Hazards to Geothermal Installations in Hawaii: Experience at Geothermal Fields in Volcanic Island Environments"; and

2) "Induced Seismicity and Ground Subsidence in Developed Geothermal Fields: Relevance to Geothermal Development in Hawaii".

I sincerely appreciate your earlier efforts to review the preliminary draft reports and would like to thank you for your comments, many of which have been assimilated within the enclosed draft reports. Any additional input and/or recommendations that you may have will be greatly appreciated.

Thank you again for your continued assistance and should you have any questions, please contact me at 586-2353.

Enclosure

cc: Maurice H. Kaya

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INDUCED SEISMICITY AND GROUND SUBSIDENCE IN DEVELOPED GEOTHERMAL FIELDS: RELEVANCE TO GEOTHERMAL DEVELOPMENT IN HAWAII

for

STATE OF HAWAII
DEPARTMENT OF BUSINESS,
ECONOMIC DEVELOPMENT AND TOURISM
Honolulu, Hawaii

by

GeothermEx, Inc.
Richmond, California

JULY 1993

DRAFT

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EXECUTIVE SUMMARY

Possible induced seismicity and subsidence from geothermal development in Hawaii are concerns to developers, financial supporters of projects, public health and safety agencies and the public. Induced seismicity and subsidence at geothermal fields have been related to production/injection activities, no numerical in geothermal projects elsewhere but no numerical formulas may be applied. Tectonic, volcanologic and hydrothermal conditions in Hawaii are dissimilar to conditions at most other geothermal fields. Injection, and possibly intense production, at geothermal fields of the Kilauea East Rift Zone (KERZ) may result in low magnitude seismic activity. A complex set of physical conditions that involves altering hydrostatic balance by removal and addition of mass by production and injection wells, as well as the less understood effect of withdrawal of heat content from rocks may affect possible seismicity. Generalizations can be made from the histories of some other geothermal fields reviewed for this study; an objective qualitative analysis of the risk to development in Hawaii can then be made.

Considerations relevant to Hawaiian geothermal development are:

- Rapid dispersal of injected fluid in high-permeability, extensive geothermal fields precludes significant probability of induced seismicity; induced seismicity typically accompanies injection into low- or medium-permeability zones, where pore fluid pressures are increased and fracture shear strength is decreased. Also, the stress field may be changed by cool injectate into fields with low permeability and limited extent.

- In low- and medium-permeability zones, the number of induced earthquakes probably is approximately proportional to the rate of water injection and/or the injection pump pressure.

- Earthquake magnitude does not appear to increase with increases in the volume of injected water or the rate of injection. Individual events have reached magnitudes of as great as 4 in the Geysers area of northern California, and are not expected to reach destructive magnitude or intensity levels.

- The magnitude-frequency distribution of induced earthquakes probably follows an exponential pattern similar to that of tectonic earthquakes.

- The maximum magnitude of induced earthquakes in geothermal fields has been historically lower than that of regional tectonic earthquakes.

- Only a very small fraction of geothermal injection induced earthquakes will be felt. Induced seismicity will be masked by the high level of tectonic and volcanic earthquakes of the region and it may be difficult to distinguish natural from cultural induced seismicity. Induced seismicity will cease almost immediately after injection ceases.

- Production may also reduce normal stress by decreasing volume and cooling fracture surfaces upon <u>in</u>-<u>situ</u> boiling.

Regarding subsidence:

- Controlling variables include fluid phase in the reservoir, percentage of fluid injected back into reservoir, rock permeability and porosity, rock compactability, and the rate of pressure decline within the geothermal system.

- Ground subsidence will be approximately proportional to fluid production, especially for reservoirs where two-phase conditions exist initially or are induced as a result of pressure declines during production.

- Statistically, the rate of ground subsidence has ranged from between one-quarter of an inch to as great as 15 inches per year in some geothermal fields around the world; subsidence depends upon physical characteristics of a region.

- Geothermal systems characterized by moderate to low permeability and porosity, dense, brittle rock, and a relatively high percentage of injection will experience the least amount of ground subsidence, while ground subsidence will be greatest in geothermal fields characterized by highly porous, weakly consolidated and/or highly fractured rocks.

- Spatially, the maximum subsidence will occur at the surface point above the area of maximum pressure decline or maximum conversion to two-phase conditions, and will diminish in amount outwards from that point.

- The size and shape of the area undergoing subsidence, and the distribution of values within the subsiding area, will be a function of the reservoir size, shape and permeability, and the distribution of production and injection wells.

- Injection cannot fully arrest ground subsidence, because usually less than 100% of production probably will be injected, and because of the lag time in pressure communication within the reservoir.

Geothermal fields of the KERZ probably will experience the smaller range of ground subsidence (perhaps one inch or less per year). Indeed, discounting the possible small effect of production from well HGP-A, it appears that natural subsidence has been occurring at about 0.5 inches per year across the well field area during the 1980s. In the KERZ, subsidence from geothermal production will be partly masked by changes in surface elevation resulting from tectonic rifting, magma intrusion into fractures, flows of lava resulting from volcanic eruptions and natural fault subsidence on the south, unbuttressed side of Mauna Loa and Kilauea volcanoes.

Conditions approximately similar to those in Hawaii may exist at geothermal fields in Iceland and Djibouti. Conditions in Hawaii and case histories of induced seismicity and subsidence at The Geysers, California; Wairakei, New Zealand; Hengill and Svartsengi, Iceland and Landarello, Italy are considered in this report.

At present, it is recommended that induced seismicity and ground subsidence in Hawaii be carefully measured against the high level of tectonic "background" activity. To understand this tectonic background better, it is useful to continue the cataloguing and analysis of the tectonic and volcanic earthquakes that occur regularly in the KERZ, as well as maintaining levelling measurements. DBEDT is currently supporting continuing measurements of subsidence by Dr. J. Anderson of UH/Hilo in the lower East Rift Zone.

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INTRODUCTION

Geothermal fields are located mostly at crustal plate boundaries and at intra-plate rifts and hot spots, and typically experience a higher level of earthquake activity than do places located within the stable plate interiors, far from boundaries, hot spots and rifts. These are tectonic earthquakes, that serve to release the strain that continually accumulates when plates move against each other and deform internally. This strain release often is destructive of man's works, while at the same time modifying the local topography. Modifications to topography may include horizontal and vertical offsets, landslides and soil liquefaction and, occasionally, the formation of open fissures. Seismic shock waves traveling through large bodies of water can generate tsunamis and seiches that in turn cause shoreline erosion.

Ground subsidence also can occur naturally, with or without the accompaniment of earthquakes, in response to tectonic processes. Mechanisms include basin downwarping, block rotation and downdrop, and magma withdrawal from shallow chambers.

In addition to these natural tectonic processes, there are cultural processes that have the possibility of inducing earthquakes or ground subsidence. Because of their potentially destructive effects, it is important to determine under what conditions and to what degree these processes operate in geothermal fields. The purpose of this study and report is to investigate and use the experience gained from development of geothermal resources at comparable islands and similar volcano-tectonic environments to assist development and appropriate regulation in Hawaii relative to seismicity and subsidence.

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CAUSES OF INDUCED SEISMICITY AND GROUND SUBSIDENCE

The injection of fluids into underground reservoirs, and under certain circumstances the withdrawal of fluids from an underground reservoir, have the potential to cause earthquakes. This is true whether the fluid is cold water, hot water, steam, natural gas, oil, or even treated sewage. The withdrawal of fluids from underground oil, gas or water reservoirs also can cause the ground surface to subside, especially in highly fractured, porous and/or poorly consolidated rocks where the voids left by fluid withdrawal are closed by compaction.

Both seismicity and subsidence may result from causes other than the withdrawal/injection of fluid, and it is sometimes difficult to distinguish between the natural and the induced causative factors. In addition to on-going tectonic processes, and to fluid withdrawal/ injection, seismicity may be due to natural volcanic activity (the movement of magma towards the surface), or to the artificial ponding of large volumes of water behind dams. Earthquakes associated with deep magmatic activity typically have a different seismic wave signature than earthquakes caused by tectonic processes, injection/withdrawal or water-loading. However, the signatures of the other types of earthquakes often are identical.

Subsidence may be due to tectonic processes, or may be caused by such non-tectonic factors as overproduction from an aquifer, the compaction of loose, dry soils during irrigation, the ponding of water behind dams, and the progressive lowering of the water table as a result of persistent drought. This, again, may occur with or without earthquake accompaniment.

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MECHANISMS OF INDUCED SEISMICITY IN GEOTHERMAL FIELDS

Significant quantities of data now are available from several geothermal fields, representing a very wide range of geologic and operational conditions. Seismicity has been noted at certain fields almost immediately upon the onset of production and injection, but at others only after the passage of considerable time (weeks or months).

Various mechanisms have been proposed to account for this sudden increase in seismicity or microseismicity (smaller earthquakes, with Richter magnitudes ranging between -1.0 and 3.0). These increases have occurred either in many-year-long "steps", or as discrete pulses; and across a spectrum of conditions, from fields where no seismicity had been recognized previously, to fields in zones of strong seismic activity.

All of the proposed mechanisms involve a change in the response of reservoir rocks to the ambient tectonic stress and deformation fields. These mechanisms are based on the presumption that the state of stress in reservoir rocks was very near the failure condition prior to field development. The processes leading to induced seismicity fall into three major categories:

1. decrease of fracture shear strength, resulting from an increase in pore-fluid pressure;
2. increase of fracture shear strength, as a result of decreased pore pressure, increased normal stress, or mineral deposition in fractures; and

3. increase or decrease of shear stress on fractures, because of increased or decreased vertical stress (most likely due to water loading or unloading over the reservoir).

4. Cooling of rock immediately adjacent to fractures from production that causes flashing of fluid to steam in the reservoir.

The first mechanism can increase the frequency of occurrence of seismic failure on small, pre-existing faults under an ambient stress field. The second may cause a change of regime from a seismic plastic deformation ("creep") to one of seismic brittle failure. The third mechanism appears to have limited application to known cases of induced seismicity in geothermal fields.

The specific mechanisms by which seismicity can be induced in a geothermal reservoir have been summarized in Eberhart-Phillips and Oppenheimer (1984) and reviewed by Stark (1990). They are as follows:

Injection-induced

1. Increased pore pressure, resulting from fluid injection, causes a decrease of effective normal stress across fractures in the geothermal reservoir. According to the well-known Hubbert-Rubey theorem, this phenomenon may induce brittle fracture along fractures or small faults. This results in the occurrence of small earthquakes, under the ambient stress field. (Effective normal stress is defined as normal stress minus pore pressure.)

2. Cooling of rock immediately adjacent to fractures in and above the geothermal reservoir, probably because of the downward penetration of the cool injectate, reduces the normal stress in and above the reservoir to some critical value. This failure mechanism is also described by the Hubbert-Rubey theorem.

3. Loading of injectate into aquifers overlying the geothermal reservoir increases the vertical component of stress, and hence the shear stress acting across dipping fractures. This perturbation may induce small earthquakes.

Production-induced

4. Volume decreases throughout the geothermal reservoir, as a result of cooling of fracture surfaces, especially if in situ boiling occurs, may reduce the normal stress, with induced seismic effects, as described in 2, above.

5. Volume decreases throughout the geothermal reservoir, resulting from withdrawal of geothermal fluid, may perturb stresses, in ways not yet defined, so as to induce seismicity.

6. Increased shear strength as a result of mineral deposition (silica, calcite, sulfide minerals, etc.) in fractures, pores or other voids during production or during phase separation of the geothermal fluid, may allow a change of regime from a seismic creep to brittle failure with accompanying seismicity.

7. Increased shear strength within the geothermal reservoir resulting from the closing of fractures by compaction, due to

fluid production and lowered water levels in the reservoir, allows shear stress to build up to seismogenic levels.

8. Declines in geothermal reservoir temperature and pressure, due to continued fluid production, increase the shear strength of the reservoir rocks, with resulting seismicity as described in 6, above.

It has been conjectured by Kauahikaua and Moore (1993, in press) that intense heat withdrawal rates may significantly drop the temperature of rock adjacent to producing fractures. If the producing fractures are also potential magma conduits then the conduits may be cooled below melt temperature at depth and require new dike material to ascend forcefully, i.e. cause seismic events. These changes would occur over long time periods and the seismic events would have subordinate effects to actual eruptions of magma.

It can be seen that several of these proposed mechanisms are mutually contradictory, citing injection on the one hand and production on the other as the principal mechanism of induced seismicity. Probably this contradiction is more apparent than real: geothermal reservoirs differ widely in permeability, enthalpy, fluid phase, existing stress field, pre-existing seismicity, and patterns, methods, rates and duration of fluid production and injection.

The most widely held belief is that the Hubbert-Rubey theorem (increased pore pressure as a result of injection) is the causative agent where injection is practiced. Where there is no injection, or where there is only limited injection testing, the mechanisms of production-cooling, volumetric change, and increased frictional strength may each operate to some degree in individual fields. However, the cases wherein seismicity has resulted exclusively from production are fewer in number than those where injection also takes place, and are less in level of seismic activity.

By contrast, the Icelandic and Hawaiian rifts, and perhaps that of Djibouti, appear to be characterized by linear, narrow zones of high permeability, within wide regions of low to moderate permeability. Kauahikaua (1993, in press) has pointed out that the KERZ is a narrower structure than that near Krafla and that seismic events may therefore be more concentrated in the KERZ. Tectonic seismicity is high, and induced seismicity is likely in response to sustained injection. The absence of induced seismicity probably reflects the absence of long-term injection activity.

It is difficult to generalize further about the absence of injection-induced seismicity because, as mentioned earlier, no two fields exhibit identical production or injection conditions.

GEOTHERMAL FIELD CHARACTERISTICS AND CASE HISTORIES

Fields with Induced Seismicity

The Geysers, California

A strong correlation has been observed between seismic activity and the injection of residual geothermal fluid at The Geysers geothermal field (Stark, 1990); to some unknown but probably lesser degree, seismic activity also can be correlated with production of geothermal steam (Stark, 1990; Peterson *et al.*, 1992).

The Geysers field is a vapor-dominated, two-phase system, characterized by fractured zones of relatively high porosity and permeability within a regionally low-permeability suite of highly indurated rock. Communication between the reservoir and the surrounding rocks appears to be very limited. Thus, The Geysers may represent the best well-studied analogy to the KERZ.

Injection of steam condensate began in 1968, has continued uninterrupted to date, and has dramatically increased in volume as the level of power production has increased through the years. Currently about 30% of produced steam is injected as condensate. This is equivalent to about 3,000 tons per hour of water. At the peak of production from The Geysers (1987-88), some 4,500 tons per hour were injected. Additional make-up water is being sought, to allow a higher total quantity of injection.

Based on his study of 14 years of production and injection data, Stark (1990) concluded that there is ". . . good spatial and temporal correlation between injection and microearthquake (MEQ) activity . . ." at The Geysers, regardless of whether injection is by gravity flow or by means of positive pump pressure. The spatial correlation is "not simple," although the clustering of MEQ (especially the deeper-focus MEQ) around injection wells is noted. Temporally, there is typically a time lag of days to weeks between the beginning/ending of injection and that of seismicity begins/ends.

The largest seismic event identified by Stark (1990) during this 14-year period had a Richter magnitude of 4.0. This was strong enough to be felt locally, but caused no damage. The vast majority of the many thousands of recorded events were too small to be felt by people. One measure of the rate of occurrence is that there are approximately 10 MEQ per day of magnitude 0.5 or less, and "several" events annually with magnitude 3.0 or greater.

Stark (1990) did not offer much support to the earlier conclusion of Eberhart-Phillips and Oppenheimer (1984) and Oppenheimer (1986) that geothermal steam production (rather than injection) is a principal cause of induced seismicity at The Geysers. Stark did acknowledge that production and tectonic activity both probably caused some of the MEQ recorded at The Geysers, but offered no numerical estimates. He also concluded that steam-production zones could be defined by the earthquake-distribution patterns, and that this might have a future use in estimating reservoir thickness and in determining steam flow paths within the reservoir. No single mechanism for inducing earthquakes at The Geysers is endorsed by Stark (1990) or Eberhart-Phillips and Oppenheimer (1984).

Focal depths of MEQ (Peterson *et al.*, 1992) range between about 5,000 and 20,000 feet, with clusters at 10,000 to 15,000 feet deep.

This is deeper than the reservoir across most of the field. Peterson *et al's* analysis of the travel times and velocities of P and S waves indicates that the degree of steam saturation within the reservoir varies widely with location. This is confirmed by pressure data from production wells. Based on this, Peterson *et al.* (1992) propose using microearthquake data to calculate the remaining steam reserves.

Tectonic earthquakes of a non-injection origin are common and widespread across that part of the northern California Coast Ranges within which The Geysers geothermal field is located (figure 2). Several historic earthquakes have exceeded Richter magnitude 5.5, and the maximum potential magnitude is still greater (on the order of 7.0 or slightly greater). These values greatly exceed the 4.0 maximum observed during 14 years of monitoring injection at The Geysers. Therefore, the conclusion is that microseismicity resulting from injection presents no additional risk to life or to structures, and that it may be of use in modeling reservoir performance or in siting future wells.

Wairakei, New Zealand

Although the Wairakei geothermal system exhibits high temperature, the analogy to geothermal reservoirs of the KERZ is not very strong. Unlike the KERZ, geology is not homogeneous, and the layered volcanic and sedimentary rocks exhibit widely different chemical and physical properties, including permeability and compactability. Production has gone on for over 30 years, but without injection during almost the entire period. As a result, the initial hot-water reservoir has developed a steam cap, in response to continued lowering of the water table and the field pressure.

Environmental considerations and concern over the declining field pressure have led to two episodes of injection testing at Wairakei, in 1984 and in 1988-89. The results from these two injection tests were strikingly different, and therefore have some relevance, despite the lack of close analogy to the KERZ.

In the 1984 test, as much as 668 tons per hour of fluid was injected into a zone at approximately 4,400 feet in depth, at pressures as high as 500 psig (Hunt *et al.*, 1990). Hydrofracturing of the reservoir rocks is inferred to have occurred, based on sudden increases in injectivity ("jumps"). Seismic activity began almost at once across an area of several square miles; the induced seismic activity stopped at once when the injection test was halted after several months. Hunt *et al.* (1990) conclude that the injection test had taken place into a zone of low permeability, rather than into an open fracture as had been hoped.

By contrast, the 13-month test conducted in 1988-89 resulted in no seismic activity greater than the approximately 4 MEQ per month of the natural state (Hunt *et al.*, 1990). No clustering of events occurred. Up to 570 tons per hour of fluid was injected at about 75 psig, into a highly permeable pumice zone located at about 1,500 feet in depth. The resulting measurements of pressure at nearby wells indicated rapid communication over a relatively large area.

From this it is concluded that the careful selection of highly permeable zones for injection in a widely heterogeneous reservoir, such as Wairakei, may prevent hydrofracturing of rock and thus prevent induced seismic activity. It is recognized, however, that the advanced state of depletion of the Wairakei reservoir, after nearly 30 years of operation without significant injection, may contribute to this absence of induced seismicity. If injection had began in the initial production year, the results of seismic monitoring might have been different. Significantly, no production-induced seismicity was reported during this 30-year production period.

Hengill, Iceland

The Hengill geothermal area represents a possible analogue to the KERZ of Hawaii. Both are areas of active fissuring, with the most recent rifting event at Hengill occurring in 1789. Both areas are characterized by locally high permeability within the rift zone, and by relative low communication in the natural state with the adjacent less-fractured basaltic terrain. In each case there has been the construction of a central volcanic edifice, although differentiation to silicic end products has occurred at Hengill. The most recent major eruptive series there is dated at about 2,000 years before present.

Exploratory drilling and development of high-enthalpy hot-water fields at Nesjavellir and Hveragerdi has gone on for over three decades (Thorhallson, 1988), despite the evident possibility of renewed volcanic or rifting activity. Microseismic activity has been "continuous" throughout this period. It is uncertain whether geothermal field operations have induced any of this seismic activity. It should be noted that no injection takes place at Hveragerdi; and that only two wells have been used intermittently for injection at Nesjavellir, and these only during the past decade. Instead, it is concluded that the cause of the earthquake activity is the cooling and contraction of intrusive bodies located at depths of about 3 to 4 miles. The cooling, in turn, supposedly reflects the quenching effect of the deep circulation of cold water within permeable fracture zones.

There is very little published information on earthquake magnitude, frequency, spatial or temporal distribution, or possible relationship to the on-going geothermal field development and operation in the Hengill area. Additional data should be obtained for comparison with the KERZ and for possible predictive use as development proceeds in Hawaii.

Hot Dry Rock Experiments

Because parts of the KERZ exhibit low permeability, and because very high temperature is found at relatively shallow depth, in future years there may be attempts to explore and develop hot dry rock (HDR) geothermal resources. In this type of operation, wells are drilled into zones of known low permeability, and fractures are created between couplet wells by the injection of water under high pressure. Water pumped into the first well circulates along these hot fractures, and steam is produced from the second well. Cooling of the rock by continued forced circulation results in further fracture formation.

This is virtually certain to induce seismicity. Induced seismicity has been reported from HDR experiments in the United States, France, Japan, Germany and England. However, the experiments appear to show that HDR production is not economically feasible. The Department of Energy is reported to have stopped funding of HDR experiments in 1993 and it is unlikely that HDR development will be promoted in the KERZ.

Because emphasis has been on the "success" of creating new fractures, and on tracking fluid movements between wells, relatively little attention has been given to the induced seismic events except as evidence of this successful fracturing. However, the induced seismicity is referred to in passing in an extensive published literature. A few examples are:

During a 70-hour injection experiment in a well drilled into granite at Le Mayet de Montagne HDR site, France (Cornet and Yin, 1992), about 100 MEQ were induced. Of these, 46 occurred when the injection was increased from approximately 30 tons per hour of water to about 75 tons per hour. The earthquakes were located within a tight cluster horizontally, but widely dispersed vertically. Cornet and Yin (1992) concluded that induced seismicity is a function of injection flow rate and pressure, and of the degree of induced fracturing, itself a function of system permeability. No information was provided on earthquake magnitudes; it is assumed herein that all were microearthquakes, below the felt earthquake threshold.

Beauce *et al.* reported 135 and 239 induced MEQ in response to HDR injection at rates of approximately 75 and 150 tons per hour of fluid in a hole at Soultz, France, also in granite, at 4,300 to 6,600 feet in depth. Seismicity began almost immediately, and progressed directionally as fracturing spread during the two 50-hour tests. Injection pressure appears to have exceeded 4,000 psig during the test at the higher flow rate. Here, again, seismicity is a function of injection flow rate and pressure, and no data are reported on magnitude distribution.

At Fenton Hill HDR site, New Mexico, large swarms of microearthquakes have been measured in connection with hydrofracturing between couplet wells. In one example, over 600 events are reported from one such test, having a magnitude distribution between Richter -3.0 and 0.0 (Robinson, 1991). A total of over 11,000 induced microearthquakes have been recorded at Fenton Hill (Fehler *et al.*, 1991).

These events are far below the felt threshold for people; however, larger-magnitude events may occur if significant quantities of fluid are injected at high pressure for prolonged periods into previously unfractured rock. The combination of high-injection pressure and cooling of the host rock as a result of continued injection, may result in continued or even increased seismicity. Seismicity probably will not cease as long as injection continues to progressively fracture the rock.

Other Areas

Microseismicity is reported to be related to production and/or injection of geothermal fluids at Larderello and Travale, Italy; Tongonan and Puhagan (Palimpinon), the Philippines; and possibly elsewhere. These fields have geologic and reservoir conditions significantly different from those of the KERZ.

In the Larderello-Travale area (Batini *et al.*, 1985), thrust-faulted sheets of sedimentary rock overlie a metamorphic basement. Steam production comes from a highly fractured evaporite sequence. Over 1,000 earthquakes were recorded between 1978 and 1982, ranging in magnitude from 0.0 to 3.2. Epicentral depth generally is less than 5 miles. The greatest concentration of epicenters is outside of the area of geothermal development, probably related to structures in the regional basement.

Some correlation is observed between the productive field and seismicity. The number of earthquakes increased almost in direct proportion to increases in the rate of fluid injection; however, there was no increase either in the maximum magnitude recorded or in the average magnitude of events (figure 3). The maximum magnitude of future events, therefore, probably will depend upon the regional structural and dynamic conditions, regardless of the quantity of fluid to be injected (Batini *et al.*, 1985).

The Asal geothermal area of Djibouti is covered by a seismic network installed over a decade ago to monitor tectonic activity at the Red Sea-Ethiopian Rift triple junction. Thousands of earthquakes have been recorded. If field development at Asal proceeds beyond the initial drilling and testing phase already accomplished, a parallel to the Hawaiian KERZ will thus be available for comparative monitoring and modeling.

Natural seismic activity occurs at several other fields, usually in association with rifting or subduction. It is reasonable to assume that some induced seismicity accompanies fluid injection at one or more fields. To date there have been no reports of damage to the field installations or to other property as a result of increased seismicity at any of these fields.

Fields Without Induced Seismicity

There is no compelling evidence of induced seismicity at several of the world's major geothermal fields. At Krafla and Svartsengi, Iceland, Cerro Prieto, Mexico and Olkaria, Kenya the probable reason why there has been no induced seismicity is that there has been no long-term injection of residual geothermal fluids. However, the background seismicity is high in the Icelandic fields (figure 1) and in the Cerro Prieto area, and there is a possibility that some level of induced seismicity accompanies production but has gone unnoticed at one or more of these fields.

At other geothermal fields where injection has occurred in quantity, there may be no induced seismicity because field permeability is sufficiently high, or because a combination of adequate permeability and low rates of fluid injection precludes the significant buildup of pore pressure during injection. Ahuachapán, El Salvador appears to be an example of the latter. The neighboring field of Chipilapa, El Salvador also experienced no induced seismicity during several short periods of injection testing (Fabriol *et al*., 1992).

Other fields with no reports of induced seismicity during injection operations or during short-term injection testing include: Ohaaki, New Zealand (Clotworthy *et al*., 1989), and Otake and Hatchobaru, Japan (Inoue and Shimada, 1985). Here, also, it is suggested that the absence of induced seismicity reflects the high degree of local permeability and the limited quantity of injectate. However, future injection and monitoring may result in a different conclusion.

The fields described above in Mexico, El Salvador, New Zealand and Japan are characterized by layered geology, volcanic and sedimentary, in which there is significant variation in permeability layer by layer; individual permeable units appear to have broad areal extent in most of these fields. This may allow injection to occur without significant increase in pore pressure, as the injected fluid spreads rapidly over a wide reservoir area. It remains unknown if long-term injection in highly permeable, areally extensive fields will lead to an increase in pore pressure sufficient to induce seismic activity.

Hawaii

Geothermal fields of the Kilauea East Rift Zone (KERZ) appear to be characterized by high-enthalpy fluid; local development of steam saturation conditions; highly indurated, largely homogeneous rocks; low regional permeability, with local high-permeability pockets associated with specific fractures; and with a moderate to low degree of horizontal communication between the reservoir zone and the ocean. Thus, the best analogies to geothermal development in the KERZ are to be sought in low- to moderate-permeability geothermal fields containing high-enthalpy fluid, preferably representing two-phase reservoirs or reservoirs in which two-phase conditions develop during years of production, in highly indurated, vertically fractured rock.

The level of natural seismicity in the KERZ resulting from tectonic and volcanic processes is among the world's highest. Many thousands of seismic events have been recorded at the Hawaiian Volcano Observatory, with Richter magnitudes ranging from below the threshold of detection up to at least 7.0. Within the KERZ, earthquake activity is believed to be related to the wedging open of the fractures to accommodate dike intrusion and to intrusion of magma into individual fissures, similar to Iceland and Djibouti. Some of the larger-magnitude earthquakes have caused damage or injury, and the potential exists for future damaging earthquakes in the KERZ in response to continued rifting.

In contrast, no set of earthquakes has been identified specifically with the HGP-A production or with subsequent production/injection testing in other parts of the KERZ. This does not preclude induced seismicity. Induced seismicity is likely to occur in the future, if it is not already occurring, as geothermal development proceeds and injection is practiced on a commercial scale. However, based on the high frequency and magnitude of natural earthquakes in the KERZ, and given the experience in other geothermal fields (see below), any geothermally induced earthquakes are likely to be of such magnitude as to present no additional risk to life or structures.

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CASE HISTORIES OF INDUCED SUBSIDENCE IN GEOTHERMAL FIELDS

Three case histories in which ground subsidence has occurred are described in the following sections. These cases represent very different geologic and tectonic settings and reservoir characteristics. Only the first case can be considered to be approximately analogous to the KERZ, and even in this first case there has been no long-term injection of residual geothermal fluids. The other cases are presented to provide a broad picture of the ground subsidence in other settings and under other conditions of production and injection.

Svartsengi, Iceland

Located in a seismically active oceanic rift, and characterized by basaltic volcanism, Svartsengi (figures 1 and 4) is a close analogue of the KERZ. The hot-water reservoir has an average temperature of nearly 240°C; fluid is produced for electric-power generation (11.6 MW) and for space heating purposes, at a combined total rate of about 900 tons per hour (Bjornsson and Steingrimsson, 1992). Since production began in 1976, some 80 million tons of fluid have been produced. Production has resulted in a pressure decline of about 320 psig, which in turn has led to the development of a steam cap at the upper surface of the reservoir. Pressure currently is declining at about 18 psig per year. As mentioned earlier, injection of residual fluids is not practiced.

The reservoir is located at depths greater than 2,000 feet, in highly fractured and locally high-permeability basalt flows, intrusive dikes, and submarine glassy rubble (hyaloclastite). The production well field covers an area of less than one-half square mile. Permeability is calculated to be 100 to 150 millidarcies in the principal fracture zones. Injection of cooled geothermal fluid (167°F) takes place without significant impact on the reservoir: neither induced seismic activity nor permanent cooling is observed (Bjornsson and Steingrimsson, 1992).

Subsidence has occurred as a result of production and pressure declines. The exact mechanism is not identified, but compaction of hyaloclastite beds is suspected. An elliptical figure 6 by 5 miles in area, centered on the wellfield, is subsiding at a rate of nearly 0.1 inch per year, and a central zone whose long diameter is approximately 1.3 miles in length is subsiding at almost one-half inch per year (Bjornsson and Steingrimsson, 1992). To date, the maximum total subsidence has been about 6 inches. Subsidence is expected to continue.

In this area of rough topography, subsidence has not yet become a significant matter. There are as yet no reports of significant disruption of pipelines, foundations or other structures. Over a presumed 30-year productive field life, using the maximum reported subsidence rate, up to one foot of ground subsidence can be anticipated. This has the potential to disrupt certain delicately balanced equipment and facilities. However, because of the slow rate of annual change, facilities can be jacked, realigned and re-leveled in sufficient time to avoid disruption. For example, in the Krafla field, where tectonic block rotation has caused up to 3 feet of tilting across the wellfield and one inch of tilting within the power plant (Thorhallsson, 1988), engineering technology has been utilized successfully to keep all facilities in operation.

Larderello, Italy

As described elsewhere in this report, the Larderello reservoir consists principally of fractured evaporate beds that unconformably overlie a metamorphic basement complex, and that in turn are overlain unconformably by other sedimentary and metasedimentary rocks. No active rifting or volcanism is known; there is continuous regional seismic activity of tectonic origin (Dini and Rossi, 1990). Thus the area geologically is quite unlike the KERZ.

The two-phase Larderello reservoir produces steam. Production, which began over 80 years ago, has resulted in extensive pressure declines across the field. Seismic activity has been observed to increase nearly in direct proportion to the quantity of injection, leading to the conclusion that injection induces seismicity (Batini *et al.*, 1985). The areas of maximum fluid withdrawal from the reservoir, and of maximum pressure decline, also are characterized by significant ground subsidence. This has led to the conclusion that subsidence is non-tectonic, and occurs in response to production from the reservoir (Dini and Rossi, 1990). The first several decades of field development were characterized by steam production without injection of steam condensate, principally because the turbine-generators were of the non-condensing type, and steam was evaporated to the atmosphere. It is only in the last twenty years that injection has been carried out in significant amounts, as condensing turbine-generators have been introduced into the field.

During the 65-year period 1921-1986, a series of precise leveling surveys was run, utilizing some 120 miles of survey lines. Subsidence of about one foot was calculated across a roughly linear NE-trending zone about 9 miles in length. The maximum subsidence, approximately 67 inches, was measured in a 2.5-mile-long section of the longer zone. This averages about one inch per year within the zone of maximum subsidence (Dini and Rossi, 1990). No reports are given of damage to facilities as a result of as much as 5-1/2 feet of total ground subsidence. The rate of subsidence appears now to be diminishing or even ceasing, although this is not fully documented.

The cause of subsidence is believed by Dini and Rossi (1990) to be compaction of both reservoir rocks and overburden, the former in response to fluid withdrawal and pressure declines. Compaction of the overburden is attributed to lowering of the local water table, perhaps related to pressure declines in the reservoir. This presupposes communication between reservoir and overburden.

Wairakei, New Zealand

The Wairakei geothermal system consists of a layered sequence of volcanic and sedimentary rocks, located in a region of Quaternary volcanism and tectonic activity probably resulting from plate subduction. This is quite different geologically from the KERZ. The hot-water reservoir has developed a two-phase cap in response to steep declines in pressure that developed during 30 years of production. During almost that entire period there was no injection of residual fluids. The results of two relatively short-term injection experiments at Wairakei are described elsewhere in this report: seismicity was induced only by injection under high pressure into a low-permeability rock sequence.

Careful measurements over a period of years (Allis, 1990) have shown that ground subsidence has been both intensive and widespread. A maximum of 38 feet of subsidence is recorded. This is equivalent to almost one foot per year on average. The rate of subsidence increased from zero in the initial year of production, to over 17 inches per year in the 1970s, decreasing to 13 inches per year by the late 1980s. Within a central area of almost one square mile, subsidence still averages 2 inches per year.

A pond of over one-half square mile in area has formed at the center of subsidence, as the result of subsidence-induced damming of a stream that flowed through the field area. A zone of tension fractures is reported to have formed at the outer subsidence boundary (Allis, 1990). Drains and pipelines within the field are reported to have been affected. No impact on the power plant or other major facilities is reported.

Subsidence is believed (Allis, 1990) to have occurred in response to compaction of a pumice breccia horizon near the top of the reservoir, located at about 500 feet in depth, sandwiched between lacustrine mudstone layers. The rate and total amount of subsidence are broadly proportional to the annual rate and total amount of pressure decline at the top of the reservoir. In addition to the production-induced subsidence, tectonism results in a block rotation ("tilt") of perhaps one-fifth of an inch annually across the entire field. Tectonic tilt is expected to continue, at some unknown rate, indefinitely. Induced subsidence, although greatly reduced in magnitude in recent years, also may continue at the present diminished level as long as production continues at current levels at Wairakei.

DISCUSSION AND CONCLUSIONS

Although induced seismicity and subsidence at geothermal fields in various parts of the world are seen to be related to production/ injection activities, no numerical expression clearly defines the relationship. Furthermore, these disparate fields do not clearly reflect the tectonic, volcanologic and hydrothermal conditions in Hawaii. It can be concluded that injection (and possibly production) at geothermal fields of the KERZ can result in seismic activity. The activity may be in the form of an increased number of microseisms and/or low magnitude seismic events. Several qualitative generalizations can be made:

Regarding seismicity:

- Controlling variables include stress field, permeability, pore fluid pressures, rate and volume of injection, pressure of injection, natural volcanism, strain buildup and mineralization in fractures.

- In geothermal fields where there is no injection of residual geothermal fluid, induced seismicity has not yet been proven to occur.

- High-permeability geothermal fields of broad areal extent probably do not experience a significant level of induced seismicity even if injection occurs, because the rapid dispersal of injected fluid precludes the strong build-up of pore pressure.

- Induced seismicity typically accompanies injection into low- or medium-permeability zones.

- In low- and medium-permeability zones, the number of induced earthquakes probably is approximately proportional to the rate of water injection and/or the injection pump pressure.

- Earthquake magnitude probably does not increase with increases in the volume of injected water or the rate of injection.

- The magnitude-frequency distribution of induced earthquakes probably follows an exponential pattern similar to that of tectonic earthquakes.

- Historically, the maximum magnitude of induced earthquakes in geothermal fields has been lower than that of regional tectonic earthquakes, perhaps because the shear stress does not build up to the magnitudes observed in adjacent cooler terrain, or because the stress field is relatively inhomogeneous. There is no evidence from any geothermal field that this condition (induced earthquakes being smaller in magnitude than regional tectonic earthquakes) will change with time.

- Induced seismicity always accompanies the hydrofracturing activities of HDR injection tests.

- Only a very small fraction of the induced earthquakes will be felt. Induced seismicity will be masked by the high level of tectonic and volcanic earthquakes of the region. Individual events have reached magnitudes of as great as 4, and are not expected to reach destructive magnitude or intensity levels.

Induced seismicity will cease almost immediately after injection ceases.

Regarding subsidence:

- Controlling variables include fluid phase in the reservoir, percentage of fluid injected back into reservoir, rock permeability and porosity, rock compactability, and the rate of pressure decline within the geothermal system.
- Ground subsidence will be greatest in geothermal fields characterized by highly porous, weakly consolidated and/or highly fractured rocks.
- Ground subsidence will be approximately proportional to fluid production, especially for reservoirs where two-phase conditions exist initially or are induced as a result of pressure declines during production.
- The rate of ground subsidence has ranged from between one-quarter of an inch to as great as 15 inches per year in some geothermal fields around the world; subsidence depends upon many variables. The greater rates of subsidence are related to intense production in regions where, unlike Hawaii, there are thick sections of saturated sediments.
- Geothermal systems characterized by moderate to low permeability and porosity, dense, brittle rock, and a relatively high percentage of injection will experience the least amount of ground subsidence.

- Spatially, the maximum subsidence will occur at the surface point above the area of maximum pressure decline or maximum conversion to two-phase conditions, and will diminish in amount outwards from that point.

- The size and shape of the area undergoing subsidence, and the distribution of values within the subsiding area, will be a function of the reservoir size, shape and permeability, and the distribution of production and injection wells.

- Injection cannot fully arrest ground subsidence, because usually less than 100% of production probably will be injected, and because of the lag time in pressure communication within the reservoir.

Based on these conclusions, geothermal fields of the KERZ probably will experience the smaller range of ground subsidence (perhaps one inch or less per year). This will likely be masked by changes in surface elevation resulting from tectonic rifting, magma intrusion into fractures, and flows of lava resulting from volcanic eruptions. Additionally, the rolling topography, locally dense vegetation, and locally thick soil development may make ground subsidence more difficult to recognize or to differentiate from tectonic/volcanic effects. The extreme conditions of subsidence observed in Wairakei, or even those of Larderello, are very unlikely to occur in the KERZ.

As discussed elsewhere in this report, conditions approximately similar to those in Hawaii may exist at geothermal fields in Iceland and Djibouti. Additional data on the history and current state of geothermal operations in these fields may prove instructive over time, especially data relating to: injection practices, changes in production or injection with time, monitoring systems, impacts upon cultural works or upon the environment, and impact mitigation (if any).

At present, no specific measures are recommended for implementation or evaluation regarding induced seismicity or ground subsidence in Hawaii, given the relatively low level of anticipated impact and the very high level of tectonic "background" activity. To understand this tectonic background better, it is useful to continue the cataloguing and analysis of the tectonic and volcanic earthquakes that occur regularly in the KERZ, and the surveying of the land surface to measure the rate of subsidence.

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FIGURES

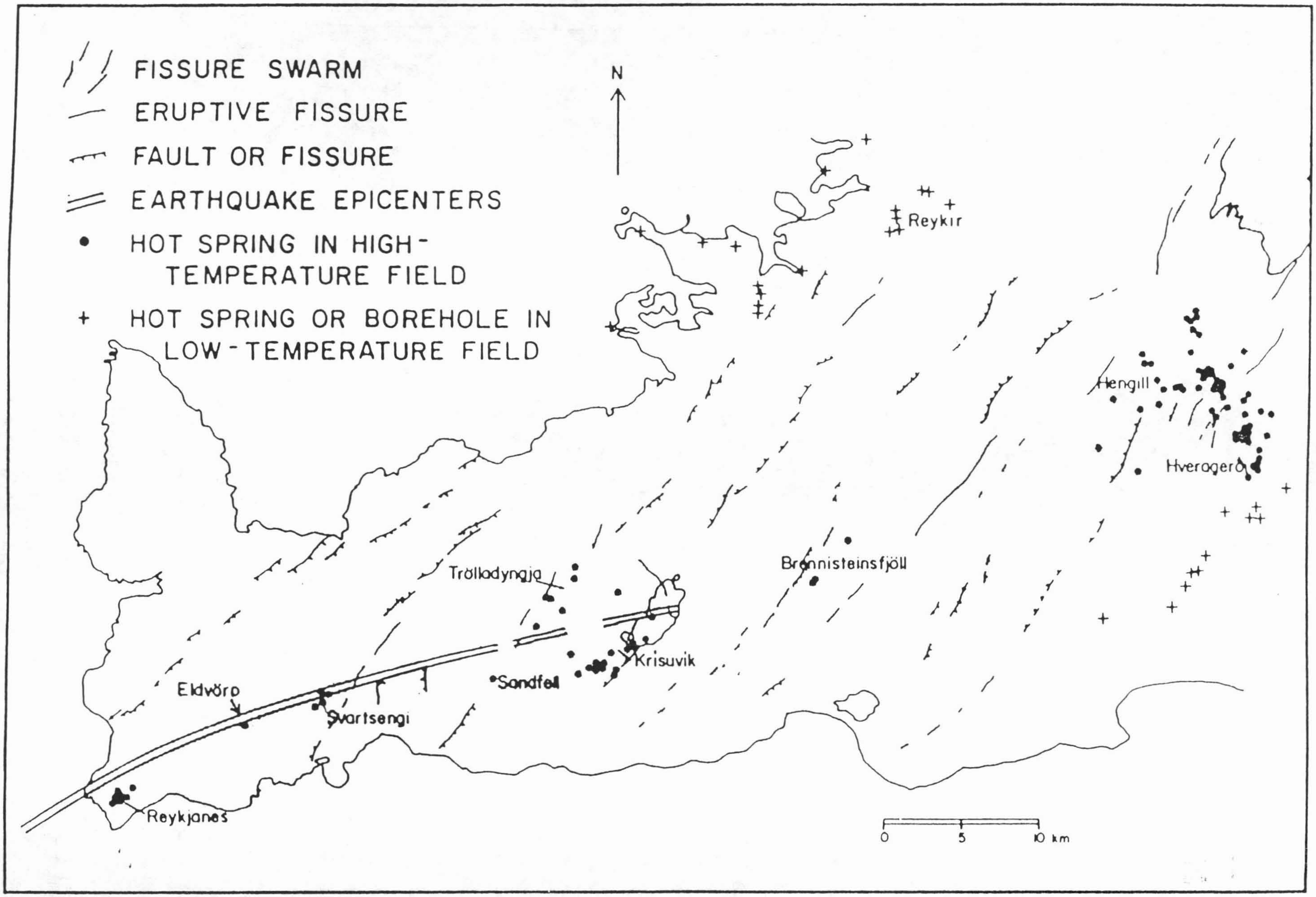

Figure 1. Geothermal features of the Reykjanes Peninsula, showing the Svartsengi and Hengill field areas in relation to rifts and the zone of high seismicity.

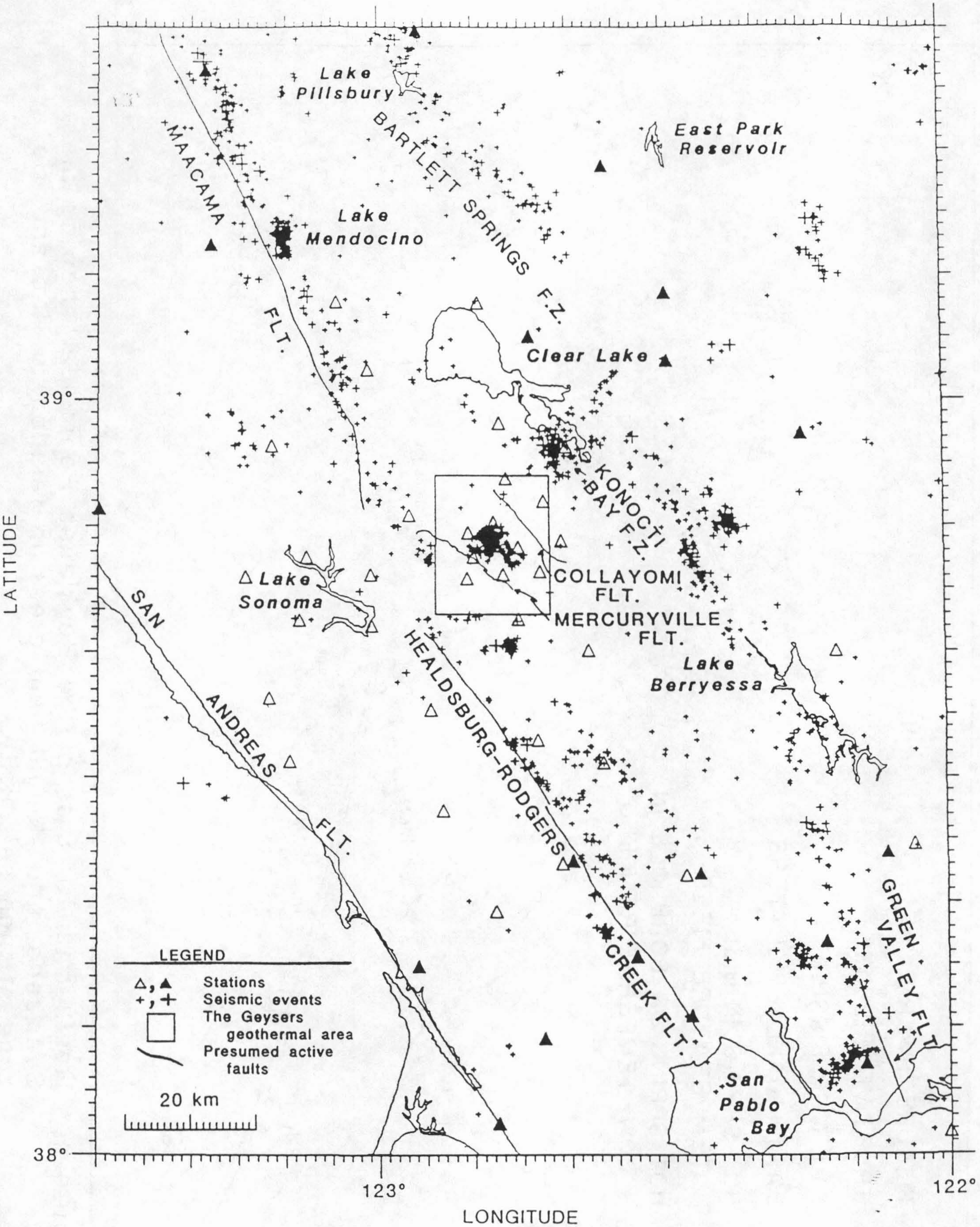

Figure 2. Seismicity of The Geysers geothermal area within the seismically active northern California Coast Ranges (Oppenheimer, 1986).

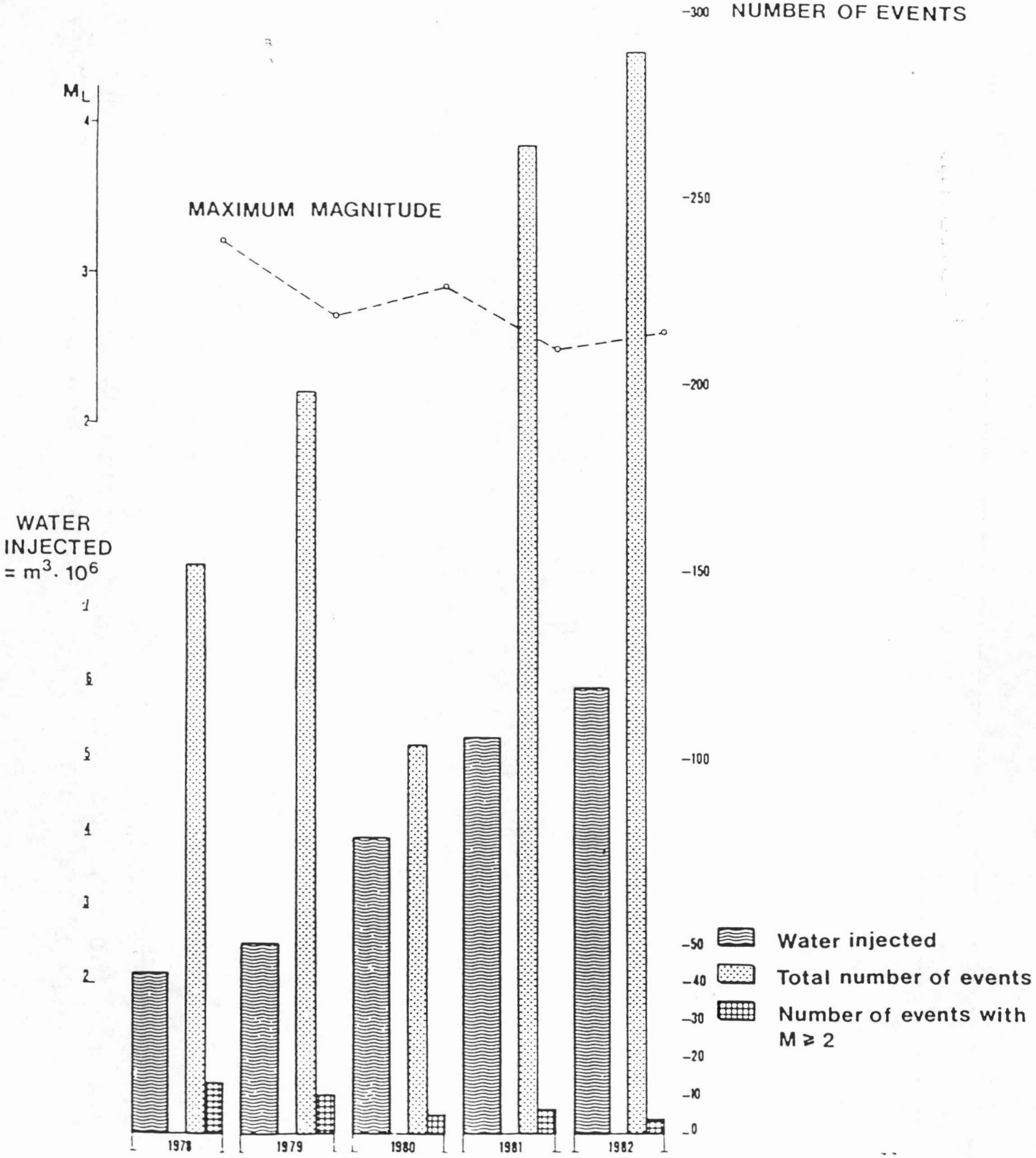

Figure 3. Comparison between water injected and seismicity, during the period 1978-1982 (from Batini _et_ _al._, 1985).

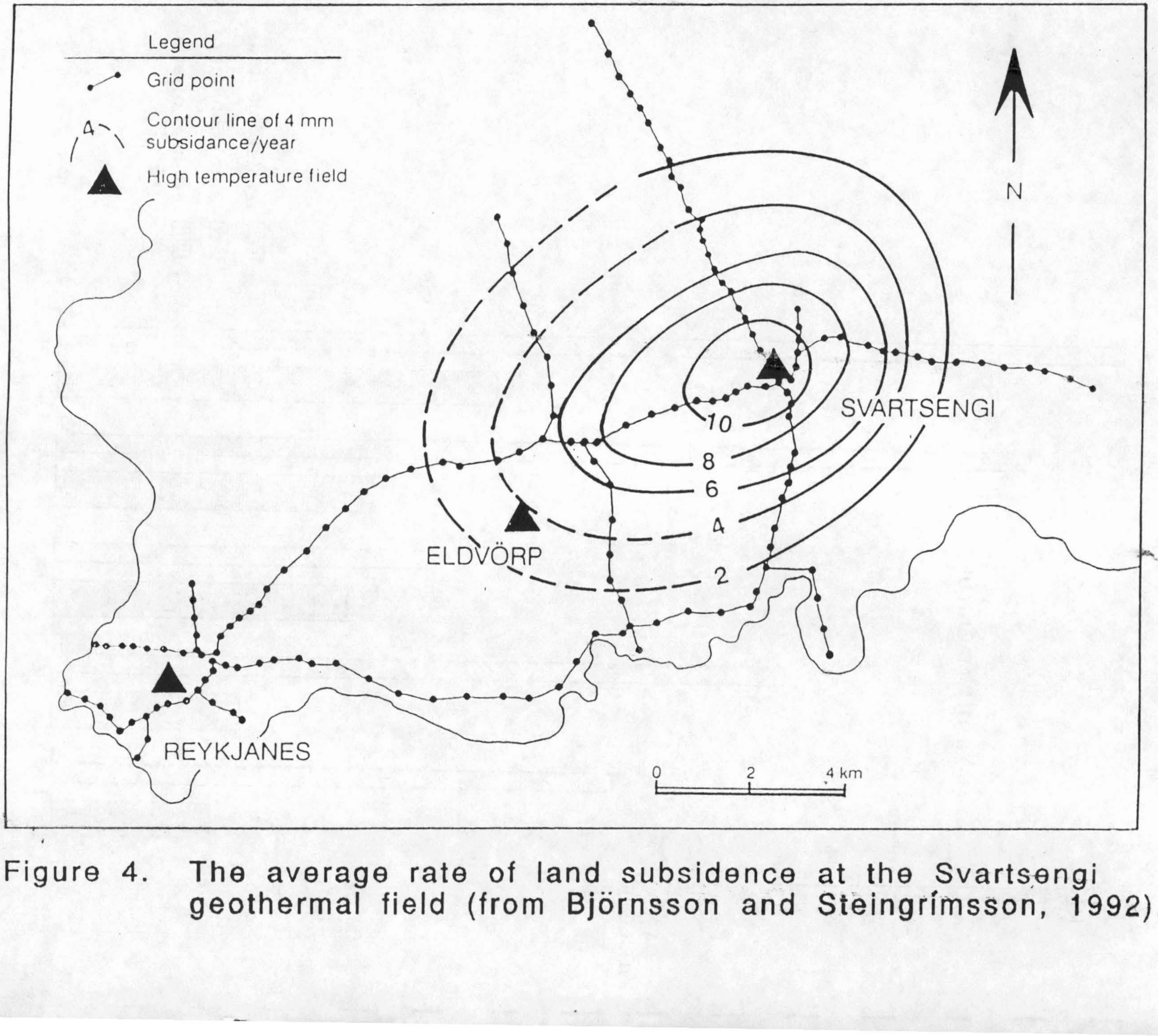

Figure 4. The average rate of land subsidence at the Svartsengi geothermal field (from Björnsson and Steingrímsson, 1992).