Final Technical Report to:

Geothermal Division, Department of Energy

on

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**A COMPREHENSIVE STUDY OF FRACTURE PATTERNS
AND DENSITIES IN THE GEYSERS GEOTHERMAL RESERVOIR
USING MICROEARTHQUAKE SHEAR-WAVE SPLITTING
TOMOGRAPHY**

Submitted by

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2. Personnel of Project

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3. Executive Summary

In this project we developed a method for using seismic S-wave data to map the patterns and densities of sub-surface fractures in the NW Geysers Geothermal Field. 1) This project adds to both the general methods needed to characterize the geothermal production fractures that supply steam for power generation and to the specific knowledge of these in the Geysers area. 2) By locating zones of high fracture density it will be possible to reduce the cost of geothermal power development with the targeting of high production geothermal wells. 3) The results of the project having been transferred to both US based and international geothermal research and exploration agencies and concerns by several published papers and meeting presentations, and through the distribution of the data handling and other software codes we developed.

Our project extended over a 3 year time period. It included extensive compilation of data from existing and past seismic networks surrounding the Geysers Geothermal area. The study focused on identifying, measuring, modeling, and interpreting the effects of fractures on seismic S-waves at this site, specifically the North West Geysers. Computer codes to handle and process such observations were developed. The last year of our project included a DOE guided, scientific and collaborative exchange with Dr. Silas Simiyu of the Kenya Electric Power Generating Company, Inc., the national power company of the Government of Kenya.

As part of our collaboration with industry and other exploration groups, we provided a training course on S-wave splitting tomography. The notes from this course are included in this Final Report, as are compressed versions of the publications resulting from our work.

A further benefit to both the geothermal research community and geothermal industry resulted from our collaboration with KenGen: after hearing our presentation of our results on this project at the World Geothermal Congress in Japan, we were approached by the World Bank and United Nations Environmental Program to begin a similar project in the East African Rift Region.

4. Comparison of the Accomplishments with Goals and Objectives

For this project our original Goals and Objectives were:

1. S-wave splitting identification and processing of microearthquake recordings from geothermal exploration and production areas. Application of this identification and processing approach to the NW Geysers
2. Determining the crack orientations around the seismic networks, past and present, in the NW Geysers.
3. Complete a 3-D inversion for the crack density distribution in the NW Geysers.
4. Develop further the computational methods for forward modeling of anisotropic wave propagation.
5. Develop a software package that can handle all of the steps above.

The Accomplishments in each of these areas of our project were:

1. We both tested the S-wave splitting analysis approaches of the University of Edinburgh group (S. Crampin, PI) and developed our own method. The new methods are summarized in Lou et al. (1997), a copy of which is attached to this Final Report.
2. We analyzed several thousand S-waves at the NW Geysers using the past and present seismic networks there. In these data we identified the S-wave splitting and mapped its directions. These results are contained in Lou et al. (1997).
3. Using the orientations and splitting times found in Goal 2, we completed an fracture orientation constrained inversion of the S-wave splitting times for crack density. This was done using a tomographic back projection method. The results are discussed in Malin and Shalev (1999), a copy of which is attached to this Final Report.
4. We met with limited success in improving the forward computation of S-wave splitting in realistic geological materials. After communication with several other groups working in this same area, we concluded that a brute force method such as Finite Elements would probably be the best way to proceed. We are continuing this development on a step-by-step basis, but have found the going slow. This was the least successful undertaking of our project goals.
5. The software package we developed for Goals 1 to 3 above is attached here and has been used by the geothermal companies in California and Kenya..

5. Activities

In the first year of our project, we focused on obtaining all the relevant data for the S-wave splitting study of the NW Geysers. We ultimately obtained these by visiting LBL and helping locate and copy the data sets needed for our work. Once we had these data we could begin evaluating them in terms of our original hypothesis that they would contain S-wave splitting that could be used to orient fractures and measure fracture densities. The results of this effort are shown below (from Lou et al. 1997).

In the second year we use these directions and the time differences between the fast and slow S-waves to calculate a 3-D map of fracture density. We then identified and measured a large number of split S-wave time differences for different parts of the reservoir volume. These measurements are then inverted using back-projection tomography to locate the spatial distribution of crack density. Standard tomographic display methods were then used to create maps of crack density for characterization and development of the reservoir. The full theory and methods behind crack-density mapping using shear-wave splitting tomography are given in Malin, 1993; Lou and Rial, 1994; Shalev and Lou, 1995, Lou et al., 1997; Shalev et al., 1998; and in a forthcoming publication that we are currently preparing (Malin and Shalev, in prep.). A sample cross section in the Geysers area is given below (Figure 5 from Malin and Shalev, 1999).

Figure 5. East-west crack density cross section for the Geysers area. The numbers refer to relative crack densities on the same scale as in Figure 3. The vertical and horizontal axes are in kilometers.

This second year we also worked on the computer codes for handling and processing the S-wave splitting data. These codes and the report describing them is attached to this final report.

In the third year of our project, we completed the assembly of our computer code package and tested it on a new Geothermal Production area provided to us via DOE supported collaboration with the Casa Diablo geothermal field. We also engaged in technology transfer with industry, both in the US and Kenya.

6. Identify Products Developed & Technology Transfer Activities,

a. Journal publications (see attached documents)

1. 2000 Simiyu, S.M., and P.E. Malin. A volcanoseismic approach to geothermal exploration and reservoir monitoring: Olkaria, Kenya and Casa Diablo, USA. World Geothermal Congress, pages 001-006, 5 color figures, June 2000. see: <http://www.wgc.or.jp/08/cdrom.html>
2. 1999 Malin, P.E., and E. Shalev. Shear-wave splitting crack density maps for the Geysers and Mammoth geothermal fields. Invited paper in: Horne, R., Editor Twenty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, SGP-TR-162, 1999.
3. 1998 Foulger, G., P. Malin, B. Julian, E. Shalev, and D. Hill. Seismic monitoring and activity increase in California caldera. A feature article in EOS: Transactions of the American Geophysical Union 79: 357–363.
4. 1997 Lou, M., E. Shalev, and P.E. Malin. Shear-wave splitting and fracture alignment at the Northwest Geysers, California. Geophysical Research Letters 24: 1895–1898.
5. 1997 Lou, M., J.A. Rial, and P.E. Malin. Modeling fault-zone guided waves of microearthquakes in a geothermal reservoir. Geophysics 62: 1278–1284

b. Web site or other Internet sites that reflect the results of this project;

See the following web site and links associated with it:

<http://www.nicholas.duke.edu/eos/research/seismo/>

c. Other products (see attachments)

Technology Transfer Course and Course Notes Including Computer Codes:

From seismic wiggles to crack-density map

By Eylon Shalev Duke University

A copy of this manual is attached to this report.

7. Computer modeling:

See attached document: 6. “From seismic wiggles to crack-density maps” by E. Shalev.

8. Attachments:

1. 2000 Simiyu, S.M., and P.E. Malin. A volcanoseismic approach to geothermal exploration and reservoir monitoring: Olkaria, Kenya and Casa Diablo, USA. World Geothermal Congress, pages 001-006, 5 color figures, June 2000. see: <http://www.wgc.or.jp/08/cdrom.html>
4. 1997 Lou, M., E. Shalev, and P.E. Malin. Shear-wave splitting and fracture alignment at the Northwest Geysers, California. Geophysical Research Letters 24: 1895–1898.
5. 1997 Lou, M., J.A. Rial, and P.E. Malin. Modeling fault-zone guided waves of microearthquakes in a geothermal reservoir. Geophysics 62: 1278–1284ents:

A “VOLCANOSEISMIC” APPROACH TO GEOTHERMAL EXPLORATION AND RESERVOIR MONITORING: OLKARIA, KENYA AND CASA DIABLO, USA

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Key Words: Olkaria, Casa Diablo, fracture detection, reservoir monitoring

ABSTRACT

We have been able to map the size, depth, and fracture density of possible shallow geothermal energy sources by analyzing microearthquake data in volcanically active areas. In this “volcanoseismic” approach to exploration and monitoring, we search for seismicity gaps, seismic velocity ratios, S-wave attenuation and splitting, reflected arrivals, and converted waves. Our analysis of shear wave split data for fracture density in the Mammoth field show two potentially fractured areas that are potential targets for drilling exploratory wells. Vp/Vs ratios in two Olkaria fields can be related to reservoir fluid phases. This ratio is 1.58 in the East Production Field and corresponds to a decrease in P-wave velocity in the area with low-pressure steam saturation in the reservoir. It is 1.71 in the high-pressure liquid-saturated North East Field. We have compared the ratios with down hole pressure, temperature and fluid chemical change measurements. These data show that Vp/Vs values depend on reservoir fluid phases and can be useful tools for reservoir monitoring.

1. INTRODUCTION

The practical objective of geothermal research is to locate potentially attractive reservoirs that can be exploited for electric power generation or other uses. Indicators such as heat sources, availability and characteristics of fluids, reservoir temperature and flow channels are the main parameters investigated. These parameters are sometimes manifested at the surface whereas in other cases there are virtually no surface expressions of an underlying resource. To evaluate these ‘blind resources’, different geological, geochemical, and geophysical methods have been applied at various geothermal fields. The geothermal industry has not commonly set up large seismic networks and developed seismic methods for resource evaluation.

Numerous studies show that recent intrusions are associated with high levels of earthquake activity (e.g. Mt. St. Helen: Nevado del Ruiz, Lees, and Crosson, 1989, Zollweg, 1989, Fehler, 1983; Krafla, Iceland: Foulger, 1983; Stromboli, Italy: Ntepe and Dorel, 1990; Mammoth: Stroujkova & Malin, 1999). Spectral analysis of individual seismic events show that they are characterized by unique, low frequency source mechanisms. The events are often emergent, lack clear phases, and contain several characteristic frequencies. These events can provide information on the dimensions of their associated magmatic and hydrothermal systems. In practical terms, these are the features that control the potential energy of a given geothermal field.

The cost of seismic instruments has been decreasing and collaboration between institutions such as pooling resources including instruments has made it more feasible to carry out

such studies. In this study, we used natural earthquake activity as a tool for:

- Mapping the location of heat sources by using spatial seismic intensity, hypocenter distribution, shear wave attenuation, and P wave reflection.
- Mapping high fracture density zones as an aid in siting wells by inverting for three-dimensional crack direction and crack density in the target volume using the polarization angle.
- Determining the fluid phase, reservoir size and characteristics by measuring the variation in seismic velocity within the field.

An 18 station seismic network was established at the Olkaria Geothermal Field from May 1996 to September 1998 and recorded 4765 local earthquakes. A temporary 40 station seismic network was deployed in the Long Valley Caldera (Mammoth Lakes) in the summer of 1997. Over 10,000 small earthquakes were recorded near the Casa Diablo geothermal field in the caldera. The data sets from Olkaria and Casa Diablo have been analyzed as part of our effort in developing microearthquake techniques for geothermal prospecting and reservoir monitoring. In this study the focus was on locating potential heat sources at Olkaria and Casa Diablo, defining areas of high fracture density (permeability) for potential drill sites at Casa Diablo, and reservoir fluid phase monitoring at Olkaria.

2. EXPLORATION AND RESERVOIR EVALUATION

2.1. Heat source mapping: Seismicity gaps, P- and S-wave attenuation and reflections.

The crust’s strength increases linearly with increasing pressure but decreases exponentially with increasing temperature. Its peak strength is expected at a transition point from the brittle (pressure controlled) seismogenic zone to the ductile (temperature controlled) zone (e.g. Kohlstedt et al., 1995). Earthquakes are generally restricted to the zone of brittle deformation and the maximum depth of seismicity delineates the brittle-ductile transition zone (Meissner and Strehlau, 1982). Thus the depth limit of earthquake activity is related to temperature.

Chen and Molnar (1981) have shown that temperature is the dominant factor in determining the maximum depth of earthquakes and elastic strain. Temperatures of less than 450° C are required for earthquakes to occur in crustal rocks. In the Olkaria Geothermal Field seismicity extends to a maximum depth of 4-6.5 km but occurs deeper in the surrounding region (Figure 1).

Figure 1. Top: map of earthquake recording stations (boxes) and earthquake locations centered on the Olkaria geothermal field. Bottom: cross section of earthquake locations in the East-West band between the dashed lines in the map.

Regional seismicity suggests that stress along the Eastapian rift is released by microearthquakes in geothermal areas. Along the rift boundary faults, stress is released by larger earthquakes (Fairhead and Stuart, 1982; Strecker and Bosworth, 1991).

A seismicity, magnitude and depth distribution analysis in parts of Olkaria shows numerous shallow microearthquakes concentrated in the center of the field where temperature. Outside the field, where temperatures are lower events are larger, deeper and less exotic. This implies that earthquake numbers and sizes are inversely correlated with temperature.

These results can map areas with high heat based on seismicity changes with depth. These changes can define field boundaries and reservoir size in advance of drilling. Areas with intense shallow seismicity and deep seismic gaps were mapped within the Olkaria field. These are interpreted to define intrusions with elevated temperatures. Comparisons with measured temperatures show that areas with the highest bottom hole temperatures and heat flow values $>200 \text{ mWm}^{-2}$ are directly above the deeper gaps. (Wheildon et al, 1994).

The size and depth of the possible magmatic bodies is related to the geothermal heat sources as areas of anomalously low S-wave amplitudes lie beneath the young volcanics of the geothermal field. Relative S and P wave amplitudes were used to back project the position of anomalies by mapping crossing ray paths. This shows an attenuating body beneath the Olkaria caldera that is also associated with a seismicity gap.

Reflected seismic waves have been used to locate magmatic structures beneath the southwestern part of the Long Valley caldera (Stroujkova and Malin 2000). A fraction of Long Valley earthquakes produce seismograms with large amplitude signals between the P- and S wave arrivals. Particle motions and travel times, suggest that some of the phases are S-to-P reflections from what appears to be a recent magma intrusion. Under this assumption, it was possible to use 1st order scattering and signal stacking methods to find the likely location and shape of the structures (e.g. Malin and Phinney,

1985). The resulting image shows a curved, few-square-kilometer zone some 7.8 km below and about 2.4 km west of Casa Diablo (Figure 2). As the reflections have reversed particle motions, it is possible that they originate from partially molten material (Stroujkova and Malin, 2000).

Figure 2. 3D plot of the Casa Diablo area shows locations of the stations, earthquakes, and scatterers. Black triangles show stations that recorded reflected arrivals. Yellow discs show earthquakes used in this study. Background seismicity is shown with black dots. The red cubes represent cells with "scattering intensity" greater than 90% in the S-P residual (From Stroujkova and Malin, 2000).

2.2. Permeability mapping: Shear wave splitting and crack density inversion.

In regions with a consistent fracture orientation, S-waves from different source and receiver locations can be split into fast and slow components. The greater the fracture density, the greater the time differences between the fast and slow components for a given path length. Also, the greater the path length in the fractured rock, the greater the time difference. With a large number of spatially distributed sources and receivers, tomographic backprojection of the time differences can be used to map the distribution of fracture density. The theory and methods of crack-density mapping using S-wave splitting topography are given in Malin, 1993; Shalev and Lou, 1995; Lou et al., 1997 and Shalev et al., 1998 and in a forthcoming publication that we are currently preparing.

The S-P splitting method has mapped regions of high crack density at Casa Diablo in. By studying the directions of motion of the fast and slow S-waves, we were able to determine the average fracture direction. Using these angles and split S-wave time differences, we inverted for the locations and fracture densities. Casa Diablo results are shown as horizontal slices 1 km apart in figure 3 and as vertical cross-sections in figure 4. Red color indicates what is interpreted to be relative high crack-density areas. There are two potential geothermal production targets in the inverted data. The first is north and east of Casa Diablo at depth of 1-3 km. The second is further east, near Mammoth airport, at a depth of 2.5 km. These possible targets can also be seen in cross section in Figure 4.

Each shear wave splitting observation consists of two data points: the polarization angle and time delay between fast and slow waves. Currently we use the polarization angle is used only to find the average fracture orientation. The time delays are used in the inversion assuming that this orientation is constant.

Fortunately, we have found that varying the orientation changes the size of the anomalies but not their spatial distribution.

Figure 3. Crack density maps for the Casa Diablo area shown as horizontal slices 0.5 km apart. The numbers refer to seismic stations and the colors to relative fracture density, with high densities in red and low densities in blue. The NW-SE line locates the cross section in Figure 4.

Figure 4. The NW-SE cross section of the fracture density map for the Casa Diablo area. Colors refer to the fracture density on the same scale as in Figure 3.

3. RESERVOIR ASSESSMENTS

3.1. Phase Separation and Vp/Vs Ratios

It is important to know the reservoir conditions before committing to expensive exploration drilling. Advance reservoir knowledge aids in decision making such as determining whether to go ahead with exploration drilling and the drilling techniques to be used. A geothermal field life span depends on the dominant fluid phase and management strategies such as injection adopted right from the start of extraction.

One of the critical aspects of a geothermal system is whether phase separation between water and steam has occurred. Phase separation is a function of temperature, pressure, fluid saturation, and the composition of advecting fluids. Phase separation produces different classes of reservoirs such as fluid dominated or vapor dominated systems. Phase separation enhances convection as it removes heat more efficiently than fluid circulation alone. At the same time, phase separation accelerates cooling of the field. It can cause rapid expansion of the fracture network. Thus geothermal systems in which phase separation has not occurred persist ten times longer than those with evidence of phase separation (Ito et al., 1979).

In sustainable geothermal power production, it is therefore necessary to know whether phase separation has taken place and the extent it impacts on the system life span.

The ratio of P-wave velocity to the S-wave velocity (V_p/V_s) and Poisson's ratio (σ) are known to be directly related

to the rock properties such as compressibility. O'Connell and Budiansky (1982) have shown that a rock's moduli are affected by the degree of water saturation. The velocity ratio (V_p/V_s) increases with pressure increases from vapor saturated (low pore-pressure) conditions to liquid saturated (high pore-pressure) conditions (Ito et al., 1979). It is also known that S-waves are more intensely affected by anisotropy than P-waves and V_p/V_s ratios are expected to vary with azimuth. This is important in delineating geological structures with contrasting physical properties within the reservoir. Such structures are normally important barriers or conduits for fluid flow in the reservoir.

Studies of V_p/V_s ratios have been done in several geothermal fields (McEvelly et al., 1978; Majer and McEvelly, 1979; Foulger et al., 1997; Julian, et al., 1996, 1998). These studies show that water dominated systems such as East Mesa, USA and Cerro Prieto, Mexico have high ratios of 1.55-1.68. These fields were also found to have low reservoir draw down during exploitation. Steam dominated fields such as Geysers and Coso hot springs, USA have lower ratios, and high reservoir draw down.

Two geothermal reservoirs are now being developed at Olkaria. The North East Field is a high-pressure water dominated field and the East Production Field is a relatively low pressure steam dominated field. These two fields to test the sensitivity of V_p/V_s ratios to reservoir characteristics and how the ratios relate to drill hole data.

3.2. Olkaria North East Field [NEF]

The North East field is at an advanced stage of development with 24 wells that have been tested for a 64 Mwe power station. Analysis of V_p/V_s ratios [Figure 5] shows that the central area is characterized by lower values, consistent with the presence of a steam zone and higher temperatures.

The low V_p/V_s zone starts from drill site OW-716, through OW-707 to OW-727 and OW-709 that have been found to have high temperatures. A NE-SW zone of high ratios extends southward from OW-704 to OW-705, OW-717, OW-718, and OW-713. This zone might be related to lower steam and higher water saturation, leading to higher water pressure and lower temperatures along this trend. This has lead to faster cooling of the energy supply system.

A contoured map of pressure values at 500 masl shows low ratios in the center of the field that decreases southwards towards the EPF area. Low-pressure sinks can be seen at wells OW-716, OW-709 and OW-726 coincident with the low V_p/V_s areas. This is interpreted to represent high temperature reservoir fluid up-flow zones.

A zone of high pressure extends along a NE-SW trend (shown by arrows on Figure 5) from OW-704 to OW-718 and OW-713. This high-pressure zone has been interpreted to represent cold recharge for the field from the NE. This result is consistent with the V_p/V_s (Figure 5) that indicate the recharge zones are characterized by higher values and the up-flow zones by lower values.

3.3. Olkaria East Production Field [EPF]

On average, V_p/V_s values in the East Production Field (Figure 6) are much lower than those determined in the NEF. This is expected because the East Production Field has been under exploitation for the last 15 years, during which there has been a steady decline in the total mass output.

Prolonged steam exploitation has the effect of lowering reservoir pressure in turn induces boiling thus expanding the

steam zone. To arrest the decline and for environmental purposes (fluid waste disposal), a re-injection and injection

program was initiated using both cold and hot fluids in the center of the field (OW-03 and OW-12). This has resulted in an increased total mass output with a slight reduction in enthalpy. Figure 6 also shows an EW trending zone that has high Vp/Vs values and divides the EPF field into northern and southern sectors. This implies steam depletion in the center of the field.

Figure 5. Map of the Olkaria North East area showing a comparison of Vp/Vs against reservoir pressure at 500 masl. The white arrows show the direction of water flow into the field.

An analysis of the reservoir total chloride concentrations within the field for the last ten years was carried out during this study (Figure 6). Also, reservoir fluid conductivity changes from 1982, when exploitation started, to 1997 were plotted for two wells. One well was chosen from the area that had high Vp/Vs values (OW-19) and the second well from the area with low values (OW-18) in order to see whether there was a relationship between fluid chemical changes and the Vp/Vs ratio.

Wells in the field coincident with low Vp/Vs zones show increased chloride concentration and conductivity with time. This increase is to be expected in view of the continuous exploitation of the field. Wells in the center of the field coincident with the high Vp/Vs zone show a decrease in the total chloride. The wells in the high Vp/Vs zone (e.g. OW-19) showed a decrease in conductivity while the wells in the low Vp/Vs zone (e.g. OW-18) showed an increase in conductivity over the period of exploitation. This implies that there is dilution of the original reservoir waters in the high Vp/Vs zone. These results are consistent with the interpretation that Vp/Vs values show steam depletion/reduction in the center of the field due to the combined effect of cold injection into the system and/or inflow of recharge fluids from the eastern edge.

Figure 6. Map of Olkaria East Production Field area showing comparison of Vp/Vs with reservoir chemical changes over 10 years. The white arrows show the direction of water flow into the field.

4. CONCLUSIONS

This study shows that the volcanoseismic approach can be useful as a stand-alone tool for analyzing geothermal resource both at the exploration and exploitation stage. Using this type of microearthquake data, we were able to identify possible heat source areas directly beneath the Olkaria geothermal field and the Casa Diablo volcanic center by looking for seismic gaps, shear wave attenuation and reflected arrivals.

Using fracture density maps deduced from shear wave splitting, we have identified two potential drilling targets in the Casa Diablo area. At Olkaria, Vp/Vs ratios vary from 1.58 in the East Production Field and 1.71 in the North East Field. The very low ratios in the East Production Field are due to phase changes during production. The higher values in the North East Field are due to the reservoir being, high pressure, saturated with water and less steam.

An important result of this study is that Vp/Vs determination and analysis can be an effective tool for determining the status of reservoir fluids within a geothermal field. Vp/Vs can be used as tools for distinguishing up-flow and recharge zones. During long-term injection programs in steam-dominated systems, Vp/Vs interpretations may give valuable information on the flow of fluids into an area of active production.

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Shear-wave splitting and fracture alignments at the Northwest Geysers, California

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Abstract. Shear-wave splitting is commonly observed on three-component microearthquake seismograms recorded at the Northwest Geysers geothermal field, California. The polarization of leading shear waves around each recording station is predominantly N10°-40°E, suggesting that the shear-wave splitting is caused mainly by pervasive, north-northeast orientated anisotropy. Time delays between the leading and second shear waves can be as large as 10ms/km to 30ms/km. We propose that the direction and magnitude of this shear wave splitting is due to the presence of pervasive, stress-aligned secondary fractures related to several northwest-trending, right-lateral faults in the Geysers area.

Introduction

Stress-aligned fractures induce seismic shear-wave velocity anisotropy in the crust. As a result, seismic shear-wave splitting has been widely observed in both low-porosity igneous and metamorphic rocks and high-porosity sedimentary sequences (Crampin 1994, Crampin and Zatsepin 1996). The polarization of the fast split shear wave is usually found to be parallel to the direction of the maximum horizontal stress, which is then interpreted as the local strike direction of vertical fractures. The time delay between fast and slow shear waves is closely related to the intensity of the fracture-induced anisotropy (Crampin, 1987; Savage et al., 1990; Crampin and Lovell, 1991; Crampin and Zatsepin, 1996, Li, 1996). Shear-wave splitting has been used to characterize the stress status and fracture pattern in geothermal reservoirs (Sato et al, 1991, Sachpazi and Hirn 1991, Shalev and Lou 1995). Here we report shear-wave splitting observations from the Northwest Geysers geothermal field, California (Figure 1).

Geological background and the microearthquake data set

The Geysers geothermal field is the world's largest net producer of electricity from geothermal energy. It is located within the central belt of the Franciscan Assemblage in the northern California Coast Ranges. The geological structure of the field has been widely studied (e.g., Blake and Jones 1974, Thompson 1992, Hulen and Walters 1993). Tectonically, the geothermal system appears to be controlled by the northwest-trending Collayami Fault, Sulphur Creek Fault, and Mercuryville Fault, all of which may be related to the right lateral San Andreas Fault system. The reservoir lies primarily within a metagraywacke and is overlain by fractured Franciscan

greenstone melanges and unfractured metagraywacke. The latter rocks are present in steeply dipping thrust packets that constitute the cap rock of the hydrothermal system. The metagraywacke sequence has been intruded at its base by silicic magmas to form a felsite batholith. The emplacement of the felsite is believed to have altered and hydraulically fractured the brittle graywacke, thereby increasing its permeability to host the present day geothermal system.

Due to geothermal energy production and return water flow (injection), the Geysers geothermal field has a very high level of seismicity. This microearthquake activity has been monitored by several networks, including ones operated by Unocal, the Central California Power Association (CCPA), and the U. S. Geological Survey (USGS). The Unocal seismic network records 15,000 to 20,000 events per year that have a mean magnitude of approximately $M_L = 0.7$ (Zucca et al. 1994). Extensive

Fig. 1. Location map of the Northwest Geysers region in northern CA. The general Geysers region is outlined for reference and the Coldwater Creek Steam Field (CCSF) area is indicated with an arrow. The known fault systems are indicated in heavy lines and segment names. Shown schematically in the CCSF area are the hypothesized secondary shear and extensional fractures suggested by our shear-wave splitting data (e.g., Twiss and Moores, 1992). The labels **R**, **R'**, and **P** refer to Riedel and **P** shears found along right lateral strike slip faults. These synthetic and antithetic structures usually form at angles of 10°-20°, 70°-80°, and 130°-140° (conjugate to **R**), respectively, to their associated fault. Also shown is the average direction of the leading shear-wave (**R'**), which in fracture controlled anisotropy normally lies parallel to the maximum principal stress, σ_1 .

Polarization Directions of Fast S-waves in NW Geysers

Fig. 2. Location map of the 16 seismic station downhole seismograph network and 300 selected microearthquake events used in this study. Triangles show station locations in the CCSF area indicated in Figure 1. Rose diagrams centered on selected stations show polarization directions for fast shear waves from our polarization analysis. Station without rose diagrams did not show consistent splitting, due to out of the shear-wave window, or lack of aligned local fracturing. The average time delays of split shear waves per unit distance (ms/km) and apparent fracture density are shown beside each polarization rose.

seismological studies have been carried out at The Geysers for imaging the P- and S-wave velocities, V_p/V_s ratios, and seismic Q values within the geothermal reservoir (e.g., Majer and McEvilly 1979, Zucca et al. 1994, Romero et al. 1995, Julian et al. 1996). This geophysical work has been useful in mapping the Geysers geothermal boundaries, rock properties and fluid saturations, and in monitoring changes in geothermal reservoir properties with time. We discuss here data on fracture orientations and densities in the Northwest Geysers using splitting in microearthquake shear waves recorded by a 16 station network (Figure 2). This network was operated by Lawrence Berkeley Laboratory during 1988 and a part period of 1994 (Romero 1995). All 16 stations had three-component downhole geophones about 30 m below the surface, signals from which were sampled at 400 Hz. The network recorded high quality, high frequency microearthquake data. For our current shear-wave splitting study, we selected about 300 events recorded in 1988, all with high signal-to-noise ratios (>20) and impulsive shear-wave signals. The focal depths of these events are between 0.5 km and 3 km below the surface. This same data set was used by Romero et al. (1995) for their seismic-velocity and attenuation inversions.

Shear-wave splitting observations

Shear-wave splitting can usually be detected by examination of the horizontal component polarization of nearly vertically-incident shear waves, inside the "shear-wave splitting window" of Booth and Crampin (1985). The shear-wave window is defined by a critical angle $i_c = \sin^{-1}(\beta/\alpha)$, where α and β are P-wave and

S-wave velocities, respectively. The critical angle defining the shear-wave window is about 35° in a half space with a Poisson's ratio of 0.25. However, ray curvature caused by low-velocity surface layers usually allows the effective window to be enlarged to angles of incidence of 45° or 50° . In a typical microearthquake survey in anisotropic media, the first-arrival shear wave is usually followed by a later shear-wave showing an abrupt change in polarized direction (usually normal to the polarization direction of the first arrival). The polarization may then evolve into elliptical motion or further linear motion along a different polarization direction, provided that the time delay is long enough to separate the late signals from the initial arrival (Crampin 1987) (see examples in Figure 3). Unfortunately, when the incidence angle of the shear waves is significantly off from vertical - i.e., outside the shear-wave splitting window - then surface conversions may obscure the slower shear wave.

Figure 3a shows a typical example of shear-wave splitting and its particle motion for the Northwest Geysers microearthquakes (in this case event 8803190110 of the LBL catalogue) at station S5. The split shear waves are identified by their orthogonal polarizations in the horizontal component shear-wave train. This splitting is most clearly seen after the seismograms are rotated into the directions corresponding to the fast and slow shear-wave polarizations. To find the azimuth of the leading shear wave's polarization, we first calculated the ratio of particle displacements on a given set of orthogonal axes in a time window including only the fast shear wave (Shih et al. 1989). When one of these axes is parallel to the fast polarization direction, the ratio is maximized (in this case 62°

Fig. 3. Examples of shear-wave splitting recorded on station S5 from events (a) 8803190110, and (b) 880422240 (Romero 1995). The fast and slow shear waves can be clearly identified after the seismograms are rotated into the polarization directions corresponding to their polarization directions. Despite coming from different azimuths, the two events have an almost identical polarization direction (difference of 3°) for fast shear waves. To the right are the appropriate particle motion diagrams.

from the X component). The second axis then lies along the slow shear-wave polarization. After rotation of the seismogram components to these coordinates, the time delay between the split shear waves can be measured either by cross-correlation of the seismograms or direct picking of the first motion difference (54 ms). Most measurements of the time delays in this research were done by the direct picking of the seismograms.

If the fracture system is uniformly aligned, then the fast and slow polarization directions should be independent of source and receiver location, provided these are within the shear-wave window. To illustrate the consistency of fast and slow shear-wave polarizations at the Northwest Geysers, Figure 3(b) shows the shear-wave splitting recorded on the same station (S5) as in Figure 3(a), but from an event that approaches the station from a different direction (880422240). The polarization direction of the fast shear wave is measured to be 59° from the X component (a 3° difference from the first event), and a time delay of 48 ms. Further, using appropriate subsets of our 300 selected events, we have identified shear-wave splitting consistent with that shown in Figure 3 at stations S1, S2, S4, S6, S7, S8 and S10 (see Figure 2).

Due partly to the shear-wave window requirement, we found no subsets of events with consistent shear-wave splitting patterns at the other 8 stations (Figure 1). For the events that should have been within the shear-wave window at the latter stations, first arrival polarizations show either no dominant direction or dependent on the arrival direction. Non-uniformly aligned fractures either beneath the station or along significant fractions of the source-receiver path may account for these observations. It is also possible that near these stations the fracture systems are not vertical, producing a complicated mix of fast and slow waves.

Fracture orientations and densities

We assume that the consistent shear-wave polarizations at stations S1, S2, S4, S5, S6, S7, S8 and S10 could be the result of fracture-induced anisotropy between the sources and receiver. Figure 4 illustrates this possibility by showing equal-area projections of the polarizations of fast split shear waves for 6 of the 8 consistent stations (S1-2, S4-7). The projections establish both the consistency of first motion polarization and limits of the shear-wave window (the inner circle of each projection). Inside the shear-wave window the polarizations of the leading shear-waves are not sensitive to the direction of the source.

From the equal-area projections we produced rose diagrams of the fast shear-wave polarization directions for each station. These diagrams are plotted on their respective stations in Figure 2. The rose diagrams show that there is a predominant, $N10^\circ-40^\circ E$ orientation of the fast shear-wave polarizations in our data set. This is interpreted as the local orientation of near-vertical fractures at the Northwest Geysers geothermal field.

After rotation into fast and slow polarization directions, we picked the time delays between the two shear-wave arrivals. For our data set these varied between 10-60ms, depending on source-receiver azimuth and distance. The average time delay per travel distance (ms/km) at each station is shown in Figure 2.

If it is assumed that shear-wave splitting is mainly caused by stress-aligned vertical microfractures in an otherwise isotropic rock, Hudson's (1981) formulation can be used to convert these delay times into fracture densities, ϵ , a dimensionless number given by $\epsilon = N a^3 / V$. In this relation, N is the number of fractures of average radius a in volume V . The average value

Fig. 4. Equal-area projections of polarizations of fast shear waves from the different microearthquake events (indicated by bars) corresponding to six selected individual seismic stations. The inner circles of the projections indicate a 50° incident angle shear-wave window. The orientations of most events within the inner circle tend to have a northeast dominant direction.

of fracture density around each station is shown on Figure 2, below its corresponding value of delay times per unit distance. The densities listed in this figure are similar to those found in other geothermal fields (Sachpazi and Hirm 1991, Sato et al. 1991, Shalev and Lou 1995). In the area around station S5 on the western edge of the geothermal field, the fracture density reaches its maximum value (0.048). This area coincides with the high P-wave attenuation anomaly mapped by Romero (1995). It is also the site of a former, major, near-surface geothermal production zone.

Discussion

By studying the shear-waves of 300 microearthquakes, we have clearly identified shear-wave splitting in the Northwest Geysers geothermal field. Observed time delays between the leading and second shear waves can be as large as 10ms/km to 30ms/km, indicating a high fracture density in the geothermal field. The northeast strike of fractures inferred from the fast shear-waves are generally consistent for 8 of the 16 stations that we studied. The other 8 stations where no consistent pattern of fast and slow shear-waves was found are most likely outside the shear-wave window, or are in areas of mixed fracturing.

The prevailing fracture orientation (N10°-40°E) as inferred from shear-wave splitting analysis, can be explained as conjugate Riedel shears found along right lateral strike slip faults (Figure 1, see also Twiss and Moore, 1992). These antithetic structures usually form at angles 70°-80° from their associated fault, which in fracture-induced anisotropy normally lies parallel to the maximum principal stress. Using the same set of earthquakes for velocity and attenuation measurements, Romero (1995) proposed the existence of a set of aligned fractures held open by a regional northeast-southwest maximum principal stress in the Northwest Geysers. This is consistent with the northwest - southeast minimum stress proposed from focal mechanisms by Oppenheimer (1986) for the Geysers region in general, and observed with our shear-wave polarizations.

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From seismic wiggles to crack-density map

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The steps:

1. Locating events
 - Data read and conversion
 - Starting 1-D velocity model
 - Stations and area information
 - Locating events
2. Identifying shear-wave splitting
 - Choosing the “right” events
 - Setup for shear-wave splitting
 - Identifying shear-wave splitting
3. Choosing area and inversion parameters
 - Target area
 - Model parameterization
 - Node density and distribution
4. S-wave velocity inversion
 - Choosing events for S-wave inversion (time file)
 - Creating 3-D velocity structure
 - Choosing inversion parameters
 - Tomographic inversion
 - Plot results
 - Repeat inversion steps
5. Crack-density inversion
 - Converting data to local-coordinates time file
 - Tomographic inversion
 - Plot results
 - Repeat inversion steps

1. Locating events

Data read and conversion

There are several (too many) seismic data “standards”. Unfortunately, none of them is a dominant standard that can force itself on the seismological community. Instead there are many conversion programs that translate between formats. The PASSCAL distribution package contains many such programs. A good source for PC based translation programs, and other seismology oriented computer programs is at <http://orfeus.knmi.nl>

A partial list of seismic standard

SEGY	Used by PASSCAL
SAC	Used by the SAC Seismic Package
AH	Used by some USGS peoples
UW	U. of Washington format, used by Duke
SEED, MSED	Used by the IRIS Data Center

The data that come out of the PASSCAL system is SEGY (or SEED). The programs at Duke require UW format. The program segy2uw translate from SEGY to UW.

Starting 1-D velocity model

Locating seismic events is similar to lifting yourself with your bootstraps. The only data we have is arrival times and stations locations. The velocity structure and the events location are the unknowns. A common solution to this problem is to assign some starting velocity structure to the target area and locate the events. Later, after locating several hundreds events, we can go back and use those location to improve the velocity structure. The UW programs utilize 1-D constant layer velocity structure similar to this example:

M2 MAMMOTH REGIONAL VELOCITY MODEL (from Sanders and Nixon, 1995)

P DEPTH	P VEL	PERR	S DEPTH	S VEL	SERR
0.00	4.55	0.00	0.00	2.54	0.00
2.00	5.05	0.00	2.00	3.12	0.00
3.00	5.67	0.00	3.00	3.20	0.00
4.00	5.75	0.00	4.00	3.30	0.00
5.00	5.90	0.00	5.00	3.41	0.00
6.00	5.99	0.00	6.00	3.44	0.00
7.00	6.00	0.00	7.00	3.48	0.00
8.00	6.04	0.00	8.00	3.49	0.00
9.00	6.06	0.00	9.00	3.50	0.00
10.00	6.07	0.00	10.00	3.51	0.00
12.00	6.09	0.00	12.00	3.52	0.00
16.00	6.14	0.00	16.00	3.54	0.00
18.00	6.18	0.00	18.00	3.57	0.00
22.00	6.34	0.00	22.00	3.66	0.00

Stations and area information

The locating program needs a list of all station locations, and a separate list of station corrections. The location should be as accurate as possible to reduce locations errors. The program locates the events below a datum line that is similar to the average elevation of the locating stations. Station corrections suppose to take care of elevation differences and near station anomalies. The way to compute station corrections is to locate several hundreds events with zero corrections and to assign the average time errors as station correction.

Example of a station file for UW programs:

```
M01Z 37N38.5100 118W55.6000 2.240
M01N 37N38.5100 118W55.6000 2.240
M01E 37N38.5100 118W55.6000 2.240
M02Z 37N38.8000 118W55.8300 2.280
M02N 37N38.8000 118W55.8300 2.280
M02E 37N38.8000 118W55.8300 2.280
M03Z 37N37.9100 118W55.5400 2.250
.
.
.
```

Example of station correction file:

```
STATION CORRECTIONS FOR MAMMOTH VEL.FIELD MODEL M2
STATION      P DEL      S DEL
M01Z          0.000      0.000
M01N          0.000      0.000
M01E          0.000      0.000
M02Z        -0.010     -0.063
M02N        -0.010     -0.063
M02E        -0.010     -0.063
M03Z          0.096      0.022
.
.
.
```

Locating events

Locating events is done with the program “xped”. xped is the graphical front end used for making the picks. Some important points when using xped:

- 1) Pick only one P arrival for one station on the vertical component.
- 2) Pick only one S arrival for one station on one of the horizontal component.
- 3) Trust your eyes. Don’t change your pick because the computer tells you that the pick should be different.

The actual location is done by another program “lquake”. The script file “run_xped” sets some variables and start “xped”.

```
# script file to run xped for mammoth
setenv XPEDLOCATE "lquake -f /vhome/mammoth/tables/setup.mammoth"
setenv XPED_STA_FILE /vhome/mammoth/tables/mammoth.online

xrdb -load ~/XPed.ad
xped -pps 50 $*
```

The setup file for “lquake” is the file setup.mammoth

```
# setup file for 'lquake'; mammoth model and delays
opt = 'scp'
spvel = '/vhome/mammoth/tables/mammoth2.vel'
spttt = '/vhome/mammoth/tables/mammoth2.ttt'
spdel = '/vhome/mammoth/tables/mammoth.del'
spsta = '/vhome/mammoth/tables/mammoth.online'
distwt = 15.0
amarq = 0.001
tol = 0.01 0.01 0.01
orig = 36.6 119.00
modflg = 'M2'
```

2. Identifying shear-wave splitting

Choosing the “right” events

Not all seismic events produce high quality shear-wave splitting. The best results in past experiments come from events of magnitude 0.8 to 1.5. If the magnitude is not computed yet, events with large number of recording stations should be chosen. To avoid bias toward areas of high swarms activity the total target area is divided into small cubes where only small number of events can be picked from each cube. The program “picsst” can be used to select this list.

```
picsst setup.picsst < mammoth.pic >! mammoth.t
```

The picsst program can be used for general choosing of events based on several criterions like: number of stations picking this event, maximum RMS of the location error, gap, and quality of location. Below is an example of a setup file for picsst:

```
${orgfil}      orgfil = origin file (input)
ac.${root}     acfile = Acard file (output)
5              stmin  = minimum number of station for eq (input)
0.06           rmsmx  = maximum rms of the eq location (input)
210           gapmx  = maximum gap in degrees (input)
A              q1     = first uw quality factor (A, B, C or D) (input)
2              sp     = 1 -> P-wave; 2 -> S-wave; 3 -> P and S (input)
2              lbox   = maximum number of eq in one box (spac^3) (input)
/vhome/mammoth/tables/mammoth.online
/vhome/mammoth/tables/mammoth.del
```

The list of events generated by “picsst” is named “filename_ac.*”. This list can be used to create a hypo71 list of events to be used for plotting or other functions. Below is an example of one line “uwp2hypo” command utilizing awk to do this.

```
uwp2hypo `nawk ' { jdy=substr($2,2,3);
printf("/dat1/mammoth/97.%s/uw/%s \n",jdy,$2) } '
filename_ac.mammoth` >! Mammoth.lst
```

We are working on software solution for detections of apparent splitting. This will eliminate events without splitting in the list.

Setup for sear-wave splitting

Picking shear-wave splitting is done with the program “xmom”. A script file “xmom_plot” start this program and also plot on the screen a map of the stations, event’s location, and which station is in the shear-wave window. “xmom_plot” can be run with event name or event number in the list and must be edited to fit the local files and disk situation. A sample configuration file for “xmom” is listed below:

```
# this is a sample configuration file for the UCSB Mom
program
# lines can be commented out using a "#" at the beginning
of the line
    #
    velmod          /vhome/mammoth/tables/mammoth1.vel
    locationfile    /vhome/mammoth/tables/mammoth.online
    startdate       970101000000
    startchannel    0
    decimation      6
    fftwinlen       1024
    fftdisptype     displacement
    fftstartfreq    5.00
    fftendfreq      80.00;
    gain            60
#
# instrument parameters
#
    naturalfrequency 4.75 ( hertz )
    sensitivity      .39 ( V / cm / s )
    damping          0.7000 ( % critical )
#
```

Identifying shear-wave splitting

Picking shear-wave splitting on “xmom” display:

- (1) Choose those events having clear, robust shear-wave arrivals, and most S-wave energy resided on two horizontal ONLY.
- (2) Use "trial and error" method to rotate the two horizontal components until the particle motion of first S waves is along or parallel to one horizontal axis (usually is "X", "E", component). This rotation angle is taken as the polarization direction to the correspondent component ("X", "E") of the fast S wave.
- (3) Pick up time delays between fast and slow shear waves from the particle motion plot. When we press space bar of keyboard, the particle motion will keep plotting in time-advancing fashion (press space bar once, the particle motion plotting moves one sampling interval, e.g., for the Mammoth data it is 2.0 ms). For near-vertical incident shear waves in a vertical aligned cracks media, the direction of particle motion of slow S-wave will be normal to the fast one. By counting space bar pressing number, we will pick up the time delays between fast and slow shear waves. For non-vertical incident, or non-vertical cracks, there is usually no orthogonal particle direction relation between fast and slow shear waves. In this case, we just pick up the time duration of the very first motion until some point it is changed abruptly by a second motion.
- (4) Take a note of pick-up results, including event number, angle of particle motion of fast shear waves, time delays between fast and slow shear waves. For tomographic inversion reason, we use grade "A, B, C" to indicate data quality: "A" means excellent example, "B" is ok, "C" is not so confident in identifying the split shear waves. The note may take the format as in the file split.list:

yr-sec	station	angle	time delay ms	Quality
7229153926	M27	61	48	c
7228172135	M02	274	102	c
7228161303	M04	270	64	b
7228161303	M39	0	102	c
7228143451	M20	320	124	c
7228143451	M26	329	90	b
7228020215	M26	324	102	a

3. Choosing area and inversion parameters

Target area

The target area for the tomographic inversion is a cube with local coordinates. The surface of the target area should include all the desirable stations and as many events as possible. The depth of the target area depends on the depth of the events. Only stations and events inside the target area will be included in the inversion.

Local coordinates are used in the inversion. For an estimate of conversion from global to local coordinates remember that 1 latitude degree is 112.11 km and 1 longitude degree is $\cos(\text{latitude}) * 112.11$.

Location and size of the target area are set by an origin file. This file sets the southwestern point of the target area and the size of the box. Example of an origin file:

```
8 8 24 18 20 0.5 0.0
37. 36.5 0.0
118. 58.0 0.0
```

The first two numbers in the first line are legacy numbers with no meaning, then the number of blocks for x, y, and z, then the size of each block. The last number in the first line is the rotation angle for the target area. If the Y-axis is to the north this rotation angle is zero. The last two lines set the southwestern point (the 0;0 points) of the target area.

Model parameterization

The real earth structure in the target area is complicated beyond any model we can create. A simplified model is needed in order to represent the target area in suitable way for computer processing. The classic way of doing it is to divide the whole target area into many small, not overlapping, boxes. All the volume inside each box has a constant value of the earth attributes in question (e.g. P-velocity, S-velocity, V_p/V_s , density). This model parameterization is the simplest and the least computational intensive way of representing the earth. One number represents the value inside the box. The limitation of this representation is the sharp boundaries between cells and the large number of model parameters (boxes) needed to describe complicated model.

Another way of representing the earth is with some interpolation scheme. The simplest interpolation model is linear interpolation. The values of the model are set on nodes (points) and the value between nodes is computed with linear interpolation. In one dimension, two nodes are needed to compute the value at some arbitrary point. That translates to eight nodes needed to compute the value of arbitrary point in three dimensions. This parameterization overcomes the sharp boundaries between boxes and also enables us to describe complicated structure with fewer model parameters (nodes). The target area structure is continuous but with sharp direction changes at the nodes, which may cause problems for computations that uses derivative like some ray tracing algorithms.

Cubic B-splines interpolation model produces smooth structure with continuous first and second derivatives. In one dimension, four nodes are needed to compute the value of one arbitrary point. This is the most computational intensive method since, in three dimensions, 64 nodes are needed for finding the value of an arbitrary point in the target area. With today's advance in computing power this is the preferred method for modeling smooth complicated structure with fewer points than the other methods.

Node density and distribution

Nodes are the locations in the model that we try to find solutions for. In boxes model, each box is a node. In interpolation model, nodes are the interpolation points from which we can compute a value for any place in the model. Tomographic inversion is a solution of a very large matrix equation where observations are the data, and node's values are the unknowns. A reasonable rule to follow is that the number of observations should be at least the number of unknowns. Complicated model requires more structure nodes to accurately image it. The optimal number of nodes (unknowns) is such that the target area can be imaged to the highest accuracy without exceeding the number of observations or the computer capacity.

Nodes location should depend on data concentration and model complexity. If we expect some areas of the model to have large changes in short distances we should increase the nodes density there. The model edges may require lower nodes concentration.

The file for setting nodes location is one like “mammoth_s.dat”:

```
13 10 10 1 50 ! nnx nny nnz starting structure jump
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 x
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 y
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 10.0 z
2.0 2.48 3.00 3.26 3.27 3.40 3.44 3.48 3.49 3.51 mammoth s
```

The first line has number of knots in x, y, and z. Starting structure and jump parameters are for two velocity structures changing at some knot in x direction. For one structure make the jump parameter larger than nnx. The last two line are knots location in x and y directions. The last two lines are the location and value of the velocity structure

FIGURE 2

4. S-wave velocity inversion

A script file “tomo.csh” runs the tomographic inversion for seismic velocity. This script file creates all needed configuration files and performs the inversion from start to finish. The user must edit this script file so that the configuration files will be right for the inversion. The first several steps before the inversion may be performed only once. Those steps may be commented (# in front of the line) in later runs of the inversion to save time. This script file may be used for running only one or two steps also by commenting the unwanted parts. Below are the steps of the inversion.

Choosing events for S-wave inversion (time file)

- A.** Create origin file as explained above.
- B.** Create one big pick file and relocate all events with consistent velocity and correction files.

```
cat /data3/mammoth/97*/uw/*p >! temp.pic  
lquake -f setup.mammoth < temp.pic >! mammoth.pic
```

If some of the pick files are bad you can chose pick files with a simple script like this:

```
foreach i ( `ls -d /data3/mammoth/97.2[3-7]? ` )  
? cd ${i}/uw  
? foreach d (`ls *p`)  
? set n=`nawk ' NR == 1 { print NF}' $d`  
? if ($n > 3) then  
? cat $d >> /vhome/mammoth/tomo/late.pic  
? endif  
? end  
? end
```

C. The program “picsst” takes the large pick file and creates a time file (*.t) and A card file (the first line of each earthquake). Remember to check that the station name and correction file are the right ones. This program makes the translation from global to local coordinates, the rest of the tomography programs are in local coordinates.

```
picsst setup.picsst < mammoth.pic >! mammoth.t
```

The “picsst” program can be used for general choosing of events based on several criterions like: number of stations picking this event, maximum RMS of the location error, gap, and quality of location. This program also spread the events through the target area by limiting the number of events from a local box defined in the origin file. Below is an example of a setup file for picsst:

```
${orgfil}      orgfil = origin file (input)
ac.${root}     acfile = Acard file (output)
5              stmin  = minimum number of station for eq (input)
0.06           rmsmx  = maximum rms of the eq location (input)
210           gapmx  = maximum gap in degrees (input)
A              q1     = first uw quality factor (A, B, C or D) (input)
2              sp     = 1 -> P-wave; 2 -> S-wave; 3 -> P and S (input)
2              lbox   = maximum number of eq in one box (spac^3) (input)
/vhome/mammoth/tables/mammoth.online
/vhome/mammoth/tables/mammoth.del
```

The list of events generated by “picsst” is named “filename_ac.*”. This list can be used to create a hypo71 list of events to be used for plotting or other functions. Below is a, very long, example of one line “uwp2hypo” command utilizing awk to do this for mammoth data.

```
uwp2hypo `nawk ' {jdy=substr($2,2,3); if(jdy < 199)
{disk="/data1"} else if(jdy < 219) {disk="/data2"} else
{disk="/data3"} printf("%s/mammoth/97.%s/uw/%s
\n",disk,jdy,$2)}' filename_ac.mammoth` >! Mammoth.lst
```

Creating 3-D velocity structure

D. The starting 3-D velocity structure with nodes locations is defined by a setup file as explained earlier. The program “put3d” insert this structure into a 3-D structure file:

```
put3d 3dmammoth_s.dat ${root}.v
```

E. Following naming convention for file names, *.v file is 3-D cubic B-splines structure only, *.V file is the structure and all ray paths to be used in the inversion. The program that trace the data set in the starting 3-D velocity is “trace_v2V”

```
trace_v2V ${root}.t ${root}.v ${root}.V
```

*.t is the time file created by “picsst”. *.v is the file created by “put3d”
*.V is the output. This file and any other *.V file consist of the B-spline structure (from the *.v file) and all the ray paths. The *.V files can be very large (~ 1 Mb for each 4000 ray).

Choosing inversion parameters

Tomographic inversion requires several damping and smoothing parameters for reasonable results. Without damping and smoothing, errors from the data will be mapped back into the solution and the results will be questionable. Also event locations may be changed due to different velocity model after the inversion. Choosing damping parameters can be done by computer search but this is very time-consuming procedure. The easiest way is to run the inversion with some set of parameters and to change these parameters according to the results. If the final result is “choppy” with small areas of high and low velocity next to each other, the smoothing is too low. If the changes in velocity are very small the damping of the velocity is too high. Below is an example of a setup file for tomographic inversion with explanation.

```
# Setup file for tom_trace
# this setup consist of four line after a line with "&" character.
# The first line is for ilap and jse only
#   ilap  0 -> regular damping,  1 -> laplacian and regular damping
#   jse for event correction
#       jse = 0 -> no correction
#       jse = 1 -> only time correction
#       jse = 2 -> only location correction
#       jse = 3 -> both time and location correction
# the second line is for the dumping parameters
# for ilap = 0
# rlamda(model damping) stdamp(station damping) evdamp(event
damping)
# for ilap = 1
# rlamda stdamp evdamp rlap(laplacian parameter) rld3(vertical
laplacian ratio)
# The third line is the name of the correction file for storing the
correction
# The fourth line is the name of station file for station names
&
1 3
100.0 100.0 100.0 100.0 0.5
corr.res
/vhome/mammoth/tables/mammoth.online
```

Tomographic inversion

F. The program that runs the inversion is “tom_trace” to run tom_trace type:

```
tom_trace ${root}.V ${root}_1.V 4 2 tom_trace.dat
```

*.V is the structure_ray file from step E

*_1.V the output file is a structure_ray file with the updated velocity structure and new ray paths

4 is the number of iteration (default=1)

2 is the minimum percent variance reduction to stop (default=2)

tom_trace.dat is the setup file (default=tom_trace.dat)

The tom_trace program writes progress report to the screen during the inversion. The important numbers to inspect are:

Total nonzero elements - depends on the computer memory max 4 mill.

Variance reduction - less than 5% is very small improvement.

Plot results

G. The cubic B-spline structure in the *.V files can be sampled at any interval to create three-dimensional plots at any place inside the model. Plotting the results will be done with the GMT package, so translation from B-spline structure to GMT readable file is necessary. The program “sh3d2gmt” will do this translation:

```
sh3d2gmt sh3d2gmt.setup
```

sh3d2gmt.setup is a setup file for this program.

```
#setup file sh3d2gmt
1      jtype (0->struc.; 1->pert. from set; 2->pert. from av; 3->hit
count)
1      itype (0->regular structure; 1->slowness 1/v)
${root}_1.V      input file with B-spline structure
0.  12.0      x coordinates limits
0.  9.0      y coordinates limits
0.2      step size (only horizontal)
2      ipath (0=own path; 1=all blocks; 2=other file path)
${root}.V      name of other file. only if ipath = 2
6      number of layers
0.5  2.12      depth and slowness (velocity) of layers (# of layers)
1.5  2.70
2.5  3.11
3.5  3.26
4.5  3.33
5.5  3.42
1      ivf (0->fixed scale; 1->variable scale)
1 1 -5.0 7.0 4 0.01 0.08 (# of scales, starting first scale, min,
max, ...)
```

H. Plot with GMT. The script file “gmt_slice” will plot horizontal slices as defined by sh3d2gmt program. Since “gmt_slice” can be used for different structures, the right root name for the file must be entered in this script file.

```
gmt_slice
```

Repeat inversion steps

As mentioned earlier the script file “tomo.csh” will create all setup files and will run all programs needed for the inversion. After the first running of “tomo.csh” the user should comment all the earlier steps (A to E) and repeat the last three steps (F to H) until satisfied the damping, smoothing, and plotting parameters are right.

5. Crack-density inversion

As in the regular inversion a script file “split.csh” runs the tomographic inversion for crack density. This script file creates all needed configuration files and performs the inversion from start to finish. The user must edit this script file so that the configuration files will be right for the inversion. The first several steps before the inversion may be performed only once. Those steps may be commented (# in front of the line) in later runs of the inversion to save time. This script file may be used for running only one or two steps also by commenting the unwanted parts. Below are the steps of the inversion.

Converting data to local-coordinates time file

A. Correct for station angle and change to *.lou format with the “tran_split” program.

```
tran_split comp_split.dat >! split_all.lou
```

“comp_split.dat” is a file with station names rotation angles and the name of the split data file from the identifying split shear wave step. A partial example:

```
/vhome/mammoth/split/final_split.list
42          # number of stations
M01  0.0    # station name and orientation (ccw = +)
M02  0.0
M03  0.0
M04  0.0
M05  90.0
M06  0.0
M07 -30.0
```

B. Create *.t file with the “pick2t” program.

```
pic2t m split_all.lou org.mammoth mammoth.online >! ${tfil}.t
```

C. (optional) Chose some stations or window with awk script.

Tomographic inversion

D. The program that runs the inversion is “tom_split” to run tom_split type:

```
tom_split ${tfil}.t ${root}.V tom_split.dat
```

*.t is the time file created in step 5.B

*.V is the best S-wave velocity structure computed in step 4.

tom_split.dat is the setup file (default=tom_split.dat)

Results of “tom_split” is a density structure file *_den.V

Example of tom_split.dat:

```
# setup file for tom_vpvs
# the setup consist of four lines after a line with only "&"
character.
# the first line is for the three dumping parameters
#   rlamda(model damping)   rlap(laplacian parameter)
#   rld3(vertical laplacian ratio)
#   If rlamda=0.0   only Laplacian.           If rlap=0.0   only
damping.
# The second line is for parameters controlling type of
inversion (iav and avb):
#   iav = 0   start from zero density,   avb is not used
#   iav = 1   start from average density level,   avb average
S-velocity
# The third line is the reginal direction (strike) of the
cracks
# the fourth line is the name of the file with stations name.
&
5.0  2.0   0.1
1    3.2
340
/vhome/mammoth/tables/mammoth.online
```

Plot results

E. The cubic B-spline structure in the `*._den.V` files can be sampled at any interval to create three-dimensional plots at any place inside the model. Plotting the results will be done with the GMT package, so translation from B-spline structure to GMT readable file is necessary. The program “sh3d2gmt” will do this translation:

```
sh3d2gmt sh3d2gmt.setup
```

sh3d2gmt.setup is a setup file for this program.

```
#setup file sh3d2gmt
0      jtype (0->struc.; 1->pert. from set; 2->pert. from av; 3->hit
count)
0                                     itype (0->regular structure; 1->slowness 1/v)
${root}_den.V                       input file with B-spline structure
0.  12.0                             x coordinates limits
0.  9.0                              y coordinates limits
0.2                                  step size (only horizontal)
2      ipath (0=own path; 1=all blocks; 2=other file path)
${root}.V                           name of other file. only if ipath = 2
6      number of layers
0.5  2.12      depth and slowness (velocity) of layers (# of layers)
1.5  2.70
2.5  3.11
3.5  3.26
4.5  3.33
5.5  3.42
1                                     ivf (0->fixed scale; 1->variable scale)
1 1 0.01 0.10 4 0.01 0.08 (# of scales, starting first scale, min,
max, ...)
```

F. Plot with GMT. The script file “gmt_slice” will plot horizontal slices as defined by sh3d2gmt program. Since “gmt_slice” can be used for different structures, the right root name for the file must be entered in this script file.

```
gmt_slice
```

Repeat inversion steps

As mentioned earlier the script file “split.csh” will create all setup files and will run all programs needed for the inversion. After the first running of “split.csh” the user should comment all the earlier steps (A to B) and repeat the last three steps (C to F) until satisfied.