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A NATIONAL RESEARCH AND DEVELOPMENT PROGRAM FOR GEOTHERMAL INDUCED SEISMICITY

WORKING DRAFT #1

PREPARED BY
C. B. ARCHAMBEAU, UNIVERSITY OF COLORADO (CIRES)
C. G. BUFE, U. S. GEOLOGICAL SURVEY
J. T. CHERRY, SYSTEMS, SCIENCE AND SOFTWARE
W. W. HAYS, U. S. GEOLOGICAL SURVEY
T. V. McEVILLY, UNIVERSITY OF CALIFORNIA, BERKELEY
C. B. RALEIGH, U. S. GEOLOGICAL SURVEY
G. G. SORRELLS, TELEDYNE GEOTECH
E. L. MAJER, UNIVERSITY OF CALIFORNIA, LBL
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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

I. INTRODUCTION

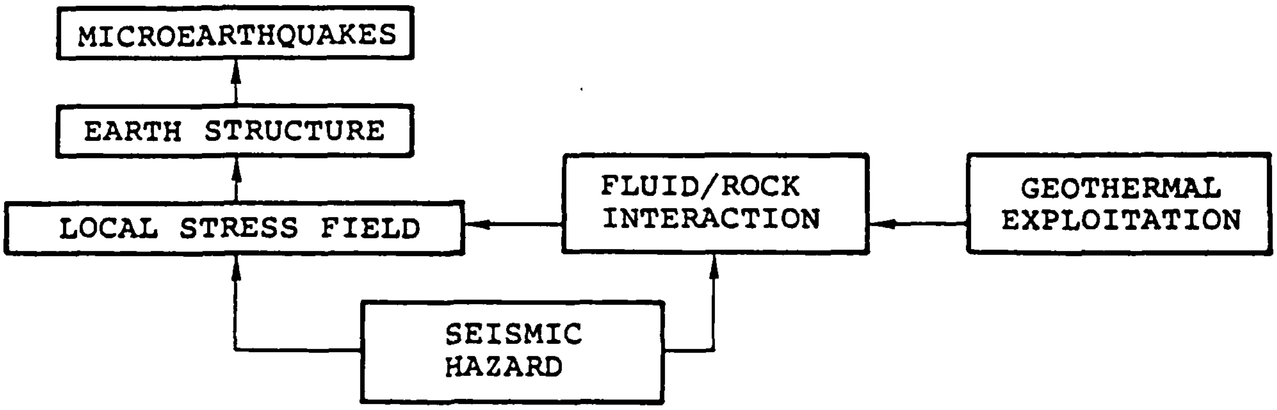
The Department of Geothermal Energy, Headquarters, has established the Geothermal Induced Seismicity Program (GISP) to develop a national research and development program plan to: (1) measure and quantify the magnitude of the problem, and (2) establish causal relationships between geothermal energy production and seismic events. The objective of the project is to gain an understanding of man-caused earthquakes resulting from the utilization of geothermal resources and the means by which such earthquakes can be predicted and safely controlled or moderated.

Seismicity induced by human activity is not unique to geothermal environments. The association of an increase in seismic activity with the filling of large reservoirs is now well documented (Bell and Nur, 1978). In several of these cases the main shock had a magnitude around six and was locally damaging. Another example of induced seismicity is the Denver earthquakes between 1962 and 1967 which were closely related to fluid injection in the Rocky Mountain arsenal disposal well in Colorado (Healy, et al., 1968). Although the injection was at only one site, several slightly damaging earthquakes occurred. Fluid withdrawal in oil fields has also been associated with several large tremors in California (Long Beach) and Texas. Finally, mining activities in underground areas have long been known to be the cause of rockbursts, which have had energy releases equivalent to magnitude five earthquakes (Jaeger and Cook, 1976).

In all these cases, the principal cause of the seismic activity was the alteration of the preexisting stress field by either fluid withdrawal or reinjection, or by removal of material from the ground. If these activities are in regions of naturally occurring seismic activity, or where there is already a dominant stress pattern, the probability of inducing earthquakes is even greater. Unfortunately, most geothermal prospects are in areas where there is active faulting. In the United States the most notable example is California, where the steam-dominated system in The Geysers and the hot water systems in the Imperial Valley both lie in regions where events greater than magnitude seven have occurred. However, almost the entire western United States is potentially seismically active, especially in geothermal areas such as Nevada, western Utah, and Wyoming. Another important case is that of the geopressurized zones of the Gulf Coast. In addition to reinjection, rapid withdrawal of fluids necesary for significant power generation may cause sudden failure and/or subsidence. Hoover and Dietrich (1969) suggested a relation between fluid removal and seismicity at the Rocky Mountain arsenal disposal well. Lastly, the extent to which hydrofracting can be controlled in hot dry rock environments is not known. The degree to which larger events may be triggered by the coalescence of smaller shocks is still uncertain.

Although induced seismicity has been studied in relation to dam sites, there are other factors which make geothermal reservoirs unique. Anomalous temperatures, pressures, strain rates, and rock types in geothermal environments all combine to alter the effective strength of the materials. In fact, geothermal prospecting involves "listening" for continuous seismic energy emitted from the system, or detecting microearthquakes caused by the dynamic processes (Liaw and McEvilly, 1979; Majer and McEvilly, 1979). The permeability necessary for the existence of a geothermal reservoir is often provided by faulting and fracturing along potentially active faults. Laboratory data on rock fracture and slip along preexisting planes or cracks suggest that the concept of effective stress (i.e., the shear strength is proportional to the difference between the normal tectonic stress and the fluid pore pressure) is the dominant effect in failure (Friedman, 1975). In producing geothermal environments where fluids are constantly being removed and reinjected at much higher than natural rates, anomalous pore pressures are inevitable. If these properties occur in regions of high stress and are coupled with the withdrawal and reinjection of fluids, then a situation exists where seismicity can easily occur. This, in addition to the fact that earthquake activity is noted in every commercially productive geothermal region indicates the need for understanding the mechanisms involved. The question seems not to be, will earthquakes be associated with fluid withdrawal or reinjection in producing geothermal regions, but how large will they be, and can they be controlled to minimize the damage to the surrounding environment and production region itself? The amount of geothermal power produced amy depend upon the induced seismicity and the extent to which it can be controlled, rather than the available heat.

The critical elements of the problem identified by the GISP panel are shown in the following schematic.



The microearthquakes which occur before and during exploitation represent the primary data base. The inversion of this data to obtain changes in the local stress field should determine the seismic hazard. An understanding of the effect of exploitation on the local stress field via fluid/rock interaction will identify the cause of the hazard and hopefully permit its control.

Each of these elements will be discussed separately in the following sections, both in terms of current status and additional research needs. Also a history of the induced seismicity and subsidence at The Geysers, California is presented as an appendix. This area will be recommended for intensive seismic monitoring and interpretation by the GISP panel.

II. DATA ACQUISITION

2.1 INTRODUCTION

Data bearing on exploitation-induced earthquake activity associated with a producing geothermal reservoir are of several types, including, of course, the details of earthquake occurrence within the field. Equally important, if we are to base an understanding of induced earthquakes on appropriate models, are the physical and chemical properties of the reservoir and their variation with time and with production. A variety of ongoing geochemical, geophysical, and geodetic measurements will be a necessary part of the development of major geothermal fields. As many of the detailed measurements involve substantial expense and manpower, it is fortunate that most are not required, and many are not in fact available, until major production begins.

2.2 PREPRODUCTION MONITORING

2.2.1 Seismic

In the preproduction period the most important measurement is that of background seismicity. Directly analogous to the now standard practice followed in the construction of major dams, where induced seismicity is a known potentiality, a high-sensitivity long-term record of natural seismicity in the project vicinity is fundamental to a meaningful analysis of any earthquake activity subsequent to field development. This preproduction monitoring program can be quite simple, e.g., a single high-quality seismograph, and it need become more elaborate only if warranted by the complexity or level of background seismicity detected in the reservoir area. Such a site-specific monitoring effort should not be confused with the general coverage provided in many areas of the western

United States by networks of seismographs (e.g., Caltech, U.C. Berkeley, USGS, University of Nevada and University of Utah, etc.) Such networks, except when concentrated for a specific study, rarely have interstation spacings less than 10 to 20 km, and thus cannot provide a long term seismicity record at very small magnitudes (less than one). Furthermore, such networks normally produce biased locations for hypocenters, with errors of several kilometers being common in areas of extreme lateral variations in crustal properties. For these reasons and because the data will be fundamental to subsequent modeling of reservoir dynamics and in the identification of induced seismicity, it is imperative that each promising geothermal prospect be instrumented on a minimal basis at such time as it becomes clear to the operators that probability is high for the development of a producing field. This timing should assure several years of preproduction monitoring.

The optimal preproduction monitoring system would seem to be a three-component downhole (at least 100 m), 4.5 Hz geophone package, operating with at least 50 Hz bandwidth and at maximum possible sensitivity into an event recorder with digital cassette recording, and located no more than 1 to 2 km from the expected field center. Such an installation is relatively inexpensive (less than $10 K, including the hole), and will provide adequate monitoring of surrounding earthquake activity. In the event that significant seismicity is seen in the immediate vicinity (within 5 km), two additional stations can be added for improved spacial resolution of the hypocenters, and subsequently the network can be expanded to the density required by the ongoing analyses of the local seismicity. In most cases, however, the single-station monitoring will suffice and data reduction will be simply a matter of cataloging a limited number of events selected by an S-P time criterion, say less than about two seconds.

2.2.2 Data Bank

The second aspect of preproduction data acquistion recommended for promising geothermal prospects involves creation of a site-specific cell in the geothermal data bank, for the prospect. Known regional and local geological, geochemical, geophysical and geothermal data can then be assigned to the prospect, and the required data base will be established for subsequent analysis as development continues.

2.3 PRODUCTION DEVELOPMENT PHASE

2.3.1 Introduction

When the prospect is shown to be economically viable and the decision is made to move the field into production, the intense phase of data acquisition should begin. Individual reservoirs will demand differing measurements, but the common goal for all is a continuous log of reservoir properties, production statistics and seismic activity, to be used in modeling reservoir dynamics for earthquake occurrence. The following list includes a wide range of measurements that would provide data crucial to the modeling efforts. It is clear that the field operator must be convinced of the need for these data if the program is to succeed.

2.3.2 Seismicity

If the reservoir area has been found to be seismically active in the course of preproduction monitoring, the network should be expanded to at least six, perferably eight to ten, stations. Interstation spacing should be no more than 1 to 2 km, and common timing with less than 10 ms error between stations is required. Individual station characteristics should be the same as those used in preproduction monitoring.

Downhole sensors should be placed as deep as is feasible. Data analysis now becomes more labor-intensive, with earthquakes to analyze on a continuing and timely basis. Routine processing should yield, in addition to precise hypocenters, source parameter estimates (fault planes, stress drops, seismic moment, rupture dimensions, etc.) and characteristics of the frequency content of the seismic waves as seen at each station. The same network can be used in experiments designed to detect changes in subsurface properties associated with reservoir exploitation. Such experiments may use local explosions or regional seismic events in monitoring wave velocities and attenuation within the reservoir volume. It is probable that the seismic network configuration will be shaped by results of the data analysis, with instruments removed or installed for specific data needs. In a seismically active field the network will thus provide a two-fold service – monitoring of earthquakes, and monitoring of reservoir properties.

Should the reservoir be found aseismic throughout pre-production monitoring, the minimum requirement during production development is a single station near the reservoir center. The existing station may well suffice, if the location is correct. This minumum system is sufficient to detect the onset of induced seismic activity, at which time a full network should be installed. It may be that the utility of a seismic network in monitoring changes in reservoir properties, as discussed above, provides sufficient rationale for its installation even in aseismic reservoirs.

2.3.3 Structure

Modeling studies for production-induced earthquake occurrence will depend heavily on structural data for the reservoir. Clearly, the developer will have the most complete picture of the reservoir, and his models provide the initial framework for analysis. To the extent possible and practical, these data should be released to the data bank on the field. It is likely that inadequacies will exist that suggest specific experiments for an improved structural picture. Acquisition of such needed data (e.g., geophysical surveys, geochemical analyses, special logging surveys, rock mechanics data, etc.) could well be supported financially by the Department of Energy, for the sake of case-history development.

2.3.4 Reservoir Pressure

For the purposes of induced seismicity research it would be desirable to detect changes in reservoir pressure of a few tenths of a bar or so and to detect temperature changes greater than 0.1°C. Instrumentation with sensitivities of this order have been developed and are typically used in reservoir engineering studies. Thus, there is no need to develop new instrumentation to sense changes in these parameters. Preliminary studies should be made to determine the spatial and temporal rates necessary to adequately characterize the pressure and temperature fields in the producing reservoir. These studies should be site specific in nature since spatial and temporal variations in these parameters can be expected to differ substantially from field to field.

2.3.5 Subsidence

Preliminary calculations indicate that volumetric strains in some producing reservoirs could be as large as 10^{-3} and that the mean strain rates could be of the order of 10^{-5} per day. Thus, rather crude instrumentation could be used to monitor volumetric changes in the reservoir. Unfortunately at the present time the sensors for making observations on this scale in geothermal reservoirs is not available. Since surface subsidence is directly linked to changes in reservoir volume (reservoir compaction) the development of both direct and indirect methods for monitoring reservoir compaction is a major goal of the geothermal subsidence research program. Studies in this area were initiated in FY '78 and appear likely to continue in FY '79. Thus, there is no need to support the development of compaction monitoring methods under the induced seismicity research program. However, lines of communication should be developed to insure that the methods developed suit the needs of both the seismic and subsidence research programs.

2.3.6 In Situ Stress

Mean stress drop calculations imply that the seismicity observed at the Geysers geothermal field is associated with changes in the *in situ* stress state of a few bars to a few tens of bars. It would, therefore, be desirable to have the capability to detect stress changes as small as a bar or so. Methods and systems for monitoring the ambient state of stress on this scale have been developed and are currently being utilized in the earthquake hazards reduction program sponsored by the U. S. Geological Survey. These should be directly applicable to monitoring the *in situ* stress state in the overburden of a producing geothermal field. However, because of the high temperatures and corrosive fluids typically found in geothermal reservoirs, some adaption of existing technology will be necessary before changes in the reservoir state of stress can be reliably measured. Thus, the development of a stress monitoring system that can perform reliably in a geothermal reservoir is a legitimate field of study for the induced seismicity research program.

2.3.7 Special Requirements

The data needed can, with exception of downhole (high temperature) logging, be acquired with existing technology and equipment. Research needs are primarily in the area of using the data in modeling reservoir dynamics.

III. SEISMIC HAZARD ESTIMATES BASED ON RESERVOIR STRESS FIELD DETERMINATIONS

A deterministic approach to the estimation of the seismic hazards associated with geothermal energy production requires knowledge of the initial tectonic stress levels within the medium, plus the changes in the stresses due to production. In addition, knowledge of the strength characteristics of the material along with variations in the strength due to effects such as water weakening and fluid pressure variations would be required. With this information, one approach would be to predict failure based on stress levels relative to the strength of the material, under specified fluid injection and/or extraction conditions, using reservoir modeling methods. In this case, reservoir production would produce perturbations in the initial tectonic stress, temperature, fluid pressure and ultimately the material strength, which could be sufficient to produce significant changes in the background microseismicity and in extreme cases, especially in regions with preexisting faults under relatively high tectonic stress, sufficient changes to trigger a fairly large seismic event.

The fully deterministic approach to an estimate of the hazard involved in an active geothermal reservoir not only requires knowledge of a large number of material parameters and state variables, such as initial temperature and stress, but also knowledge of geologic structure including the fracture and fault zone geometry. Obviously acquisition of this information will require an extensive field program; and the elements of such a program are discussed in earlier sections of this report. Further, details of the production history of the field would be required in order to specify the time dependent boundary conditions for the reservoir modeling and an observational program designed to obtain surface and downhole tilt, strain, compaction and subsidence measurements with time is required in order to, at least partially, verify the modeling predictions. Finally, the rhyologic and chemical behavior of rocks as a function of stress level, temperature, fluid content, strain rate, etc. must be known with reasonable certainty for meaningful predictions of failure phenomena to be made. While considerable research in this area of rock physics is underway, in particular under other areas of the geothermal program and under the earthquake prediction program, it is premature to conclude that sufficient knowledge of rock failure under high temperature reservoir conditions is presently available for very accurate modeling predictions to be made at this time. Consequently, it is important that the present program include support for rock physics experiments designed to more precisely define rock rhyology near and at failure, as a function of temperature, strain rate, fluid content and chemistry.

Since seismic hazard estimates based on reservoir modeling can only be expected when the initial tectonic stress state of the reservoir is specified, it is critical that stress level estimates be accomplished under this program. Specification of the stress state can be achieved in part by hydrofracturing experiments in the field, but this direct measurement of the ambient stress state, while critical, gives limited information spatially and is expensive to obtain. Applications of seismic techniques for estimates of stress changes associated with the microearthquakes that constitute the background activity in tectonically active areas, is therefore of great importance in estimating the initial stress distribution within the reservoir area.

In this case, passive seismic monitoring of the region may be used to record the commonly occurring small earthquakes within a field and estimates of the stress changes produced by the events can be obtained. These stress changes are, in fact, nbe amount of local ambient stress that can be released by an earthquake (the "recoverable ambient stress") and so is an important quantity in itself. Further, methods have proposed to relate the observed recoverable stress inferred from the seismic observations to the ambient stress local to the seismic event. However, these currently provide a rather wide range of estimates which are dependent on particular earthquake model assumptions and approximations. Thus, while additional research in the use of seismic data for stress estimates is required for accurate delineation of the initial ambient stress state, it is nevertheless necessary that the program incorporate an observational seismic study designed to give both recoverable and ambient stress estimates spatially throughout the prospective reservoir in order that reservoir modeling be an effective method of predicting seismicity changes.

The seismic observations of microearthquake activity are also an important tool for the location and delineation of fault zones within the field and can be used to give stress field orientations with a rather high degree of certainty. These observations are clearly important in defining the initial state of the reservoir as well as its dynamic state during production. In this regard, continuous seismic monitoring of the reservoir region could be used to provide a basis for monitoring the changes in seismicity during production, so that modeling predictions could be checked, and so that an empirical basis for correlations between production procedures and seismic activity could be established. Equally important, this approach offers the possibility of inferring the stress field by observational means during production. Thus, an independent determination of the seismic hazard could be based on the seismicially inferred (spatially variable) stress levels, stress field orientation and seismicity levels. In this approach one would require sufficient seismic instrumentation to detect and locate the numerous small events. Further the detector array must be adequate to determine the azimuthal radiation patterns from each event and the spectral properties of the radiated seismic field. With this capability it would be possible to determine the stress drop (or recoverable stress) associated with each event along with an inferred ambient stress and the orientation of the failure plane, as well as the event location. Given a spatially distributed occurrence of small seismic events within the field which would provide a spatial sampling of the stress, then it would be possible to delineate regions of high stress and potential large scale failure during any field production program.

In view of these possibilities for quantitative seismicity estimates, it is appropriate to recommend a comprehensive program with complementary observational-empirical and modeling components designed to provide a documented basis for seismic hazards assessment. The essential elements of this program are:

1. To obtain production and seismicity data from an operating geothermal field, specifically the Geysers field, to determine the quantitative nature of any correlations between seismic activity, reservoir structure and production history. This information to be used as an empirical means of estimating expected effects, and to verify reservoir modeling predictions.

2. To employ passive seismic monitoring of geothermal field seismicity to obtain estimates of the nonhydrostatic stress, both initially and as a function of production history and to also compare these estimates with <u>in situ</u> ambient stress estimates using hydrofracturing measurements. From the combined stress data to then base predictions of future

seismicity on the stress field estimates obtained from microearthquake occurrences and available in situ stress measurements during production.

3. Based on quantitative material property and field structure data coupled with initial stress state estimates, use reservoir modeling methods to predict stress field variations to be expected as a function of field production programs and, from these stress predictions, to infer seismicity changes based on fault locations and rock strength properties. Finally, to also correlate the results with production histories and general time dependent seismicity data, including the seismically estimated stress state variations, in order to establish a verified, deterministic, predictive capability.

4. Based on the inferred stress levels and the material strength, which serves to define stress levels at which failure may occur, provide an estimate of the probable locations, maximum dimensions, magnitudes and expected ground motion from the largest events to be expected.

Some of the essential aspects of this program are discussed in more detail in the following sections. In particular, we address the basic questions of how geothermal reservoir energy production may affect seismicity and how the effects can be predicted by reservoir modeling. In addition, a more detailed discussion of how seismic observations are used to infer failure plane orientations and stress levels within a tectonically active region is included.

IV. PHYSICAL BASIS FOR TRIGGERING OF EARTHQUAKES BY GEOTHERMAL PRODUCTION OR REINJECTION

To understand the relationship between production or reinjection of geothermal fluids and earthquakes we require an evaluation of the perturbations in the mechanical, thermal or chemical environment caused by exploitation. These perturbations act upon rocks whose initial state is the other unknown which we need to measure, i.e., are there preexisting faults in the rocks and are they stressed to near the point of failure?

This section lays out an experimental approach to measuring the static physical parameters in an appropriate rock mass and determining the effect most likely to trigger earthquakes in that body of rock. Because it is presently seismicially active and it is the principal producing geothermal field in this country, the Geysers area offers the best laboratory for such an experiment.

4.1 THE INITIAL STATE

It is now possible to measure the absolute state of stress in boreholes where temperatures reach 250°C. The method, hydraulic fracturing, has been extensively used in recent years for this purpose, although not in the high temperature application. In addition to the unforeseen problems likely to develop in high temperature environments, the hydrofracturing technique does not work well in highly fractured rock. Otherwise, the technique has worked successfully and is the only method available for other than surface measurements.

The faulting and fracture state in the rocks can be approached by using a borehole televiewer, an ultrasonic device which maps the orientation and distribution of fractures intersecting the borehole. This device has been modified for use at temperatures up to 220°C. The radiation pattern from microearthquakes also can be used to estimate fault plane orientations, in active zones.

The fluid pressure is one of the principal parameters influencing earthquakes. The presence of a large number of drill holes at the Geysers makes it possible to determine the fluid pressure in the reservoir at the focal depths of the earthquakes easily, provided access to pressure data can be obtained. Use of the boreholes is a prerequisite to conducting the experimental plan outlined here.

The foregoing measurements, along with seismic methods designed to infer the stress changes associated with background microearthquakes, can be used to establish the ambient stress field and its variability. The strength properties of local rocks at the appropriate temperatures and pressures should then be measured, and this capability is available at several existing laboratories.

With these data, it becomes possible to estimate the likelihood that any perturbation caused by production or reinjection could lead to shear failure and earthquakes. The possible perturbations affecting seismicity are examined in the following sections.

4.2 FLUID PRESSURE CHANGES

Production of steam from the Geysers has led to a maximum reduction in the reservoir pressure of 225 psi. The reduction in fluid pressure would act to strengthen the rock against frictional failure, although the indirect effect of subsidence might ultimately trigger earthquakes. Reinjection of water apparently does not lead to significant increases in the fluid pressure except, possibly, in the immediate vicinity of the injection wells. A series of bottom-hole pressure measurements over hours to days following a period of injection should be carried out to establish the spatial and temporal extent of any such increase. Such data have not been gathered to date, but are relatively easy to obtain.

4.3 FLUID PRESSURE GRADIENTS

Local reductions or increases in reservoir pressure due to production or reinjection result in pressure gradients in the fluid or vapor phase. These gradients in turn generate stress differences in the solid medium and conceivably, may contribute to increasing local shear stress (or decreasing the normal stress) on faults sufficient to trigger earthquakes. From existing production data, the maximum gradients in the vapor phase are low, no more than 1.5×10^{-2} bars/meters so that the effect, though finite, is not large. Once fault plane orientations and slip directions are determined from focal mechanism studies, the effect of the known gradients can be estimated from the known fluid pressure gradients.

4.4 STRESS CORROSION CRACKING

The dependence of brittle fracture strength on the chemical environment needs some detailed study. Enough is known to suggest that such an effect may be important, although whether there has been sufficient change in the reservoir to affect the fracture strength significantly is only poorly understood.

4.5 THERMAL STRESS

Temperature gradients induce stress differences which might contribute to initiation of seismic activity. In a vapor dominated reservoir, gradients should be quite small and the stresses correspondingly low. However, reinjection of relatively cool water could lead to a more substantial effect. Lack of knowledge of the geometry of the fracture system into which the reinjected fluid flows will make calculation of local stress variations in discrete fractures rather crude. Although a difficult problem, some order-of-magnitude estimates need to be attempted.

4.6 SUBSIDENCE

Removal of steam has resulted in a maximu subsidence of about 15 cm since production began at the Geysers. The effect of such deformation on local stresses can be estimated provided adequate leveling data exist. As it is suspected that subsidence in oil fields may play a role in local fracturing, and that it may lead to damaging earthquakes, suggests that this effect is likely to be a significant one.

4.7 PHYSICAL MODELING

The relative effects on faults of known orientation, by the perturbation discussed above, can be estimated in the first year, at least to within an order of magnitude. It appears likely that all but one or two of the above effects can be eliminated as having little significance, particularly as the current seismicity patterns and focal mechanisms are available for comparison with expectations from the calculations. For example, the strains induced by known subsidence can be compared with the strain release pattern derived from focal mechanism studies to judge whether any reasonable relationship exists.

In the second year, it should be possible to conduct measurements of absolute stress and the fracture distribution to provide the foundation for more refined calculation of the seismogenic effects. Finally, and most important, the three-dimensional pattern of faults, stress and the relevant perturbing effects should be incorporated into a model which leads to a prediction of the maximum probable earthquakes. The latter study is critical not only to the Geysers, but to the general problem of induced seismicity.

4.8 STRESS FIELD AND FAILURE PREDICTIONS BY RESERVOIR MODELING METHODS

In many areas of the world, land subsidence and small earthquakes have been observed to accompany the production of fluids (oil, gas, water, steam, etc.) from undergground reservoirs. Subsidence is generally believed to be caused by the compaction of the semi-consolidated strata of the reservoir as the effective overburden stress (defined as lithostatic stress minus fluid pressure) is increased due to fluid withdrawal. Fluid production can also produce relatively large localized stress changes in the reservoir (and overlying) rock. The localized stress buildup has potential for activating faults. (Thus, for example, increase in horizontal stress can lead to growth of normal faults whereas a buildup in shear stress may cause shear failure in the overburden/underburden.)

The geohydrological effects described above involve thermomechanical interactions between the rock and fluid components. Theoretical models describing the thermomechanical response of the rock and fluid (water and/or steam) composite material in terms of the isolated components have been developed and are currently operational. In these models, the stress-strain equations for the rock matrix are coupled with the diffusion equations for the fluid. Some of the more advanced modeling methods appear to be adequate for analyzing subsidence and stress buildup in a geothermal aquifer undergoing production and/or injection and it appears that no new theoretical development effort is required at this stage, at least until further comparative studies are completed.

In the modeling theory, the fluid flow and the solid response problems can be decoupled if one assumes that the fluid withdrawn (or reinjected) is small, so that the overburden essentially remains constant. The restriction to uniaxial (vertical) compaction together with the assumption of constant overburden implies that the reservoir porosity can be regarded as a function of pore fluid pressure and temperature only. During the past few years, several reservoir programs (incorporating the uniaxial compaction assumption) have become available. Given basic reservoir engineering data (rock porosity, permeability, specific heat, thermal conductivity and compressibility; fluid equation of state, etc.; and the initial state of the reservoir), the reservoir simulators can be employed to yield perturbations in the fluid state (pressure, temperature, etc.) introduced by exploitation/reinjection. Several of the reservoir simulators possess considerable flexibility as far as fluid and rock properties, problem geometry and boundary conditions are concerned. Thus, for example, a current advanced reservoir modeling program can treat multiphase, multispecies (water/steam, water with dissolved methane/free methane, water with dissolved salt/steam/precipitated salt) fluid flow in one-, two- or three-dimensions. In this program each computational zone in the finite-difference grid may contain a different rock type and provisions are also made for all practical boundary conditions.

In order to model the effect of time-varying fluid flow on matrix stress in a geothermal reservoir, finite element solid equilibrium codes are employed. Any such finite element code is basically a program for solving linear elastic continuum problems; however, problems requiring treatment of nonlinear material behavior may be solved by iteration using effective elastic moduli in the element. Given rheological properties of the reservoir rocks and the fluid pressure history in the reservoir, these programs may be employed to yield the time varying stress field and the deformation in the matrix. These programs can also be used to model overburden changes. Interactive codes have also been developed that couple fluid response programs with finite element solid matrix response codes. In the coupled fluid-solid matrix computations, the system is marched through any desired number of time steps in each of which a flow cycle calculation is performed yielding values of pore pressure, temperature and fluid density at the end of the time step. This information is then used in the finite element solid matrix calculation to yield the instantaneous equilibrium condition (i.e., rock displacements, stress, etc.) as functions of rock properties and fluid variables.

Most approaches for the analysis or subsidence and stress buildup are based on decoupling the fluid flow and rock response calculations. (For example, changes in the fluid state cause perturbations in the rock stress state; however, the perturbations in the rock stress field are not allowed to affect the fluid response.) Although this procedure is computationally very efficient, it may be that, for very accurate predictions, it will be necessary to develop new computer codes which solve the fully coupled fluid flow and rock response problem. Also, one may want to calculate aseismic slip (as a result of fluid preduction/injection) on discrete faults. The numerical techniques for treating the latter problems already exist and may be adapted to these problems.

4.9 SEISMIC METHODS: STRESS ESTIMATES, FAULT PLANE GEOMETRY AND SEISMICITY LEVELS

An objective of this part of the research program is to determine the spatial and temporal variations of recoverable tectonic stress. In this context the term "recoverable tectonic stress" refers to that part of the nonhydrostatic stress field within the earth that can be released, in the form of seismic radiation, by an earthquake. This stress is therefore distinct from the absolute or ambient nonhydrostatic stress, a part of which may not contribute to the radiation from a spontaneous failure process. The recoverable stress then, is that part of the ambient nonhydrostatic stress that can be released as seismic radiation.

A second objective is to relate this recoverable stress level, which can be inferred from seismic observations of the wave radiation from small earthquakes, to the ambient stress level which acts to initiate a failure process. The relationship between recoverable stress and ambient stress is quite uncertain in that the earthquake model theory required is still being developed and in any case requires verification. In this regard, measurements of ambient stress by hydrofracturing can be compared to seismically estimated recoverable stress values obtained from events at, or very near, the ambient stress measurement. These independent stress estimates could then be used to establish a relationship between the recoverable and ambient stresses. However, given that a determination of the recoverable stress can be obtained, it may be possible to identify spatial regions as hazardous in terms of the existing recoverable stress levels alone and to also predict the size and locations of likely large earthquakes, the former in terms of the detailed nature of the seismic radiation to be expected. Furthermore, it is reasonable to expect that inferred recoverable stress levels themselves can be used to predict the time of failure, if we are able to resolve time variations of the of the stress and monitor stress buildup with time to some critical level and spatial configuration.

The approach to the estimation of the recoverable stress is to use observations of the seismic radiation from the numerous very small to moderate sized earthquakes in the tectonic region of interest and to infer the stress changes associated with these events. The stress changes are largely local to the failure zone, in view of the rapidity of stress change falloff with distance, and, for these small events, constitute perturbations to the regional stress field. The changes can, however, be used to provide a sampling of the regional stress and hence provide the desired stress sampling mechanism.

Observational and interpretational methods for estimating stress using large numbers of small events require automated procedures to cope with the large amount of data recorded. Currently employed procedures involve the following:

1. The acquistion of a large event data base spanning as long a time period as possible, with events recorded in digital form over a reasonable wide frequency range.

2. The processing of the event data, using multi-station recording to determine fault orientations and locations, and extraction instrument corrected spectral data from which variable frequency, compressional (P) wave magnitudes may be computed at "low" (near 1 Hz) and high frequencies (near 10 Hz).

3. Using regional earth structure models and an appropriately general dyanmical model for the earthquakes, to generate theoretical variable frequency magnitude results for the variety of earthquake types and sizes contained in the

observed data set (this involves generating synthetic seismograms at the distance range and azimuths comparable to those from which the observations are made, and then generating the theoretical variable frequency magnitudes by the same spectral analysis procedure used with the observed data).

4. Classification of events as to type (i.e., strike-slip, thrust, etc.) and determination of both the recoverable stress and the failure zone dimensions of the observed events by comparison with the theoretical magnitude results.

The results generated by these operations include:

1. Locations of events, which define active faults or tectonic zones within the region.
2. "Recoverable stress" or stress drop determinations associated with the events, giving estimates of the background stress that can be released by an earthquake.
3. The failure zone dimensions that are associated with each event.
4. The orientation of the failure zone or fault plane for each event, which provides information on the stress field orientation as well.
5. The numbers of events versus event magnitude (or energy release).

These data would clearly provide necessary initial data for the reservoir modeling and, with continuous seismic monitoring, can provide a check on the modeling predictions of the stress field changes during production.

In addition, time variations in seismicity (cummulative numbers of events versus event magnitude), microearthquake event clustering (spatial distribution of events), and fault plane orientation at a given location, as well as the stress itself, appear, at least on occasion, to be premonitory indicators of relatively large earthquakes. Therefore the seismic monitoring results may in themselves provide important empirical results for larger event prediction.

V. RECOMMENDED PROGRAM

5.1 Background seismicity measurements prior to exploitation should begin immediately at all promising geothermal prospects. At least two years of preexploitation monitoring is recommended. The optimal monitoring system would consist of a three-component (possibly 100 m downhole), 4.5 Hz geophone package, operating with at least 50 Hz bandwidth and at maximum possible sensitivity into an event recorder with digital cassette recording, and located no more than 1 to 2 km from the expected field center. In the event that significant seismicity is seen in the immediate vicinity (within 5 km), two additional stations should be added for improved spatial resolution of the hypocenters, and subsequently the network can be expanded to the density required by the ongoing analysis of the local seismicity.

5.2 An intensive, site specific data acquisition and interpretation program should be initiated immediately at the Geysers, California. A summary of the induced seismicity and subsidence history of this area is given in the appendix. The recommended program for the Geysers is as follows.

5.2.1 Continue operation of the telemetered network to provide continuous mapping of seismicity ($M \geq 1$) as the production zone expands in 1979 and 1980. Increase station density near future power plants especially Unit No. 13, a 100 MWe unit which begins operation in FY '80. It will be located in a part of the steam field that is presently aseismic.

5.2.2 Invert the microearthquake travel time and gravity data to obtain an estimate of the elastic properties and density of the earth structure in the areas of microearthquake clustering. Constrain the inversion with all geophysical data available from the operators of the field.

5.2.3 Determine the stress drop and fault orientation of the microearthquakes. Identify the spatial and temporal variation of the these fault parameters and correlate with production and injection procedures. Delineate regions of high stress drop and estimate the potential for large scale faulting.

5.2.4 Model the effect of time-varying fluid flow on the stress in the rock matrix in the vicinity of injection and production wells. Determine if the stress buildup is sufficient to explain the observed microearthquake and in particular the stress drops associated with these earthquakes. The operators of the field should be encouraged to furnish injection and production data (bottom hole pressure measurement) and the properties of the reservoir (permeability and porosity) for this project.

5.2.5 Install strong motion recorders near critical facilities. Continue geodetic and gravity measurements. Install tiltmeters near Unit No. 13.

5.2.6 Perform hydraulic fracturing measurements in selected boreholes to determine the absolute state of stress in the field.

5.3 A site specific cell in the geothermal data bank should be created for each prospect. Geological, geochemical, geophysical and geothermal data can be assigned to the prospect for analysis as development of the prospect proceeds.

We recommend that the above elements (5.1, 5.2 and 5.3) be initiated during the first year and be assigned the highest priority. The priority of the following elements will be determined after the results of the Geysers project are evaluated.

5.4 Seismicity measurements and reservoir properties should be obtained for all prospects undergoing exploitation. The field operator must be convinced of the need for these data if the program is to succeed. Seismic monitoring is essential. For seismically active areas the preexploitation network should be expanded to at least six, perferably eight to ten, stations. Interstation spacing should be no more than 2 km and common timing with less than 10 ms error between stations is required. If the reservoir is aseismic, a single station near the reservoir center would be sufficient. If induced seismicity is detected then a full network should be installed. The USGS telemetered network at the Geysers should be reviewed and upgraded, if necessary, in order to meet the requirements of elements 5.2.2, 5.2.3 and 5.2.4. Bottom hole pressure measurements and reservoir properties including elastic constants, density, porosity and permeability will be required for each seismically active field.

5.5 *The dependence of brittle fracture strength on the* chemical and temperature environment needs some detailed study. This activity should be coordinated with other areas of the geothermal program and the earthquake prediction program.

5.6 Prediction of the ground motion from the largest expected events will be required. Coordination with research activities conducted by NSF, USGS and NRC is recommended. However, it is clear that the transmission path contributes a large percentage of the overall uncertainty in seismic design. The microearthquake data should be interpreted to provide a site specific calibration of the attenuation of seismic waves from the fault to critical facilities. This interpretation would also provide an estimate of changes in the Q structure of the reservoir as a function of production and injection rates.

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APPENDIX A

A SUMMARY OF INDUCED SEISMICITY AND SUBSIDENCE AT THE GEYSERS, CALIFORNIA

A.1 STEAM PRODUCTION HISTORY

The first geothermal well at the Geysers was drilled in 1921, but extensive steam withdrawal did not begin until Pacific Gas and Electric Company began generating electricity in 1960 with Unit No. 1. Power production rose from 11 MWe in 1960 to 51 MWe in 1966, expanding to the current 502 MWe in 1975. When operating at full capacity, the field production rate is approximately 8.5 million pounds (19 million kg) per hour. Pacific Gas and Electric Company is currently constructing four new power plants, which will nearly double the generating capacity (to 908 MWe) within the next year or so. Ad additional 900 MWe could be added by the mid- 1980's (Lipman, Strobel and Gulati, 1977).

A.2 EARTHQUAKES AT THE GEYSERS

The sparse northern California network of the University of California at Berkeley provides the only preproduction data on seismicity at the Geysers. The location threshold over most of this period was about magnitude 1, so little can be said about the number of smaller earthquakes at the Geysers before power production began. However, the Berkeley data does show an increase in the number of earthquakes at the magnitude 1 level since production began. In addition, larger earthquakes

Several brief microearthquake surveys have been conducted at the Geysers over the years. Results of these studies, by Lange and Westphal (1960), Hamilton and Muffler (1973) and

Majer and McEvilly (1977), suggest that microearthquake activity at the magnitude 0 level may have increased as power production increased.

In 1973 the U. S. Geological Survey extended their central California seismographic network northward to the Geysers (Figure A.1). Station density was increased in 1975 and gain in 1977 to 1978. The present Geysers network is shown in Figure A.2; average interstation spacing is 4 km. Approximately 1000 earthquakes ($M \geq 1$) have been located at the Geysers since 1975. Marks, et al., (1978) and Bufe, et al., (1979) have examined the distribution of earthquakes with respect to the steam production zones and injection wells (Figures A.3 and A.4). The contours of the two zones of decreased steam pressure are interpreted by Lipman, Strobel, and Gulati (1977) as the consequence of steam production from two reservoirs. Estimated points of water injection are also shown in Figure A.3; data on the exact points of injection and condensate injection rates have not been made available by the producers. The correlation between the two clusters of microearthquakes and the two reservoirs is compelling circumstantial evidence that the earthquakes are induced.

Marks, et al., (1978) have also compared the 1975 to 1977 regional seismicity at $M \geq 2$ to the seismicity in the early (1962-1963) days of steam production when U. C. Berkeley operated a single station at Calistoga, 30 km southeast of the Geysers. They found the number of regional events had increased from 25 a year to 47 a year. The difference of 22 a year is near the 1975 to 1977 occurrence rate at the Geysers, suggesting that seismicity at the Geysers was significantly less in 1962 to 1963.

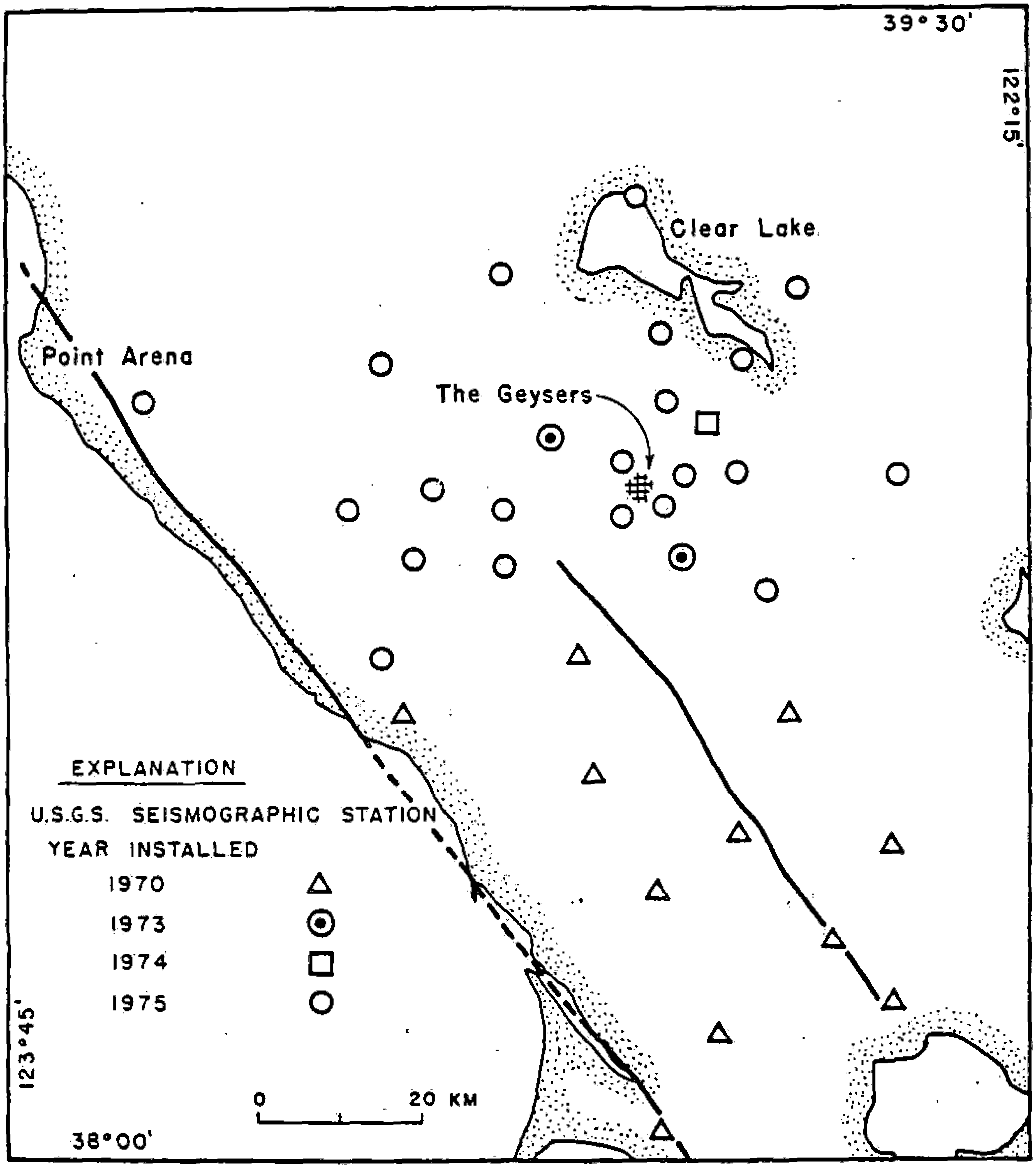

Figure A.1. U. S. Geological Survey seismographic stations, 1977. The stations immediately around the Geysers are shown in more detail in Figure A.2.

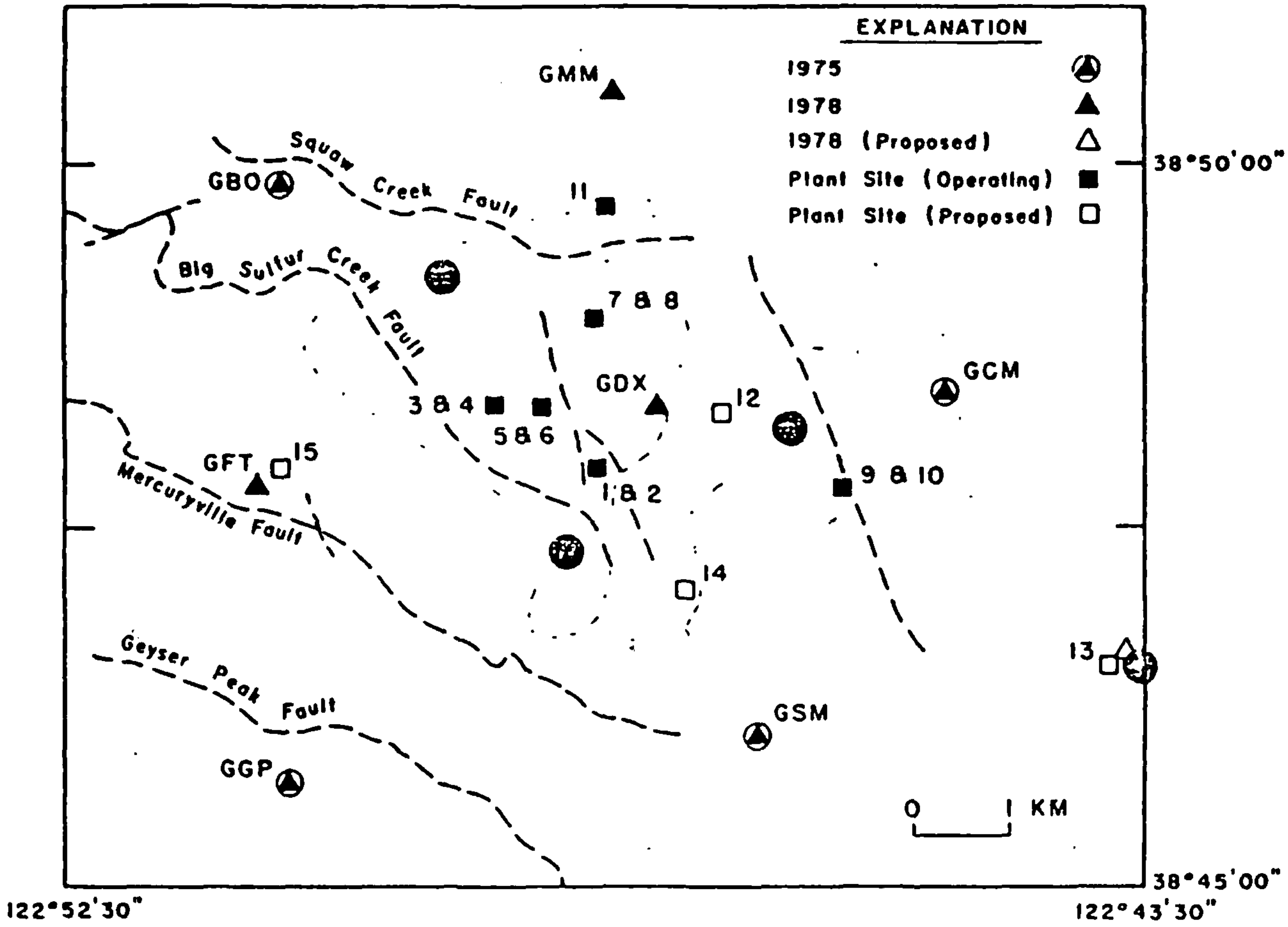

Figure A.2. Network of telemetered seismographs at the Geysers, May 1, 1978. Also shown are (numbered) geothermal power plants. Units 1 through 11 are generating power at the present; 12 through 15 will begin operation in the near future. Faults are from a compilation by R. McLaughlin of the USGS. In addition to the telemetered stations, a roving network of three-component digital seismographs is being deployed at the Geysers. Initial locations of these portable stations are indicated by solid circles.

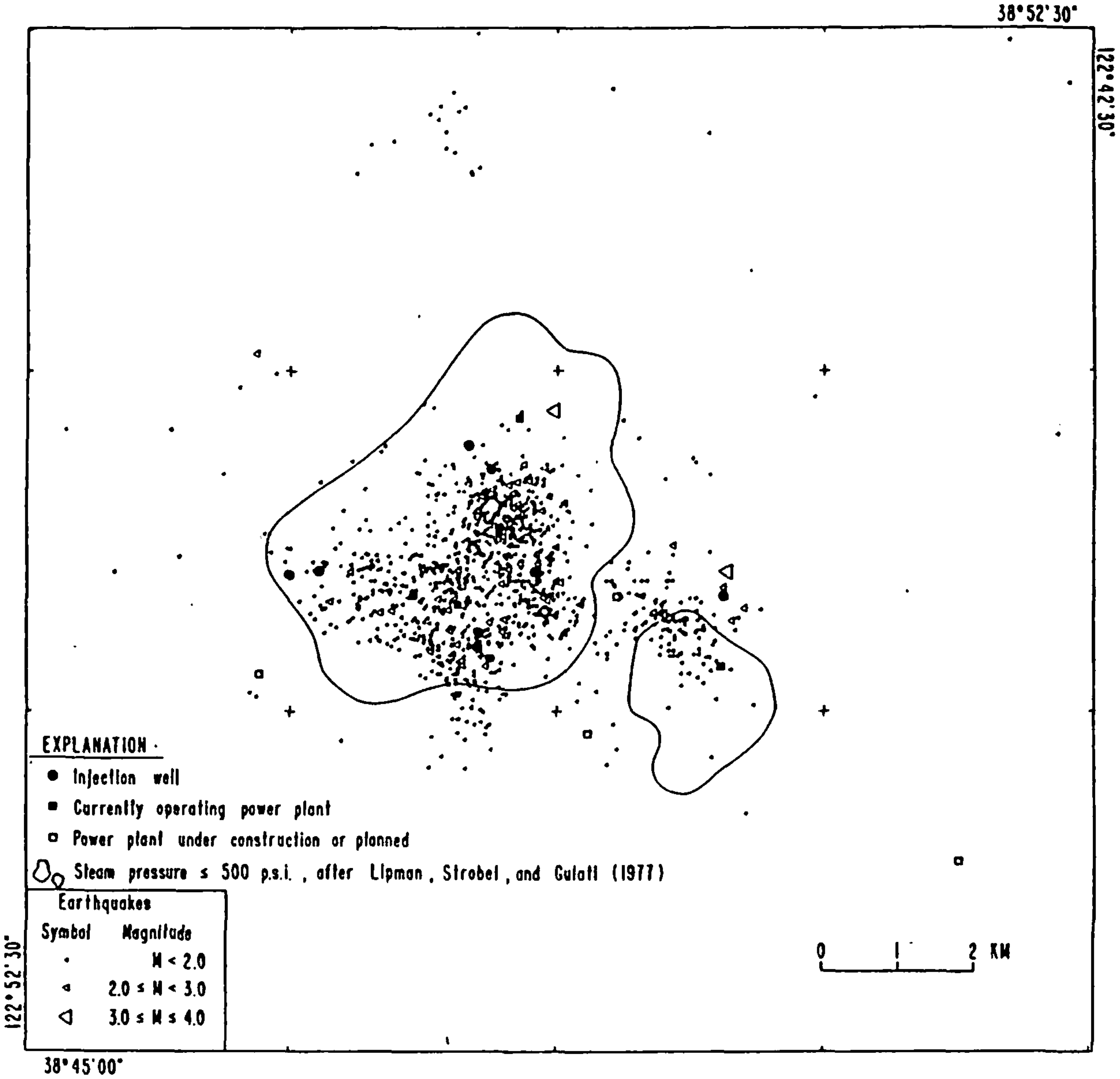

Figure A.3. Earthquake distribution and steam production zones, the Geysers Geothermal Area, California.

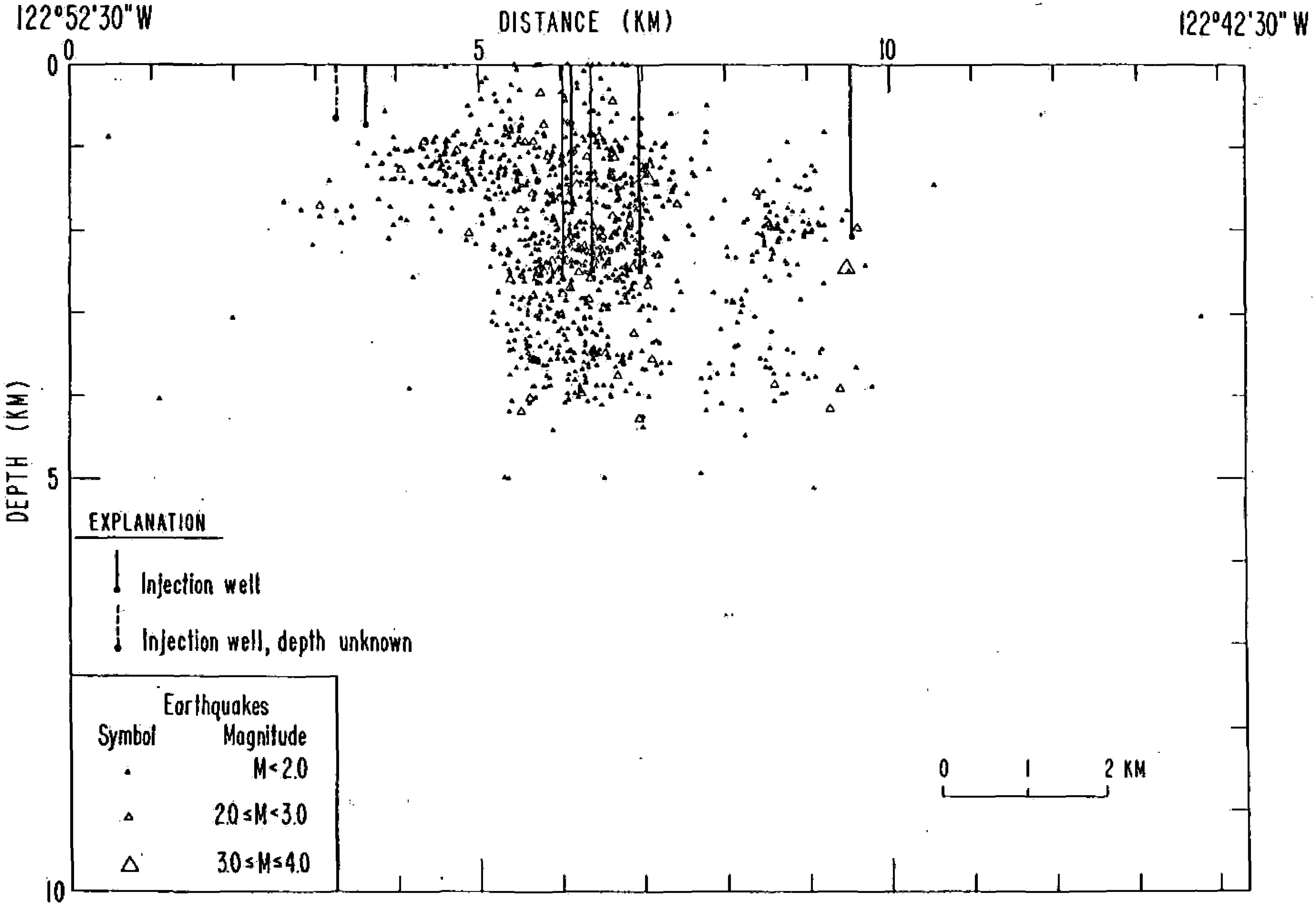

Figure A.4. Steam production zone and cross section, the Geysers Geothermal Area, California.

A.3 CHARACTERISTICS OF THE EARTHQUAKES AND THE RESERVOIR

Several studies of earthquake characteristics and reservoir properties which bear upon induced seismicity at the Geysers are in progress or have been completed. Marks, et al., (1978), conducted a comparative study of seismicity rates and b values at the Geysers and elsewhere in the Clear Lake region. They found no significant difference in b values (range 1.1 to 1.5) between the Geysers production zones and the surrounding geothermal and tectonic regimes. The earthquake occurrence rate in the production zones was found to be higher and more constant (less episodic) than in the surrounding regions.

Peppin and Bufe (1978) found no significant differences in spectral characteristics of earthquakes at the Geysers and those at Alexander Valley, 10 km to the south.

Bufe and others (1979) have detected a change in the faulting pattern at the Geysers since late 1977. Earthquakes in the lower ($h > 2$ km) part of the reservoir have changed from predominantly strike-slip to predominantly normal faulting. The shallower earthquakes are strike-slip or thrust, and are very simliar to mechanisms of earthquakes in the surrounding region.

Majer and McEvilly (1978) have examined the shallow crustal structure at the Geysers, using results of a seismic refraction profile and spectral studies of microearthquakes. They find the vapor dominated reservoir to be characterized by relatively high P- and S-wave velocities and low attenuation, a situation possibly reversing with depth. Iyer, et al., (1979) find large travel time delays and Ward, et al., (1979) find excessive attenuation in teleseismic P arrivals at the Geysers. Denlinger and Kovach (1979) conducted a shallow vibroseis reflection survey at the Geysers and have examined gravity data from the developed and undeveloped parts of the field.

Lofgren's (1978) 1973 to 1977 geodetic results have shown horizontal (2 cm/yr, convergence) and vertical (3 cm/yr subsidence) changes which suggest that the geothermal reservoir is being compressed both vertically and horizontally as fluid pressures within it are drawn down by production. Isherwood (1979) interprets gravity decreases as large as 120 mgal as resulting from steam withdrawal with no significant natural recharge. These results suggest a trend of decreasing porosity in the reservoir; a process reflected in the high level of microearthquake activity.

Notes:

1. In July entered into letter agreement between NVOO & HQ re this program. —
2. In first 1/4 FY79 got group together to write program plan -
3. Proposed a two pronged attack
   a) better effort at the Geysers - more instrumentation
   b) set up data bank similar to GRID - set up a primary model against which to check other models
   c) select 4-5 "proving" sites -- Simple passive instrumentation to get a history - 1-2 years - if area turns out to be aseismic, may quit.

4. we just don't have enough data -- a major problem -

5. Only area presently selected for study is the Geysers -

6. Geysers monitoring has been DOE funded for past 2 yrs —

7. what they want to do now
   a) monitor Geysers
   b) start data acquisition all @ LBL

WRIGHT

A NATIONAL RESEARCH AND DEVELOPMENT PROGRAM FOR GEOTHERMAL INDUCED SEISMICITY

WORKING DRAFT #1

PREPARED BY
C. B. ARCHAMBEAU, UNIVERSITY OF COLORADO (CIRES)
C. G. BUFE, U. S. GEOLOGICAL SURVEY
J. T. CHERRY, SYSTEMS, SCIENCE AND SOFTWARE
W. W. HAYS, U. S. GEOLOGICAL SURVEY
T. V. McEVILLY, UNIVERSITY OF CALIFORNIA, BERKELEY
C. B. RALEIGH, U. S. GEOLOGICAL SURVEY
G. G. SORRELLS, TELEDYNE GEOTECH
E. L. MAJER, UNIVERSITY OF CALIFORNIA, LBL
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E. L. MAJER, UNIVERSITY OF CALIFORNIA, LBL
R. CREWDSON, OCCIDENTAL PETROLEUM

JANUARY 26, 1979

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

I. INTRODUCTION

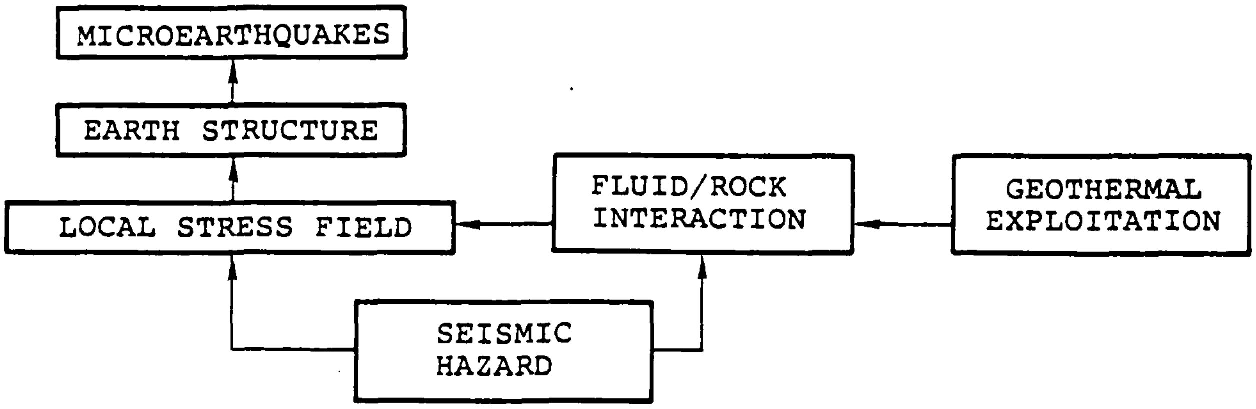
The Department of Geothermal Energy, Headquarters, has established the Geothermal Induced Seismicity Program (GISP) to develop a national research and development program plan to: (1) measure and quantify the magnitude of the problem, and (2) establish causal relationships between geothermal energy production and seismic events. The objective of the project is to gain an understanding of man-caused earthquakes resulting from the utilization of geothermal resources and the means by which such earthquakes can be predicted and safely controlled or moderated.

Seismicity induced by human activity is not unique to geothermal environments. The association of an increase in seismic activity with the filling of large reservoirs is now well documented (Bell and Nur, 1978). In several of these cases the main shock had a magnitude around six and was locally damaging. Another example of induced seismicity is the Denver earthquakes between 1962 and 1967 which were closely related to fluid injection in the Rocky Mountain arsenal disposal well in Colorado (Healy, et al., 1968). Although the injection was at only one site, several slightly damaging earthquakes occurred. Fluid withdrawal in oil fields has also been associated with several large tremors in California (Long Beach) and Texas. Finally, mining activities in underground areas have long been known to be the cause of rockbursts, which have had energy releases equivalent to magnitude five earthquakes (Jaeger and Cook, 1976).

In all these cases, the principal cause of the seismic activity was the alteration of the preexisting stress field by either fluid withdrawal or reinjection, or by removal of material from the ground. If these activities are in regions of naturally occurring seismic activity, or where there is already a dominant stress pattern, the probability of inducing earthquakes is even greater. Unfortunately, most geothermal prospects are in areas where there is active faulting. In the United States the most notable example is California, where the steam-dominated system in The Geysers and the hot water systems in the Imperial Valley both lie in regions where events greater than magnitude seven have occurred. However, almost the entire western United States is potentially seismically active, especially in geothermal areas such as Nevada, western Utah, and Wyoming. Another important case is that of the geopressurized zones of the Gulf Coast. In addition to reinjection, rapid withdrawal of fluids necesary for significant power generation may cause sudden failure and/or subsidence. Hoover and Dietrich (1969) suggested a relation between fluid removal and seismicity at the Rocky Mountain arsenal disposal well. Lastly, the extent to which hydrofracting can be controlled in hot dry rock environments is not known. The degree to which larger events may be triggered by the coalescence of smaller shocks is still uncertain.

Although induced seismicity has been studied in relation to dam sites, there are other factors which make geothermal reservoirs unique. Anomalous temperatures, pressures, strain rates, and rock types in geothermal environments all combine to alter the effective strength of the materials. In fact, geothermal prospecting involves "listening" for continuous seismic energy emitted from the system, or detecting microearthquakes caused by the dynamic processes (Liaw and McEvilly, 1979; Majer and McEvilly, 1979). The permeability necessary for the existence of a geothermal reservoir is often provided by faulting and fracturing along potentially active faults. Laboratory data on rock fracture and slip along preexisting planes or cracks suggest that the concept of effective stress (i.e., the shear strength is proportional to the difference between the normal tectonic stress and the fluid pore pressure) is the dominant effect in failure (Friedman, 1975). In producing geothermal environments where fluids are constantly being removed and reinjected at much higher than natural rates, anomalous pore pressures are inevitable. If these properties occur in regions of high stress and are coupled with the withdrawal and reinjection of fluids, then a situation exists where seismicity can easily occur. This, in addition to the fact that earthquake activity is noted in every commercially productive geothermal region indicates the need for understanding the mechanisms involved. The question seems not to be, will earthquakes be associated with fluid withdrawal or reinjection in producing geothermal regions, but how large will they be, and can they be controlled to minimize the damage to the surrounding environment and production region itself? The amount of geothermal power produced amy depend upon the induced seismicity and the extent to which it can be controlled, rather than the available heat.

The critical elements of the problem identified by the GISP panel are shown in the following schematic.



The microearthquakes which occur before and during exploitation represent the primary data base. The inversion of this data to obtain changes in the local stress field should determine the seismic hazard. An understanding of the effect of exploitation on the local stress field via fluid/rock interaction will identify the cause of the hazard and hopefully permit its control.

Each of these elements will be discussed separately in the following sections, both in terms of current status and additional research needs. Also a history of the induced seismicity and subsidence at The Geysers, California is presented as an appendix. This area will be recommended for intensive seismic monitoring and interpretation by the GISP panel.

II. DATA ACQUISITION

2.1 INTRODUCTION

Data bearing on exploitation-induced earthquake activity associated with a producing geothermal reservoir are of several types, including, of course, the details of earthquake occurrence within the field. Equally important, if we are to base an understanding of induced earthquakes on appropriate models, are the physical and chemical properties of the reservoir and their variation with time and with production. A variety of ongoing geochemical, geophysical, and geodetic measurements will be a necessary part of the development of major geothermal fields. As many of the detailed measurements involve substantial expense and manpower, it is fortunate that most are not required, and many are not in fact available, until major production begins.

2.2 PREPRODUCTION MONITORING

2.2.1 Seismic

In the preproduction period the most important measurement is that of background seismicity. Directly analogous to the now standard practice followed in the construction of major dams, where induced seismicity is a known potentiality, a high-sensitivity long-term record of natural seismicity in the project vicinity is fundamental to a meaningful analysis of any earthquake activity subsequent to field development. This preproduction monitoring program can be quite simple, e.g., a single high-quality seismograph, and it need become more elaborate only if warranted by the complexity or level of background seismicity detected in the reservoir area. Such a site-specific monitoring effort should not be confused with the general coverage provided in many areas of the western

United States by networks of seismographs (e.g., Caltech, U.C. Berkeley, USGS, University of Nevada and University of Utah, etc.) Such networks, except when concentrated for a specific study, rarely have interstation spacings less than 10 to 20 km, and thus cannot provide a long term seismicity record at very small magnitudes (less than one). Furthermore, such networks normally produce biased locations for hypocenters, with errors of several kilometers being common in areas of extreme lateral variations in crustal properties. For these reasons and because the data will be fundamental to subsequent modeling of reservoir dynamics and in the identification of induced seismicity, it is imperative that each promising geothermal prospect be instrumented on a minimal basis at such time as it becomes clear to the operators that probability is high for the development of a producing field. This timing should assure several years of preproduction monitoring.

The optimal preproduction monitoring system would seem to be a three-component downhole (at least 100 m), 4.5 Hz geophone package, operating with at least 50 Hz bandwidth and at maximum possible sensitivity into an event recorder with digital cassette recording, and located no more than 1 to 2 km from the expected field center. Such an installation is relatively inexpensive (less than $10 K, including the hole), and will provide adequate monitoring of surrounding earthquake activity. In the event that significant seismicity is seen in the immediate vicinity (within 5 km), two additional stations can be added for improved spacial resolution of the hypocenters, and subsequently the network can be expanded to the density required by the ongoing analyses of the local seismicity. In most cases, however, the single-station monitoring will suffice and data reduction will be simply a matter of cataloging a limited number of events selected by an S-P time criterion, say less than about two seconds.

2.2.2 Data Bank

The second aspect of preproduction data acquistion recommended for promising geothermal prospects involves creation of a site-specific cell in the geothermal data bank, for the prospect. Known regional and local geological, geochemical, geophysical and geothermal data can then be assigned to the prospect, and the required data base will be established for subsequent analysis as development continues.

2.3 PRODUCTION DEVELOPMENT PHASE

2.3.1 Introduction

When the prospect is shown to be economically viable and the decision is made to move the field into production, the intense phase of data acquisition should begin. Individual reservoirs will demand differing measurements, but the common goal for all is a continuous log of reservoir properties, production statistics and seismic activity, to be used in modeling reservoir dynamics for earthquake occurrence. The following list includes a wide range of measurements that would provide data crucial to the modeling efforts. It is clear that the field operator must be convinced of the need for these data if the program is to succeed.

2.3.2 Seismicity

If the reservoir area has been found to be seismically active in the course of preproduction monitoring, the network should be expanded to at least six, perferably eight to ten, stations. Interstation spacing should be no more than 1 to 2 km, and common timing with less than 10 ms error between stations is required. Individual station characteristics should be the same as those used in preproduction monitoring.

Downhole sensors should be placed as deep as is feasible. Data analysis now becomes more labor-intensive, with earthquakes to analyze on a continuing and timely basis. Routine processing should yield, in addition to precise hypocenters, source parameter estimates (fault planes, stress drops, seismic moment, rupture dimensions, etc.) and characteristics of the frequency content of the seismic waves as seen at each station. The same network can be used in experiments designed to detect changes in subsurface properties associated with reservoir exploitation. Such experiments may use local explosions or regional seismic events in monitoring wave velocities and attenuation within the reservoir volume. It is probable that the seismic network configuration will be shaped by results of the data analysis, with instruments removed or installed for specific data needs. In a seismically active field the network will thus provide a twofold service — monitoring of earthquakes, and monitoring of reservoir properties.

Should the reservoir be found aseismic throughout preproduction monitoring, the minimum requirement during production development is a single station near the reservoir center. The existing station may well suffice, if the location is correct. This minumum system is sufficient to detect the onset of induced seismic activity, at which time a full network should be installed. It may be that the utility of a seismic network in monitoring changes in reservoir properties, as discussed above, provides sufficient rationale for its installation even in aseismic reservoirs.

2.3.3 Structure

Modeling studies for production-induced earthquake occurrence will depend heavily on structural data for the reservoir. Clearly, the developer will have the most complete picture of the reservoir, and his models provide the initial framework for analysis. To the extent possible and practical, these data should be released to the data bank on the field. It is likely that inadequacies will exist that suggest specific experiments for an improved structural picture. Acquisition of such needed data (e.g., geophysical surveys, geochemical analyses, special logging surveys, rock mechanics data, etc.) could well be supported financially by the Department of Energy, for the sake of case-history development.

2.3.4 Reservoir Pressure

For the purposes of induced seismicity research it would be desirable to detect changes in reservoir pressure of a few tenths of a bar or so and to detect temperature changes greater than 0.1°C. Instrumentation with sensitivities of this order have been developed and are typically used in reservoir engineering studies. Thus, there is no need to develop new instrumentation to sense changes in these parameters. Preliminary studies should be made to determine the spatial and temporal rates necessary to adequately characterize the pressure and temperature fields in the producing reservoir. These studies should be site specific in nature since spatial and temporal variations in these parameters can be expected to differ substantially from field to field.

2.3.5 Subsidence

Preliminary calculations indicate that volumetric strains in some producing reservoirs could be as large as 10^{-3} and that the mean strain rates could be of the order of 10^{-5} per day. Thus, rather crude instrumentation could be used to monitor volumetric changes in the reservoir. Unfortunately at the present time the sensors for making observations on this scale in geothermal reservoirs is not available. Since surface subsidence is directly linked to changes in reservoir volume (reservoir compaction) the development of both direct and indirect methods for monitoring reservoir compaction is a major goal of the geothermal subsidence research program. Studies in this area were initiated in FY '78 and appear likely to continue in FY '79. Thus, there is no need to support the development of compaction monitoring methods under the induced seismicity research program. However, lines of communication should be developed to insure that the methods developed suit the needs of both the seismic and subsidence research programs.

2.3.6 In Situ Stress

Mean stress drop calculations imply that the seismicity observed at the Geysers geothermal field is associated with changes in the *in situ* stress state of a few bars to a few tens of bars. It would, therefore, be desirable to have the capability to detect stress changes as small as a bar or so. Methods and systems for monitoring the ambient state of stress on this scale have been developed and are currently being utilized in the earthquake hazards reduction program sponsored by the U. S. Geological Survey. These should be directly applicable to monitoring the *in situ* stress state in the overburden of a producing geothermal field. However, because of the high temperatures and corrosive fluids typically found in geothermal reservoirs, some adaption of existing technology will be necessary before changes in the reservoir state of stress can be reliably measured. Thus, the development of a stress monitoring system that can perform reliably in a geothermal reservoir is a legitimate field of study for the induced seismicity research program.

2.3.7 Special Requirements

The data needed can, with exception of downhole (high temperature) logging, be acquired with existing technology and equipment. Research needs are primarily in the area of using the data in modeling reservoir dynamics.

III. SEISMIC HAZARD ESTIMATES BASED ON RESERVOIR STRESS FIELD DETERMINATIONS

A deterministic approach to the estimation of the seismic hazards associated with geothermal energy production requires knowledge of the initial tectonic stress levels within the medium, plus the changes in the stresses due to production. In addition, knowledge of the strength characteristics of the material along with variations in the strength due to effects such as water weakening and fluid pressure variations would be required. With this information, one approach would be to predict failure based on stress levels relative to the strength of the material, under specified fluid injection and/or extraction conditions, using reservoir modeling methods. In this case, reservoir production would produce perturbations in the initial tectonic stress, temperature, fluid pressure and ultimately the material strength, which could be sufficient to produce significant changes in the background microseismicity and in extreme cases, especially in regions with preexisting faults under relatively high tectonic stress, sufficient changes to trigger a fairly large seismic event.

The fully deterministic approach to an estimate of the hazard involved in an active geothermal reservoir not only requires knowledge of a large number of material parameters and state variables, such as initial temperature and stress, but also knowledge of geologic structure including the fracture and fault zone geometry. Obviously acquisition of this information will require an extensive field program; and the elements of such a program are discussed in earlier sections of this report. Further, details of the production history of the field would be required in order to specify the time dependent boundary conditions for the reservoir modeling and an observational program designed to obtain surface and downhole tilt, strain, compaction and subsidence measurements with time is required in order to, at least partially, verify the modeling predictions. Finally, the rhyologic and chemical behavior of rocks as a function of stress level, temperature, fluid content, strain rate, etc. must be known with reasonable certainty for meaningful predictions of failure phenomena to be made. While considerable research in this area of rock physics is underway, in particular under other areas of the geothermal program and under the earthquake prediction program, it is premature to conclude that sufficient knowledge of rock failure under high temperature reservoir conditions is presently available for very accurate modeling predictions to be made at this time. Consequently, it is important that the present program include support for rock physics experiments designed to more precisely define rock rhyology near and at failure, as a function of temperature, strain rate, fluid content and chemistry.

Since seismic hazard estimates based on reservoir modeling can only be expected when the initial tectonic stress state of the reservoir is specified, it is critical that stress level estimates be accomplished under this program. Specification of the stress state can be achieved in part by hydrofracturing experiments in the field, but this direct measurement of the ambient stress state, while critical, gives limited information spatially and is expensive to obtain. Applications of seismic techniques for estimates of stress changes associated with the microearthquakes that constitute the background activity in tectonically active areas, is therefore of great importance in estimating the initial stress distribution within the reservoir area.

In this case, passive seismic monitoring of the region may be used to record the commonly occurring small earthquakes within a field and estimates of the stress changes produced by the events can be obtained. These stress changes are, in fact, nbe amount of local ambient stress that can be released by an earthquake (the "recoverable ambient stress") and so is an important quantity in itself. Further, methods have proposed to relate the observed recoverable stress inferred from the seismic observations to the ambient stress local to the seismic event. However, these currently provide a rather wide range of estimates which are dependent on particular earthquake model assumptions and approximations. Thus, while additional research in the use of seismic data for stress estimates is required for accurate delineation of the initial ambient stress state, it is nevertheless necessary that the program incorporate an observational seismic study designed to give both recoverable and ambient stress estimates spatially throughout the prospective reservoir in order that reservoir modeling be an effective method of predicting seismicity changes.

The seismic observations of microearthquake activity are also an important tool for the location and delineation of fault zones within the field and can be used to give stress field orientations with a rather high degree of certainty. These observations are clearly important in defining the initial state of the reservoir as well as its dynamic state during production. In this regard, continuous seismic monitoring of the reservoir region could be used to provide a basis for monitoring the changes in seismicity during production, so that modeling predictions could be checked, and so that an empirical basis for correlations between production procedures and seismic activity could be established. Equally important, this approach offers the possibility of inferring the stress field by observational means during production. Thus, an independent determination of the seismic hazard could be based on the seismicially inferred (spatially variable) stress levels, stress field orientation and seismicity levels. In this approach one would require sufficient seismic instrumentation to detect and locate the numerous small events. Further the detector array must be adequate to determine the azimuthal radiation patterns from each event and the spectral properties of the radiated seismic field. With this capability it would be possible to determine the stress drop (or recoverable stress) associated with each event along with an inferred ambient stress and the orientation of the failure plane, as well as the event location. Given a spatially distributed occurrence of small seismic events within the field which would provide a spatial sampling of the stress, then it would be possible to delineate regions of high stress and potential large scale failure during any field production program.

In view of these possibilities for quantitative seismicity estimates, it is appropriate to recommend a comprehensive program with complementary observational-empirical and modeling components designed to provide a documented basis for seismic hazards assessment. The essential elements of this program are:

1. To obtain production and seismicity data from an operating geothermal field, specifically the Geysers field, to determine the quantitative nature of any correlations between seismic activity, reservoir structure and production history. This information to be used as an empirical means of estimating expected effects, and to verify reservoir modeling predictions.

2. To employ passive seismic monitoring of geothermal field seismicity to obtain estimates of the non-hydrostatic stress, both initially and as a function of production history and to also compare these estimates with in situ ambient stress estimates using hydrofracturing measurements. From the combined stress data to then base predictions of future

seismicity on the stress field estimates obtained from microearthquake occurrences and available <u>in situ</u> stress measurements during production.

3. Based on quantitative material property and field structure data coupled with initial stress state estimates, use reservoir modeling methods to predict stress field variations to be expected as a function of field production programs and, from these stress predictions, to infer seismicity changes based on fault locations and rock strength properties. Finally, to also correlate the results with production histories and general time dependent seismicity data, including the seismically estimated stress state variations, in order to establish a verified, deterministic, predictive capability.

4. Based on the inferred stress levels and the material strength, which serves to define stress levels at which failure may occur, provide an estimate of the probable locations, maximum dimensions, magnitudes and expected ground motion from the largest events to be expected.

Some of the essential aspects of this program are discussed in more detail in the following sections. In particular, we address the basic questions of how geothermal reservoir energy production may affect seismicity and how the effects can be predicted by reservoir modeling. In addition, a more detailed discussion of how seismic observations are used to infer failure plane orientations and stress levels within a tectonically active region is included.

IV. PHYSICAL BASIS FOR TRIGGERING OF EARTHQUAKES BY GEOTHERMAL PRODUCTION OR REINJECTION

To understand the relationship between production or reinjection of geothermal fluids and earthquakes we require an evaluation of the perturbations in the mechanical, thermal or chemical environment caused by exploitation. These perturbations act upon rocks whose initial state is the other unknown which we need to measure, i.e., are there preexisting faults in the rocks and are they stressed to near the point of failure?

This section lays out an experimental approach to measuring the static physical parameters in an appropriate rock mass and determining the effect most likely to trigger earthquakes in that body of rock. Because it is presently seismicially active and it is the principal producing geothermal field in this country, the Geysers area offers the best laboratory for such an experiment.

4.1 THE INITIAL STATE

It is now possible to measure the absolute state of stress in boreholes where temperatures reach 250°C. The method, hydraulic fracturing, has been extensively used in recent years for this purpose, although not in the high temperature application. In addition to the unforeseen problems likely to develop in high temperature environments, the hydrofracturing technique does not work well in highly fractured rock. Otherwise, the technique has worked successfully and is the only method available for other than surface measurements.

The faulting and fracture state in the rocks can be approached by using a borehole televiewer, an ultrasonic device which maps the orientation and distribution of fractures intersecting the borehole. This device has been modified for use at temperatures up to 220°C. The radiation pattern from microearthquakes also can be used to estimate fault plane orientations, in active zones.

The fluid pressure is one of the principal parameters influencing earthquakes. The presence of a large number of drill holes at the Geysers makes it possible to determine the fluid pressure in the reservoir at the focal depths of the earthquakes easily, provided access to pressure data can be obtained. Use of the boreholes is a prerequisite to conducting the experimental plan outlined here.

The foregoing measurements, along with seismic methods designed to infer the stress changes associated with background microearthquakes, can be used to establish the ambient stress field and its variability. The strength properties of local rocks at the appropriate temperatures and pressures should then be measured, and this capability is available at several existing laboratories.

With these data, it becomes possible to estimate the likelihood that any perturbation caused by production or reinjection could lead to shear failure and earthquakes. The possible perturbations affecting seismicity are examined in the following sections.

4.2 FLUID PRESSURE CHANGES

Production of steam from the Geysers has led to a maximum reduction in the reservoir pressure of 225 psi. The reduction in fluid pressure would act to strengthen the rock against frictional failure, although the indirect effect of subsidence might ultimately trigger earthquakes. Reinjection of water apparently does not lead to significant increases in the fluid pressure except, possibly, in the immediate vicinity of the injection wells. A series of bottom-hole pressure measurements over hours to days following a period of injection should be carried out to establish the spatial and temporal extent of any such increase. Such data have not been gathered to date, but are relatively easy to obtain.

4.3 FLUID PRESSURE GRADIENTS

Local reductions or increases in reservoir pressure due to production or reinjection result in pressure gradients in the fluid or vapor phase. These gradients in turn generate stress differences in the solid medium and conceivably, may contribute to increasing local shear stress (or decreasing the normal stress) on faults sufficient to trigger earthquakes. From existing production data, the maximum gradients in the vapor phase are low, no more than 1.5×10^{-2} bars/meters so that the effect, though finite, is not large. Once fault plane orientations and slip directions are determined from focal mechanism studies, the effect of the known gradients can be estimated from the known fluid pressure gradients.

4.4 STRESS CORROSION CRACKING

The dependence of brittle fracture strength on the chemical environment needs some detailed study. Enough is known to suggest that such an effect may be important, although whether there has been sufficient change in the reservoir to affect the fracture strength significantly is only poorly understood.

4.5 THERMAL STRESS

Temperature gradients induce stress differences which might contribute to initiation of seismic activity. In a vapor dominated reservoir, gradients should be quite small and the stresses correspondingly low. However, reinjection of relatively cool water could lead to a more substantial effect. Lack of knowledge of the geometry of the fracture system into which the reinjected fluid flows will make calculation of local stress variations in discrete fractures rather crude. Although a difficult problem, some order-of-magnitude estimates need to be attempted.

4.6 SUBSIDENCE

Removal of steam has resulted in a maximu subsidence of about 15 cm since production began at the Geysers. The effect of such deformation on local stresses can be estimated provided adequate leveling data exist. As it is suspected that subsidence in oil fields may play a role in local fracturing, and that it may lead to damaging earthquakes, suggests that this effect is likely to be a significant one.

4.7 PHYSICAL MODELING

The relative effects on faults of known orientation, by the perturbation discussed above, can be estimated in the first year, at least to within an order of magnitude. It appears likely that all but one or two of the above effects can be eliminated as having little significance, particularly as the current seismicity patterns and focal mechanisms are available for comparison with expectations from the calculations. For example, the strains induced by known subsidence can be compared with the strain release pattern derived from focal mechanism studies to judge whether any reasonable relationship exists.

In the second year, it should be possible to conduct measurements of absolute stress and the fracture distribution to provide the foundation for more refined calculation of the seismogenic effects. Finally, and most important, the three-dimensional pattern of faults, stress and the relevant perturbing effects should be incorporated into a model which leads to a prediction of the maximum probable earthquakes. The latter study is critical not only to the Geysers, but to the general problem of induced seismicity.

4.8 STRESS FIELD AND FAILURE PREDICTIONS BY RESERVOIR MODELING METHODS

In many areas of the world, land subsidence and small earthquakes have been observed to accompany the production of fluids (oil, gas, water, steam, etc.) from undergground reservoirs. Subsidence is generally believed to be caused by the compaction of the semi-consolidated strata of the reservoir as the effective overburden stress (defined as lithostatic stress minus fluid pressure) is increased due to fluid withdrawal. Fluid production can also produce relatively large localized stress changes in the reservoir (and overlying) rock. The localized stress buildup has potential for activating faults. (Thus, for example, increase in horizontal stress can lead to growth of normal faults whereas a buildup in shear stress may cause shear failure in the overburden/underburden.)

The geohydrological effects described above involve thermomechanical interactions between the rock and fluid components. Theoretical models describing the thermomechanical response of the rock and fluid (water and/or steam) composite material in terms of the isolated components have been developed and are currently operational. In these models, the stress-strain equations for the rock matrix are coupled with the diffusion equations for the fluid. Some of the more advanced modeling methods appear to be adequate for analyzing subsidence and stress buildup in a geothermal aquifer undergoing production and/or injection and it appears that no new theoretical development effort is required at this stage, at least until further comparative studies are completed.

In the modeling theory, the fluid flow and the solid response problems can be decoupled if one assumes that the fluid withdrawn (or reinjected) is small, so that the overburden essentially remains constant. The restriction to uniaxial (vertical) compaction together with the assumption of constant overburden implies that the reservoir porosity can be regarded as a function of pore fluid pressure and temperature only. During the past few years, several reservoir programs (incorporating the uniaxial compaction assumption) have become available. Given basic reservoir engineering data (rock porosity, permeability, specific heat, thermal conductivity and compressibility; fluid equation of state, etc.; and the initial state of the reservoir), the reservoir simulators can be employed to yield perturbations in the fluid state (pressure, temperature, etc.) introduced by exploitation/reinjection. Several of the reservoir simulators possess considerable flexibility as far as fluid and rock properties, problem geometry and boundary conditions are concerned. Thus, for example, a current advanced reservoir modeling program can treat multiphase, multispecies (water/steam, water with dissolved methane/free methane, water with dissolved salt/steam/precipitated salt) fluid flow in one-, two- or three-dimensions. In this program each computational zone in the finite-difference grid may contain a different rock type and provisions are also made for all practical boundary conditions.

In order to model the effect of time-varying fluid flow on matrix stress in a geothermal reservoir, finite element solid equilibrium codes are employed. Any such finite element code is basically a program for solving linear elastic continuum problems; however, problems requiring treatment of nonlinear material behavior may be solved by iteration using effective elastic moduli in the element. Given rheological properties of the reservoir rocks and the fluid pressure history in the reservoir, these programs may be employed to yield the time varying stress field and the deformation in the matrix. These programs can also be used to model overburden changes. Interactive codes have also been developed that couple fluid response programs with finite element solid matrix response codes. In the coupled fluid-solid matrix computations, the system is marched through any desired number of time steps in each of which a flow cycle calculation is performed yielding values of pore pressure, temperature and fluid density at the end of the time step. This information is then used in the finite element solid matrix calculation to yield the instantaneous equilibrium condition (i.e., rock displacements, stress, etc.) as functions of rock properties and fluid variables.

Most approaches for the analysis or subsidence and stress buildup are based on decoupling the fluid flow and rock response calculations. (For example, changes in the fluid state cause perturbations in the rock stress state; however, the perturbations in the rock stress field are not allowed to affect the fluid response.) Although this procedure is computationally very efficient, it may be that, for very accurate predictions, it will be necessary to develop new computer codes which solve the fully coupled fluid flow and rock response problem. Also, one may want to calculate aseismic slip (as a result of fluid preduction/injection) on discrete faults. The numerical techniques for treating the latter problems already exist and may be adapted to these problems.

4.9 SEISMIC METHODS: STRESS ESTIMATES, FAULT PLANE GEOMETRY AND SEISMICITY LEVELS

An objective of this part of the research program is to determine the spatial and temporal variations of recoverable tectonic stress. In this context the term "recoverable tectonic stress" refers to that part of the nonhydrostatic stress field within the earth that can be released, in the form of seismic radiation, by an earthquake. This stress is therefore distinct from the absolute or ambient nonhydrostatic stress, a part of which may not contribute to the radiation from a spontaneous failure process. The recoverable stress then, is that part of the ambient nonhydrostatic stress that can be released as seismic radiation.

A second objective is to relate this recoverable stress level, which can be inferred from seismic observations of the wave radiation from small earthquakes, to the ambient stress level which acts to initiate a failure process. The relationship between recoverable stress and ambient stress is quite uncertain in that the earthquake model theory required is still being developed and in any case requires verification. In this regard, measurements of ambient stress by hydrofracturing can be compared to seismically estimated recoverable stress values obtained from events at, or very near, the ambient stress measurement. These independent stress estimates could then be used to establish a relationship between the recoverable and ambient stresses. However, given that a determination of the recoverable stress can be obtained, it may be possible to identify spatial regions as hazardous in terms of the existing recoverable stress levels alone and to also predict the size and locations of likely large earthquakes, the former in terms of the detailed nature of the seismic radiation to be expected. Furthermore, it is reasonable to expect that inferred recoverable stress levels themselves can be used to predict the time of failure, if we are able to resolve time variations of the of the stress and monitor stress buildup with time to some critical level and spatial configuration.

The approach to the estimation of the recoverable stress is to use observations of the seismic radiation from the numerous very small to moderate sized earthquakes in the tectonic region of interest and to infer the stress changes associated with these events. The stress changes are largely local to the failure zone, in view of the rapidity of stress change falloff with distance, and, for these small events, constitute perturbations to the regional stress field. The changes can, however, be used to provide a sampling of the regional stress and hence provide the desired stress sampling mechanism.

Observational and interpretational methods for estimating stress using large numbers of small events require automated procedures to cope with the large amount of data recorded. Currently employed procedures involve the following:

1. The acquistion of a large event data base spanning as long a time period as possible, with events recorded in digital form over a reasonable wide frequency range.

2. The processing of the event data, using multi-station recording to determine fault orientations and locations, and extraction instrument corrected spectral data from which variable frequency, compressional (P) wave magnitudes may be computed at "low" (near 1 Hz) and high frequencies (near 10 Hz).

3. Using regional earth structure models and an appropriately general dyanmical model for the earthquakes, to generate theoretical variable frequency magnitude results for the variety of earthquake types and sizes contained in the

observed data set (this involves generating synthetic seismograms at the distance range and azimuths comparable to those from which the observations are made, and then generating the theoretical variable frequency magnitudes by the same spectral analysis procedure used with the observed data).

4. Classification of events as to type (i.e., strike-slip, thrust, etc.) and determination of both the recoverable stress and the failure zone dimensions of the observed events by comparison with the theoretical magnitude results.

The results generated by these operations include:

1. Locations of events, which define active faults or tectonic zones within the region.
2. "Recoverable stress" or stress drop determinations associated with the events, giving estimates of the background stress that can be released by an earthquake.
3. The failure zone dimensions that are associated with each event.
4. The orientation of the failure zone or fault plane for each event, which provides information on the stress field orientation as well.
5. The numbers of events versus event magnitude (or energy release).

These data would clearly provide necessary initial data for the reservoir modeling and, with continuous seismic monitoring, can provide a check on the modeling predictions of the stress field changes during production.

In addition, time variations in seismicity (cummulative numbers of events versus event magnitude), microearthquake event clustering (spatial distribution of events), and fault plane orientation at a given location, as well as the stress itself, appear, at least on occasion, to be premonitory indicators of relatively large earthquakes. Therefore the seismic monitoring results may in themselves provide important empirical results for larger event prediction.

V. RECOMMENDED PROGRAM

5.1 Background seismicity measurements prior to exploitation should begin immediately at all promising geothermal prospects. At least two years of preexploitation monitoring is recommended. The optimal monitoring system would consist of a three-component (possibly 100 m downhole), 4.5 Hz geophone package, operating with at least 50 Hz bandwidth and at maximum possible sensitivity into an event recorder with digital cassette recording, and located no more than 1 to 2 km from the expected field center. In the event that significant seismicity is seen in the immediate vicinity (within 5 km), two additional stations should be added for improved spatial resolution of the hypocenters, and subsequently the network can be expanded to the density required by the ongoing analysis of the local seismicity.

5.2 An intensive, site specific data acquisition and interpretation program should be initiated immediately at the Geysers, California. A summary of the induced seismicity and subsidence history of this area is given in the appendix. The recommended program for the Geysers is as follows.

5.2.1 Continue operation of the telemetered network to provide continuous mapping of seismicity ($M \geq 1$) as the production zone expands in 1979 and 1980. Increase station density near future power plants especially Unit No. 13, a 100 MWe unit which begins operation in FY '80. It will be located in a part of the steam field that is presently aseismic.

5.2.2 Invert the microearthquake travel time and gravity data to obtain an estimate of the elastic properties and density of the earth structure in the areas of microearthquake clustering. Constrain the inversion with all geophysical data available from the operators of the field.

5.2.3 Determine the stress drop and fault orientation of the microearthquakes. Identify the spatial and temporal variation of the these fault parameters and correlate with production and injection procedures. Delineate regions of high stress drop and estimate the potential for large scale faulting.

5.2.4 Model the effect of time-varying fluid flow on the stress in the rock matrix in the vicinity of injection and production wells. Determine if the stress buildup is sufficient to explain the observed microearthquake and in particular the stress drops associated with these earthquakes. The operators of the field should be encouraged to furnish injection and production data (bottom hole pressure measurement) and the properties of the reservoir (permeability and porosity) for this project.

5.2.5 Install strong motion recorders near critical facilities. Continue geodetic and gravity measurements. Install tiltmeters near Unit No. 13.

5.2.6 Perform hydraulic fracturing measurements in selected boreholes to determine the absolute state of stress in the field.

5.3 A site specific cell in the geothermal data bank should be created for each prospect. Geological, geochemical, geophysical and geothermal data can be assigned to the prospect for analysis as development of the prospect proceeds.

We recommend that the above elements (5.1, 5.2 and 5.3) be initiated during the first year and be assigned the highest priority. The priority of the following elements will be determined after the results of the Geysers project are evaluated.

5.4 Seismicity measurements and reservoir properties should be obtained for all prospects undergoing exploitation. The field operator must be convinced of the need for these data if the program is to succeed. Seismic monitoring is essential. For seismically active areas the preexploitation network should be expanded to at least six, perferably eight to ten, stations. Interstation spacing should be no more than 2 km and common timing with less than 10 ms error between stations is required. If the reservoir is aseismic, a single station near the reservoir center would be sufficient. If induced seismicity is detected then a full network should be installed. The USGS telemetered network at the Geysers should be reviewed and upgraded, if necessary, in order to meet the requirements of elements 5.2.2, 5.2.3 and 5.2.4. Bottom hole pressure measurements and reservoir properties including elastic constants, density, porosity and permeability will be required for each seismically active field.

5.5 The dependence of brittle fracture strength on the chemical and temperature environment needs some detailed study. This activity should be coordinated with other areas of the geothermal program and the earthquake prediction program.

5.6 Prediction of the ground motion from the largest expected events will be required. Coordination with research activities conducted by NSF, USGS and NRC is recommended. However, it is clear that the transmission path contributes a large percentage of the overall uncertainty in seismic design. The microearthquake data should be interpreted to provide a site specific calibration of the attenuation of seismic waves from the fault to critical facilities. This interpretation would also provide an estimate of changes in the Q structure of the reservoir as a function of production and injection rates.

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APPENDIX A

A SUMMARY OF INDUCED SEISMICITY AND SUBSIDENCE AT THE GEYSERS, CALIFORNIA

A.1 STEAM PRODUCTION HISTORY

The first geothermal well at the Geysers was drilled in 1921, but extensive steam withdrawal did not begin until Pacific Gas and Electric Company began generating electricity in 1960 with Unit No. 1. Power production rose from 11 MWe in 1960 to 51 MWe in 1966, expanding to the current 502 MWe in 1975. When operating at full capacity, the field production rate is approximately 8.5 million pounds (19 million kg) per hour. Pacific Gas and Electric Company is currently constructing four new power plants, which will nearly double the generating capacity (to 908 MWe) within the next year or so. Ad additional 900 MWe could be added by the mid- 1980's (Lipman, Strobel and Gulati, 1977).

A.2 EARTHQUAKES AT THE GEYSERS

The sparse northern California network of the University of California at Berkeley provides the only preproduction data on seismicity at the Geysers. The location threshold over most of this period was about magnitude 1, so little can be said about the number of smaller earthquakes at the Geysers before power production began. However, the Berkeley data does show an increase in the number of earthquakes at the magnitude 1 level since production began. In addition, larger earthquakes

Several brief microearthquake surveys have been conducted at the Geysers over the years. Results of these studies, by Lange and Westphal (1960), Hamilton and Muffler (1973) and

Majer and McEvilly (1977), suggest that microearthquake activity at the magnitude 0 level may have increased as power production increased.

In 1973 the U. S. Geological Survey extended their central California seismographic network northward to the Geysers (Figure A.1). Station density was increased in 1975 and gain in 1977 to 1978. The present Geysers network is shown in Figure A.2; average interstation spacing is 4 km. Approximately 1000 earthquakes ($M \geq 1$) have been located at the Geysers since 1975. Marks, et al., (1978) and Bufe, et al., (1979) have examined the distribution of earthquakes with respect to the steam production zones and injection wells (Figures A.3 and A.4). The contours of the two zones of decreased steam pressure are interpreted by Lipman, Strobel, and Gulati (1977) as the consequence of steam production from two reservoirs. Estimated points of water injection are also shown in Figure A.3; data on the exact points of injection and condensate injection rates have not been made available by the producers. The correlation between the two clusters of microearthquakes and the two reservoirs is compelling circumstantial evidence that the earthquakes are induced.

Marks, et al., (1978) have also compared the 1975 to 1977 regional seismicity at $M \geq 2$ to the seismicity in the early (1962-1963) days of steam production when U. C. Berkeley operated a single station at Calistoga, 30 km southeast of the Geysers. They found the number of regional events had increased from 25 a year to 47 a year. The difference of 22 a year is near the 1975 to 1977 occurrence rate at the Geysers, suggesting that seismicity at the Geysers was significantly less in 1962 to 1963.

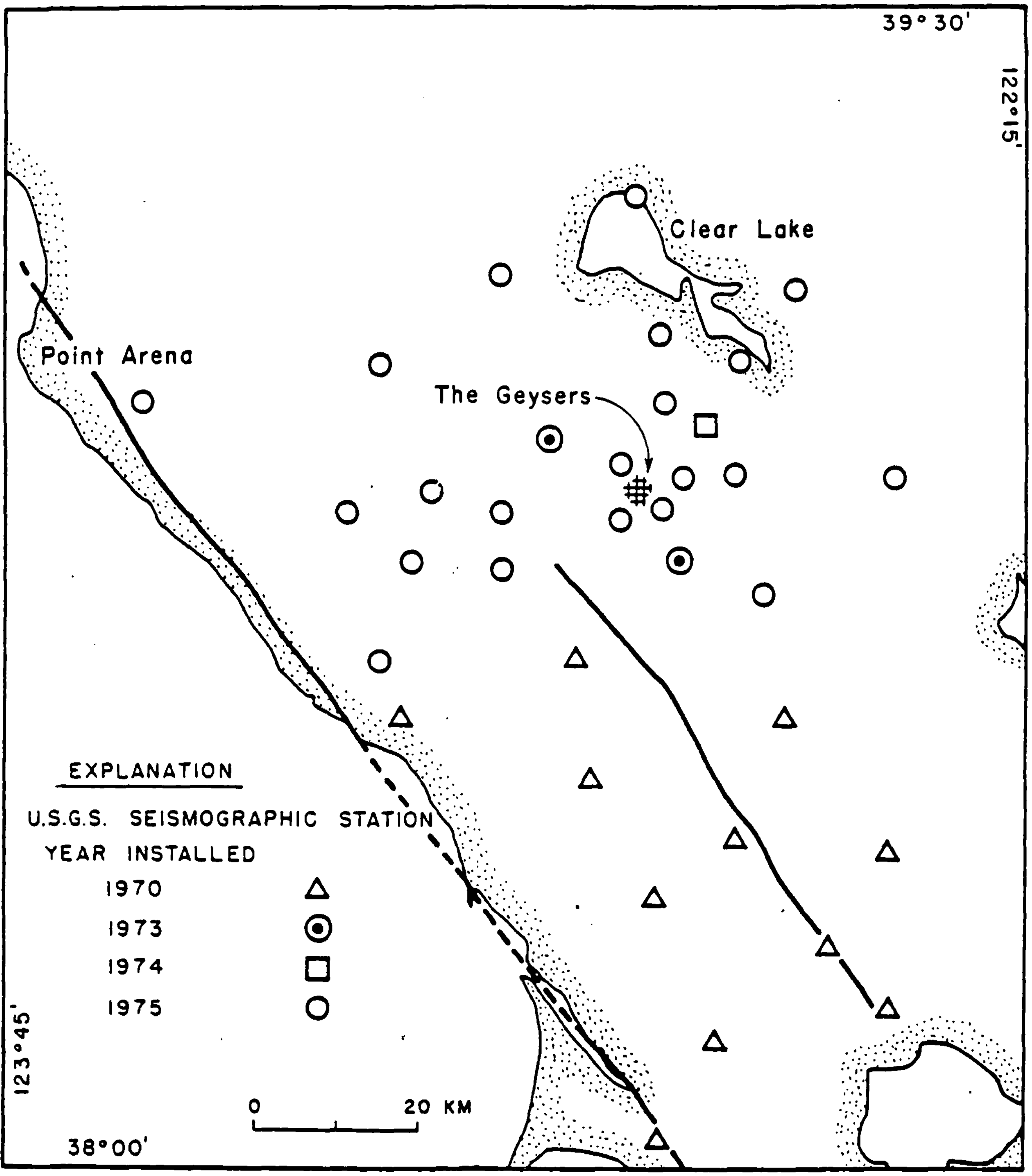

Figure A.1. U. S. Geological Survey seismographic stations, 1977. The stations immediately around the Geysers are shown in more detail in Figure A.2.

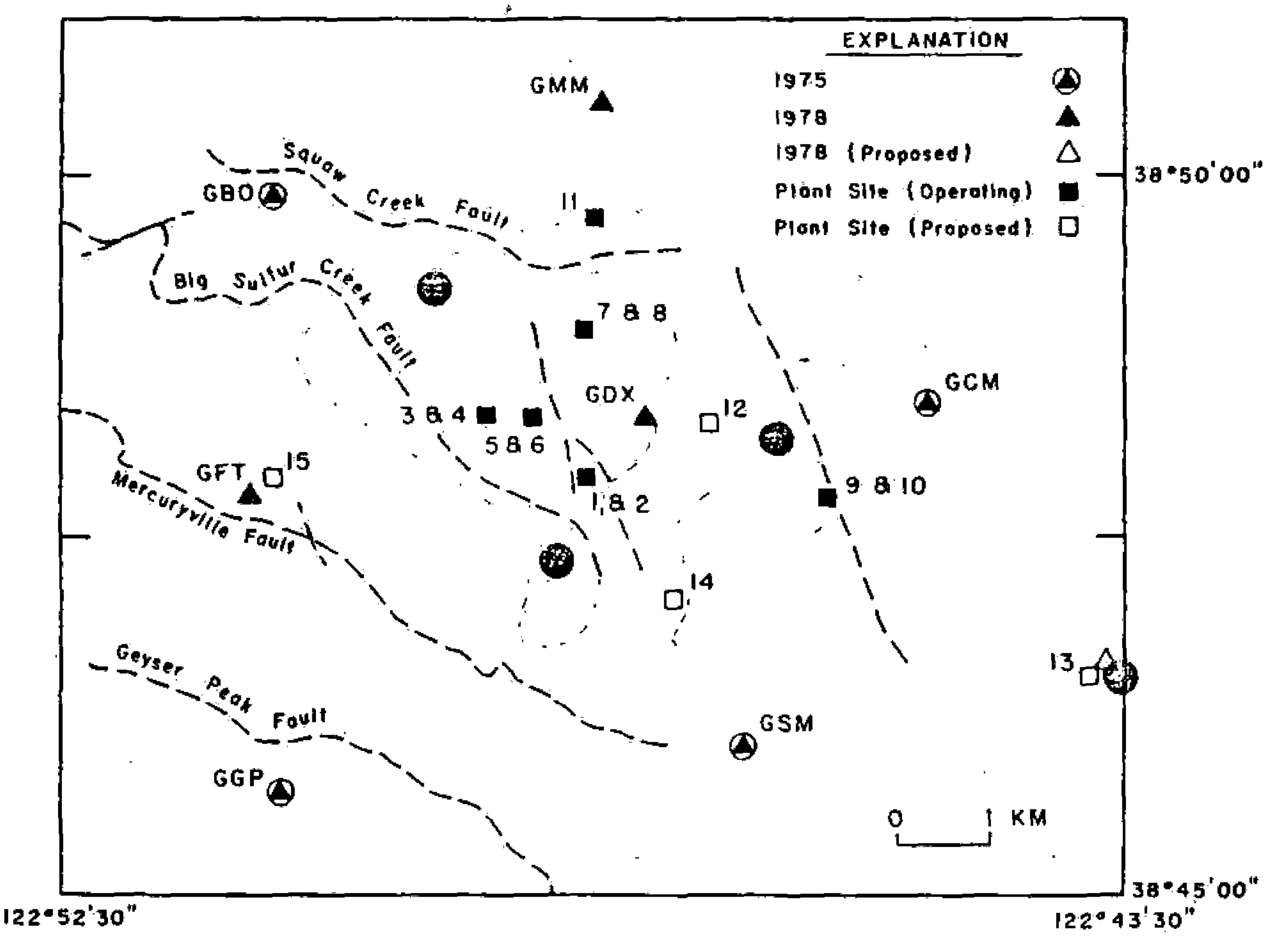

Figure A.2. Network of telemetered seismographs at the Geysers, May 1, 1978. Also shown are (numbered) geothermal power plants. Units 1 through 11 are generating power at the present; 12 through 15 will begin operation in the near future. Faults are from a compilation by R. McLaughlin of the USGS. In addition to the telemetered stations, a roving network of three-component digital seismographs is being deployed at the Geysers. Initial locations of these portable stations are indicated by solid circles.

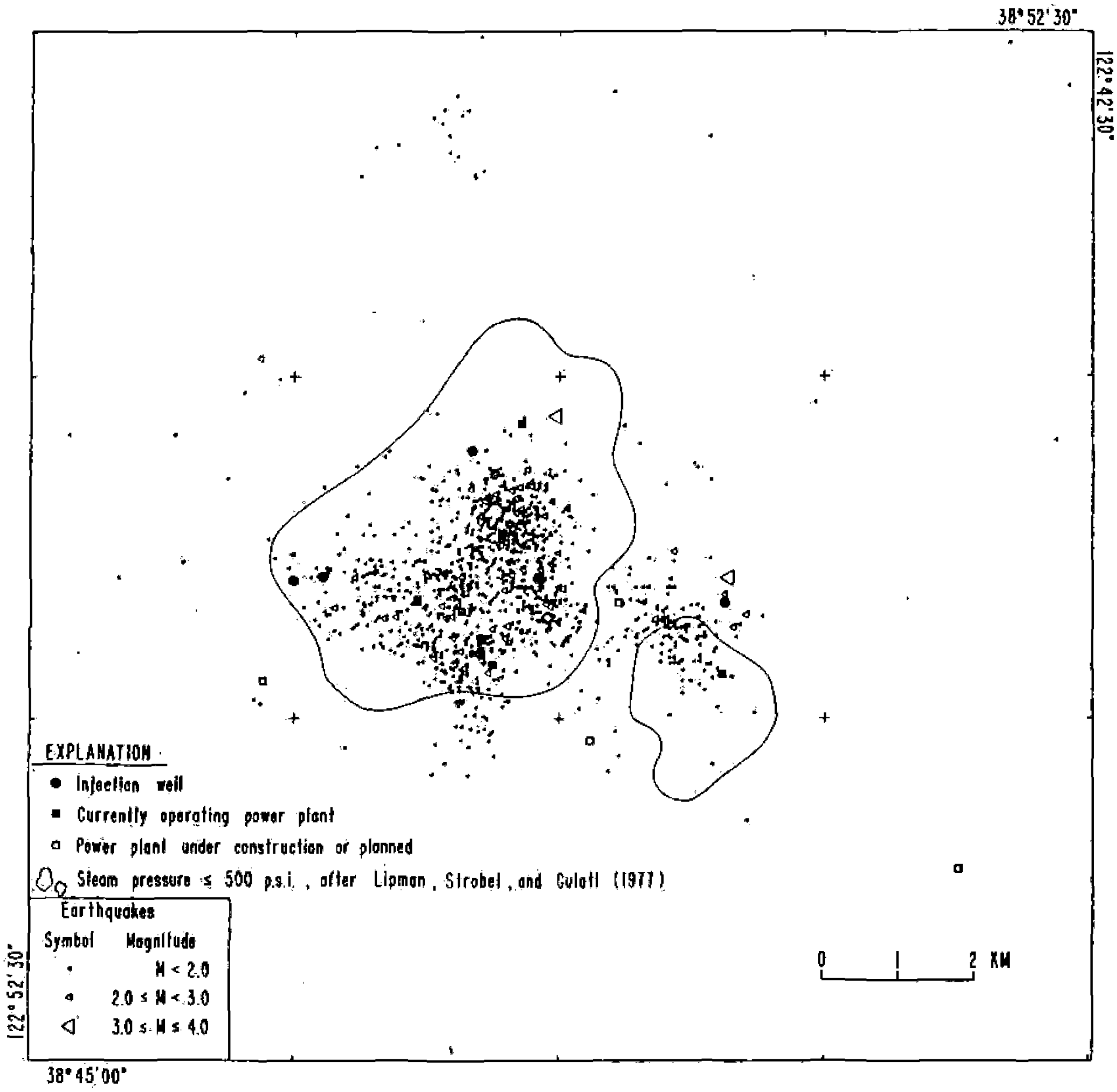

Figure A.3. Earthquake distribution and steam production zones, the Geysers Geothermal Area, California.

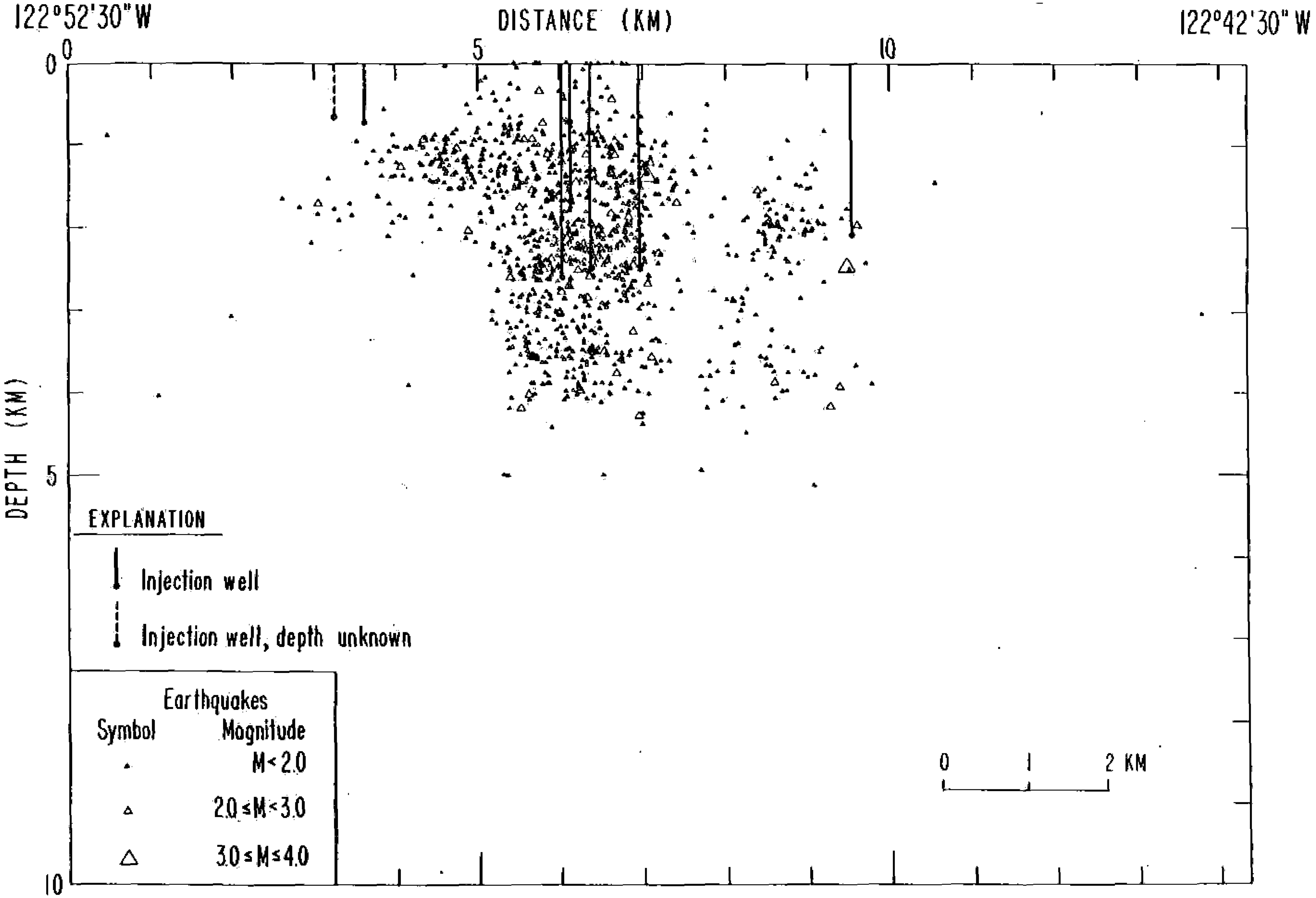

Figure A.4. Steam production zone and cross section, the Geysers Geothermal Area, California.

A.3 CHARACTERISTICS OF THE EARTHQUAKES AND THE RESERVOIR

Several studies of earthquake characteristics and reservoir properties which bear upon induced seismicity at the Geysers are in progress or have been completed. Marks, et al., (1978), conducted a comparative study of seismicity rates and b values at the Geysers and elsewhere in the Clear Lake region. They found no significant difference in b values (range 1.1 to 1.5) between the Geysers production zones and the surrounding geothermal and tectonic regimes. The earthquake occurrence rate in the production zones was found to be higher and more constant (less episodic) than in the surrounding regions.

Peppin and Bufe (1978) found no significant differences in spectral characteristics of earthquakes at the Geysers and those at Alexander Valley, 10 km to the south.

Bufe and others (1979) have detected a change in the faulting pattern at the Geysers since late 1977. Earthquakes in the lower (h > 2 km) part of the reservoir have changed from predominantly strike-slip to predominantly normal faulting. The shallower earthquakes are strike-slip or thrust, and are very simliar to mechanisms of earthquakes in the surrounding region.

Majer and McEvilly (1978) have examined the shallow crustal structure at the Geysers, using results of a seismic refraction profile and spectral studies of microearthquakes. They find the vapor dominated reservoir to be characterized by relatively high P- and S-wave velocities and low attenuation, a situation possibly reversing with depth. Iyer, et al., (1979) find large travel time delays and Ward, et al., (1979) find excessive attenuation in teleseismic P arrivals at the Geysers. Denlinger and Kovach (1979) conducted a shallow vibroseis reflection survey at the Geysers and have examined gravity data from the developed and undeveloped parts of the field.

Lofgren's (1978) 1973 to 1977 geodetic results have shown horizontal (2 cm/yr, convergence) and vertical (3 cm/yr subsidence) changes which suggest that the geothermal reservoir is being compressed both vertically and horizontally as fluid pressures within it are drawn down by production. Isherwood (1979) interprets gravity decreases as large as 120 mgal as resulting from steam withdrawal with no significant natural recharge. These results suggest a trend of decreasing porosity in the reservoir; a process reflected in the high level of microearthquake activity.

Notes:

1. In July entered into letter agreement between NVOO; HQ re this program. –
2. In first 1/4 FY79 got group together to write program plan –
3. Proposed a two pronged attack
    a) better effort at the Geysers – more instrumentation
    b) set up data bank similar to GRID – set up a primary model against which to check other models
    c) select 4-5 "promising" sites – – Simple passive instrumentation to get a *history* – 1-2 years – if area turns out to be aseismic, may quit.

4. we just don't have enough data – – a major problem –
5. Only area presently selected for study is the *Geysers* –
6. Geysers monitoring has been DOE funded for past 2 yrs –
7. what They want to do now
    a) monitor Geysers
    b) start data acquisition all @ LBL