MEMORIES FROM AN APSMAGS WORKSHOP
FT. BURGWIN RESEARCH CENTER
OCTOBER 1-5, 1978

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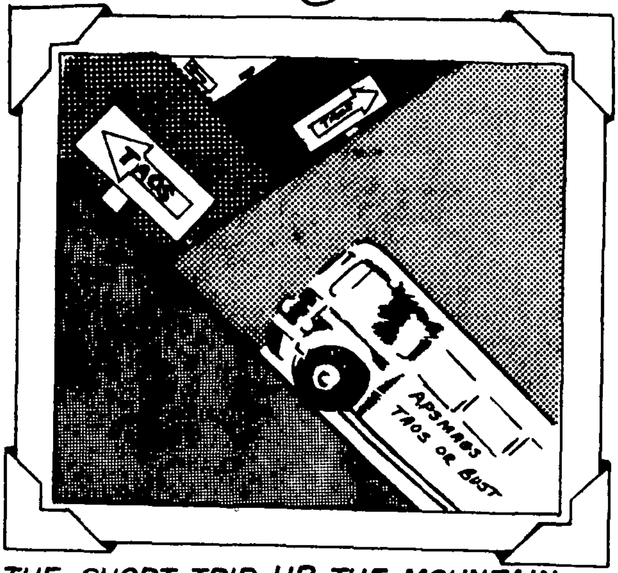
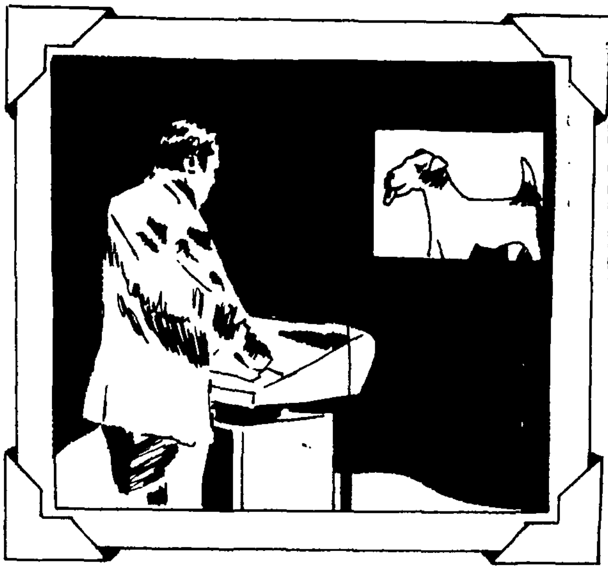
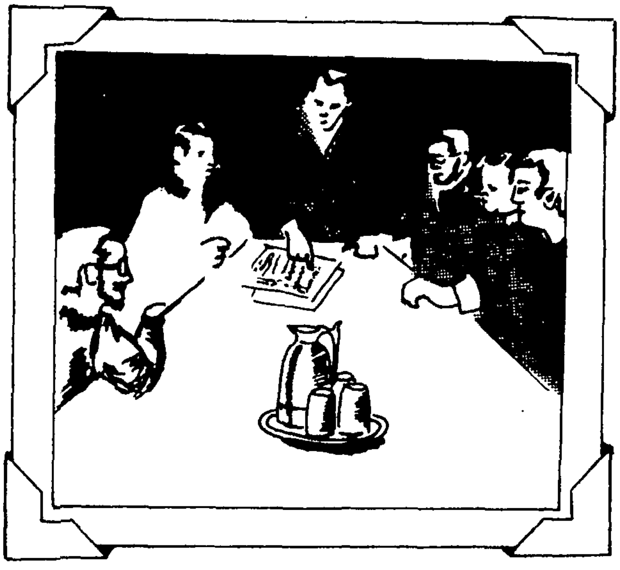


THE SHORT TRIP UP THE MOUNTAIN

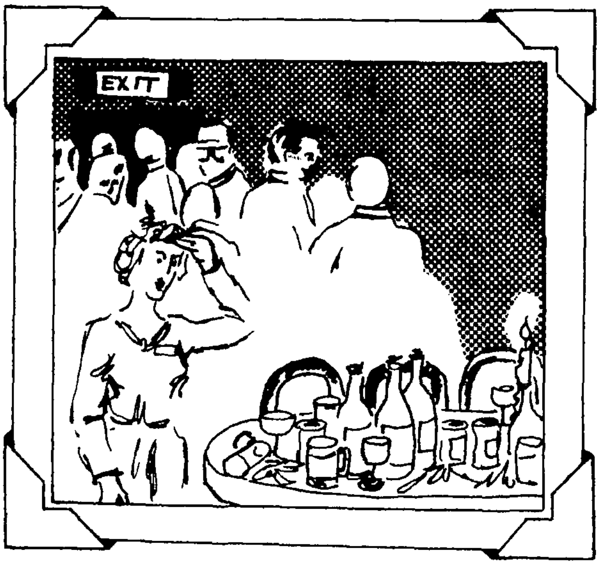
SOMETHING STRANGE IN THE DATA



OOPS! NEXT SLIDE, NEXT...



... AND THE COWBOY-REDSKIN'S GAME AT 2:00



A FOND FAREWELL

WORKSHOP ON

ACTIVE AND PASSIVE SEISMIC METHODS APPLIED TO GEOTHERMAL SYSTEMS (APSMAGS)

FT. BURGWIN RESEARCH CENTER
TAOS, NEW MEXICO
OCTOBER 1-5, 1978

ORGANIZED BY

CENTER FOR ENERGY STUDIES
UNIVERSITY OF TEXAS AT DALLAS
P.I. — R. W. WARD

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U.S. GEOLOGICAL SURVEY
GEOTHERMAL RESEARCH PROGRAM
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INTRODUCTION

Within the past two years it has become evident from papers presented at national meetings and those appearing in the literature that there is a need to foster greater communication between seismologists working in the academic environment, government laboratories, and those in industry who are developing seismic methods for the exploration and assessment of geothermal systems. At one end of the spectrum are experimentalists and theoreticians studying the effects of high temperature, liquid vapor phases, and partial melting on the seismic properties of rocks. Other seismologists are developing regional tectonic models. At the other end are exploration geophysicists acquiring contract seismic surveys to explore and assess the economic potential of geothermal systems. A group of seismologists lie between the extremes and are actively engaged in various levels of research on the application of seismic techniques to geothermal systems. Many different seismic studies have recently been performed on different geothermal systems filling some of the voids in the case studies. It is felt that the most effective way to foster communication between diverse groups of seismologists and obtain a current evaluation of the utility of active and passive seismic techniques is through a workshop. The workshop should be held in an isolated area, which would provide a relaxed atmosphere for discussion and individual interaction between seismologists. This report contains the summaries of such a workshop.

A workshop, funded by the U. S. Geological Survey Geothermal Research Program thru USGS Grant No. 14-08-001-G-542, was organized by Ronald Ward, Director of the Center for Energy Studies of the University of Texas at Dallas on Active and Passive Seismic Methods Applied to Geothermal Systems (APSMAGS) and held at the Ft. Burgwin Research Center near Taos, New Mexico, October 1-5, 1978

He was assisted by a steering committee composed by Drs. Dave Boore, Charlie Swift, John Savino, Dave Butler, Tom McEvilly and Keiiti Aki. Don Klick, Program Manager for the USGS Extramural Geothermal Research Program and H. M. Iyer, USGS Project Monitor, provided invaluable guidance and assistance as well in the planning and conduct of a successful workshop. The organizational details of the workshop was assumed by Glenda Max, Administrative Services Officer, assisted by Charlotte Scott and Libby Hodge.

A group of forty seven attendees and five observers arrived at Ft. Burgwin late on the afternoon of Sunday October 1, 1978, in time for an informal buffet dinner to allow attendees to renew old friendships and make new ones. The formal program covered three long work days (Monday, October 2, through Wednesday, October 4). An optional geological field trip was organized by Jim Albright of the Los Alamos Scientific Laboratory for the attendees on the day after the close of the program (Thursday, October 5) enroute to Albuquerque airport. The geologic field trip of the Rio Grande Rift, Valles Caldera, and Hot Dry Rock Deep Drilling Project at Fenton Hill was led by John Eichelberger and Grant Heiken.

The formal program was designed to address the problems actually encountered in utilizing seismic methods in exploration and assessment of geothermal systems. It consisted of two main sessions, on regional seismic studies and on prospect seismic studies. This presentation of studies grouped by the scope of the survey area was chosen rather than grouping the talks by seismic methods, since it seemed better suited to address the problems that are encountered. An introductory group of review talks were presented to set the stage for these two sessions and for later discussion. These talks covered geologic models of geothermal systems, laboratory measurements of physical rock properties, and status and controversies of seismic methods applied to geothermal systems. The various topics within the two main session on regional seismic studies and on prospect seismic studies are noted in the agenda, which follows.

Each major session of the program was followed by several concurrent, individual group discussion. Each discussion group was composed of seven or eight members with differing background. The format of the discussion within each group was unstructured but the charge was to review the usefulness of seismic techniques and to discuss objectives for further research and development of these techniques. A leader was chosen from each group to record the conclusions (or lack of conclusions) of each discussion and present these to the entire workshop. These presentations stimulated additional discussion by the entire group. A summary session focused the groups attention on (1) the advances that have been made in utilizing seismic methods in the past few years, (2) the current methods and problems that promise greatest break throughs, with short term and long range, and (3) the most efficient mode of transfering information from the research laboratory to the geophysicist assessing a geothermal prospect.

ACTIVE AND PASSIVE SEISMIC METHODS

APPLIED TO GEOTHERMAL SYSTEMS

AGENDA

Sunday, 1 October 1978

6:00 p.m. - 7:00 p.m.	Buffet Dinner
8:30 p.m. - 10:00 p.m.	Get acquainted reception

Monday, 2 October 1978

	7:00 a.m. - 7:45 a.m.	Breakfast
	7:45 a.m. - 8:10 a.m.	Opening remarks
Abstract	8:10 a.m. - 8:40 a.m.	Model of a Geothermal System - Bob Christenson
Abstract	8:40 a.m. - 9:10 a.m.	Laboratory Measurements of Physical Rock Properties - Roger Stewart
Abstract	9:10 a.m. - 9:45 a.m.	Status of Seismic Methods in Geothermal Application - H. M. Iyer
Abstract	9:45 a.m. - 10:15 a.m.	Problems and Controversies of the Application of Seismic Methods to Geothermal Systems- Tom McEvilly
	10:15 a.m. - 10:45 a.m.	Discussion
	10:45 a.m. - 11:00 a.m.	Coffee Break

Regional Seismic Studies

11:00 a.m. - 12:00 p.m.	Basin and Range - Keith Priestly
12:00 p.m. - 12:45 p.m.	Lunch
12:45 p.m. - 1:45 p.m.	Imperial Valley - Shawn Biehler
1:45 p.m. - 2:40 p.m.	Yellowstone - Snake River Plain - Bob Smith
2:40 p.m. - 4:00 p.m.	Free time for individual discussion
4:30 p.m. - 5:15 p.m.	Hawaii - Fred Klein
5:15 p.m. - 5:45 p.m.	Rio Grande Rift - John Schlue
5:45 p.m. - 6:15 p.m.	Cascades - Steve Malone
7:15 p.m.	Leave for dinner

Tuesday, 3 October 1978

7:00 a.m. - 8:00 a.m.	Breakfast
8:00 a.m. - 10:00 a.m.	Individual group discussion - Role of Seismic Methods in Regional Surveys
10:00 a.m. - 10:30 a.m.	Coffee break
10:30 a.m. - 11:30 a.m.	Presentation of Conclusions of Individual Groups
11:30 a.m. - 12:15 p.m.	Lunch

Tuesday, 3 October 1978 (continued)

Prospect Seismic Studies

12:15 p.m. - 1:00 p.m.	Geysers - Tom McEvilly
1:00 p.m. - 1:35 p.m.	East Mesa - John Savino
1:35 p.m. - 2:15 p.m.	Wasatch Front - Dave Butler
2:15 p.m. - 4:45 p.m.	Grass Valley - Ernie Majer
4:45 p.m. - 5:30 p.m.	Coso - Ron Ward
5:30 p.m. - 6:15 p.m.	Long Valley - Dave Hill
7:30 p.m.	Leave for dinner

Wednesday, 4 October 1978

7:00 a.m. - 8:00 a.m.	Breakfast
8:00 a.m. - 8:30 a.m.	Mt Hood - Craig Weaver
8:30 a.m. - 9:00 a.m.	Kilauea Iki - Bernard Chouet
9:00 a.m. - 9:45 a.m.	Hot Dry Rock - Keiiti Aki
9:45 a.m. - 11:45 a.m.	Individual group discussion - Role of Seismic Methods in Exploring Geothermal Prospects
11:45 a.m. - 12:30 p.m.	Lunch
12:30 p.m. - 1:30 p.m.	Report of Individual Group Discussion of Seismic Methods Applied to Geothermal Prospects
1:30 p.m. - 2:30 p.m.	Research, Development, and Applications of Seismic Methods to Geothermal Systems - Ron Ward
2:30 p.m. - 6:30 p.m.	Free time for individual discussions of return
7:30 p.m.	Leave for dinner

Thursday, 5 October 1978

7:00 a.m. - 8:00 a.m.	Breakfast
8:30 a.m.	Leave for field trip through Valles Caldera on trip to Albuquerque

APSMAGS ATTENDEES AND INVITEES

I. GOVERNMENT

Participants

1. Hans Ackerman, USGS
2. Chuck Bufe, USGS
3. Elliot Endo, USGS
4. John Evans, USGS
5. Dave Hill, USGS
6. H. M. Iyer, USGS
7. Fred Klein, USGS
8. Dave Oppenheimer, USGS
9. Paul Reasenberg, USGS
10. Roger Stewart, USGS
11. Craig Weaver, USGS

Observers

1. Larry Ball, DOE
2. Bob Christiansen, USGS
3. Perry Halstead, DOE
4. Paul Kentzinger, LASL
5. Don Klick, USGS

Invitees

1. John Colp, Sandia (Observer)
2. Allan Jalacic, DOE*
3. Art Lachenbruch, USGS
4. Bill Laughlin, LASL (Observer)
5. Pat Muffler, USGS
6. A. M. Pitt, USGS
7. Bob Potter, LASL
8. Pete Ward, USGS

II. INDUSTRIAL

Participants

1. Paul Brown, Micro Geophysics
2. Dave Butler, Micro Geophysics
3. Bob Crewdson, Occidental Petroleum
4. Robert Edmiston, Anadarko Production
5. Pierre Goupillaud, Systems, Science and Software
6. Gary Hoover, Phillips Research Center
7. Art Lange, AMAX
8. Allan Lattanner, Union
9. Ed Page, ENSCO
10. Allan Ramo, Sun
11. John Savino, Systems, Science and Software
12. Charlie Swift, Chevron

Invitees

1. Jim Combs, Geothermal Service Inc.
2. Gary Crosby, Phillips*
3. Mike Sorrels, Teledyne Geotech

* Sent representative

(APSMAGS Attendees and Invitees, continued)

III. ACADEMIC

Participants

1. Keiiti Aki, MIT
2. Armando Albores, CICESE
3. Jim Albright, LASL
4. Shawn Biehler, Univ. of Calif. Riverside
5. Dave Boore, Stanford
6. Larry Braile, Purdue
7. Bernard Chouet, MIT
8. John Costain, VPI
9. Bob Daniel, Stanford
10. Ed Douze, Univ. of Tulsa
11. Mike Fehler, MIT
12. Dave Hadley, Cal Tech
13. Randy Keller, UT El Paso
14. Ernie Majer, LBL
15. Steve Malone, Univ. of Washington
16. Tom McEvilly, UC Berkeley
17. Ken Olsen, LASL
18. Keith Priestly, Univ. of Nevada
19. Alfonzo Reyes, CICESE
20. John Schlue, NM mines
21. Bob Smith, Univ. of Utah
22. Ron Ward, UT Dallas
23. Debbie Wechsler, Univ. of Utah
24. Chi Yuh Young, UT Dallas

Invitees

1. Gunnar Bodvarsson, Univ. of Oregon
2. Larry Brown, Cornell
3. Harsh Gupta, National Geophysical Res. Institute
4. Carl Johnson, Cal Tech
5. Tom Jordan, UC San Diego
6. Sid Kaufman, Cornell
7. Bob Kovach, Stanford
8. Stan Laster, Univ. of Tulsa*
9. Antonio Razo-M., Ing., CFE
10. Rus Robinson, DSIR
11. Howard Ross, Utah University Research Inst.
12. Allan Sanford, New Mexico Inst. of Mining and Technology
13. Bill Schneider, Colorado School of Mines
14. Gian Carlo Stefani, ENEL

Elements of Geothermal Systems

Robert L. Christiansen, USGS, Menlo Park, CA

A systematic review of the basic elements of geothermal systems provides a framework for their seismic exploration and characterization. For exploitable systems, these elements consist of a heat source, a heat-storage reservoir, and a fluid heat-transfer medium.

Heat sources may be localized upper-crustal magma chambers (active or solidified but still hot) or may be dispersed and represented by a regional geothermal gradient. In the latter type, exploitation depends upon either above-normal gradients or deep circulation of the hydrothermal fluid (or both).

Some geothermal reservoirs are porous stratified rocks or sediments having a high intergranular permeability. Commonly, however, the reservoir system and the avenues of hydrothermal circulation are interconnected fractures. The fracture sets controlling hydrothermal convection systems range in scale from crustal features like basin-range fault systems through fault and joint sets with dimensions of a few kilometers to local joint sets with dimensions of a few meters or tens of meters. It has been proposed that artificial geothermal reservoirs may be created by inducing fractures in hot rock of low permeability and circulating water from the surface.

Transfer of thermal energy from a geothermal reservoir, where most of the energy is stored in the rocks, is by an aqueous fluid. For some systems, generally of relatively low temperature, this may be by the regional groundwater. For many others the fluid may be a more or less saline brine, commonly of meteoric origin but generally affected by high-temperature chemical and isotopic reactions with the reservoir rocks. The fluid in such systems may be a single liquid phase or may be a two-phase fluid, but at depths of a few kilometers or less, liquid hot water is the continuous phase in the interconnected pores or fractures. In a few favorable vapor-dominated systems, the continuous phase is steam, which thus controls the pressure and temperature.

Abstract

Wave propagation in rocks is controlled by the following variables:

A. State
   1. Stress distribution
   2. Temperature

B. Composition
   1. Mineralogical composition, including strength of fabric
   2. Concentration and geometry of defects (cracks, pores)
   3. Properties of defect fillings (water, air, magma)

The effect on wave velocity of each of these variables has been explored in the laboratory, and compilations of results will be presented. The major points may be summarized as follows:

A. For nominally defect-free rock (low porosity rock at high pressure) average pressure derivatives of wave velocity are well determined, show systematic decrease with increasing velocity, and are some 3 to 5 times larger than those for single crystals (because of cracks in rocks).

   Temperature derivatives of velocity in these rocks show more scatter than pressure derivatives, change systematically for metasedimentary rocks, show no trend with velocity in crystalline rocks, and are not pronouncedly different from temperature derivatives in single crystals.

   For isochemical rocks, compressional velocity is a linear function of density (which expresses compositional change), pressure, and temperature over the range 0-300°C, 2-8 kb. Rocks not isochemical but having similar mean atomic weight show similar velocity dependence on density at room temperature. At constant density, increasing mean atomic weight decreases velocity.

B. Introducing defects in rocks decreases velocity, the effect depending strongly upon geometry of the defect (flat cracks <u>vs</u> equant shapes). In dry rocks, compressional (V_p) and shear (V_s) wave velocity decrease as much as 100% for 1% flat crack porosity, and by some 1% for 1% of equant-pore porosity. Filling cavities with condensed fluids of low viscosity (eg water) increases V_p by as much as 100% for 1% crack porosity (relative to dry state), and by some 10% for equant-pore porosity of 20%. Little change of V_s is seen upon saturation regardless of crack shape or porosity. Rigidity increases in rocks as viscosity of the saturating fluid increases.

Status of Seismic Methods in Geothermal Application

H. M. Iyer

INTRODUCTION

If we look at the conceptual model of a geothermal system, it appears as if seismology is ideally suited for geothermal exploration. In the model proposed by White (1973), for example, we have, thermally altered surface layer, low-permeability cap rock, permeable layer, magma (heat source), faults and fractures. In addition, the model implies turbulent water movements and phase changes from water to steam. The geothermal properties of each of the elements of the system have specific seismic properties associated with them and therefore, seismology is useful in their delineation. Seismology is also useful for evaluating earthquake hazard in geothermal areas and to understand possible induced seismicity related to fluid withdrawal and injection.

Seismic studies in geothermal areas can be broadly classified into active and passive methods. In the active methods, controlled sources such as explosions or vibrators are used in conventional experiments, such as reflection and refraction surveys, and unconventional experiments such as travel-time residual and attenuation studies. Passive seismic methods consist of seismicity and related studies, travel-time residual and attenuation studies using natural sources such as local and regional earthquakes and teleseisms, and locating seismic noise sources associated with geothermal sources.

ACTIVE METHODS

Compared with oil exploration in which active seismic techniques have been extensively used with spectacular results, they have not been used effectively in geothermal exploration. Only a few case histories of reflection and refraction surveys, and travel-time residual and attenuation studies are available.

Hill (1976) did a seismic refraction survey in Long Valley, California, as part of the U. S. Geological Survey's multi-disciplinary program in the region. In addition to evolving an average crustal model, he was able to see reflections from the roof of an underlying magma chamber and also demonstrate that strong attenuation of high-frequency seismic waves were associated with one of the areas showing surface geothermal phenomena.

Combs and Jarzabek (1978) looked for similar attenuation under the East Mesa geothermal anomaly in Imperial Valley using shots around the anomaly, but did not detect any attenuation. However, they did see strong attenuation of high-frequency waves from earthquakes located about 25 km from the anomaly, thus proving that the source of the anomaly is deeper than 2 km.

Majer and McEvilly (1978) looked for velocity and attenuation anomalies in the Geysers production area by recording two shots using a closely-spaced (average spacing about 1 km) array of seismometers. They found evidence for the presence of high-velocity, high-Q material in the top 1 km from the surface underlain by rock with lower velocity and Q.

Ackerman (personal communication), based on a seismic refraction survey in the Raft River geothermal area, Idaho, finds zones of anomalous velocity and attenuation which can be related to hydrothermal alteration.

Data from other seismic surveys in the Coso geothermal area, Roosevelt Hot Springs, Mt. Hood, The Geysers, Grass Valley (Nevada), Yellowstone, and Snake River Plain should be available in the near future.

Active seismic techniques have also been used to look for the heat source in geothermal systems (magma). Two examples are the exploration of the Kamchatka volcanoes (Utnasin et al, 1976) and the COCORP Vibroseis survey (no reference available) in the Rio Grande Rift. Stauber and Boore (1978) have found evidence for thinning of the crust under the Battle Mountain Heat Flow High in Nevada, based on seismic refraction surveys.

PASSIVE METHODS

Microearthquakes

Microearthquake studies in geothermal areas can be divided into six categories: exploration, tectonic evolution, upper-crustal models, location of magma pockets, environmental and miscellaneous studies.

1. Exploration. Geothermal areas are invariably located in regions of active tectonism and hence it is not surprising that most of them are seismically very active. Ward and Jacob (1971) demonstrated, using seismic data in the Ahuachapan geothermal field in El Salvador, how microseismicity can be used to delineate fracture zones which provide paths for hot water to reach the surface. In a detailed study in Iceland, Ward and Bjornsson (1971) found that out of 154 sites surveyed 13 were seismically active, each a geothermal area. They showed that stress along faults in geothermal areas is relieved by earthquake swarms, whereas, outside the geothermal areas, main shock-after shock sequences seem to be the prominent mode of stress release. They postulated that two well-known effects of fluids, namely, pore pressure and stress corrosion may be responsible for the earthquake swarms. These two aspects of seismicity in geothermal areas, namely, location of fractures and swarm activity seem to be the basis for using micro-earthquakes in geothermal exploration. However, numerous available case histories indicate that the picture could be much more complicated than in El Salvador or Iceland.

Even in Iceland, recent work by Klein, Einarsson, and Wyss (1977) has shown that a large swarm of earthquakes in a geothermal area near the southwest corner of the Reykjanes Peninsula, does not seem to be related to the

the near-surface hydrology. Lange and Westphal (1969) and Hamilton and Muffler (1972) have studied the seismicity of The Geysers geothermal area using portable stations. Marks and Bufe (1978) have published a detailed seismicity map of The Geysers-Clear Lake region using data from a large USGS telemetered network which has been in operation in the area since 1975. The greatest concentration of earthquakes occur in the vicinity of the power plants in the production area and these are believed to be caused by environmental factors such as fluid withdrawal and injection. The diffused zone of seismic activity occurring over the Clear Lake Volcanics, and short-lived swarms on the south shore of Clear Lake, have not yet been interpreted for geothermal significance. The two important results of the seismic study in The Geysers-Clear Lake region are shallowness of earthquakes in the volcanic zone and the change in the orientation of the stress field in the production area with respect to the surrounding area. The cause of the former is postulated to be the proximity of partially molten rock to the surface and the latter is attributed to the effects of fluid withdrawal and re-injection (Chuck Bufe, personal communication).

A two-year seismicity map of Imperial Valley prepared by Gary Fuis (personal communication) using data from the 22-element, USGS telemetered network not only shows swarm activity in some of the geothermal areas, but also continuous activity associated with the fault system there. The difficult question arising from such activity is, can seismicity studies carried out in a small area of such a region tell anything about the geothermal potential of that area? In the East Mesa geothermal area of Imperial Valley where no earthquakes are detected by the USGS network, Combs and Hadley (1977) have located several earthquakes using a closely-spaced array and postulated the presence of an unmapped Mesa fault. They also report that one of their stations recorded several hundred very small earthquakes (which they call nano-earthquakes).

Study of micro-earthquakes in geothermal areas is further complicated by the fact that some regions do not seem to have any earthquakes. Ward and Bjornsson (1971) found one such area in Iceland. No earthquakes have been reported inside the Long Valley caldera (Steeples and Pitt, 1976) and the Raft River geothermal area. Some of the Cascade volcanoes are sparsely seismic.

2. Tectonic evolution. Whether microearthquakes are useful to locate geothermal drill holes or not, their study forms an integral and important part of the process of understanding the tectonic and volcanic evolution of geothermal areas. Clear examples are provided by the study by Hill et al. (1975) of the Brawley, Imperial Valley, swarms of 1973 and Weaver and Hill's (1978) study of the seismicity of the Coso geothermal area. In both these instances the authors have been able to show that the geothermal areas act as a miniature continental spreading centers with offset strands of a major regional fault acting as transform faults. Less obvious studies, such as in Yellowstone provide a lot of information on the volcano-tectonic evolution of geothermal areas on a macro-and micro scale. Of particular importance is understanding the stress field in geothermal areas using earthquake fault plane solutions.

3. Upper crustal structure. Earthquakes in geothermal areas can be used in lieu of controlled sources to look for velocity and attenuation anomalies in geothermal areas. The technique is similar to that used by Majer and McEvilly at The Geysers. Olson and Smith (1976) have found P-delays, and S-wave attenuation in the Roosevelt Hot Springs area, Utah. Using a slightly different technique, Combs and Rotstein (1976) have found that V_p/V_s ratio and Poisson's ratio at Coso are lower than normal. They infer from this possible presence of a dry-steam reservoir.

Seismic sources, in conjunction with a fan-shooting seismic profile have been used by Combs and Jarzabek (1977) in the Coso geothermal area to look for anomalous delays and attenuation. Beyer et al. (1976) using an explosion 45 km away from the Leach hot springs, Nevada, found that faster arrivals could be attributed for travel paths under the hot springs.

4. Location of magma pockets. Kubota and Berg (1967) and Matumoto (1971) have used shear wave attenuation from local earthquakes to map magma pockets in the Katmai volcanic range in Alaska. Sanford et al. (1977) have used reflections from microearthquakes to identify magma pockets in the Rio Grande Rift, New Mexico.

5. Environmental. Geothermal areas invariably occur in highly seismic areas and many in the USA (The Geysers, ImPerial Valley, Coso, Yellowstone) have had damaging earthquakes in the recent past in their vicinity. Hence, one aspect of environmental seismology is to evaluate the earthquake risk in geothermal areas. The second aspect is to understand the effect of fluid withdrawal and injection in the seismicity of a geothermal region. I have already indicated how the high seismicity in the steam-production zone at The Geysers could be man-made. It is therefore important to evaluate the regional seismicity in a potential area of geothermal production for seismic risk and to start seismic monitoring in the production area long before operation begins.

6. Miscellaneous. Is it possible to distinguish some property of earthquakes in a geothermal area to discriminate them from earthquakes in the neighboring non-geothermal areas? This question has often been asked and its pursuit has led to the term 'geothermal earthquakes', which I think, is a misnomer. No doubt the presence of fluids, pore pressure and heat, helps to relieve regional tectonic stress in a geothermal area, but the ultimate product is still tectonic earthquakes. Discriminants worth pursuing are, b-values (related to swarm nature of activity), changes in orientation of stress

axes, nono-earthquakes, etc.

Teleseisms

1. P-delays. Teleseismic residuals are mainly useful to delineate the heat source(s) in the crust and upper mantle under geothermal areas. The minimum size of the magma body that can be detected using teleseisms is about 10 km as the waves have wavelength of that order. However, the resolution can be improved by using high-frequency P-waves from regional events. The technique is well known (Steeples and Iyer, 1976a) and several case histories are available.

Based on relative delays of the order of 0.4 sec, Steeples and Iyer (1976a,b) inferred the presence of a magma chamber under the Long Valley caldera. The size of the body was estimated to be 10-15 km diameter and the percentage of decrease of velocity inside it from surrounding normal rock was 10-15%.

In Yellowstone, the relative delays were much higher than in Long Valley, reaching values as high as 2 sec. Based on the large delays and their extensive spatial distribution it has been postulated that a deep magma body is present under the Yellowstone caldera, with a velocity contrast near the top (about 10 km below the surface) of about 20% and about 3% at 200 km depth (Iyer, 1975a; Iyer and Stewart, 1977; Iyer, 1978; Iyer et al., in preparation).

The P-delay pattern in The Geysers-Clear Lake area outlines two zones where delays are greater than 1 sec, one near Mt. Hannah the center of recent volcanism, and the second in the steam production zone. The results have been interpreted in terms of a magma chamber under Mt. Hannah and fractured dry-steam geothermal system in the production area. The velocity decrease in both cases is estimated to be abnormally large, 15 to 25% (Iyer et al., 1978; Iyer et al., under preparation).

In the Coso geothermal area also P-delay results indicate the presence of a low-velocity body with a contrast of about 5%, under the zone outlined by high heat flow (Reasenberg, personal communication).

What is the importance of P-delay work in geothermal exploration? The presence of a magma chamber shows that the heat source required to make the geothermal system function is there. However, the absence of a magma chamber does not mean that the geothermal area is unproductive. Smaller magma pockets, undetectable by teleseismic methods, may be present providing the required heat source. Techniques should be developed to detect these pockets. In regions like the Battle Mountain High, and the Cascades (especially Mt. Hood and Mt. Baker where data are available), no large or small magma bodies are detectable in the crust. The heat sources in these regions are therefore deep in the lithosphere or asthenosphere and may in fact be perturbations of the asthenosphere. Regional experiments are needed to detect these. At present we do not want to pretend that magma detection can provide geothermal exploration information. However, it is a very fundamental problem in volcanology and as such deserves all the support it can get.

2. P-attenuation. Young and Ward (1978) have developed techniques to estimate attenuation of teleseismic P-wave data. Their results at The Geysers show a zone of large attenuation coinciding with the zone of large delays. In the Coso geothermal area they find smaller, but significant attenuation (Young and Ward, 1978b).

3. Shear and surface wave studies. P-wave residual data by themselves are not adequate to estimate the extent of partial melt in magmatic bodies. Both P and S delay and attenuation data are required to determine the composition of magma bodies with some degree of uniqueness. Anomalous shear velocities have been observed, using teleseismic shear waves and surface waves, by Robert Daniel in Yellowstone and Keith Priestly in the Basin and Range province, Nevada (personal communication).

4. Joint inversion methods. Joint inversion of several geophysical parameters to improve the uniqueness in determining geothermal anomalies are also under development. Savino et al. (1977) have jointly inverted teleseismic and gravity data in Imperial Valley and found thinning of the crust or lower densities in the crust, under virtually all the geothermal zones in the region. Evoy (1978) carried out a joint inversion of gravity and teleseismic residual data in Yellowstone and found a more detailed structure for the top of the magma body than was shown by teleseismic methods alone.

Seismic Noise

Since Clacy (1968) showed that high levels of seismic noise were present in the geothermal areas of New Zealand, numerous case histories have been produced. However, many basic questions still remain unanswered. I shall briefly discuss some of these questions and answers.

1. Are their seismic noise anomalies in geothermal areas? Tens of anomalies have been reported, but attempts to discriminate the noise (if any) produced by geothermal systems from cultural noise have not been very successful. Iyer (1975b) showed that freeway noise and canal noise, amplified by the soft sedimentary layers in Imperial Valley were responsible for the observed noise anomaly over the East Mesa geothermal anomaly.

In Long Valley, Iyer and Hitchcock (1976) showed that the omnipresent background noise, amplified by the surficial river valley deposits was responsible for the observed noise anomaly. The ground amplification contours, computed using telesisms almost coincided with the anomaly.

In Yellowstone National Park, Iyer and Hitchcock (1974) found almost all the geyser basins to be noisy. The question here is whether the noise is produced by purely surface activity or at some depth. If the second mechanism can be proved to exist at least in some geothermal areas, seismic noise could be of some exploration value.

The current trend in seismic noise studies, therefore, is to abandon the old method of looking for amplitude anomalies but to actually locate the noise sources in three dimensions using closely-spaced arrays and high resolution analysis techniques.

Whiteford (1976), using simple tripartite arrays, located several noise sources under the geothermal areas of New Zealand. Using a seismic attenuation model, he estimated their depths to be of the order of 100m.

Page (1977) has developed an array processing technique assuming a body wave model for seismic noise. He finds noise anomalies in Long Valley (Page, 1977) and in the Roosevelt Hot Springs area (personal communication).

The question of body wave emanation from geothermal sources is controversial. Liaw(   ) using a closely-spaced seismic array and high-resolution analysis technique has shown near Leach Hot Springs, Grass Valley, Nevada, the noise propagates as surface waves guided by valley fill.

Oppenheimer (personal communication) has recently located seismic noise in the Norris Geyser Basin, Yellowstone National Park, using high-resolution arrays and finds that if body waves are present in the noise it is very difficult to separate them from surface waves.

2. Is seismic noise useful in geothermal exploration? The usefulness depends on locating depths of noise sources in geothermal areas. If the noise originates in the top few meters of the surface due to boiling, fumaroles etc. if is of no exploration value.

3. Where and how is geothermal seismic noise generated? The abundant literature on the origin of storm and ocean-wave generated microseisms shows that coherent seismic pulses applied to an elastic medium can generate seismic surface waves. Douze and Sorrells (1972) have proposed a model in which surface noise is produced by randomly varying pressure fluctuations at depth. Gunnar Bodvardson (personal communication)proposes that noise may be generated by resonances in long, fluid-filled cracks. It appears that turbulent fluid

or gas transport accompanied by phase changes in a geothermal system can also be the mechanism of generation of noise.

Hot rock and geopressured systems

Even though the exact role of seismology in the exploration of hot rock and geopressured systems is not clearly understood, I shall, for the sake of completion touch upon these topics here.

In the hot-dry-rock project seismic techniques as outlined earlier can be used to locate zones heated by recent magma intrusions. Since the knowledge of stress distribution is important source-mechanism studies of earthquakes in the region may be important. Environmental monitoring of potential hot-dry-rock experimental sites may also be important to ensure measuring possible seismicity changes that may occur during fracturing and fluid-injection. Potter (1976) and Albright (1976) have located seismic events during hydro-fracturing at the Los Alamos scientific Laboratory's hot-dry-rock project site at Fenton Hill. The seismic waves are of much higher frequency than in normal microearthquake seismology. Aamodt (1977) has studied location, attenuation, and scattering of pressured cracks at Fenton Hill. Seismic arrays, using high-resolution analysis techniques may be useful to study the progress of fracturing and to locate the fractures. However, no work has been done in this area, to my knowledge.

Occurrence of geo-pressured reservoirs have similarity to oil reservoirs and hence active seismic techniques used in oil exploration seem to be applicable to geopressured system exploration. In addition, since geo-pressured reservoirs seem to occur beneath thick layers of sedimentary deposits, seismic noise and seismic waves from earthquake may be used to infer layer thickness from ground amplification.

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CONCLUSION

The powerful techniques of seismology have not been optimally used in geothermal exploration. Though case histories using numerous seismic techniques are available I am as yet unaware of a complete seismic model of any geothermal system in which the macro-and micro-elements of the system are fully defined.

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PROBLEMS AND CONTROVERSIES OF THE APPLICATION OF SEISMIC METHODS TO GEOTHERMAL SYSTEMS

I. Problems

A. Credibility of Seismic Techniques and a Clear Indication of Their Role in an overall exploration architecture.

We have at present no clearly established successes attributable to seismological methodology which may help firm the roles of any of the following in exploration:

1. Microearthquakes
2. Acoustic or infrasonic emanation from a geothermal reservoir
3. Velocity or attenuation anomalies
4. Conventional seismic reflection profiling

In an exploration architecture the lack of such established successes relative to their expense leaves us with no case for the routine inclusion of such methods in a geothermal exploration program. And this brings up a second problem.

B. The total lack of statistics on cost-to-success ratios for seismological methods in geothermal exploration, and the resulting hesitancy to commit dollars.

This lack of established cost-benefit data contrasts strongly to petroleum exploration where it is clear, on the average, what return can be expected in terms of discovered oil per dollar of seismic exploration investment. Both the credability problem and the lack of cost-benefit information are due to a third problem.

C. No Case Histories

There are no documented geothermal successes or failures which used seismology as a substantial exploration tool, in the literature. There is an analogy and a contrast to the situation extant in the petroleum industry in the 1920's.

There had at that time been successes based on geology, on surface manifestations, and on torsion balance and other gravity data. The question must have arisen on how much to invest in new methodology, such as the fledging seismic reflection exploration technology. There is however, a big flaw in that analogy. Preseismic petroleum exploration encompassed a firm model. The role of the anticline and the concept of structural traps within a sedimentary section was well established. As a result the development of reflection seismic exploration was a technical not a conceptual problem. The point is that we have no equivalent model in terms of acoustic impedance or attenuation variations with depth that is generally applicable as a target in geothermal exploration. Also contributing to the lack of case histories are several additional factors. There is much tight data; proprietary information that is not generally available. There are very few clear successes in geothermal exploration, perhaps ten globally; and none of those to my knowledge can be termed a seismological success. The known major fields represent very different structures, and we can contrast this to the situation that obtained early-on in petroleum, with salt dome exploration in the Gulf Coast. There it was very clear that salt dome after salt dome after salt dome would very likely produce in the Gulf Coast environment.

D. Consequences of the problems.

1. There are no clear models thus no clear methodology

2. There is much empiricism in seismic exploration for geothermal reservoirs.

3. There are undefinable targets (in terms of elastic properties) precluding development of a clear seismological exploration architecture.

4. The methodology is consequently very expensive and not demonstrably cost-effective, as is clearly needed. Much of this difficulty was presented

eloquently by Roger Stewart earlier this morning in terms of the wide variability of expected physical properties in geothermal reservoir environments for typical rock materials.

II. Present methods

Following and summarizing the earlier presentation by Dr. Iyer, it seems clear that we can characterize the present seismic methodology in geothermal exploration as a set of techniques directed toward the detection and the mapping of variations in

1. reflectivity of the subsurface for structure and phase (dry, wet) boundaries
2. Q(attenuation) for state (dry or wet) temperature, stress levels, fracture density, and associated permeability
3. Velocity of compressional and shear waves for state, temperature, degree of alteration
4. Acoustic/infrasonic emission (ground noise) for direct indication of turbulence and hydrothermal activity at depth (not surface manifestation)
5. Microearthquake occurrence data and spacial/temporal distribution, for stress relief information indicating hydrothermal activity, high thermal gradients (field boundaries?), weakened zones, high pore pressures, enhanced permeability.

III. Controversies

Controversies are basically over either (a) the utility of a method e.g., what evidence exists to justify its application, or (b) procedures, both field and data processing, in the application of a specific method. These two areas of controversy are not always separable since the common retort we have all used to negative evidence is "he didn't do the experiment properly". As illustration we enumerate some specific controversies that now exist in geothermal seismology.

A. Ground noise.

Does any evidence exist for body wave emission (acoustic or infrasonic) from a known or very probable geothermal reservoir at depth? Or, alternatively, can most of the evidence be explained by relatively shallow propagation of high wavenumber surface waves from near-surface sources such as hot springs. In the present seismic methodology for geothermal exploration, there are those on both sides of this question. This specific controversy is amenable to a crucial test. It would be possible to collect the needed data in the field for full frequency-wavenumber analysis and imaging in two or three areas of established or highly promising geothermal areas. This experiment would require a nonaliased array for data collection, requiring perhaps one day of seismic reflection field crew time for collection of a number of records, without source, near potential target areas. Charlie Swift has mentioned that such an experiment has been done in the field and may become generally available through the DOE-Industry program. It is extremely important that such data are collected in several areas to apply the most modern analysis techniques to an extremely high-quality data set.

B. Microearthquakes

What role do microearthquakes play in a geothermal seismic exploration program? There are two levels to this question. At the first level, the question addresses the necessity of the existence of microearthquakes, preproduction, associated with a viable geothermal reservoir. There are, clearly, geothermal reservoirs which are seismic prior to production. The question remains as to whether or not the seismicity is a necessary phenomenon. The Geysers field in California is probably an example of a field with preproduction seismicity. On the other hand, it is probably also an example of a field in which seismicity has been modified due to production. East Mesa may be an aseismic structure.

The second level of the question involves the "geothermal" earthquake;

that is, an earthquake that is uniquely definable as being characteristic of a viable geothermal reservoir. The controversy is simple - is this earthquake a real or an imaginary quantity? It is easy to enumerate implications of the role of microearthquakes in geothermal exploration. Earthquakes, micro- or macro-, imply an active mechanism of stress relief, associated with fault permeability, high thermal stress gradients, induced seismicity, reservoir dynamics, or fault weakening by hydrothermal activity. Are these crucial observations which bear on the microearthquake role? It is not clear. I believe that a simple step should be incorporated in geothermal exploration at the stage in considering a prospect at which it is raised from a regional curiosity to a specific high-potential prospect. We should routinely install a single high-gain, wide dynamic range, three-component (probably triggered digital) seismographic station in advance of any drilling program. This cost would be of the order of a maximum of $10,000 per site and would provide the background seismic data for the prospect. This procedure is much the same as that which has become routine in the consideration of an area for major dam construction. Such an installation would bear also on the effects of production and related induced or modified seismicity, but this is a question separate from topics of this meeting.

C. Anomalies in velocity and attenuation.

There is controversy over both their nature and their significance. With respect to velocity, we can see that a low velocity anomaly can infer high temperature, high pore pressure, water saturation, a magma chamber, partial melt, or fracture permeability - or any of the things enumerated by Roger Stewart this morning. Yellowstone would be a good example. On the other hand a high velocity anomaly could respresent a dry steam environment or heavy precipitation such as silicification. An example would be a basin-and-range environment such as Leach Hot Springs. In terms of attenuation we can see evidence for low attenuation because of the dry rock environment or the heavy precipitation.

The Geysers would be an example, or again Leach Hot Springs. An example of high attenuation may indicate high fracture density, high temperature, or heterogeneity, either mechanical involving fractures or chemical, or hydraulic in some sense. A partial melt would be another example. Cerro Preito field seems to be characterized by higher than regional attenuation. There seems to be no crucial test for elucidating the role of velocity and attenuation anomalies in geothermal exploration that will produce black-or-white experimental results. Our answer must lie in more detailed surveys of fields and with rock properties studies on representative materials. It is important to survey existing fields and it is extremely important, particularly in light of some of the strange Poisson's Ratios that are both measured in the field and observed in the laboratory near melting, to get both attenuation and velocity information on S-waves propagating through potential reservoirs areas.

D. The role of commercial seismic surveys

Here we find the controversy couched in terms of "what for?". There are seismic sections for The Geysers, for the Imperial Valley at East Mesa, for the Basin and Range at Leach Hot Springs, and probably others, which generally show a no-record area at the potential reservoirs. The structural targets are unknown or are very difficult at best to define. In the area of geothermal reservoir we typically have extremely poor velocity control and very weak, if existent, reflection returns - precisely the worst place to conduct commercial seismic reflection profiling. Are these crucial tests to shed more light on the utility of commercial seismic exploration techniques? This is not clear, but a minimal effort is needed on several fields. The problem, of course, lies also with the expense, but it would seem extremely valuable to obtain minimal reflection profiling in several high potential geothermal prospects. It is important that high quality ground noise data can be acquired simultaneously.

IV. Cost Considerations

Here we have a well-definable problem. We need more seismological data and crucial tests at a handfull of existing fields and high potential prospects to develop some case histories, even if they are proprietary at the present time. However, this effort may prove to be too great of an expense in general to be justified on the basis of an established track record which is amenable to a cost/benefit analysis. In other words, the 'D' in R & D needs more work directed toward modification of present seismological technology in exploration to make things less labor-intensive in the early stages of geothermal exploration, and to incorporate multipurpose field survey methods, if we are going to get off dead-center in seismological methodology.

V. Conclusions

There are major problems and serious controversies. We should look very carefully at the data we have and that will be presented in this workshop, as well as at those proprietary data which many of you have, in the context of possibly finding answers or directions for future work on these major problems and controversies that exist today in the role of seismological methodology in geothermal technology. The general methods have potential, and we must now figure out how to apply them in this new and difficult exploration role.

REGIONAL SEISMIC STUDIES

BASIN AND RANGE

Keith Priestley (Session Leader)
Dave Boore
Randy Keller
Bob Smith
Paul Brown
H. M. Iyer

Seismic Structure of the Basin and Range

Keith Priestley

Body wave travel-time data and surface wave dispersion data have been used to examine the seismic structure of the crust and upper mantle of the Basin and Range, primarily the Great Basin of Nevada and western Utah.

P-wave structure--NTS refraction data and earthquake travel-time data have been used to map apparent P_n velocity variations within the northern Basin and Range. Apparent P_n velocities vary from 7.3 to 8.3 k/s. P_n-delays and teleseismic P-delays have been used to estimate the crustal thickness and most of the P_n velocity variation can be attributed to Moho topology. Crustal thickness in the Great Basin varies from greater than 40 km in the Mono Lake--Long Valley area to less than 25 km in the Battle Mountain Heat flow high. Gravity predicted from our crustal model is in general agreement with the observed gravity field. The P_n velocity within the Great Basin after considering Moho dip in 7.8 ± 0.1 k/s.

S-wave structure--fundamental and higher mode surface wave data have been analysed to determine the shear wave structure of the Basin and Range. The average crustal thickness is 35 km in the Great Basin and 31 km in the Basin and Range of Arizona. The average lithospheric thickness is 65 km. The shear wave velocity within the mantle lid is 4.5 k/s. Below the lithosphere there is a broad (approximately 120 km thick) low velocity zone for shear waves (average V_s=4.1/k/s). Our data does not support the low velocity zone to the base of the crust. Higher crustal mode group velocity data show crustal thinning in the Battle Mountain High in agreement with refraction results. Observed, long-period (> 40 sec. period) Rayleigh wave phase velocity data for the Great Basin are very similar to the African Rift and East Pacific Rise possibly indicating similar mantle structure.

Seismic Studies in the Battle Mountain Heat Flow High and Surrounding Region

Dave Boore

Nuclear explosions at the Nevada Test Site (NTS), mine blasts at Copper Canyon and Carlin, and a chemical explosion near Quinn River have been used as seismic sources by Douglas Stauber and myself in studies of the crust and upper mantle structure in north-central Nevada, with emphasis placed on the structure near Battle Mountain. The NTS results are summarized in a recent paper published in the Bulletin of the Seismological Society of America (v. 68, p. 1049-1058). The data suggest the following:

1. The overall crustal structure is approximated by three layers of P velocities 4.6, 6.0, 6.6 km/sec, in order of increasing depth.
2. The bottom two layers decrease in thickness below the Battle Mountain area, resulting in a crustal thinning of about 8 km, from over 30 km outside the Battle Mountain Heat Flow High to less than 23 km inside the High.
3. The crustal thinning is such that partial melting immediately below the Moho is not required by inferred geotherms in the region of heat flow.
4. The upper boundary of the intermediate layer appears to coincide with the saturated granodioute solidus, suggesting that the location of the boundary is controlled by a dynamic process in which the boundary moves up until no more partial melt is found. This does not imply that partial melt necessarily exists in the bottom of curst; the melt may have

escaped into the upper crust, taking water with it and thereby increasing the melting temperature.

5. The P_n velocity shows lateral changes from about 7.4 km/sec to the northwest of Battle Mountain to 7.8 km/sec south of Battle Mountain.

The southeastern arm of the Basic and Range province extends through southern Arizona, southwestern New Mexico, and far west Texas. This region possesses the same general geophysical and geological characteristics as the Great Basin portion of the Basin and Range. In particular, numerous KGRA's are present and high heat flow values observed. Recent surface wave dispersion measurements for the path NTS to TUC indicate an average crustal thickness of approximately 26 km, and a P_n velocity of about 7.6 km/sec (assuming $\sigma = 0.25$). Also, dispersion data from LRSM stations along the Colorado Plateau - Basin and Range boundary suggests that Basin and Range crustal structure extends beneath the transition zone between these provinces.

Bob Smith - University of Utah

BASIN AND RANGE

A new compilation of Utah earthquakes from 1962 to 1977 (over 2200 events) shows general N-S trends east of the Great Basin--Colorado Plateau boundary. There is a poor correlation of eartuquakes with Late Cenozoic faulting. Focal depths are shallow from near-surface to 13 km. Crustal thinning, low P_n-velocity, high earthquake occurrence and high heat flow are characteristic of the Great Basin. These features extend up to 100 km eastward into the Colorado Plateau and suggests that this area that should be investigated for its geothermal potential. General seismicity disperses into broad W to SW trending zones in the vicinity of the Roosevelt Hot Springs-Cove Fort KGRA's. Earthquakes that occur typically in swarm occurrences characterize the Cove Fort area whereas the Roosevelt Hot Springs has been relatively aseismic.

A preliminary multi-spread, time-term interpretation of a 30-km (7-shot, 1000 ft spacing) E-W refraction profile across the Milford Valley--the Roosevelt Hot Springs KGRA-Mineral Mountains was shown. The preliminary interpretation shows a P-wave 1.5-1.8 km/sec, 1 km-thick alluvial basin beneath the Milford Valley. Beneath the Roosevelt Hot Springs area a high velocity, 5.2 km/sec layer at $\sim$ 1/4 km depth characterizes what might be a high velocity cap over the geothermal reservoir. Low P-wave velocities of $\sim$2.7 km/sec, characterize the Mineral Mountain granite probably because they are highly fractured and weathered.

Black Rock Desert Nevada

Paul Brown

The Blackrock Gerlach project area is located in the northwestern region of the basin and range. This prospect has been the target of extensive exploration both privately and in the public domain. In conjunction with a program conducted by the National Science Foundation, Microgeophysics conducted a twenty day microearthquake survey in the southern black rock desert. The results of the survey indicate that:

1. The microearthquake activity occurrs clustered both in time and space.
2. The microearthquake activity occurred in a specific area not historically active.
3. The microearthquake activity occurred within and below an area with no surface manifestation, such as faulting or spring activity.
4. The microearthquake first motion studies indicate that the expected regional stress (an extensional east-west system) was also seen in the microearthquake activity.

P-Wave Residual Measurements Over The Battle Mountain Heat Flow High, Nevada

H. M. Iyer

During March and April 1977, the U.S. Geological Survey operated 14 portable seismic stations to record teleseisms along a northwest trending profile across the region of anomalous heat flow around Battle Mountain, Nevada. More than half the length of the 350-km long profile was located over a region where heat-flow values are reported to be greater than 2.5 h.f.u. About 50 teleseisms were recorded during the experiment. However, in this report we have used data from only 10 events. The events from the southeast azimuth showed the most striking residual pattern. The relative residuals (with respect to station 1, the second southeasternmost station) were slightly positive in the 100 km southeastern segment of the profile, half of which was within the Battle Mountain High. However, then they rapidly started becoming negative reaching a minimum value of -1 sec at station 6 and remaining at that level for the rest of the profile. The relative residuals for northwest and southwest events, were quite small and showed very little variation across the profile.

The rapid increase of negative residuals for southeast events in the middle of the Battle Mountain High and the absense of a corresponding feature for northwest events can be explained only by postulating the presence of a deep high velocity anomaly in the upper mantle. It is estimated that the top of the high-velocity body is located at a depth of 150-250 km underneath the

Battle Mountain High. The absence of negative residuals for southwest events show that the teleseismic rays from this azimuth do not travel through the anomalous body implying that the body has finite dimensions in the southwest azimuth. Our results are basically similar to those reported by Koizumi, Ryall, and Priestley, (Bull. Seismol. Soc. Am., 63, 2135-2144, 1973), who interpret the negative residuals in terms of a paleo-subduction-plate under Nevada. However, there are some inconsistencies between our observations and those of Koizumi, Ryall, and Priestley, and detailed analysis is required to evolve an appropriate upper-mantle model for the Battle Mountain High. Our data do not show the effect of the proposed crustal thinning under the Battle Mountain High (Stauber and Boore, Bull. Seismol. Soc. Am., 1049-1058, 1978).

IMPERIAL VALLEY

Shawn Biehler (Session Leader)
John Savino
Dave Hadley
Dave Hill
Alfonso Reyes

IMPERIAL VALLEY

Chairman--Shawn Biehler

The following people contributed to the Imperial Valley Session:

1. John Savino--The Inversion of P-wave travel time delays and Bouguer Gravity Anomalies
2. Dave Hadley--P Delays and Crustal structure of Southern California
3. Dave Hill--Earthquake Swarms and Dike emplacement
4. Alfonzo Reyes--Microseismicity studies in the Mexicali Valley
5. Shawn Biehler--Seismic refraction studies of the Salton Sea Geothermal Field

The following conclusions were made by the contributors.

1) Inversion of the P-delay data and the gravity anomalies (after smoothing) assuming a Birch type velocity-density relationship permits a three-dimensional interpretation or the basement, crustal, and upper mantle structure in the Imperial Valley after removing effects of the sedimentary blanket. The gravity data is the controlling information for shallow structure and the P delay data controls the Lower Crustal--Upper Mantle Model. The technique is not unique because unknown near surface structures which may not be taken into account in the stripping process can produce artifically larger effects in the deep structure.

2) P-delay studies within Southern California show azimuthal variations larger than 1 sec. Models consistent with these observations show a high velocity (8.3 km/s) ridge-like structure within the shallow upper-mantle. As this feature is not offset by the San Andreas fault, we suggest that the plate boundary at depth is laterally displaced from the surface expression. The P-delay data also show that the upper mantle low velocities of the Salton Trough extend into the Eastern Mojave, an area of recent volcanism. A comparison with the gravity and P-delay data demonstrate that large velocity variations within the upper mantle are not accompanied by significant gravity changes. This observation is well explained by partial melting in the shallow upper mantle. Refraction data extending north from the southern end of the Salton Sea indicate a crustal thickness of 16-19 km, as compared with 30-35 km typical

of most of Southern California. Studies of earthquake swarms show strike-slip motion on the Imperial and Brawley faults. Oblique-slip is observed on northeast striking traverse structures associated with the right-stepping offset of these two fault zones. The transverse structures appear to be either "mini" spreading centers or "leaky" transform faults.

Although these swarms appear to be associated with crustal extension and possible intrusion into the base of the crust, heat flow data show that these current swarm areas are not consistently associated with geothermal anomalies. We suggest that as the current plate boundary evolves, areas of active intrusion at the base of the crust will develope heat flow anomalies at the surface. By analogy, current KGRA's may mark the position of active crustal extension within the recent geologic past.

Dave Hadley
Sierra Geophysics
Arcadia, California

3) Resolution of the spatial and temporal distribution of earthquakes in the Imperial Valley was greatly enhanced with the installation of a 16-station seismographic network in 1973. Data from this network show that seismic activity within the Imperial Valley (during the past 5 years at least) is dominated by a more or less linear trend that follows the Imperial and Brawley faults from below the International border into the southeastern part of the Salton sea. The right-stepping offset between the Imperial and Brawley faults near Brawley is characterized by epicenter lineations both parallel and perpendicular to the regional trends of the Brawley and Imperial faults. Focal meahanics are predominantly strike-slip but include a few normal solutions. The T-axes (the direction of relative extension) for these focal mechanisms is nearly invariant and oriented in a E-W direction. This suggests that local crustal spreading is taking place by strike-slip motions on a system of conjugate fault planes together with normal (dip-slip) motion along faults that strike at an intermediate direction to the conjugate strike-slip faults.

Seismicity Study in the Mexicali Valley

D. Albores*, A. Reyes*, J. N Brune**

4) An array of seven stations has been operated continuously in the region of the Cerro Prieto steam field, from July 1977 to June 1978. The study is designed to obtain a better understanding of the tectonic processes which are taking place in the Valley, and to characterize the steam field within this framework. The study has been funded by the Federal Power Commission (CFE), through the Institute de Investigaciones Electricas (IIE) and by CICESE.

The over-all results on epicental determination, focal depths and composite focal mechanisms suggest that the Cerro Prieto-Imperial Transform fault system is connected by a system of leaking transform faults, striking almost NS, and indicates a tectonic pattern similar to that observed in the Imperial Valley (Imperial-Brawley Transform fault system). Seismic activity in the region of the Cerro Prieto steam field is characterized by swarm sequences controlled by normal faulting occuring at a range of local depths from 8 to 12 km. The seismicity to the N-NE, five km from the steam field is also characterized by a swarm activity controlled by normal faulting. A four km depth well drilled recently by the CFE did not show any significant geothermal activity.

An array of nine digitally telemetered short period stations has been installed. The data base to be obtained, will increase our epicental determinations, and eventually will allow a better understanding of the regional tectonic processes in the Mexicali Valley.

* Centro de Investigacion Cientificay Educacion Superior de Ensenada (CICESE)

**Institute of Geophysics and Planetary Physics (IGPP), University of San Diego

5) Seismic refraction studies in the Salton Sea Geothermal Field show little variation in the velocity depth section as compared to that observed in the known geothermal areas of the Imperial Valley. A sharp, local basement high of about 2 km is suggested by the east west profile from Obsidian Butte to the East Highline Canal. This relief could account for a significant portion of the observed gravity and aeromagnetic anomalies.

YELLOWSTONE - SNAKE RIVER PLAIN

Bob Smith (Session Leader)
Larry Braile
H. M. Iyer
Craig Weaver
Mitch Pitt
Bob Daniels
David Oppenheimer

Bob Smith - University of Utah

Yellowstone - Snake River Plain

A presentation of the shot and station plan of the 1978 NSF-USGS sponsored Yellowstone-Snake River Plain seismic experiment was shown. Eleven chemical shots, one NTS explosion and some quarry blasts were recorded with 186 seismographs at 2.5 to 7.0 km spacing.

A general seismicity map (2000 epicenters) of the Snake River Plain-Yellowstone region taken from detailed surveys and network telemetered data (1972 to the present) were shown. These data show a NE trend of earthquakes parallel to the SRP in SE Idaho; a dense E-W zone of earthquakes along the Hebgen Lake-Norris geyser basin trend; N-S and E-W zones of earthquakes in the eastern Yellowstone caldera and an active zone in central Idaho that trends toward Hebgen Lake.

An analytic stress model of the SRP by K. Furlong due to a crack dislocation was assumed to represent a propagating fracture. This model shows principal directions of tension in good agreement with focal mechanisms in SE Idaho, but not at Yellowstone which is thought to reflect a localized and complex stress field. The deviatoric stresses are a minimum along the trend of the SRP and may account for the aseismicity of this feature.

First-order releveling at Yellowstone demonstrates a NE-SW relative uplift of up to 700 mm coincident with the Yellowstone caldera and maximum near the resurgent domes. Uplift rates up to 14 mm/yr and 11 mm/yr. occur near the resurgent domes.

Joint inversion of the USGS teleseismic P-wave delays and the regional gravity data shows that Birch's law for the slowness/density ratio gives a good fit to the observed data. The density model for Yellowstone shows a body with density contrasts of - 0.25 gm/cc from 0-30 km and -0.15 gm/cc from 70-100 km. The body extends laterally beyond the caldera boundary. A -30 mgal mismatch near the Mallard Lake dome shows that the linear slowness/density ratio is not a correct assumption and suggests the presence of a low velocity, partial melt or magma source in the crust.

High precision gravity data at the microgal precision level were taken over the first-order level lines at Yellowstone as a means of later evaluating the uplift and mass transport by gravity methods--a much cheaper but less accurate technique than leveling.

Larry Braile

Yellowstone Snake River Plain Session

Seismic refraction and surface wave studies of the Snake River Plain (SRP) are interpreted to indicate crustal thinning northeastward along the eastern Snake River Plain. The crust thins from greater than 40 km in the western SRP to less than 30 km in the eastern SRP. Pn velocities vary from 7.9 km/sec in the western SRP to 7.6 km/sec in the eastern SRP. It is suggested that the Pn velocity may be as low as 7.5 km/sec under Yellowstone. This seismic model is consistent with observed gravity data. A statistically significant linear relationship between observed Pn velocities and heat flow has been demonstrated for a large data set of continental refraction profiles. Pn velocity and heat flow data inferred for the Snake River Plain and the Yellowstone region are consistent with this empirical relationship. A general correlation exists between several observations along a northeastward direction in the Snake River Plain--Yellowstone region including crustal thinning, decrease in Pn velocity and uppermost mantle density, increase in surface elevation, decrease in the age of silicic volcanism, decrease in Bouguer Gravity and increase in heat flow.

A deep magma body under Yellowstone: delineation using teleseismic P-wave residuals

H. M. Iyer

It has been proposed that the spectacular surface geothermal phenomena in Yellowstone National Park result from a large, deep-seated magma body. In this paper we attempt to delineate the shape of the magma body and determine the velocity structure inside it using teleseismic P-wave residuals. Our data were collected using twenty-six telemetered and three groups of portable seismic stations operated by the U.S. Geological Survey in the Yellowstone region.

Two hundred and twenty-two teleseisms from three main azimuths (approximately southeast, southwest, and northwest) and in the distance range 20 to 95 degrees were used in the study. The spatial distribution of relative residuals with respect to a reference station well outside the Yellowstone caldera, showed the following features:

(a) The delays were quite large (1-1.5 sec) within the caldera for all event azimuths.

(b) The southeast events produced delays as big as 0.7 sec over a large region to the west and northwest of the Yellowstone caldera indicating that seismic waves travelling deep under Yellowstone caldera, Island Park and the northeastern segment of the Snake River plain encounter a low-velocity body.

(c) The northwest events produced similar large delays in a region to the southeast of the caldera.

(d) The southwest events produced an entirely different pattern of large delays which was shaped like the caldera, but much larger in size.

Several techniques, such as, making azimuth-distance plots, plotting residual profiles across the caldera, projecting residuals on a vertical plane passing through the center of the caldera, and plotting anomalous ray paths, were used to interpret the data. The results indicate the presence of a low-velocity body of horizontal dimensions almost twice as much as the caldera and extending to a depth of about 250 km. The P-waves velocity contrast inside the body with respect to normal rock outside varied from about -15% near the top to about -3% at a depth of 200 km. The depth to the top of the body, inferred from other geophysical data is estimated to be about 10 km. The results are substantiated to a depth of 100 km by three-dimensional inversion of the residual data.

In view of the recent volcanism and the large heat output in Yellowstone we have interpreted the low-velocity body to be composed of partially molten rock providing the heat source for the Yellowstone geothermal phenomea. Our results seem to indicate that Sublithospheric melting, rather than a deep mantle plume is responsible for the origin of the Snake River Plain-Yellowstone system.

Yellowstone Session

Seismicity and Preliminary Crustal Studies

Craig Weaver and Mitch Pitt

Seismicity in the Yellowstone region has undergone a marked shift in the last four years. Prior to 1972, seismicity in the Yellowstone region was dominated by events in the 1957 Hebgen Lake earthquake aftershock zone, with relatively fewer events within the Yellowstone caldera. Since 1974, seismicity has undergone a pronounced shift into the caldera, with a marked decrease in events in the Hebgen Lake area. The 1975 Norris earthquake (M_b = 6.0) was within the calera, indicating that in this area, the caldera is capable of supporting substantial shear stresses. Following the Norris earthquake two parallel NW trending aftershock zones developed. One zone crossed the caldera boundary, while the second zone, offset 5 km to the SW from the first zone, trended 15 km into the caldera. A series of magnitude 4.0+ earthquakes occurred in late 1976 in the Mammoth-Norris corridor. Extensive earthquake swarms were recorded near Yellowstone Lake and south of Old Faithful during 1977 and 1978.

Focal mechanisms from the 1975 Norris earthquake sequence show normal faulting with the T axes oriented NW, consistent with the T axis orientation published for events NW of the caldera. Coupled with the general agreement between the length of the caldera earthquake zones, 8-10 km, and the mapped normal fault segments north of the caldera, these observeations indicate that the regional tectonic stress field is continuous across the caldera boundary. Current work on focal mechanisms in the lake area suggest a similar T axes orientation.

Finally, using both a shot (funded by MIT) at the western edge of the Park and well located earthquakes recorded on a variety of portable arrays, we have dtermined several preliminary seismic velocities within the caldera. The surface layer has a velocity of 5.3 km/sec with a higher velocity of

5.9-6.0 km/sec indicated near 5 km depth. A 6.3-6.4 km/sec velocity is indicated both across the caldera and outside the caldera at a still undetermined depth. These velocities are in general agreement with those found by Braile (see abstract, this section) for the eastern Snake River Plain.

Bob Daniel, Geophysics Department, Stanford University

Intermediate Period Seismic Studies in Yellowstone Park, Wyoming

To investigate teleseismic shear wave and surface wave propagation in the Yellowstone caldera, an array of three 3-component intermediate period seismographs was deployed in the south-central part of the caldera. A fourth station was deployed outside the caldera to the northeast of Yellowstone Park as a reference for body wave travel times. Each station recorded the low-pass filtered output of short period seismometers on magnetic tape.

Amplitudes of teleseismic shear waves recorded in the caldera were very similar to arrivals at the reference station, with predominant periods between 8 and 20 sec. Average relative travel time residuals for shear waves vary from 6 1/2 sec for rays that enter the subcaldera zone from the northwest and southwest at an angle of incidence i = 10 deg to approximately 4 sec for rays with i = 40 deg. At a station near the southern boundary of the caldera, residuals were 2 to 4 sec smaller for rays from the southeast than for rays from the northwest and southwest. This dependence of travel time residuals on angle of incidence is not well explained by a thin slow layer.

Measured surface wave phase velocities in the caldera range between 2.1 km/sec at 7 sec period to 3.2 km/sec at 23 sec. This dispersion curve can be modeled by a shear wave velocity profile that ranges from 2 km/sec at 2 km depth to 3 km/sec at 20 km depth. This shallow zone of low shear velocities can account for only about 2 sec of the body wave travel time residuals; the Rayleigh wave phase velocities together with the shear wave residuals imply an average drop in shear wave velocity of 10 to 15 percent for ray paths beginning at depths of 80 to 100 km beneath the Yellowstone caldera.

David Oppenheimer

Frequency Wavenumber Analysis of Seismic Noise at the Norris Geyser Basin, Yellowstone National Park

In September, 1977 the USGS operated two seismic arrays within 5 km of the Norris Geyser Basin, Yellowstone National Park, Wyoming. Seismic noise recorded by the arrays was analyzed by the frequency-wavenumber technique to determine the azimuth and mode of the seismic energy propagation. For the L-shaped array consisting of 31 vertical stations with 5 meter inter-station spacing, no appreciable energy was found with wavenumber magnitude greater than 5 cycles/km. For the expanded L-shaped array with 33 meter inter-station spacing, f-k analysis from 2-6 Hz revealed significant energy propagating from the geyser basin in the form of surface waves. At frequencies higher than 6 Hz data coherence greatly diminished. The presence of body wave arrivals at low frequencies could not be established due to the resolution of the array.

HAWAII

Fred Klein (Session Leader)
Elliot Endo
Paul Brown

Fred Klein

Seismicity of the Kilauea Magma System

Earthquakes have proven a useful tool in locating and following magma through the conduit system of Kilauea Volcano. The whole island of Hawaii is seismically active, but most earthquakes occur near the active Mauna Loa and Kilauea Volcanoes: on Kilauea's south flank and the Kaoiki Fault System between the two volcanoes. Earthquakes define a vertical magma conduit directly below the Kilauea summit caldera. A narrow (1 to 2 km) conduit is defined by earthquake concentrations at 2-4 km, 7-11 km, and 13-19 km. A more diffuse earthquake zone (10-15 km diameter) fans out to the south between 26 and 35 km depth.

The eruptive rift zones of Kilauea are well defined by shallow 2-4 km depth earthquakes during periods of magma intrusion from the summit storage reservoir below Kilauea Caldera. Periods of summit inflation and extension are generally marked by high caldera siesmicity, perhaps due to keystone type faulting as the magma reservoir fills below. Intense earthquake swarms in the summit caldera or upper rift zones accompany summit deflation. This magma intrusion in the rift zones is marked by rift inflation, southward displacement of the south flank, or eruption. Earthquakes propagate down the rift zones as the magma front progresses. A zone of reduced seismicity occurs at about 3 km depth under the south end of the caldera. This point is the origin of the two seismically defined rift zones and the buried inflation center derived from surface tilt. The earthquake distribution alone probably would not be enough to define the magma reservoir, but seems to locate magma movement within the volcano.

Kilauea is a geothermal system, but is unusual in that the "working fluid" is magma instead of water or steam. Earthquakes and other geophysical data define the magma movement and hence the primary heat source.

Elliot Endo

Focal Mechanisms of Large Magnitude Earthquakes Associated with a Magma Intrusion into a Rift System of Lilauea

For a well documented eruption and magma intrusion into the southwest rift system of Kilauea, earthquake focal mechanisms suggest strike-slip faulting as the dominant type of faulting associated with the intrusion process. During a ten day period, extending from 4 hours after the cessation of eruptive activity of the December 31, 1974 eruption, 42 earthquakes with body wave magnitudes ranging from 3.5 to 5.3 were recorded by the observatory network. Thirty two events gave well constrained focal mechanism solutions. The orientation of inferred maximum and least stress axes for the events were consistent with the trend of the southwest rift zone of Kilauea. Maximum stress axes(pressure) were oriented parallel to the rift system and least stress axes (tension) were oriented perpendicular to the rift. A 20 degree mean dip for the least stress axes point out the possibility of a 70 to 80 degree dip of the rift to the east. The trend of epicenter locations and a current understanding of Kilauea suggest a preferred nodal plane which strikes N171° with a dip of 80 degrees to the east. Right lateral strike-slip motion on this plane is consistent with other studies of Kilauea which indicate that the south flank of Kilauea is moving to the south in response to forceful intrusion into the rift systems.

Hawaii

The Kiluea caldera and associated east rift of Hawaii, in the Hawaiian Islands, is a potential or possibly a proven geothermal resource area.

The three necessary ingredients for a successful geothermal area are present on the east rift. These ingredients are the heat source, reservoir or plumbing systems and a water supply.

In particular, seismic methods in Hawaii can be used to delineate both the presence of a heat source and the plumbing. The historic seismic (earthquake record) and abundant eruption data in the east rift area indicates that a plumbing system exists for molten magma to a distance of 30 km along the east rift. The nearly semi-decade intrusion of magma along the rift system seems to provide commercial heat to the near surface. This heat intrusion is evidenced by a demonstration of the existence of two commercial grade systems (two wells) on the summit of Kiluea (NSF) and on or near the termination of activity on the east rift near puna (HGI).

The microearthquake survey conducted for 10 days in the summer of 1975, near the puna district by Microgeophysics Corporation resulted in several conclusions:

1. The microearthquake levels are consistent with historic levels.
2. The microearthquake trends along the rift are terminated on a geologically mapped cross feature near the site of the HGI well.
3. The first motion studies suggest a normal fault dislocation model. The fault strikes are along the rift and the fault dips are south and/or north.

This dislocation model is consistent with an east rift interpretation which includes the existence and activity of a keystone Graben structure along the rift.

RIO GRANDE RIFT

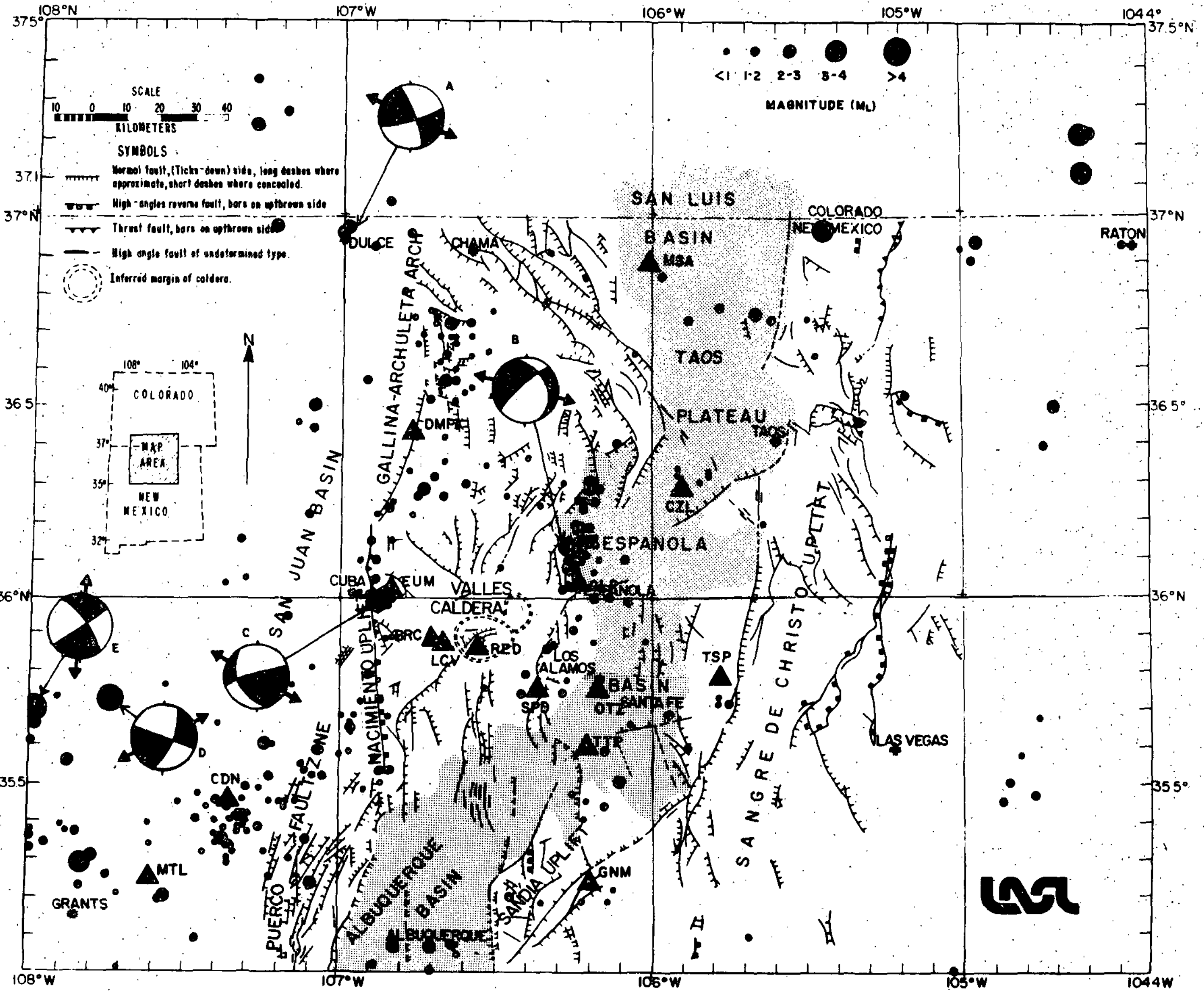
John Schlue (Session Leader)
Ken Olsen
Randy Keller

J. W. Schlue

RIO GRANDE RIFT SESSION

Interpretation of COCORP data taken in the Rio Grande rift indicates a high degree of complexity in the upper crust. A notable feature of the data is a strong reflection at a depth of ∿7 sec, which corresponds well with the 18-20 km depth of an S-wave reflection found in the same area by Sanford and co-workers at New Mexico Tech using microearthquake data.

Inversion of Rayleigh wave phase and group velocities for paths within the Rio Grande rift indicate crustal thicknesses of ∿36 km or less with a P_n velocity of ∿7.7 km/sec (Keller et al., 1978). This indicates a thinning of the crust under the rift relative to both the Great Plains and the Colorado Plateau.


108°N
107°W
106°W
105°W
1044°
375°
37.5°N
37.1
37°N
36.5
36.5°
36°N
35.5
35.5°
108°W
107°W
106°W
105°W
1044W
SCALE
10 0 10 20 30 40
KILOMETERS
SYMBOLS
Normal fault, (Ticks-down) side, long dashes where approximate, short dashes where concealed.
High-angles reverse fault, bars on upthrown side
Thrust fault, bars on upthrown side
High angle fault of undetermined type.
Inferred margin of caldera.
<1 1-2 2-3 3-4 >4
MAGNITUDE (ML)
A
B
C
D
E
N
108° 104°
40°
COLORADO
37°
MAP AREA
35°
NEW MEXICO
32°
SAN LUIS
BASIN
MSA
TAOS
PLATEAU
TAOS
CZL
COLORADO
NEW MEXICO
RATON
DULCE
CHAMA
GALLINA-ARCHULETA ARCH
DMP
SAN JUAN BASIN
CUBA
EUM
VALLES
CALDERA
ESPANOLA
ESPANOLA
BRC
LCV
RED
LOS ALAMOS
SPD
BASIN
OTZ
SANTA FE
TSP
SANGRE DE CHRISTO UPLIFT
LAS VEGAS
TTR
NACIMIENTO UPLIFT
PUERCO FAULT ZONE
ALBUQUERQUE BASIN
ALBUQUERQUE
SANDIA UPLIFT
GNM
CDN
MTL
GRANTS

Regional Seismicity of the Northern Rio Grande Rift and Jemez Mountains

K. H. Olsen, Los Alamos Scientific Lab.

The seismicity patterns in north central New Mexico appear to be significantly influenced by the details of terrestrial heat flow. High heat flow values (> 2.5 HFU) occur generally in a 'band' along the western margin of the Rio Grande rift (Reiter and co workers) and specifically, higher values (> 3-5 HFU) occur in the Jemez mountains and Valles Caldera and at the south end of the Taos plateau. The observed regional seismicity (attached figure) for the period from 1973 to 1978 displays several features of possible significance to the understanding of the regional geothermal resources:

1. Many of the more seismically active regions and trends are associated with tectonic features that define the transition zones between physiographic provinces and subprovinces. For example, the majority of microearthquakes in the figure occur where the San Juan basin borders the southern Rocky Mountains and also intermittently along the flanks of the Rio Grande rift.
2. One of the more striking features of the figure is the almost complete aseismicity of a large area of the Valles Caldera and the northern portion of the Albuquerque basin. This is the region of high heat flow and in analogy with the Yellowstone and the Long Valley calderas, the lack of earthquakes can probably be attributed to the dominance of strain release by stable sliding at shallow depths over a deeper (cooling?) magma chamber.
3. The most consistently active earthquake zone in the figure is a belt to the northwest of Espanola, N.M. An analysis of geodetic leveling data has revealed a zone of relative subsidence (5 cm in 5 years) about 10 km east of this belt. In analogy with a similar uplift

feature has been hypothesized to be caused by deflation of a magma body at mid crustal depths (∿ 20 km). However, because of the limited data now available, the depression feature could also be explained by normal faulting.

Focal mechanism solutions obtained from both regional (Pn) observations and composite readings from local networks are consistent in showing a general east-west trend of crustal tension associated with the Rio Grande rift.

G. R. Keller

The Dice Throw III chemical explosion, which was detonated in the northwest portion of the White Sands Missile Range, provided a unique opportunity to conduct a relatively detailed seismic refraction study along a profile completely confined to the Rio Grande Rift. The results of this study indicate that the earth's crust is ∿33 km thick in the central Rio Grande Rift and that the upper mantle velocity (P_n) is ∿7.6 km/sec. Of particular interest is a strong intracrustal reflector which originates from a discontinuity approximately 20 km deep. Synthetic seismogram modeling suggests that the material below this discontinuity has a Poisson's ratio of at least 0.35. This result indicates that careful waveform analysis of reflection data may be a useful tool in geothermal exploration.

September 14, 1978

Geophysics Open-File Reports
Geoscience Department
New Mexico Tech
Socorro, N.M. 87801

The following reports are on Open File at the Geoscience Office (Room 63, Workman Center). In addition to being available for inspection, copies can be obtained at a cost of 6 cents per page.

1. Wongwiwat, Kraiwut (May, 1970) Gravity survey in southern end of Albuquerque-Belen basin, Socorro County, New Mexico, M.S. Independent Study, NMIMT, 58 p.

2. Oralratmanee, Komol (May, 1972) A gravity survey in northern end of Socorro basin, Rio Grande rift zone, New Mexico, M.S. Independent Study, NMIMT, 66 p.

3. Dee, Mark (May, 1973) A crustal and P-wave velocity study of portions of SW New Mexico and SE Arizona using open pit mining explosions, M.S. Independent Study, NMIMT, 23 p.

4. Hassen-Bey, Tarek, M. (April, 1974) The use of microearthquakes in mapping the base of the low rigidity layer beneath Socorro, New Mexico, M.S. Independent Study, NMIMT, 23 p.

5. Sakdejayont, K. (May, 1974) A study on Poisson's ratio and Vp/Vs ratio in the Rio Grande rift, M.S. Independent Study, NMIMT, 28 p.

6. Sanford, A. R., R. P. Mott, Jr., E. J. Rinehart, and P. J. Shuleski (Dec., 1975) Seismic investigation of a magma layer in the crust beneath the Rio Grande rift near Socorro, New Mexico, Final report to the Energy Resources Board, State of New Mexico, Santa Fe, 14 p.

7a. Mott, R. P., Jr. (May, 1976) The relationship of microearthquake activity to structural geology for the region around Socorro, New Mexico, M.S. Independent Study, NMIMT, 64 p.

7b. Sanford, A. R., T. R. Toppozada, R. M. Ward, and T. C. Wallace (May, 1976) The seismicity of New Mexico: 1962-1972. Text of paper presented to Rocky Mountain Section GSA, Albuquerque, N.M., May 1976.

8. Shuleski, P. J. (Oct., 1976) Seismic fault motion and SV screening by shallow magma bodies in the vicinity of Socorro, New Mexico, NMIMT M.S. Independent Study, 94 p.

9. Sanford, A. R., R. P. Mott, Jr., P. J. Shuleski, E. J. Rinehart, F. J. Caravella, and R. M. Ward (Nov., 1976) Microearthquake investigations of magma bodies in the vicinity of Socorro, New Mexico. Text of paper presented to National GSA Meeting, Denver, Colo., Nov. 9, 1976.

10. Rinehart, E. J. (Dec., 1976) The use of microearthquakes to map an extensive magma body in the Socorro, New Mexico area, NMIMT M.S. Independent Study, 60 p.

11. Caravella, F. (Dec., 1976) A study of Poisson's ratio in the upper crust of the Socorro, New Mexico area, NMIMT M.S. Independent Study, 80 p.

12. Yousef, A. A. (Feb., 1977) A study of time residuals in the Socorro area for P_n arrivals from mining explosions at Santa Rita, Tyrone, New Mexico and Morenci, Arizona, NMIMT M.S. Independent Study, 30 p.

13. Shuleski, P. J., F. J. Caravella, E. J. Rinehart, A. R. Sanford, T. C. Wallace, R. M. Ward (March, 1977) Seismic studies of shallow magma bodies beneath the Rio Grande rift in the vicinity of Socorro, New Mexico, Text of paper presented to South-Central Section GSA Meeting, El Paso, Texas, March 17, 1977. 8 p.

14. Ficher, J. A. (May, 1977) The use of relative travel time residuals of P phases from teleseismic events to study the crust in the Socorro, New Mexico area, NMIMT M.S. Independent Study, 65 p.

15. Sanford, A. R. (July, 1977) Temperature gradient, heat-flow measurements in the vicinity of Socorro, N.M., 1965-1968. Open File Report NMIMT Geoscience Dept., Socorro, N.M. 19 p.

16. Sanford, A. R. and J. Oliver (Aug., 1977) Comparison of microearthquake and COCORP studies of magma bodies beneath the Rio Grande rift in the vicinity of Socorro, New Mexico. Text of paper presented at the Joint General Assemblies of the International Associations of (1) seismology and Physics of the Earth's Interior and (2) Volcanology and Chemistry of the Earth's Interior in Durham, England, 9 p.

17. Sanford, A. R., R. P. Mott, Jr., P. J. Shuleski, E. J. Rinehart, F. J. Caravella, R. M. Ward, and T. C. Wallace (Sept., 1977) Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico. AGU Geophysical Monograph 20, pp. 385-403, reprints available.

18. Sanford, A. R., (July 1977) Seismic Investigation of a Magma Layer in the Crust Beneath the Rio Grande Rift near Socorro, New Mexico, Final Technical Report to the National Science Foundation, Grant DES74-24187, 21 p.

19. Sanford, A. R., E. J. Rinehart, P. J. Shuleski, and J. A. Johnston (Dec. 1977) Evidence from microearthquake studies for small magma bodies in the upper crust of the Rio Grande Rift near Socorro, New Mexico. Text of paper presented at the Fall Meeting of the American Geophysical Union, San Francisco, Dec. 5-9, 1977. 13. p.

20. Sanford, A. R., S. Sandford, F. Caravella, L. Merritt, J. Sheldon, and R. Ward (Jan. 1978) Seismic studies of the Los Medanos area in Southeastern New Mexico, a report to Sandia Laboratories on the seismicity of the proposed nuclear waste disposal site in southeastern New Mexico. 59 p.

21. Schlue, J. W. (Feb. 1978) Report on a Gravity Survey in the Northern Jornada del Muerto, New Mexico. 19 p.

22. Guynn, P. C. (March 1978) Spectral analysis of P-phases from Mining Explosions recorded in the Socorro, New Mexico Area. NMIMT M.S. Independent Study, 86 p.

23. Tang, S. (March 1978) Three dimensional crustal velocity model beneath the Socorro, New Mexico area from inversion of relative travel-time residuals. NMIMT M.S. Independent Study, 36 p.

24. Johnston, James A. (May 1978) Microearthquake Frequency Attenuation of S phases in the Rio Grande Rift near Socorro, New Mexico. MNIMT M.S. Independent Study, 84 p.

25. Fender, John J. (Sept. 1978) A study of Poisson's ratio in the upper crust in the Socorro, New Mexico area, (Continuation of the Caravella (Dec. 1976) study), NMIMT M.S. Independent Study, 75 p.

CASCADES

Steve Malone (Session Leader)
Fred Klein
Craig Weaver

Steve Malone, Fred Klein, Craig Weaver

CASCADES

Introduction: There has been little seismic work done in the Cascades for the purpose of defining geothermal reservoirs. An experiment at Mount Hood by the USGS and reported on elsewhere is the only study done specifically for geothermal work.

The area consists of a chain of recent andisitic volcanoes which occur in response to the slowly subducting Jaun de Fuca plate below North America. This regional tectonic picture is well defined in the seismicity, gravity, and heat flow. The Cascade volcanics are fairly typical of the acidic volcanism associated with subducting plates elsewhere. Most of the some two dozen major volcanic centers have erupted within the last few thousand years and almost half of them have had at least minor eruptions within the past few hundred years. There are active thermal areas associated with many of the volcanics though many of these areas are low temperature springs.

Short term seismicity studies of many of the volcanoes run in the late 60's indicated that most of the volcanoes had some earthquake activity associated with them. Subsequent studies on three of the northern mountains indicated a great variability in the number of earthquakes associated with each mountain. Many seismic events previously thought to be earthquakes associated with the volcanoes have been shown to be glacier related noises. The several vocanics studied are described individually.

Mount Lassen: A small USGS seismograph network of six stations now monitors earthquakes in and near Lassen Volcanic National Park. The first 14 months of recording has revealed a northwest-trending seismic zone passing through the park. This zone is the resolved equivalent of a diffuse zone of historical epicenters passing through Lassen Park and Truckee, California, and is parallel to nearby lineaments in California, Oregon, and Nevada recognized from surface geology.

Three dense concentrations of earthquakes correlate very closely with three geothermal areas. One concentration also outlines the north and east sides of the 4 km-diameter Mt. Tehama caldera. The recent dacite plug domes of Lassen Peak and Chaos Crags are nearly aseismic, however. Several approximate focal mechanism solutions indicate primarily normal faulting with east-west extension.

Mount Shasta: There is no known seismicity associated with Mount Shasta. A recent intense swarm of earthquakes in the area, with events up to magnitude 4, has been located using temporary stations some 30 km to the north east of Mount Shasta.

Mount Hood: A study using a 16 station seismic network operated by the USGS around Mount Hood is described in detail elsewhere. Briefly, this study determined the seismicity of Mount Hood to be very low and there are no obvious teleseismic P-wave delays associated with the mountain.

Mount St. Helens: The seismicity of Mount St. Helens is about one microearthquake per day. Previous studies, like at Mount Rainier, have over estimated the microearthquake rate by including glacier quakes in the counts. The very large and complicated velocity contrasts high on the mountain make accurate event location difficult.

Mount Baker: Like Mount Hood, Mount Baker is virtually aseismic despite the fact there was a large increase in fumarolic activity in the spring of 1975. Heat flux went from about 2 meagawatts to nearly 30 megawatts during this period. Seismic refraction work in a fan shorting configuration using over 20 receiver sites and 5 shot points has failed to show a travel time anomaly centered on the volcano though there are large anomalies associated with the regional geologic structure.

Conclusions: Seismic research directed toward geothermal resource evaluation in the Cascades is almost non existent. In comparison to other prospective geothermal areas the Cascades are far behind. Those seismic techniques deemed appropriate from experience in other areas should be brought to bare on the Cascade mountain range.

DISCUSSION GROUPS -- REGIONAL SEISMIC STUDIES

DISCUSSION GROUPS -- Regional Seismic Studies

Group A

Paul Brown
Allan Lattanner (Leader)
Shawn Biehler
Mike Fehler
John Schlue
Chuck Bufe
Craig Weaver
John Evans

Group B

Dave Butler
Ed Page
Dave Boore
Randy Keller (Leader)
Bob Smith
Elliot Endo
Larry Ball

Group C

Bob Crewdson
Alan Ramo (Leader)
Larry Braile
Ernie Majer
Debbie Wechsler
Dave Hill
Bob Christiansen

Group D

Robert Edmiston
John Savino
Bernard Chouet
Steve Malone
Dave Haldey
H. M. Iyer
Paul Kintzinger

Group E

Pierre Goupillaud
Charlie Swift (Leader)
John Costain
TomMcEvilly
Jim Albright
Fred Klein
Don Klick

Group F

Gary Hoover (Leader)
Keiiti Aki
Bob Daniel
Keith Priestly
Ken Olsen
Dave Oppenheimer
Perry Halstead

Group G

Art Lange (Leader)
Armando Albores
Ed Douze
A. Reyes
Hans Ackerman
Roger Stewart
Paul Reasenberg

Regional Seismic Studies-Discussion Group A

Alan V. Lattanner - Chairman

CONCLUSIONS OF GROUP

1. Regional seismic study:
    a. Definition: 30 km x 30 km area, such as the Clear Lake volcanic area in Northern California.
2. Target of regional study:
    a. help define the seismic parameters and structural configuration of a magma chamber and cooling pluton.
    b. locate areas of shallow crust such as the Battle Mountain heat flow anomaly.
    c. define the seismic properties of a caldera by comparative studies
    d. locate new areas with caldera - magma - shallow crust type seismic properties.
3. Seismic methods applicable:
    a. Microearthquake (MEQ) studies to map Poissons ratio and aid with application of rock properties studies to field situations; to locate regions of above average microearthquake occurrence and locate active fault zones.
    b. P and S wave delay and attenuation studies of caldera, plutons, KGRA's.
    c. refraction - reflection surveys of the Snake River Plain type should be continued in volcanic provinces. COCORP-type work should be encouraged by academia requesting industry support.
    d. noted that while refraction surveys show consistent structure across Imperial Valley geothermal anomalies and non-geothermal areas, reflection surveys show sharp attenuation over the geothermal areas.

4. Equipment:
   a. regional network may be inadequate in some western US areas such as southern Oregon and northern California. Studies of regional seismicity and attenuation are useful and we encourage gathering data on an increasingly dense network of stations.
   b. electronic technology innovation should be encouraged in the geothermal field to develop reliable event detectors and digital recording systems for 3 component stations.
5. DOE-USGS exploration research is sometimes hidden from view by lack of information dissemination regarding programs and preliminary results. We encourage publication of annual programs and timely release of open file reports.

Randy Keller

<u>Discussion Group B:</u> Role of Seismic Methods in Regional Surveys

Randy Keller, Dave Butler, Ed Page, Dave Boore, Bob Smith, Elliot Endo, Larry Ball

Our group engaged in a wide ranging discussion in which agreement was reached on the following points:

1. A variety of seismic methods have application in regional studies (100 km x 100 km), and no one method seems to be universally successful or unsuccessful.
2. All seismic methods are still in the research stage, primarily because the complex structures, velocity variations, and attenuation variations usually associated with high temperature geothermal systems heavily tax classical interpretation techniques.
3. It is extremely important to integrate as many types of data (seismic, non-seismic, and geologic) as possible in any regional study.
4. Thin crust, anomalous crustal velocities, and low Pn velocities may be regional indicators of geothermal potential, and it is desirable to have good crustal structure information at intervals no greater than 100 km.
5. A knowledge of regional seismicity patterns in three dimensions is desirable as is a knowledge of regional wave propagation characteristics.
6. Deep crustal reflection data could be very useful in regional studies.
7. Large scale cooperative experiments may be the most efficient method to generate quality regional structural data.

Regional Seismicity

Two questions:

1. Is a definition of regional seismicity useful in geothermal exploration?
2. Are the regional pictures which are currently available adequate?

To first question - geothermal systems result from tectonic processes which act in such a manner as to concentrate heat, e.g. high level magma chambers and regional seismicity provides an understanding of the tectonic framework.

To second question - one always learns new information which alters the previous picture, by doing additional studies. Adequacy is relative to objectives.

One can conclude that much additional work is necessary to adequately understand and apply regional seismicity to geothermal exploration. In particular, the spatial and temporal variations and relations of seismicity to geothermal systems require further effort as does the relationship of focal mechanisms to geothermal systems. Regional statistics on processes and properties require much additional work in order to recognize those conditions which are truly "anomalous" and might be related to geothermal systems.

Wave Propagation - P delay and attenuation studies

This application is capable of isolating upper mantle and crustal anomalies which could be related to geothermal heat sources.

However, much work is required to increase the data base and to increase our understanding of the relationship of anomalous areas, located by those methods, to a regional framework.

Bob Crewdson
Larry Braile
Ernie Majer
Debbie Wechsler
Dave Hill
Bob Christiansen
Alan Ramo, Group Reporter

Group D - Regions

Robert Edmiston
John Savino
B. Chouet
Steve Malone
D. Hadley
H. M. Iyer (Group Leader)
Paul Kintzinger

The discussion started with the question, "are regional studies important in geothermal exploration? If yes, how can we use these effectively?". Edmiston said that by analogy with oil exploration where regional surveys are carried out only for 25000 ft. thickness, geothermal surveys seems to cover large areal extent and deep into mantle. It was agreed that the word region in geothermal exploration context should not be large physiographic units like Basin and Range but smaller units like Imperial Valley, Battle Mountain High, Snake River Plain, etc. Seismic studies such as refraction surveys, P-delays etc. should be definitely done in such areas with an eye to identifying smaller anomalies for more detailed studies. One problem in using seismic techniques to explore small areas is our ignorance of the mechanical properties of the system we are trying to describe. For instance, are we looking for high Q or low Q; high velocity or low velocity? It was pointed out that once a target looks promising from regional surveys seismic techniques may be useful only for a limited extent for identifying the target. However, combined with other geophysical and geological techniques sucessful results may be obtained. There was considerable emphasis on integrating a variety of seismological surveys and the seismic results with other geophysical surveys both on a micro-scale and macro-scale. (Chouet's experience is Kilauea Iki where even under almost laboratory conditions it was not possible to reconcile results from individual experiments was discussed at some length.) We did not go into a detailed critique of seismological techniques. It was agreed, P-delay, refraction, and microearthquake surveys are useful.

Conclusion: A variety of seismic techniques should be used to study in detail sub-regions with a view to identifying potential geothermal zones for more detailed exploration and exploitation. These studies should be integrated with other geophysical and other studies.

Discussion Group E--Regions

Our group discussed the relative effectiveness of seismic methods to assess a region, defined as 100 km x 100 km. Initially, we stated our support for a regional P_n velocity map of the western US, at a data density sufficient to highlight a 100 km x 100 km. The correlation between P_n velocity and temperature, as outlined by Keller, supports the use of a P_n map as a regional heat flow map.

The use of seismic methods depends upon the geology of the region--the Imperial Valley versus Yellowstone versus the Battle Mtn Heat flow high; and the application--hot water (tensional stress) versus hot dry rock (compressional stress). For active techniques, a 3 km station spacing is sufficient to provide areal coverage of Δt, v_p, and v_s. We particularly support the further analysis of v_s data. The particularly low surface mode v_s defined by Daniel at Yellowstone is a good example. Seismicity patterns, as defined by passive arrays, define geothermal provinces by delineating tectonic features. However, except for swarms, local seismicity is not a necessary condition for geothermal prospects.

Charlie Swift (Group leader)
Pierre Goupillaud
John Costain
Tom McEvilly
Jim Albright
Fred Klein
Don Klick

G. M. Hoover - Session F

Seismic Methods in Regional Surveys on a World Wide Scale

The use of seismic methods in Regional Surveys on a world wide scale must be considered with respect to the useful information generated and the cost. Listed below are the methods thought to be appropriate from the initial regional exploration stage up to the detailed investigation of prospects. They are approximately listed in order of increasing cost per unit area and their stage of application in developing a prospect. Geothermal models are diverse in character and all geophysical and geological data available must be utilized. There can be no cook book methodology at this stage of the game - all available information must be brought to bear.

Conclusions:

1. Regional Seismic Network - size of network 200-500 km.
   Understand active and inactive areas and define general tectonic grain
2. Teleseismic P and S-wave delays - measure velocity distribution to define large scale manifestations of geothermal resource.
3. Frequency - wave number structure of microseismic noise.
   (.1-10 hz) with joint Magnetotelleric survey - 20-30 stations with aperature 20 km.
   Obtain shear wave vs depth distribution to locate low rigidity structures and general lithology and temperature distribution.
4. Refraction - Survey - 40 stations, 5 km spacing
   Define deeper structures in specific areas to better define heat source.
5. Deep Reflection - COCORP
   Supplement understanding of deep heat source.

GROUP G REPORT

Art Lange

The regional geophysical survey is one of the most valuable functions of government and universities in geothermal exploration. Three reasons are as follows:

1. Geothermal areas are anomalous with respect to the surrounding terrain;
2. Regional stress and faulting patterns are closely related to geothermal phenomena;
3. Heat sources tend to exhibit anomalous seismic and other properties, whose discovery may lead to over-or outlying geothermal reservoirs.

Regional seismic surveys can contribute to resolving the different possibilities of heat-source models; for example,

1. zones of spreading and crustal thinning,
2. mantle plumes,
3. cooling plutons,
4. perched bodies of magma or still-cooling rock within the crust,
5. Non-igneous heat concentrations; such as,
    a. thermal conductivity contrasts,
    b. Deeply circulating waters,
    c. Radiogenic heat.

Some discussion ensued on whether or not these crustal/mantle features might be better viewed in terms of isotherm perturbations.

Seismic tools of especial value in identifying and mapping heat sources are:

1. P- and S-wave travel time analysis,
2. Attenuation studies of the same,
3. Frequency distribution of P- and S- wave trains,
4. Distribution of microearthquakes,
5. Refraction profiles,
6. Deep reflection profiles,

Teleseisms, regional and local earthquakes, microearthquakes, mining, construction and nuclear blasts may serve as sources for passive seismic surveys.

Ambiguties in the interpretation of seismic results must be resolved by other tools; eg., MT and deep EM sounding, geomagnetic observations, geologic mapping and age dating, and of course, heat flow analysis. Seismic surveys, in turn, may be applied as a confirmative method following the other disciplines.

PROSPECT SEISMIC STUDIES

GEYSERS -- CLEAR LAKE

Tom McEvilly (Session Leader)
Bob Crewdson
Chuck Bufe
Dave Oppenheimer
Ron Ward
H. M. Iyer
Chi-Yuh Young
Ernie Majer
Bob Kovach
Roger Denlinger

SEISMIC REFLECTION INVESTIGATIONS IN THE CASTLE ROCK SPRINGS - GEYSERS GEOTHERMAL AREA, CALIFORNIA

Roger P. Denlinger and Robert L. Kovach

Department of Geophysics
Stanford University
Stanford, CA 94305

A Vibroseis survey was carried out in the Castle Rock Springs-Geysers geothermal area in northern California. The purpose of the survey was to assess the feasibility of using modern seismic reflection techniques to detect the pervasively fractured zones of the subsurface from which steam is produced in this area. Twelve fold coverage was obtained and both floating point (relative amplitude) and fixed point (equalized amplitude) sections were produced. Despite the geologic complexity inherent in the Franciscan formation reasonably good signal quality was obtained. The velocity resolution was somewhat limited, however, by the relatively short cable lengths used and the presence of high velocity material in the near surface. Surface geology and subsurface lithologic data available from producing steam wells located along the seismic profiles indicated a layered thrust plate structure. The inferred depths to the reflecting horizons correspond well to the depths of shear zones observed in the producing wells. These shear zones occur at the base of the thrust plates, and although laterally continuous, vary in thickness and degree of fracturing. Amplitude anomalies were also observed which correlated well with the known locations of fracture systems and steam zones in the producing wells.

Steam entries in wells drilled in the Castle Rock Springs-Geysers area are always found at fault contacts - in fracture systems within graywacke or in fault bounded greenstone and/or black shale slivers within graywacke found in the Franciscan assemblage. The seismic results demonstrate that seismic reflection techniques hold promise as an exploration tool for geothermal targets.

THE GEYSERS

Seismological data available on The Geysers comprise a wide-ranging set, from regional P-delay, attenuation, and seismicity studies to fine-scale investigation of the source parameters within the field, and a reflective profile in the general field area. While we have admitted the extreme variability in geothermal reservoir characteristic, the Geysers data provide perhaps the most complete set which approximates, after the fact, an explanation program from regional to detailed emphasis. The presentations are ordered generally with increasing resolution. Results point to a broad regional anamoly of low P-wave velocity and low-Q centered on the gravity low presumably associated with the deep magnetic heat source, and a local high-velocity, high-Q, high-seismicity anomaly coincident with the production zone. The local anomalies may be associated with production of the field.

THE REGIONAL SETTING OF THE GEYSERS

Geysers - A

Production of dry steam is from a fractured graywacke reservoir at about 240°C, 20-40 bars pressure, with mass flow rates of 50-300,000 lb/hr. The fields are within the Late Mesozoic Franciscian Formation composing the southeast plunging Maacamas antiform, which is in fault contact with the Late Mesozoic Great Valley Sequence to the northeast and southwest. These subduction zone-island arc type rocks are overlain by two piles of Pliocene-Pleistocene non-basaltic volcanic rocks. Normal and strike-slip motion earthquakes occur in the producing areas and along the major San Andreas system and related faults. Gravity lows over Mt. Hannah and the steam field suggest the presence of a magmatic heat source heating an under-recharged boiling brine which underlies a fractured reservoir with steam-dominated porosity. Temperature gradients decrease rapidly away from the production areas in conduction-dominated rocks. Resistivity, geochemical and hydrologic data suggest that reservoirs northeast of the Collayomi Fault will be hot-water dominated.

Chuck Bufe

SEISMICITY OF THE GEYSERS-CLEAR LAKE REGION

Geysers - B

Microearthquake activity in The Geysers-Clear Lake region has been monitored continuously since 1975. The seismogenic zone across the geothermal area and gravity low is relatively shallow; earthquake focal depths are generally less than 5 km. The absence of deeper earthquakes is consistent with the hypothesis of elevated temperatures associated with a magma body at depth. Present tectonic stress orientation, deduced from P-wave first motions, indicates maximum compression at N 30° E and minimum compression at N 60° W over most of the region. This stress orientation is rotated 30° clockwise from that producing maximum right lateral shear on faults subparallel to the San Andreas, possibly accounting for the diffuse pattern of epicenters in the regions. Most fault-plane solutions suggest right lateral strike-slip motion on short, possibly en echelon faults trending more northerly than the geologically well-defined Maacama and Collayomi systems. Most of the earthquakes in the geothermal region occur in two clusters at The Geysers development area. Earthquakes in the steam production area and in the surrounding region are characterized by high b values corresponding to an unusually large increase in number of earthquakes with decreasing magnitude. The present seismicity at The Geysers is essentially continuous, in contrast to the episodic nature of earthquake activity in the surrounding region. The spatial distribution of earthquakes with regard to the producing steam field and the continuous nature of seismicity at The Geysers strongly suggests that much of the earthquake activity is induced. Since September, 1977, the pattern of faulting at The Geysers has changed from predominantly strike-slip to predominantly normal faulting, indicating a decrease in northeasterly tectonic compression.

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Chi Yuh Young and Ronald W. Ward

TELESEISMIC P-WAVE ATTENUATION AT THE GEYSERS-CLEAR LAKE REGION CALIFORNIA

<u>Geysers - C</u>

During July and September, 1976, the U. S. Geological Survey deployed an array of 14 portable short-period seismographs along a line trending roughly NW-SE between Clear Lake and The Geysers KGRA, California. The array was deployed to study the traveltime delays of teleseismic P-waves associated with magma or partially molten zones beneath the geothermal systems. Such zones are expected to produce pronounced seismic wave attenuation as well.

The P-waves of a total of 22 teleseismic events were recorded, which were suitable for attenuation analysis. The events were digitized and spectrally analyzed using both periodogram and Maximum Entropy Method (MEM) techniques with a final prediction error criteria. The seismograms of these events recorded above the source of the geothermal anomaly exhibited both a significant drop in amplitude as well as wave form broadening.

The location and extent of the zones of high attenuation were qualitatively inferred from the lateral variation of the frequency of the peak in the power density spectrum. The reduced spectral ratio technique was applied to determine the differential attenuation factor, δt^*, quantitatively, assuming that Q is independent of frequency. The maximum value of δt^* is about 0.2 second, which roughly corresponds to a 10 km thick zone with Q equal to 25 embedded in a high Q medium. The lateral variation of δt^* was used to infer the Q structure in the frequency range 0.25 - 2.5 Hz. assuming that the teleseismic wave propagating to each station is identical when it enters the bottom of the crust-upper mantle model. The average effect of sedimentary layers, crustal reverberation, and frequency dependent on the frequency spectrum of the waves focusing are assumed small compared to the effect of attenuation when a large number of events are used at a variety of azimuths and distances. The zone of high attenuation determined in this study is broad and shallow extending from The Geysers steam field, an undertermined distance toward the NE with a width of 15 km. The zone of high attenuation deepens toward

Mt. Konocti (NW) between stations CL07 and CL08. The zone of high attenuation toward the SE near station CL05 is unexplained. The thickest part of the high attenuation zone is probably located shallow beneath station CL06 (Mt. Hannah) and a vapor dominated anomaly at station CL12, where the zone of high attenuation is very close to the surface. This anomaly extends southwesterly toward The Geysers steam field, which is associated with the vapor dominated hydrothermal reservoirs inferred from other geophysical surveys. In a future study quantitative Q model will be obtained using a generalized inversion algorithm.

David H. Oppenheimer & H. M. Iyer

TELESEISMIC P-DELAYS AT THE GEYSERS GEOTHERMAL AREA, CALIFORNIA

Geysers - D

Teleseisms recorded by the USGS seismic network in The Geysers geothermal area from 1975 to 1977 were analyzed for P-wave delays. The 48 teleseisms observed were grouped into three azimuths, northwest, southwest, and southeast. Significant waveform change was observed for teleseisms recorded in the vicinity of The Geysers production area and Mt. Hannah. For teleseisms arriving from the southwest, a general delay field of 0.5 sec was found to extend over a large area south of Clear Lake including the production zone, Mt. Hannah, and Mt. Konocti. Two distinct peaks of 1.0 and 1.5 sec in the delay field were observed near the production zone and Mt. Hannah, respectively. The relative delay patterns for teleseisms recorded from the northwest and southeast azimuths were diminished in both magnitude and extent with respect to those from the southwest. Furthermore, only one peak in the delay pattern with magnitude equal to approximately 1.0 sec was observed in the teleseismic delay fields for both the southeast and northwest azimuths.

Simple modeling to determine the length of the raypath necessary to account for the observed delays for rays traveling through a body with a given percent velocity decrease relative to the regional velocity was performed to give an indication of the size and depth of the anomalous body. The small spatial extent of the observed relative residuals requires the depth of the body to be limited to approximately 25-30 km with a 25% velocity decrease beneath Mt. Hannah and the production zone. The lateral extent of the body is approximately bounded by the 0.5 sec relative delay contour and suggests a depth of about 10-15 km with a 15% velocity decrease. The large delays observed near the production zone may be associated with the highly fractured, dry-steam reservoir, while the delays associated with Mt. Hannah may be associated with a partially molten body.

AN INTEGRATED FINE-SCALE SEISMIC STUDY AT THE GEYSERS

Geysers - E

Studies with a 12-station network at 0.5 km spacing in The Geysers steam field reveal significant velocity and attenuation anomalies associated with the production zone. V_p/V_s data from Wadati diagrams indicate lower Poisson's Ratios in the field than in surrounding areas. P-wave velocity and attenuation data indicate a shallow high velocity - high Q zone, (1-2 km) overlying a lower velocity - lower Q region. Fault plane solutions are largely consistent with right lateral strike-slip movement and NE-SW compression. Microearthquake spatial distribution and source parameters from P- and S-wave spectral characteristics suggest a close relationship to the high gradients in pressure and temperature bounding the steam reservoir. A b-value of 1.1 ± 0.1 is possibly slightly anamous compared to the 0.83 ± 0.04 regional value, but b-values depend critically on the magnitude scale utilized. Although additional data are required, the microearthquake activity seems closely associated with steam production, and should prove useful in monitoring field dynamics during development.

EAST MESA

John Savino (Session Leader)
Shawn Biehler
Pierre Goupillaud
Tom McEvilly
B. Schechter
H. M. Iyer

EAST MESA SESSION: John Savino, Chairperson

Combined use of P and SH Seismic Waves in Geothermal Reservoir Characterization of East Mesa

Pierre L. Goupillaud

This is a brief description of a seismic reflection survey conducted in December 1976 over the East Mesa Reservoir. The project was funded by ERDA.

Two crews participated in the test: a Western Geophysical Company party with four vibrators and 48 channel digital data acquisition system and a skeletal Continental Oil Company shear wave experimental crew with two shear wave vibrators, contributed at no cost to the project.

Two lines were shot in both P and SH while a total of three lines were shot in P. The P-data was very good while the SH-data proved more difficult to use. The shear data was only 20 fold while the P-data was 24-fold, which may explain part of the difference in quality. However, using the P-velocities and reasonable values for the V_P/V_S ratio it was found possible to enhance the shear data sufficiently that a good correlation between the two depth sections was obtained. Estimates of the V_P/V_S ratio along the section and its evolution with depth were also produced.

Using true amplitude sections, the P data showed good reflections, somewhat intermittent which we interpret as reflecting lithological changes and ancient fluid circulation and cementation. Also the quality of the data appears to be an important and valuable criterion for reservoir characterization.

The conclusions and recommendations resulting from the test are as follows:

1. The seismic reflection method is a very valuable tool for characterizing geothermal reservoirs of the type found in the Imperial Valley.
2. While P-data is certainly the preferred mode, more experience with the combined use of P and SH waves may provide additional lithological information of great importance.

3. This test is of a preliminary nature and has demonstrated that equipment and techniques developed for oil exploration can produce results. However, tools specifically designed for the Imperial Valley conditions and for the relatively shallow targets of geothermal exploration should prove much superior.

Our recommendations are to conduct more tests of this nature in order to accumulate enough experience to make the improvements in performance needed to render the seismic method more cost effective. Also, consider designing and building a combined P and SH source specifically aimed at the investigation of the Imperial Valley, the largest geothermal area in the U.S.

Tom McEvilly and B. Schechter

East Mesa

Network Analysis

In 18 months of monitoring the U. S. Bureau of Reclamation 6-station network at East Mesa, no earthquakes have been detected at an estimated threshold of magnitude around 1.0. Ther is some indication of increased attenuation of S-waves from regional earthquakes passing through the SW portion of the network.

H. M. Iyer

Search for Geothermal Seismic Noise in the East Mesa Area, Imperial Valley, California

A seismic noise experiment was conducted in the East Mesa area of Imperial Valley, California, by the U. S. Geological Survey (USGS) in May 1972. There is a pronounced heat flow anomaly over the area, and between July 1972 and the present five deep test wells have been drilled over the anomaly by the U. S. Bureau of Reclamation (U. S. Bureau of Reclamation, 1974). At the time of our survey, we were aware of results from a preliminary seismic noise survey in East Mesa by Teledyne Geotech (Douze and Sorrells, 1972). A detailed noise survey was conducted by Teledyne Geotech soon after our experiment (Geothermal Staff of Teledyne Geotech, 1972). Both the Teledyne Geotech surveys show noise levels (in the 3.0 to 5.0 hz band) 12-18 db higher over the area where the thermal gradients and heat flow reach maximum values than in the surroundings. Our results, on the other hand, show that the seismic noise field in the area is dominated by cultural noise, and it is impossible to see a noise anomaly that can be related to the geothermal phenomena in East Mesa. We think that it is important to take into account this disagreement between the two results in order to make a critical evaluation of the utility of seismic noise as a geothermal prospecting tool. The purpose of this note is to put our findings on record.

WASATCH FRONT

David Butler (Session Leader)
Ed Page
Ed Douze

Ground Noise Measurements Near the Watsch Front, Utah

David Butler

The two accompanying papers are an excellent description of the results of state-of-the art ground noise measurements. The results are contradictory. However, two other papers given at the session, one by Swift and one by McEvilly, indicated results which cannot be described as an unqualified success. The interference of surface waves create a formidible signal-to-noise problem which cannot be overcome without high precision data. At this date, pessimism about the data and the modes of propagation of the energy have prevented consideraion of more fundamental questions about models, occurrences, and detectibility of commercial reservoirs at the surface. Such research, if favorable, might encourage an upgrading of both field techniques and processing manipulations.

One definite result of the conference was that single-station Fourier-transform methods were not found to give useful or reliable results.
To resolve the controversy outlined in the two accompanying papers, publication of comprehensive descriptions of the experiments should be encouraged. Any other experiments that have been done should be correspondingly publicized to aid in the evaluation of this method.

Ed Page

Mapping Ground Noise Using Seismic Arrays

Seismic activity mapping of a 4 x 4 mile region of both Roosevelt Hot Springs and Cove Fort were computed from ground noise data recorded using arrays of geophones.

The mapped region in the Roosevelt area was in the vicinity of Big Cedar Cove. For this survey, four arrays, consisting of five geophones spaced at 100 ft were used. The array processing allows one to look at specific locations within this region and determine whether emissions originated from a given location. This determination was based on the magnitude of interarray correlations corresponding to the set of time delays expected for this location. These time delays were estimated from a body wave half space velocity model.

Three wells capable of production were located in the northeast corner of the mapped region. The important result was that each of the four arrays, spaced over a mile apart and recorded on different days, detected strong emissions from the northeast corner. Over 20 minutes of ground noise data recorded during quiet periods of the night were processed for these results.

In analyzing these results one needs to establish that the correlation levels corresponding to source detection are statistically significant and that the results originate from body wave emission and not spatially aliased surface waves. To establish the significance we computed a statistical background distribution of correlation levels by randomizing the Fourier phases of the data, such that the frequency content was unchanged, but the waveforms or the different channels should not correlate. This data was then processed to compute seismic activity maps in the identical manner the data was processed, from which a statistical distribution of the background correlation levels was obtained. This typically showed a maximum background correlation of $\sim$ .008 compared with $\sim$ .1 associated with dominant ground noise source features observed.

Evidence that we are truly detecting sources of deep body wave emissions and not observing effects of surface wave aliasing is present in these results. This stems from the fact that apparent source location originating from the aliasing effect is very dependent on array geometry. Since the array geometry significantly differs for the arrays used in this survey, it is extremely unlikely that four arrays would see emissions from the same source location, if surface waves were the dominant contributor.

Roosevelt Hot Springs and Cove Fort Noise Studies

S. Lasater and E. Douze

Two studies were conducted using 6-element seismic arrays with interelement spacings of 50 to 100 m, at Roosevelt Hot Springs and Cove Fort. The objective of the study was to determine the types of waves present in the background noise. The analysis technique used was usually the computation of frequency-wave number spectra, although a time-domain method based on beam-steering was sometimes employed. In both cases the validity of peaks in the wavenumber space was determined using Fisher statistics.

At Roosevelt Springs one array was located directly above the geothermal reservoir, with the hope of finding body waves from the reservoir at high phase velocities in the wavenumber spectra. However, a detailed study of the wavenumber plots showed no high-velocity energy that could be connected with the reservoir. The waves appear to be low-velocity Rayleigh waves from all directions. Only one array, in the Mineral Mountains, showed the presence of waves at high velocities appropriate to body waves. However, the direction of approach was N 30 E, not the direction from the geothermal reservoirs to the array.

The results of array analyses at Cove Fort were similar to those obtained in the valley at Roosevelt Hot Springs. The noise appears to consist of surface waves, no statistically significant peaks appear in the frequency-wavenumber at body wave velocities.

GRASS VALLEY

Ernie Majer (Session Leader)
Tom McEvilly
Charlie Swift

E. Majer

Passive and Active Seismological Studies at Grass Valley, Nevada

Concentrated observations in Grass Valley around Leach Hot Springs revealed moderate microearthquake activity on a trend crossing the southern end of the valley, with occasional swarms in the area of high heat flow, (4-6 hfu) at the north end of the 1915 Pleasant Valley earthquake (mag = 7.5) fault trace. In the context of Basin and Range tectonics and seismicity, the Grass Valley microearthquakes are not anomalous in spatial or temporal occurrence. Studies of source properties obtained from P-wave spectral characteristics are inconclusive in so far as defining a unique geothermal earthquake. Refraction and reflection studies indicate normal faulting, with major faults bounding the valley and controlling spring activity. Heat flow models indicate small anomalies (3-5 hfu) may be conductive rather than convective in origin, controlled by basement topography. Fluid flow is required to account for the heat flow anomaly associated with Leach Hot Springs and that in the southern part of Grass Valley. Modeling also revealed that shallow (2-3 km), moderate temperature (200°C) hot water reservoirs can be present without large surface heat flow anomalies (7-8 hfu).

Tom McEvilly Noise Studies at Grass Valley

Frequency-wavenumber (f-k) spectra of seismic noise in the bands $1 < f < 10$ Hz in frequency and $|\underline{k}| < 35.7$ cycles/km in wavenumber, measured at several places in Grass Valley, Nevada, exhibit numerous features which can be correlated with variations in surface geology and sources associated with hot spring activity. Exploration techniques for geothermal reservoirs, based upon the spatial distribution of the amplitude and frequency characteristics of short-period seismic noise, are applied and evaluated in a field program at a potential geothermal area in Grass Valley, Nevada. A detailed investigation of the spatial and temporal characteristics of the noise field was made to guide subsequent data acquisition and processing. Contour maps of normalized noise-level derived from carefully sampled data are dominated by the hot spring noise source and the generally high noise levels outlining the regions of thick alluvium. Major faults are evident when they produce a shallow lateral contrast in rock properties. Conventional seismic noise mapping techniques cannot differentiate noise anomalies due to buried seismic sources from those due to shallow geological effects. The noise radiating from a deep reservoir ought to be evident as body waves of high phase velocity with time-invariant source azimuth. A small two-dimensional array was placed at 16 locations in the region to map propagation parameters. The f-k spectra reveals local shallow sources, but no evidence for a significant body wave component in the noise field was found. With proper data sampling, array processing provides a powerful method for mapping the horizontal component of the vector phase velocity of the noise field. This information, as well as the accurate velocity structure, will enable us to carry out seismic ray tracing and eventually to locate the source region of radiating microseisms. In Grass Valley, and probably in most areas, teh 2-10 Hz microseismic field is predominantly fundamental mode Rayleigh waves controlled by the very shallow structure.

Charlie Swift

Noise Studies around Beowawe Hot Springs, Nevada

A site specific noise study in the Beowawe, Nevada Region by Chevion to determine plumbing characteristics of the hydrothermal system revealed noise propagation from inconsistent directions. An additional noise study using an "x" array with geophone spacing of 10 meters and width of 300 meters was deployed in the center of the valley to resolve the direction and source of the noise.

COSO HOT SPRINGS

Ron Ward (Session Leader)
Craig Weaver
Paul Reasenberg
Chi-Yuh Young

Coso Hot Springs, California, KGRA

Geologic Setting

Ron Ward

The Coso Hot Springs, California KGRA, situated in Southern California has been selected by the U. S. Geological Survey and the Department of Energy as one of the primary sites for geothermal exploration case studies. The Coso Geothermal Area is located at the western margin of the Basin and Range physiographic province (Fig. 1). The basement rocks of the Coso Geothermal Area consist of Mesozoic granitic and metamorphic units which are similar to that of the Sierra Nevada blocks. The area is overlain by upper Cenozoic volcanic rocks. The scattered small basins are filled with Quaternary alluvical deposites. To the west, it is bounded by the vertical dipping Sierra Nevada frontal fault zones. At the east, typical Basin and Range normal faults separate the Coso Range from the Argus Range, and an extension of west to northwest trending strike slip faults mapped in the southern Argus Range appears to truncate the Coso Range on the south. The northern boundary is a structural warp towards Owens Lake.

Unlike other elongated ranges in the Basin and Range, the Coso Range is almost a circular uplift. Duffield (1975) mapped an oval-shaped zone of late Cenozoic ring faulting encompassed the area that measures about 40 km east to west and 45 km north to south (Fig. 1). A large portion of the area was covered by Cenozoic volcanic rocks. The K-Ar age determined by Lanphere and others (1975) showed that the ages of the rhyolitic volcanism is in the range of .9 million to 4 thousand years. The basaltic and rhyolitic flows are overlapped in ages, which might indicate a different magma source.

The extrusions and surface geothermal manifestation appear to be controlled by the fracture systems (Koenig and others, 1971). There are two major steeply dipping normal fault systems across the area. One is north to northeast trending active normal faults that border the eastern scarps of the Sierra Nevada Mountains. The other is northwest trending fault systems. Recent studies of the seismicity (Weaver and Hill, 1977) suggests a right lateral strike-slip focal mechanisms. This system is interrupted and offset by the north and northeast trending normal faults.

The fault zones combined with the ring structure and the associated young volcanic activities gives us a general impression of a caldera-like structure. That is, the Coso Geothermal Area was undergoing uplift and fracture accompanied by large amount extrusions and surficial subsidence. The field relations suggests that there may have been there a large magma chamber existing beneath the area (Duffield, 1975) at sometime in the past which is deflated today. Teleseismic P-wave travel delays and attenuation support the possible existence of a small shallow magma chamber between Volcano Peak on the south and Coso Hot Springs area on the north.

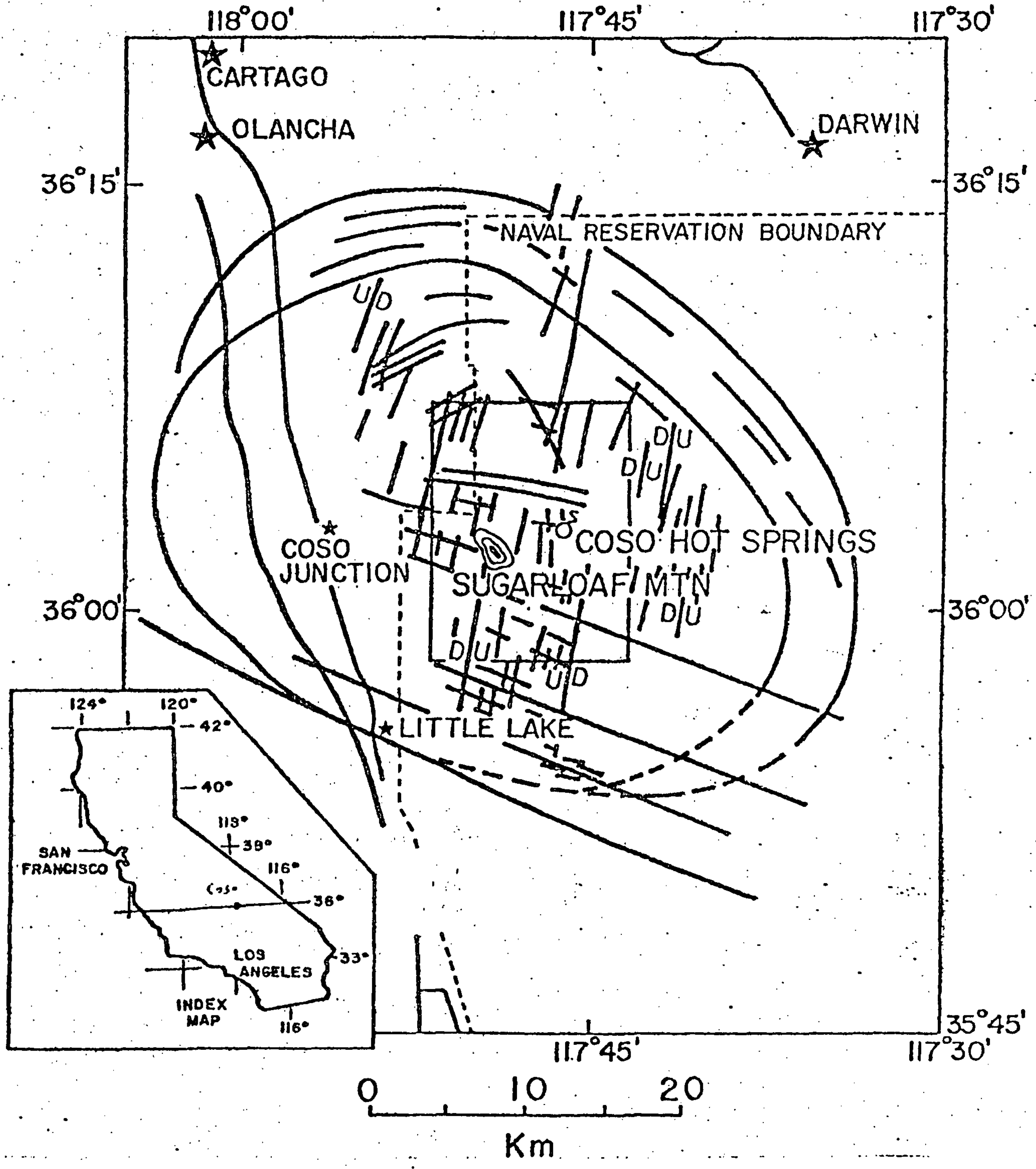

Figure. 1. Location map of the Coso Geothermal Area and regional fault patterns (modified from Duffield, 1975).

Coso Session

Coso Seismicity and Refraction

Craig Weaver

The U. S. Geological Survey has operated a 16-station seismic network since 1975 in the Coso Range. Station spacing avearges 5 km in the rhyolite dome field, giving excellent control on earthquake hypocenters. A 45 km long refraction line, running northeast across the rhyolite domes, shows a simple, well defined layered velocity structure, reflecting the homogeneous nature of the granitic basement. A shallow near surface layer (depth less than 1 km) is underlain by a 5.5 km/sec leyar down to 2.5 km. A velocity of 6.0 km/sec is seen below 2.5 km.

For the two year period from September 1975 through October 1977, some 4,000 earthquakes have been located in the Coso Range. Magnitudes for the located earthquakes range from 0.5 to 3.9. The seismicity defines a conjugate strike-slip system with NW right lateral trends and NE left lateral trends. These strike-slip zones are offset at the rhyolite dome field, where seismicity trends change orientation to parallel the dome field. Focal mechanisms in the dome field show predominately normal faulting with north-wouth fault planes. Earthquake swarms, limited both spacially and temporally, are peridically recorded in the rhyolite dome field. Earthquakes in the dome field do not appear to be shallower than along the strike-slip zones.

From the fault plane solutions, the inferred direction of the maximum compressive stress is nearly north-south along the strike-slip zones, and vertical in the dome field. The maximum compressive stress direction is east-west throughout the Coso Range. Thus, the seismicity in the Coso Range defined the tectonic stress geometry of a continental crustal spreading center. The young rhyolites are injected in the direction of the maximum regional compressive stress (north-south) with crustal spreading to accomodate the volcanism in an east-west direction.

Paul Reasenberg

"Teleseismic P-wave Delays at the Coso Geothermal Area"

The U.S. Geological Survey has operated a 16-station telemetered seismic network at the Coso Mountains region since September, 1975. During May - June, 1977, a 25-station portable network (Centipede) was also operated in the same area. One-hundred-thirty-seven teleseisms recorded by these networks were timed for the 1-second period P wave arrival. From these data relative residuals were computed and averaged at each station over events from each azimuthal quadrant (NW, NE, SE, SW). A consistent pattern is seen in the contoured residual delays. For events from each azimuthal quadrant, an area of delay (approximately 0.2 sec ± 0.04 sec) appears as a shadow with respect to a central location near Coso Hot Springs and Devil's Kitchen. This delay zone remains 2 to 5 km down range of the central location, moving with changing event azimuth. An attempt was made to interpret the delays by assigning a low velocity segment to each ray path of length proportional to the magnitude of its residual delay, thereby modelling a data-consistant low velocity body (Iyer's method). The result indicated a low velocity body located below Coso Hot Springs and Devil's Kitchen. The size, depth and percent velocity decrease were not uniquely determined. Application of the generalized block inversion (Aki's method) to the same data also indicates a low velocity body located below Devil's Kitchen. Preliminary results indicate the depth of body to be in the 5 to 20 km range, lateral size of the body to be 5 to 10 km, and velocity to be approximately 5 percent less than surrounding rock. The location of this low velocity zone coincides closely with the locations of high heat flow (Combs), high ground noise (Teledyne Geotech), and surface manifestations of hydrothermal activity.

C. Y. Young and R. W. Ward

Attenuation of Teleseismic P-waves in Coso KGRA, California

The differential attenuation factor, δt^*, is obtained using reduced spectral ratio technique. About 50 events were analyzed for sixteen USGS stations covered the Coso KGRA. The maximum value of δt^* is 0.1 sec, which reveals that the attenuation effect in the Coso KGRA is smaller than other geothermal areas such as Geysers (maximum $\delta t^* > 0.2$ sec). The surface distribution of the δt^* showed that shallow higher attenuation zones exist b beneath Devil's Kitchen and southeast of the Coso KGRA.

The linealized inversion of the δt^* data from 5 stations on a NW - SE line across Devil's Kitchen and Coso Hot Spring areas generated 2-dimensional 3 and 4-layer discret Q models. Shallow high attenuation zone ($Q < 50$) is found beneath Devil's Kitchen area, this may be directly related to the surface geothermal activity. Shallow high attenuation zone to the southeast may be related to the surface geology. Another high attenuation zone was found at depth greater than 20 km below station BCH. It is possible that small percent of partial melting exists in this zone.

LONG VALLEY

Dave Hill (Session Leader)
H. M. Iyer

Long Valley

Results from the seismic experiments preformed by the US Geological Survey in Long Valley, California, during 1972-73 were reviewed as one example for the session on Prospect Seismic Studies. Details of this work are fully described in the following papers:

Hill, D. P., 1976, Structure of Long Valley caldera, California, from a seismic refraction experiment, J. Geophys. Res., 81, 745-763.

Iyer, H. M. and T. Hitchcock, 1976, Seismic noise surveys in Long Valley, California, J. Geophys. Res., 81, 821-840.

Steeples, D. W., and H. M. Iyer, 1976, Low-velocity zone under Long Valley as determined from telesdismic events; 1976, J. Geophys. Res., 81, 849-860.

Steeples, D. W., and A. M. Pitt, 1976, Microearthquakes in and near Long Valley, California, J. Geophys. Res., 81, 841-847.

Seismic Noise Survey in Long Valley, California

In June 1973, seismic noise measurements were made in Long Valley, California, as part of the U. S. Geological Survey's geothermal investigations. Spatial variation of the average noise power shows high levels of noise extending over most of the eastern half of the Long Valley caldera. Since the noise high is almost similar in extent to the soft sedimentary Owens River basin, it is possible that ground amplification of seismic waves is at least partially responsible for the noise anomaly. Two lines of evidence indicate that geothermal noise may be present in Long Valley. (1) Relative amplification of teleseismic waves over soft ground, with respect to a reference station on hard rock, is about 12 dB. Ths noise anomaly, however, is at least 13 dB higher than this value. It is therefore difficult to explain the anomaly by postulating ground anomaly. At wave frequencies below 2 Hz, river and cattle noise do not contribute much to the anomaly. (2) Group velocities of seismic noise, measured by using arrays, are in general quite low except at a few stations along the southern edge of the noise anomlay. The wave azimuths in the low-velocity areas show random propagation, whereas azimuths associated with the high-velocity waves point to the area where surface geothermal phenomena are found. The high-velocity waves also have frequencies below 2 Hz. If a noise source is present under the southern edge of the sedimentary basin, it could excite the basin much more than it does the hard ground directly above it and thus produce the observed noise anomaly.

H. M. Iyer

Low-Velocity Zone Under Long Valley as Determined From Teleseismic Events

A temporary seismograph station network was used to estimate teleseismic P wave residuals in the vicinity of Long Valley geothermal area, California. Relative P wave delays of 0.3 s persist at stations in the west central part of the Long Valley caldera after regional and near-surface effects have been removed. Ray tracing indicates that low-velocity material exists beneath the caldera at depths greater than 7 km and less than 40 km, probably less than 25 km. The velocity contrast with normal crust must be at least 5% to satisfy the data and is probably in the range 10-15%. We believe that the low velocity indicates anomalously hot rock at depth and that relative teleseismic P residuals may be useful for investigation of sources of geothermal energy.

MT. HOOD

Craig Weaver (Session Leader)
Hans Ackermann

Mt. Hood Session -- Prospects

Chairperson: Craig Weaver, USGS

Mt. Hood, a Quaternary Cascade volcano, has been selected by the Department of Energy in cooperation with the State of Oregon for a complete geophysical and geological characterization. Unlike most of the prospects in this session, Mt. Hood completely lacks surface geothermal manifestations. Utilization interest in Mt. Hood is generally toward warm water development, possibly to provide space heating for Portland (80 km west) or for Timberline Lodge on the south flank of the mountain. A hole has been drilled to 4000 ft in Old Maid Flat, 10 km west of the summit. The hole is dry with an unstabilized bottom-hole temperature of 175°F (Joe Riccio, Oregon Department of Geology, Personal Communication).

The U. S. Geological Survey installed a 16-station telemetry network in November 1977. Construction blasts from three separate sites were used to determine a first layer P-wave velocity of 5.7 km/sec, in general agreement with Ackermann's(see next summary below) refraction results. No travel-time anomaly is seen for data passing beneath Mt. Hood.

Only six earthquakes were located during the first ten months of array operations. All events are located in a zone running southeast from the summit, with the largest event ($M_L=3.3$) located 6 km beneath the summit. Focal mechanisms are well constrained, and five mechanisms have nearly pure strike-slip solutions, while the sixth indicates normal faulting.

Teleseismic P-wave delays, using events from three azimuths, NW, SE, and SW, show early arrivals for the western network stations relative to the eastern array sites. As the pattern is generally independent of azimuth, the delays are attributed to differences in upper crustal structure. No P-delay (either positive or negative) is associated with Mt. Hood.

Hans Ackermann

Seismic Refraction Survey at Mt. Hood

A detailed refraction seismic survey targeted to depths of less than 2500 meters was done along two 5000 meter long lines in the Mt. Hood area. The results indicate that much, if not all of the area is underlain by a very thick, crudely horizontal layer of 4.6 to 5.3 km/sec velocity. This result is in basic agreement with the sonic log from a 4000 ft deep geothermal test well near the end of one of the seismic spreads. The mountain proper appears to consist of material with velocity of roughly three km/sec. It should be kept in mind that these velocity generalizations are based on a small, possibly non-representative sampling.

Interpretations were done using a new interactive computer method which permits varying both depths and velocities for any given horizon to determine a model which very closely satisfied the arrival time data.

KILAUEA IKI

Bernard Chouet

KILAUEA IKI

In November - December, 1959, an eruption of Kilauea volcano, Hawaii, produced a stagnant pond of lava in Kilauea Iki, a pit crater adjacent to Kilauea caldera in the upper east rift zone of the volcano. The pit crater, originally about 200 m deep, was partially filled to a depth of 111 m with an estimated 30,000,000 m^3 of fresh lava. Today, this partly solidified and easily accessible lava lake provides a natural laboratory for the study of cooling, crystallization, and differentiation of basaltic magma. In addition, it offers an excellent opportunity to test various geophysical methods for the exploration of a magma body buried in the earth and to study at close range the physical environment associated with such a body.

The use of multiple methods is essential for the determination of the seismic properties of a complex structure such as a partially frozen lava lake. In a set of active and passive seismic experiments (Aki et al., 1978) performed in Kilauea Iki during March 1976 (1) the spatial distribution of seismic events originating within the crust of the lake best defined the lateral extent of the magma lens, (2) the S-waves transmitted through the lens and dispersion of Love waves generated by explosive sources in the Iki crust constrained the S-wave velocity structure, and (3) P-waves from explosions revealed an extremely low P-velocity zone below the crust. From Love and S-wave data we infer a rather thin (less than 10 m) magma lens, which, in response to a weak seismic signal, behaves like a viscous liquid with an apparent viscosity of about 10^7P and an apparent shear velocity of about 0.2 km/s. Apparent high viscosity at low stress level was reported by Shaw et al. (1968), who made in situ measurements of viscosity at Makaopuhi, Hawaii, and attributed its possible source to the presence of vesicles. A liquid containing vesicles apparently behaves like a Bingham body with the characteristics of a solid below, and liquid above a threshold stress. The presence of vesicles of a few volume percent in the melt can also reduce the apparent bulk modulus to a value as low as the apparent rigidity inferred from Love and S-wave data. A P-velocity of about 0.3 km/s is possible in a melt with 5% vesicles. The observed refraction data require the P-velocity in the lower crust to be as low as 0.9 km/s. This low velocity may be attributed to dry cracks unfilled with liquid magma.

About 8000 seismic events per day were counted at the center of the pond with a seismograph having a peak magnification of 280,000 at 60 Hz. The frequency-amplitude relation for these shocks obeys the Ishimoto-Iida or Gutenberg-Richter law very well with a b-value of 1.19 (± 0.06). Locations of a few selected events indicate that they occur both above and below the layer of melt, although the seismic activity appears to be much higher in the upper crust. Whenever clear, the first motion is always outward from the source suggesting that a crack opening under tensile stress due to cooling is the responsible source mechanism. A simple kinematic model of a circular tensile crack nucleating at a point and growing at subsonic velocity can match the far-field P-wave from these sources fairly well. Typical parameters for a large event inferred from the model are: radius, 2.7m; maximum tensile displacement between crack faces, 2.9μ; cavity volume, $4.4 \times 10^{-5} m^3$; and a seismic moment tensor with diagonal elements only, having the values 3.8×10^{12}, 4.5×10^{12}, and 3.8×10^{12} dyne cm. The magnitude of the event is about -1 and its stress drop is on the order of 0.01 bar. A Q as low as 10 is required to satisfy the shape of the observed waveforms. Using the observed b-value, the total cavity volume integrated over all cracks which is generated daily in the upper crust of Kilauea Iki is on the order of 1 to 20 m^3, in rough agreement with the amount of volume contraction expected on the basis of our knowledge of the thermal history of the crust.

References:

Aki, K., Chouet, B., Fehler, M., Zandt, G., Koyanagi, R., Colp, J. and Hay, R. G., Seismic properties of a shallow magma reservoir in Kilauea Iki by *active and passive experiments*, J. Geophys. Res., 83, 2273-2282, 1978.

Shaw, H. R., Peck, D. L., Wright, T. L. and Okamura, R. The viscosity of basaltic magma: An analysis of field measurements in Makaopuhi lava lake, Hawaii, Amer. J. Sci., 266, 225-264, 1968.

HOT-DRY ROCK

Keiiti Aki (Session Leader)
Jim Albright
Mike Fehler

Hot Dry Rock

K. Aki, J. Albright, and M. Fehler

As described by Bernard Chouet, the Kilauea Ike study showed the importance of multiple-approaches using various waves, namely, P wave, Love wave, S wave, in both passive and active experiments.

The seismic study of the fracture system of the Los Alamos Hot Dry Rock site at Fenton Hill presents another case of emphasizing the importance of multiple approaches.

We find that a simple conceptual model of the fracture system has to be modified as different types of data accumulate.

There are two unique aspects of the seismic data from the Los Alamos experiments, which have been carried out by Group G-3, Jim Albright, Bob Potter, Lee Aamodt and Rod Spence over the past several years.

First, we can control the pressure in the reservoir, and compare seismic measurements between the pressurized and unpressurized conditions.

In early experiments, when geophones were placed at the surface, recorded motions were of low frequencies around 10 Hz, and it was recognized that the measurements in the bore hole are essential in order to record high frequency waves needed for a high resolution result.

Even in the early experiment using surface geophones, however, an interesting observation was made because of the ability to control the down hole conditions. The period of seismic noise gradually increased as more water was pumped into the fracture. Probably, the noise is caused by the vibration of the water-filled crack and the period was proportional to the diameter of crack which increased by pressurization. I mention this, although our discussion today is concerned with the bore-hole data, because of the possibility of defining the fracture system using the noise measured on the surface, as Charlie Swift suggested yesterday.

The bore-hole experiments were done in three major series. The first one is a passive experiment in which a 3-component seismometer located in one of the holes listened to microseismic events generated by pressurization. The second and third are active experiments in which a seismic source was located in one of the holes, and a receiver was located in another.

The results of quantitative analysis of data provide another unique opportunity to apply laboratory measurements and theoretical models of rock containing cracks to study in-situ conditions.

The proximity to the Rio Grande rift zone suggests that the regional tectonic stress in the Fenton Hill may have the minimum principal axis in the NW - SE direction.

Ken Olsen showed three fault plane solutions in agreement with this direction. On the other hand, the local effect of Caldera topography suggests the NE - SW minimum principal stress direction. Unfortunately, the results from the impression packer was inconclusive about the orientation of the Fenton-Hill crack formed by the hydro-fracturing.

Let us now summarize major results from the seismic experiments.

1. The microearthquakes generated by pressurization were located along a zone striking NW - SE, suggesting the fracture plane striking NW - SE.
2. High frequency waves ($f > 1$ KHz) were absorbed in the propagation through the fracture, while low frequencies were amplified. The latter phenomenon suggests resonnance due to multiplicity of cracks.
3. The complexity of the fracture system was demonstrated by the presence of reflected S waves polarized in NW - SE direction which cannot be explained by the crack oriented in NW - SE inferred from the micro-earthquake locations.
4. The seismogram types at frequencies higher than 10 KHz can be classified into 3 types; namely, P., S. and D (diffuse) type. The distribution

of different types along the bore hole before and after the pressurization suggest smooth cracks in the upper reservoir and highly jointed, three-dimensional crack system in the middle of the heat extraction region.

5. More quantitative analysis of P arrival data revealed a velocity decrease by pressurization (100 bars) amounting to 3%. This observation was interpreted in terms of a model of rock with cracks, which also satisfactorily explain the observed attenuation.
6. The velocity decrease varies with the distance along the bore hole. The variation is smooth in the periphery and rough (with wave-length of a few meters) in the middle of the heat extraction region, giving more quantitative measure of the complexity of the crack inferred from the observation of seismogram types.

DISCUSSION GROUPS -- PROSPECTS

DISCUSSION GROUPS -- Prospects

Group A

Paul Brown (Leader)
Gary Hoover
A. Albores
Mike Fehler
Keith Priestly
Hans Ackerman
Craig Weaver

Group B

Robert Edmiston (Leader)
Ed Page
Larry Braile
Steve Malone
Bob Smith
Dave Hill
Paul Kintzinger

Group C

Art Lange
Charlie Swift (Leader)
Bob Daniel
A. Reyes
Jim Albright
Dave Oppenheimer
Paul Reasenberg

Group D

Dave Butler (Leader)
Alan Ramo
Shawn Biehler
Randy Keller
Debbie Wechsler
Chuck Bufe
Larry Ball

Group E

Pierre Goupillaud
Keiiti Aki
Bernard Chouet
Tom McEvilly
Ken Olsen (Leader)
H. M. Iyer

Group F

Allan Lattanner
Dave Boore
Ed Douze
John Schlue (Leader)
Elliot Endo
Rogert Stewart
John Evans

Group G

Bob Crewdson (Leader)
John Savino
John Costain
Ernie Majer
Dave Hadley
Fred Klein
Perry Halstead

Discussion Group B -- Prospects

Bob Edmiston (Chairman)
Ed Page
Larry Braile
Steve Malone
Bob Smith
Dave Hill
Paul Kintzinger

Group B discussed the application of each of the active and passive seismic to the exploration of individual geothermal prospects and then considered a typical exploration problem involving a Basin and Range prospect. In general it was concluded that active methods hold more promise for prospect scale exploration because of the need for the highest possible resolution of geologic features and rock properties.

The following comments were made regarding the individual techniques:

Reflection and Refraction

1. Combined P-S, CDP surveys, such as the one at East Mesa appear promising but more experimental work is needed.
2. More data is needed from a variety of goethermal prospects for which subsurface control is available.
3. Studies are needed involving combined reflection and refraction.
4. Surveys should extend beyond the thermal anomalies for the purpose of rock property comparisons.
5. Attenuation and V_p/V_s appear promising and need further study.

Microearthquakes

1. The necessity of having microearthquakes in a geothermal field has still not been proven.
2. Poor velocity models may cause unacceptable errors in event location limiting the usefulness of the survey.
3. Microearthquakes are a useful P and S source.

4. As above, attenuation and V_p/V_s appear promising but need more study.

Teleseisms

1. P wave delays and attenuation useful on regional scale but may not have sufficient resolution for prospect scale exploration.

2. Additional research is needed to demonstrate utility on prospect scale.

Groundnoise

1. Approaches are different, difficult to compare.

2. Problem of array design and aliasing needs to be resolved.

3. The source is still not known.

The exploration problem we discussed involved a Basin and Range prospect located within the Battle Mountain heat flow high. It was assumed that exploration had resulted in a shallow thermal anomaly located along a major normal fault. Limestones and dolomites are exposed on the upthrown side while low density Quaternary and Tertiary sediments occur in the basin on the downthrown side. A well lcoation must be decided on in six months. The group was nearly unanimous in deciding that under these conditions a CDP survey should be undertaken to locate possible zones of high porosity and fracturing within drillable depth. The survey should have high to moderate resolution. Off end shots should be used to gather refraction as well as reflection data. A fixed microearthquake type array could be employed around the line to gather additional data on velocities and attenuation. Surface waves should be recorded and studied for shear wave velocities which may indicate large scale fracturing. Approximately 15 line miles of reflection data would be shot. Total cost of the overall survey would be about $150,000. This would be cost effective if drilling risk could be reduced by 50%.

Discussion Group C - Prospects

Hot Dry Rock

Exploration for hot dry rock resources should be similar to that for hydrothermal geothermal sources, except that prospects should represent aseismic blocks, with little internal fracturing, away from zones of tensional and strike-slip stress. Such areas may occur isolated, and more probably peripheral to hydrothermal zones such as the Fenton Hill-Valles Caldera situation. A hot but impermeable exploration hole-an economic failure-can be considered a seismic hot dry rock prospect.

Hydrothermal Systems

We considered the following questions:

Seismicity

1. Are geothermal systems seismic sources, and at what threshold?
2. Can we differentiate tectonic from hydrothermal sources?
3. Should we preferentially drill an active fault?
4. How much v_P/v_S, Δtv_P, Δtv_S analysis is cost-effective in a seismicity array study?

Groundnoise

1. Even if the surface manifestations of seismic sources appear to be surface waves in nature, cannot we utilize this information?

Active Reflection

1. With the constant references to the significance of shear wave information, why aren't more P and S reflection surveys done?
2. Aside from hole placement, are CDP reflection surveys cost-effective?

C. Swift
for A. Lange, B. Daniel, A. Reyes, J. Albright,
D. Oppenheimer, and P. Rosenburg

Summary - Discussion Group D
David Butler

Prospect Evaluation

This group chose to discuss microearthquake methods, refraction and P-wave delay in detail rather than ranging over the entire suite of method available for seismic evaluation of geothermal prospects.

Two special uses of microearthquakes were mentioned as being exceptionally interesting and then dropped because the uses were beyond the scope of the discussion. It was felt that μeq methods were very useful for reservoir evaluation at the Geysers, may be so elsewhere and are a facet of reservoir delineation that should be pursued. In fact the detail of data now available is sufficient that more production data would be useful to understand the correlation of μeq and the production.

With respect to hot dry rock, μeq studies will be useful in a null sense; to detect where active faults are not. Additionally, μeq at the fringes of hot dry rock bodies can be used as sources of seismic energy to study the interior of a probably aseismic region. Measurement of the bulk Poisson's Ratio is one potential product of such a survey.

The use of microearthquakes to find active faults, to unravel contemporary tectonics and to hint at gross velocity anomalies was felt to be productive by the group. In an exploration atmosphere, the direct correlation to earth energy was felt to be unproven.

Turning to refraction, it has been demonstrated by quite detailed refraction studies tha the Salton Trough fields do not have a velocity expression at or above the basement. The Roosevelt refraction data was felt to be a significant contribution to the structural understanding of the area. Improvements which were felt necessary were a greater reluctance to put forth complicated non-unique models, and to use the entire seismogram for interpretation rather than just first breaks. The measurement of attenuation was discussed and it was felt that changes of at least 20% in the target would be necessary before present methods could detect such an anomaly. To lower this figure by an order of magnitude, it was flet that the funding for refraction work would have to be increased by more than an order of magnitude. Three-dimensional analysis will be forthcoming in areas where the data is sufficient. Shear-wave refraction was also mentioned as a promising research target.

The specific use of old refraction data to plan a casing program for a wildcat well was brought up as an engineering applicaiton of the refraction method.

Cost-effecriveness measurements were called for and the commercial survey was discussed. The costs are readily available from contractors and the deliverables are specified. These deliverables include microearthquake interpretations (if any are recorded). Close-spaced P-wave delay studies, ground-noise contours, velocity and bulk rock properties studies, attenuation studies, and blast interpretation (from either nearly industrial blasting or from survey-specific shots. Measurement of the effectiveness was beyond the scope (and probably the competence) of this discussion group.

The other techniques, ground noise, reflection and downhole techniques were neglected because of time limitations and not because of distaste.

Discussion Group E -- Prospects

K. Olsen (Chairman)
P. Goupillaud
K. Aki
B. Chouet
T. McEvilly
H. M. Iyer

We assumed that, based on regional surveys, the prospect has already been narrowed down to a 10 x 10 km area and it is required to site the first production well. After discussing which of the seismic techniques are suitable, the group soon concluded that not enough was known to rely only on a few techniques. It was agreed that an integrated survey using several techniques as required. It was considered important to begin seismic monitoring as soon as possible, long before expected production. For this purpose a good, high quality, triaxial instrument located in a heat flow-hole, perhaps, was considered adequate to monitor background seismicity. No need was felt for a large telemetered seismic network at this stage. For detailed seismic survey, it was felt that ideally, a closely-spaced, dense, two-dimensional seismic network was needed. Using such a network (probably by changing network configuration and seismometers with differing, frequency response) various studies such as, P and S delays from local, regional and distant earthquakes, noise, attenuation of P and S, V_p/V_s, surface waves, refraction and reflection surveys can be made. Though such a system may be expensive it is technologically feasible. For example the GUSS BUSS data acquisition system, currently available, can collect 512 seismic data channels, multiplex and transmit them by just two wires. Such a system using a variety of sources such as teleseisms, local and regional earthquakes, and shots can form the basis for a wide variety of active and passive seismic experiments.

The group wholeheartedly agreed to the suggestion of one member that dry wells drilled in geothermal area may conveniently be used for the hot-dry-rock system. Thus in a single geothermal field it may be possible to exploit hot water/steam and hot rock technologies. Survey for hot dry rock project could probably be an intensificiation of regional survey techniques that called attention to a thermal anomaly in the first place. The survey need not be as elaborate as in the search for wet geothermal systems because there are fewer detectable seismic properties in a dry rock system. Thus the large two-dimensional network described earlier may not be required. There was some discussion on the potential risk of triggering a damaging earthquake and producing induced seismicity by the hydro-fracturing process and subsequent exploitation of a hot-dry-rock system. It was felt that seismic monitoring using a high quality bore-hole tri-axial seismograph should be commenced long before fracturing operation commences, to document background seismicity. The seismic monitoring may have to be extended some time before full operation of the system and continued.

Report written by H. M. Iyer from Ken Olsen's notes.

DISCUSSION GROUP F

Dave Boore
Ed Douze
Elliot Endo
John Evans
Allan Latanner
John Schlue
Roger Stewart

Hot, dry rock: Some comments to the effect that, at this time, hot, dry rock is not of commercial interest because of

a) having to drill too deep, and

b) not confident of the fracturing technique

It was pointed out that if we assume such rock is a crystallized pluton intruded into sediments then standard seismic exploration techniques could be used to look for a lithologic contrast rather than for temperature effects.

Reflection methods: Strong feeling that reflection methods are currently the best seismic technique for geothermal prospects. At a minimum, one can expect to learn something about

a) fractures,

b) structure,

c) lithology (maybe),

d) presence or absence of quantities of water.

In particular, it should be an ideal technique for finding steam fields.

It was pointed out that to become as useful a tool as possible, current oil-field reflection techniques must be modified for the more complex structures to be expected in geothermal areas.

Lab-field interaction: Need to apply laboratory measurements to data obtained from field surveys in order to do better resevoir evaluations.

Microearthquakes: Where available, microearthquakes should be used to delineate active faults (if possible). They should also be used for studies of

a) seismicity patterns,

b) P and/or S wave attenuation,

c) P and S wave velocities,

d) Poisson's ratio,

even though we may not yet know how to interpret the results of such studies in terms of geothermal prospects.

Role of seismic methods: Seismic techniques have a definite role at the prospect level, especially if one is dealing with an area that is not obviously a geothermal area. In some cases, the cost of a microearthquake seismicity survey may be less than or comparable to a magnetotelluric survey.

Group Discussion Summary

Prospect, Group G

In the application of seismology to geothermal resources we define the seismicity of an area by characterizing the natural source properties such as magnitude, occurrence rate, location, source type; and by the wave path properties including velocity, attenuation, delays, scattering, Q, focusing, etc. In exploration we define the seismicity of successively smaller domains until the geothermal prospect is circumscribed. We suggest that the "seismicity" of a 20 x 20 km area can be defined with acceptable confidence and cost effectiveness with a minimum of 100 events or a minimum of 3 weeks continuous recording time. At present, we recognize these geothermal signatures: that for geothermal prospects within broad regions of seismicity, clustering and swarming tends to relate spacially to the surface manifestations. We suspect that a spacial change in source characteristics such as rise time, amount of slip, stress drop, and source dimensions may accompany the primary and secondary effects of heat. We suspect that a V_p/V_s anomaly of unknown magnitude will result from the preferential slowing of P-energy due to path changes through fractured rock. We think that a vapor-dominated system may have a "bright spot" response. We question the utility of present b-slope calculations because of undersampling at higher magnitudes and because of poor magnitude estimates at magnitudes less than 2.

We recommend research and/or application in several areas. Measurement of the shear wave propagation should be routinely applied. Within the cost limitations of data transmission and recording logistics, greater use of 3-component instruments should be made. Source characteristics, as previously mentioned, are worth the various expenses involved for the high quality broadband equipment necessary. We suggest that the separation of random vs. non-random events within an area, compared to the same study of the surrounding region will show geothermal character. Similarly, we recommend swarm vs.

shock-after shock studies. We note with caution that laboratory petrophysical analyses are often made with unnaturally high frequencies and that there is uncertain correspondence between lab sample and bulk in-situ properties. Nevertheless, we believe it is important to continue evaluating various property derivatives, especially for sign (+ or -). Finally, we recognize that studies are needed to recognize and quantify the best way to measure P-wave attenuation recognizing such things as wave propagation effects, geometrical spreading, focusing--defocusing mechanisms, and structure.

We believe that highly redundant (24-48 fold) CDP reflection seismic will give excellent resolution in generally difficult areas. Furthermore, it may be the best tool presently to do V_p/V_s studies, and certainly for "bright spot" exploration.

We reached the consensus that the seismic noise technique is not generally useful for exploration. We might use it to solve a specialized problem. We suggest perhaps that monitoring a crossed-spread of geophones to test for suspected noise will work as well as present techniques.

We conceptualized a hot dry rock reservoir simply as an homogeneous region with a zone of elevated temperature. We suspect that rock properties do not change sufficiently in the 200-300°C range to be measured at a remote location. Furthermore, conduction and convection of heat away from the "reservoir" may yield gradual lateral changes that are either unmeasurable or too diffuse to be interpretable.

Finally, we recognize that engineering-type seismic studies have been neglected. For community and plant-site safety, and other environmental-legal considerations, we, as seismologists should address the following questions. First, how much monitoring is necessary to define the seismicity of an area? Secondly, what levels of seismicity are to be considered safe or hazardous? And finally, who is going to make these decisions?

The members of this group included John Costain, Robert Crewdson, David

Hadley, Perry Halstead, Fred Klein, Ernie Majer, and John Savino.

APSMAGS Directory

ACKERMAN, Hans
U. S. Geological Survey
Denver Federal Center
Denver, Colorado 80225
(303) 234-3736

AKI, Keiiti
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617) 253-6397

ALBORES, Armando
Centro de Investigacion Cientifica y
Educacion Superior de Ensenada
Espinoza #843
Ensenada
Baja, California

ALBRIGHT, Jim
Los Alamos Scientific Laboratory
Group 3
Los Alamos, New Mexico
(505) 667-4318

BALL, Larry
Department of Energy
Division of Geothermal Energy
20 Massachusetts Avenue, NW
Washington, D. C. 20545
(202) 376-4914

BIEHLER, Shawn
University of California
Riverside, California 92502
(714) 787-3434

BODVARSSON, Gunnar
Oregon State University
School of Oceanography
1377 Alta Vista Drive
Corvallis, Oregon 97330
(503) 754-3504

BOORE, Dave
Department of Geophysics
Stanford University
Stanford, California 94305
(415) 497-3718

BRAILE, Larry
Purdue University
Lafayette, Indiana 47907
(317) 494-8171

BROWN, Larry
Cornell University
Ithaca, New York 14850

BROWN, Paul Larry
Micro Geophysics Corporation
P.O. Box 1106
Golden, Colorado 80401
(303) 279-0226

BUFE, Chuck
U. S. Geological Survey
Office of Earthquake Studies
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

BUTLER, Dave
Micro Geophysics Corporation
P.O. Box 1106
Golden, Colorado 80401
(303) 279-0226

CHOUET, Bernard
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617) 253-6397

COLP, John
Sandia Lab
Division 4731
Albuquerque, New Mexico 87185
(505) 264-5678

COMBS, Jim
Geothermal Services, Inc.
10072 Willow Creek Road
San Diego, California 92131

COSTAIN, John
Virginia Polytechnic Institute
Blacksburg, Virginia 24061
(703) 951-6521

CREWDSON, Bob
Occidental Petroleum
5000 Stockville
Bakersfield, California 93309
(805) 327-7351

CHRISTIANSEN, Robert L.
U. S. Geological Survey
Office of Geochemistry and Geophysics
345 Middlefield Road, Mail Stop 18
Menlo Park, California 94025
(415) 323-8111

CROSBY, Gary
Phillips Research Center
Bartlesville, Oklahoma 74004

DANIEL, Bob
Department of Geophysics
Stanford University
Stanford, California 94305
(415) 497-3718

DOUZE, Ed
University of Tulsa
600 College Avenue
Tulsa, Oklahoma
(918) 939-6351

EDMISTON, Robert
Anadarko Production Co.
P.O. Box 1330
Houston, Texas 77001
(713) 526-5421

ENDO, Elliot
8228 30th Avenue, NE
Seattle, Washington 98115

FEHLER, Mike
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617) 253-6397

GOUPILLAUD, Pierre
Systems, Science and Software
P.O. Box 1620
LaJolla, California 92038
(714) 453-0060

GUPTA, Harsh
National Geophysical Research Institute
Council of Scientific & Industrial Research
Hyderabad-500 007
India

HADLEY, Dave
California Institute of Technology
Pasadena, California

HALSTEAD, Perry
Department of Energy
Las Vegas, Nevada

HILL, David P.
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

HOOVER, Gary
Phillips Research Center
71-C-PRC
Bartlesville, Oklahoma 74004
(918) 661-3241

IYER, H. M.
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

JALACIC, Allan
Department of Energy
20 Massachusetts Avenue, NW
Washington, D. C. 20545

JOHNSON, Carl
California Institute of Technology
MC 21-252
Pasadena, California 91109
(213) 795-6811

KAUFMAN, Sid
Cornell University
Ithaca, New York 14850

KELLER, Randy
Department of Geological Sciences
University of Texas at El Paso
El Paso, Texas (915) 747-5501

KINTZINGER, Paul
Los Alamos Scientific Research Laboratory
Los Alamos, New Mexico
(606) 667-4318

KLICK, Don
U. S. Geological Survey
12201 Sunrise Valley Drive
Reston, Virginia 22092
(703) 860-6681

KLEIN, Fred
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

KOVACH, Bob
Department of Geophysics
Stanford University
Stanford, California 94305
(415) 497-3718

LACHENBRUCH, Art
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

LANGE, Art
AMAX Exploration, Inc.
4704 Harlan Street
Denver, Colorado 80212
(303) 433-6151

LASTER, Stan
Department of Geology and Geophysics
University of Tulsa
600 College Avenue
Tulsa, Oklahoma 74102
(918) 939-6351

LATTANNER, Allan
Union Oil Geothermal
P.O. Box 7600
Los Angeles, California 90051
(213) 486-6455

LAUGHLIN, Bill
MS 978
P.O. Box 1663
Los Alamos Scientific Laboratory
Los Alamos, New Mexico
(505) 667-6711

MAJER, Ernie
Lawrence Berkeley Laboratory
Berkeley, California 94720
(415) 422-1100

MALONE, Steve
University of Washington
Seattle, Washington 98105
(206) 543-1190

McEVILLY, Tom
Department of Geology and Geophysics
University of California
Berkeley, California 94720
(415) 642-4494

MUFFLER, Pat
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

OLSEN, Ken
Los Alamos Scientific Laboratory
Los Alamos, New Mexico
(505) 667-4318

OPPENHEIMER, Dave
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

PAGE, Ed
ENSCO, Inc.
Seismic Exploration Inc.
8001 Forbes Place
Springfield, Virginia 22151
(703) 321-9000

PITT, A. M.
U. S. Geolgoical Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

POTTER, Bob
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

PRIESTLY, Keith
University of Nevada
Reno, Nevada 89507
(702) 784-6050

RAMO, Allan
SUNEDCO
12700 Park Central Place
Suite 1500
Dallas, Texas 75251
(214) 233-2600

RAZO-M., Antonio, Ing.
Commissionaire Federale Electricitig
Melchor Ocanpo #463
Mexico 5 DFS
Mexico
(905) 553-7133

REYES, Alfonso
Cento de Investigacion Cientifica y
Educacion Superior de Ensenada
Espinoza #843
Ensenada, Baja California

ROBINSON, Russ
Department of Scientific and
Industrial Research
Geophysics Divison
P.O. Box 1320
Wellington
New Zealand

ROSS, Howard
Utah University Research Institute
Salt Lake City, Utah 84112
(801) 581-7162

SANFORD, Allan
New Mexico Institute of Mining
and Technology
Socorro, New Mexico 87801

SAVINO, John
Systems, Science and Software
P.O. Box 1620
LaJolla, California 92038
(714) 453-0060

SCHLUE, John
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801
(505) 835-5634

SCHNEIDER, Bill
Colorado School of Mines
Golden, Colorado 80401

SMITH, Bob
University of Utah
714 Mineral Science Building
Salt Lake City, Utah 84112
(801) 581-7129

SORRELS, Mike
Teledyne Geotech
3401 Shiloh Road
Garland, Texas 75040
(214) 271-2561

STEFANI, Gian Carlo
ENEL
Compartemainto di Firemxe 50136
FIREMZE
Lungarno, Colombo, 54
ITALY

STEWART, Roger
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

SWIFT, Charlie
Chevron Resources Company
320 Market Street
San Francisco, California 94119
(415) 894-7800

WARD, Peter
U. S. Geological Survey
Office of Earthquake Studies
345 Middlefield Road
Menlo Park, California 94025

WARD, Ronald W.
Center for Energy Studies
University of Texas at Dallas
P.O. Box 688
FN 3.1
Richardson, Texas 75080
(214) 690-2445

WEAVER, Craig
U. S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
(415) 323-8111

WECHSLER, Debbie
University of Utah
714 Mineral Science Building
Salt Lake City, Utah 84112
(801) 531-7129

YOUNG, Chi-Yuh
University of Texas at Dallas
P.O. Box 688
FN 3.1
Richardson, Texas 75080

SUMMARY

In spite of the diverse training experience and current responsibilities of seismologists attending APSMAGS, there was surprising unanimity on the following observations of the current status of knowledge and on suggestions for future work:

1. Not enough is known about the effect of temperature, pressure and fluids on the seismic properties of rocks. Recent laboratory measurements have enhanced our understanding of thermal effects on the physical properties of rocks but much more is needed if we are going to adequately interpret seismic observations to evaluate a geothermal resource.
2. No single universal model exists for the various kinds of geothermal systems. Models, based upon the tectonic setting, thermal regime and crustal composition, dictate the priority and utility of the suite of seismic techniques which would be employed in an exploration architecture for such systems.
3. The application of seismic techniques to the exploration and assessment of geothermal resources is still in a research and development stage. Each seismic survey requires sophisiticated interpretation and integration with other studies.
4. Though data from some seismic surveys of geothermal areas are available, additional types of surveys are needed to obtain complete case histories, complete case histories are a prerequisite for defining the utility and reliability of seismic methods. This is necessary for an evaluation of the cost/benefit ratio of seismic methods in an exploration architecture.

All types of data, seismic, non-seismic, and geologic, must be integrated in any regional survey to infer the existence of anomalous zones justifying further detailed exploration. A typical regional survey would cover an area 100 km x 100 km and must be inexpensive to perform to be cost-effective. Seismic surveys as a group are more expensive than other geophysical methods which hinders their widespread use. Among the passive seismic surveys regional seismicity surveys meet this cost requirement and are useful to define the regional tectonic setting. The active faults must be mapped and this information must be integrated into the tectonic picture of the region.

A regional passive seismic survey can identify crust-upper mantle features associated with a geothermal prospect. Examples of such features associated with geothermal systems are zones of crustal thinning, cooling plutons, and perched magma chambers among others. Regional seismic array observations of regional earthquakes and teleseisms can also be used to infer P-wave velocity and attenuation anomalies within the region, which may define localities for further exploration.

Earthquakes generate S-wave which are required to map the variations of rigidity or Poisson's ratio, much more efficiently than artificial sources. In the past body waves have been most frequently used. It was emphasized that one tool that has been largely overlooked in regional surveys is surface wave dispersion studies from which the rigidity can also be determined in the frequency range appropriate for resolving the anomalies associated with the thermal regimes of the crust. Such studies have been successfully conducted at the Yellowstone KGRA, though they are not in widespread use.

Among the active surveys that are cost-effective in regional work are refraction surveys. These measurements can help identify regions of crustal thinning and of lowered seismic velocity and high seismic attenuation, which may warrant further investigation as a geothermal resource prospect. Frequently, nearby mine blasts can be used to lower the cost of such surveys.

It is easier to justify expensive seismic surveys for the exploration of a prospect (a 10 km x 10 km area) prior to drilling than for regional reconnaissance. Faced with a decision to target a well within a short time frame the CDP reflection survey promises to provide the most detailed structural information as well as the possibility of identifying a vapor dominated system, and mapping lateral velocity and attenuation anomalies. Too few reflection surveys appear in the published literature to determine their utility of determing a realistic cost-benefit ratio. It must be recognized that reflection surveys may fail to produce the same quality data in geothermal areas as they have in sedimentary basins.

Shear wave data is definitely needed, but the best type of survey is not known. The S-wave reflection survey recorded in the Imperial Valley was of marginal usefulness. If a prospect is known to be seismically active, then detailed passive surveys which use microearthquakes as sources might be conducted very much as an active source reflection survey.

The relationship between a geothermal reservoir and either seismic groundnoise or microearthquakes has not been established. While teleseismic observations of P-wave velocity residuals and attenuation are very useful in regional surveys for determining the potential of a geothermal system, they fail to provide the resolution needed to target wells. However, detailed surveys using microearthquakes or near regional events do provide the resolution needed for well placement. It was that felt that research on using the entire seismogram to define the geologic structure of the survey area would be worthwhile.

The exploration for geothermal systems is in the stage petroleum exploration was during the first years of this century when oil seeps were drilled. The development of seismic techniques with proven economics will require the development and evaluation of a variety of novel as well as conventional seismic surveys to be able to define a seismic model for a geothermal system. A complete suite of seismic surveys must be conducted at a number of sites to aid in this evaluation.