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3-D Seismic Methods for Geothermal Reservoir Exploration and Assessment--Summary

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Introduction

A wide variety of seismic methods covering the spectrum from DC to kilohertz have been employed at one time or the other in geothermal environments. The reasons have varied from exploration for a heat source to attempting to find individual fractures producing hot fluids. For the purposes here we will assume that overall objective of seismic imaging is for siting wells for successful location of permeable pathways (often fracture permeability) that are controlling flow and transport in naturally fractured reservoirs. The application could be for exploration of new resources or for in-fill/step-out drilling in existing fields. In most geothermal environments the challenge has been to separate the “background” natural complexity and heterogeneity of the matrix from the fracture/fault heterogeneity controlling the fluid flow. Ideally one not only wants to find the fractures, but the fractures that are controlling the flow of the fluids. Evaluated in this work is current state-of-the-art surface (seismic reflection) and borehole seismic methods (Vertical Seismic Profiling (VSP), Crosswell and Single Well) to locate and quantify geothermal reservoir characteristics. The focus is on active methods; the assumption being that accuracy is needed for successful well siting. Passive methods are useful for exploration and detailed monitoring for in-fill drilling, but in general the passive methods lack the precision and accuracy for well siting in new or step out areas. In addition, MEQ activity is usually associated with production, after the field has been taken to a mature state, thus in most cases it is assumed that there is not enough MEQ activity in unproduced areas to accurately find the permeable pathways. The premise of this review is that there may new developments in theory and modeling, as well as in data acquisition and processing, which could make it possible to image the subsurface in much more detail than 15 years ago. New understanding of the effect of fractures on seismic wave propagation are now being applied to image fractures in gas and oil environments. It now may be appropriate to apply these methods, with modifications, to geothermal applications. It is assumed that to implement the appropriate methods an industry coupled program tightly linked to actual field cases, iterating between development and application will be pursued.

Purpose

The goal of this work is to evaluate the most promising methods and approaches that may be used for improved geothermal exploration and reservoir assessment. It is not a comprehensive review of all seismic methods used to date in geothermal environments. This work was motivated by a need to assess current and developing seismic technology that if applied in geothermal cases may greatly improve the chances for locating new geothermal resources and/or improve assessment of current ones.

Background

The application of seismic methods for geothermal applications has employed almost every aspect of the seismic spectrum, using both active and passive methods. Early studies focused on using ground noise and microearthquake (MEQ) data to infer fault and fluid locations. Liaw (1977) showed that ground noise was mainly measuring surface waves rather than any signals from geothermal resources. MEQ arrays are still used, mainly for assessing changes in reservoir production rather than for exploration. MEQ and other passive methods (tilt and ground deformation) may be promising as reconnaissance methods, but the main focus of this work will be on evaluating recent advancements in active imaging methods. This is because the active methods will most likely provide the necessary definition of fracture and fault characteristics for successful well siting in undeveloped or underdeveloped geothermal regions. Also, although MEQ methods have shown to be very effective in some cases, there are not always MEQs to monitor. Other passive methods such as teleseismic and regional P- and S-wave delay methods while useful, are more of initial reconnaissance and lack the resolution to find "the" fracture or permeable features controlling production.

Recent Advances in Surface Seismic Applicable to Geothermal Environments

Surface seismic reflection has been tried in a variety of geothermal environments (Majer, 1978, Denlinger and Kovach, 1981, Majer and McEvilly 1982, Daley et al 1988, Majer et al 1988, Okaya and Thompson 1985, Okaya, 1986, Okaya and Thompson and 1986, Larkin et al 1996, Severson, 1985, Feighner et al 1998, Feighner et al 1999, Honges et al 1998, Gritto et. al 2000,). All of these studies, except for Feighner et al and Gritto et al used conventional 2-D surface reflection layouts with P-wave sources. Honjes did, however, use long offsets to derive attenuation and lateral velocity information to map structure and control velocities for improved migration results. Except for the work by Honjes the studies were aimed at getting the best "reflection image" to define layering and/or fault offsets (it should be noted that Honjes also obtained an improved image). In most cases the 2-d seismic approach failed to identify targets which were successfully drilled, especially in the early work. It became quickly obvious that geothermal environments are not 2-D layered geologies, or that high heterogeneity in the form of fractures or matrix complexity complicated the seismic sections. Such effects as severe scattering and attenuation led to many "no record" sections. Thus leading to the general conclusion at the time that surface reflection was not as useful or routine as in the gas and oil sector.

In an attempt to overcome the problems of the 2-D surveys and the general complexities of many geothermal areas, a small (3 square mile) 3-D P-wave reflection survey was carried out at the Rye patch Nevada geothermal field. Off the shelf 3-D P-wave was tried to image faults and structure controlling the hot water (Feighner et al 1998). The objective of the work was not to extend or develop new technology, but to test existing technology in the geothermal environment. Prior to the work a multicomponent VSP was carried out at the site to determine if there was adequate subsurface impedance contrasts to result in reflection, derive velocity control for any subsequent surface work, and to determine if the known resource had any specific seismic signature (Feighner et al 1998, Feighner et al 1999). Shown in Figure 1 is the design of the survey with the shot and receiver points. Shown in Figure 2 is one of the many a cross sections of the final 3-D processed data. The data has been processed by three different groups for the “best” image. Shown on the left if Figure 2 is the processing performed by the contractor who collected the data (first cut at velocity picks), The figure on the far right is the same data processed by a commercial processing house to enhance the reflectors (heavy dip and coherency filtering) and the figure in the middle is the data after laborious hand statics correction, velocity picks and a variety of different imaging being performed. The geologic evidence from mapping and drilling suggest that there are dipping beds, thus then middle image is most likely closest to the reality. It is the judgement of the authors (Feighner et al) that although useful for confirmation of geologic structure, the imaging results were marginal for well siting. Although this work was used as information in designing a new program in drilling at the Rye patch area, it still did not by itself yield definitive targets as originally hoped.

Another use of surface seismic methods has been to determine anomalous geologic structure. Honjes (per comm) and Gritto et al (2000) have used the variation in the first arrival to derive a psudeo-tomographic image which maps the velocity variation. This has two uses, to refine the lateral velocity model such that better migration and imaging can be performed, and an indication of high and low velocity areas that may yield insight into anomalous rock properties. For example, many geothermal areas have extensive mineralization associated with hot water flow; this is often a high velocity area. Majer (1978) noticed this effect in the reflection data in several Basin and Range Hot Springs areas. Fractures may on the other hand slow down and attenuate the seismic waves, causing low velocity areas. There are several limitations to this approach, however. The first is the lack of resolution, and the second is that due to the long offsets required to derive deep enough data both resolution and depth are sometimes difficult to achieve.

Although the conventional reflection methods have not yielded the desired results there are approaches which may hold promise for application to geothermal environments. In general, imaging of fractures and heterogeneity may be categorized into two different approaches, the equivalent media approach and the discrete fracture approach. In the equivalent media approach the earth is treated as having a matrix which has aligned cracks or fractures that affect the P and S wave velocities depending on the angle at which the wave cross the aligned cracks and fractures. In the discrete fracture approach the individual fractures individually affect the propagation of the seismic wave and in theory, given the appropriate data, such features as fracture spacing, density and filling can be determined. This is because in this approach each fracture represents a significant mechanical anomaly, different from the matrix. These methods are now being developed in order to obtain maximum resolution of the features that will possibly affect the transport of fluids.

Characterization using 3-D surface seismic methods

There are many different combinations of surface seismic methods, using 2-D, 3-D, P-wave sources, and S-wave sources. The application will depend upon the need (depth, resolution, geology, etc) and resources.   It is clear that for many geothermal areas 2-D surface seismic has it limitations. Scattering, side reflections and lack of coherent reflectors make interpretation and processing of the data very difficult and sometimes useless, especially if one is trying to site a well for exploration purposes. The advantages of the 2-D methods are the relatively low cost of the methods compared to 3-D methods and the large volume of off-the-shelf data processing codes available. Recent advances in field systems, however, are reducing the cost difference between 2 and 3-D data acquisition and in some cases the cost per trace is much less than a 2-D system Therefore, unless it is known to be a 2-D system (layer cake) for fracture and fault definition the most logical approach will most likely be 3-D. As stated above we are assuming that the targets will be faults and fractures for most geothermal cases. In some cases like the Salton Trough in southern California, and possibly some Basin and Range valleys (most are fault controlled) the layering and matrix porosity may be such that the fracturing and faulting may play a secondary role. Even in these cases fracture properties play a significant role in the transport of fluids.

3-D P-Wave reflection Surveys (P to P and P to S)

The basic premise of this method is that it is mainly based in equivalent media theory, although recent work is attempting to incorporate discrete fracture theory (Lynn et al 1999a, 1999b, Macbeth, 1999, Tsvankin et al 1999) or other seismic attributes such as amplitude versus offset (AVO) or amplitude versus azimuth (AVA) (Verm and Hilterman, 1995, Sayers and Rickett, 1997, see also the reference list at the end, plus the special issue of Geophysics on P-wave anisotropy V64 No. 4)). The basic approach is to assume that the fractures are causing the P-wave anisotropy where the "fast" and high amplitude direction is parallel to the fractures and the "slow" and low amplitude direction is perpendicular to the fractures. It is assumed that the cracks are compliant and causing slowing and attenuation of the P-wave. If the cracks are steam or gas filled then they would be even more compliant, causing even more slowing and attenuation. Stress can close the cracks and if the cracks are water filled and not connected then these cracks would be less "visible" than if the cracks were connected, gas filled or under less stress. Therefore, it is necessary to have as many azimuths as possible at different offsets to compare the velocities and amplitudes for fracture definition. One can quickly see that many different combinations of cracks, filling, orientation and density can all combine to provide non-unique solutions. In addition, as the seismic wave travels down and back up it is affected every time it encounters a fracture system. If different layers have different orientations then the wave will be turned each time. If not processed carefully conversion of P to S, and just incorrect interpretation can cause difficulties. An important subset is the variation of the reflection coefficient as a function of angle from a layer containing cracks (Schoenberg et al, 1999). In this case the layer need not be penetrated but only reflected from. In any case, different offsets and ray path angles can eliminate some combinations, but there is always some ambiguity. It is also necessary to have different reflecting horizons to separate the fracturing in the different layers. Early work used mainly the coherent wave field, but more recent work is considering using the incoherent part of the wave field. The general idea of the method is to gather the different azimuths and offsets into "supergathers" averaging the different bins. This cuts down on computations but it can also average out effects which may be important. The assumption is made that if it is averaged out it is not that a productive of a fracture zone.

Figure 3 shows a large 3-D P-wave survey area in the San Juan basin of Colorado (several hundred square mile area, data courtesy of Conoco and Bulington Northern Resources). In the red box is a 20 square mile study area that was selected to apply a variety of advanced surface seismic, VSP and borehole methods in order to improve fracture definition for targeting in-fill gas wells. Shown in Figure 4 is a before and after image of an extensive reprocessing effort by Conoco in the 20 square mile study area to improve the reflectivity of the data. This was done by improved velocity picks, statics and careful editing. Shown in Figure 5 is a typical cross section from the 20-square mile data set, showing the different major reflectors. Figure 6 is a 3-d slice at depth which shows the difference in fault picks between the 2-D data set (there was extensive 2-D data in this area before the 3-D data were acquired) and the picks of faults after the 3-D data set was acquired. This is a rather striking example of how 3-D can improve resolution by virtue of properly migrating the data into correct space and time coordinates. 2-D cannot distinguish between side reflections and true reflections, whereas 3-D can separate out the proper reflection arrivals. One of the many different processing steps that can be done with these types of data is shown in Figure 7 and 8. Figure 7 shows the data gathered as a function of azimuth between zero offset and 15,000 feet offset. The procedure is to look at the variation in amplitude as a function of azimuth. The theory being that the faults and fractures will attenuate (and slow down) the P-wave when wave travels across the fracture. Figure 8 shows the azimuthal variation in the amplitude of a particular reflector (the Menefee in this case).

Another example of advanced processing and interpretation is shown in Figures 9, 10, and 11 This is also an amplitude analysis where frequency content is examined as a function of the entire 3-D volume. The approach is to plot the average frequency content in an interval and examine the changes over the area. Figure 9 shows this analysis between the interval of two reflectors, with the blue colors indicating higher frequency content and the reds showing lower frequency content. In the case shown in Figure 9 production data were also available to correlate with the surface seismic. There was a weak correlation with production, but not dramatic. Figures 10 and 11 show the data and the analysis in areas where two wells are proposed. The prediction is that in one case (LS-7c, Figure 10) this well will not be as productive as in the other case (LS-7b, Figure 11). The reasoning being that in the case of LS-7b the average frequency for SE trending rays inn the analysis interval is much less (20 hertz) thus inferring NE-SW trending fractures, whereas the average frequency for the other well site is about the same in both directions (26 hertz)

Current methods relying on this approach provide a gross definition of fracture properties such as P-wave anisotropy. While these methods are useful for gross fracture detection these do not define "THE" fracture or fracture sets which control the permeability. Past work has shown that even single fractures can control the flow field over very large volumes (Majer et al 1997). This work has also shown that, to identify and map these features, much higher resolution is needed than conventional surface techniques. Current practice is to mainly use reflection methods using P-wave solely from the surface (see attached reference list).

Beyond P-wave studies

In the earth we are dealing with complex structures. In geothermal reservoirs we have saturated and partially saturated rock which, because of its usually heterogeneous nature, is difficult to image. Because earth materials are elastic solids, wave propagation in rock is complicated by the presence of the fractures. However, this complication also presents an opportunity in that the highest resolution images can be constructed using the information contained in the shear and converted waves, along with the compressional waves. Imaging geothermal reservoirs will involve a wide range of scales and distances. The frequencies and wavelengths required will vary by orders of magnitude, depending upon the problem at hand. For example, to characterize within 10 meters a target at a depth of 3000 meters, an image resolution of centimeters is unnecessary. On the other hand, if delineation of flow processes is required around the wells, meter-scale or better resolution is needed. For most applications a three-dimensional picture of the elastic properties in the earth on a scale less than a meter near the surface to no more than a few tens of meters at depths of several kilometers would suffice. The greatest obstacle, however, is that once an image is obtained, what is the significance of the image. The challenge is to define the properties that control the flow properties and reservoir permeability, rather than just the geologic features. Given the proper conditions, i.e., enough measurement points and computing power, sufficient frequency content, etc., it is possible, in theory, to attain this resolution, but many practical obstacles now inhibit achieving this goal.

Image resolution of current techniques is limited by the amplitude and frequency content of the seismic waves, and by the level and complexity of the ambient and signal-generated noise fields. With surface sources, a heterogeneous surface weathered layer, often tens of meters thick, the high frequency content and the coherence of the signal that is input through the ground is severely limited. Vertical Seismic Profiling (VSP) solves this problem in part, by placing the receivers beneath the highly attenuating and variable surface layer, so that the signal is not required to pass through the surface layer twice, and also by recording the wave field with a vertical array in the borehole, so that up going and down going waves can be identified and separated.

An approach that does begin to address the fundamental imaging limitations is the use of multi-component data, i.e., one which incorporates properties of the secondary (S) and the converted waves (P to S, S to P). Potentially by incorporating amplitude and converted waves into the analysis, surface based methods could be very useful. This approach is particularly well suited for applications where the primary (P), secondary (S), and converted waves can be examined directly. In the recent years the use of S-waves has become more common, particularly in defining anisotropy and fracture content of rock. Fracture detection using P- and S-waves, surface reflection coupled with VSP methods, and is increasingly demonstrating that the full potential of seismic methods requires 3-component data. Three component data allow improved discrimination of the phases over single component recording. (Douma gives an excellent review of crack-induced anisotropy and its effect on seismic waves.)

In addition to the continuum properties approach on shear wave splitting, recent laboratory and theoretical work explains shear wave anisotropy in terms of mechanical properties of the fracture discontinuity itself, i.e., a surface of a finite stiffness affecting velocity as well as attenuation of a seismic wave of any wavelength. In the stiffness theory the lateral extent of a target fracture is still important to seismic resolution, but with sufficiently low fracture stiffness, the thickness of the fracture can be much less than the seismic wavelength and still have a detectable frequency-dependent effect on the seismic wave. A large amount of information exists in the properties of the secondary waves, which offers promise for substantial improvement in the resolution of seismic methods.

Tasks Towards Improved Geothermal Applications

The purpose of characterizing the behavior of a reservoir is to create a model that will be a useful tool for planning the development of the geothermal resource. In highly heterogeneous and fractured reservoirs, the characterization process is both difficult and critical to efficient recovery. In such systems, current practice does not provide sufficiently accurate predictions. Fundamentally there are two ways to create a model of a heterogeneous system. In the first approach, one takes measurements of the relevant physical parameters (permeability, porosity, etc.) and develops a technique to assign these values to areas of the reservoir where the parameters have not been measured. Forward calculations of the reservoir behavior can then be made. The advantage of this approach is that it is based on physical laws relating parameters to behavior. The disadvantage is that there may not be enough data available to adequately specify the model. In the second approach, the behavior of the reservoir during some testing phase is used to infer the physical properties throughout the field. This approach is what we call the "inverse" method. The advantage of the inverse approach is that the model focuses directly on the behavior of the system which is what we want to predict. The disadvantage is that the technique may be computationally intensive as it essentially requires performing forward calculations repeatedly, and non-unique.

These two approaches are not mutually exclusive; they can be combined in a variety of ways. This is one means to address the non-uniqueness of the problem. For example, one might design a statistical simulation technique to create a series of models, all of which honor the measured physical parameter data and stochastically generate data where there are no measurements. Then the stochastic generator can be used in an inverse process such that it simulates only those models which also match the observed behavior of the reservoir.

Improved seismic imaging technology can result from three different efforts: collecting higher resolution data, improved processing, and more accurate interpretation. Better data will come with improved sources which enhance bandwidth and amplitude of the signals. Multi-component data acquisition, 3-d surface seismic, random geophone acquisition, and the development of a downhole seismic sources for use in a crosshole environment are examples. Others include phased arrays of sources and/or multicomponent sources that can be focused in controlled directions. In terms of processing, the object of any processing sequence is an image representative of the variation of the elastic properties of the target. Processing in this context represents everything from data acquisition to image display. Ideally, this image would be a 3-D representation provided in real time in the field. An analogue lies in medical imaging, where with today's technology one can obtain an image of any part of the body almost instantly, providing valuable feedback to the operator, and allowing algorithms and processing sequences to be improved "on the fly." In the more complex seismic case, improvements can include enhanced timing resolution, reduction of the interference from scattered, diffracted, and attenuated waves through beam-forming or multi-spectral image display, and easy manipulation of the data.

Compared to the oil and gas industry there has not been an effort to integrate the best and most promising points of a broad program into a concentrated effort for improved imaging of geothermal reservoirs. The somewhat interdependent elements which collectively span the needs for evaluating imaging technology include: 1. Application and integration of theory of seismic wave propagation in complex media (i.e. discretely faulted and fractured media, extreme heterogeneity, layering, etc) 2. Improved modeling and interpretation, 3. Data acquisition, field methods and equipment, 4. Processing, i.e., three-dimensional background structure estimation, 5. Interactive and manipulative data presentation with in-field smart acquisition/processing/display systems, 6. Reservoir modeling of flow and transport in fractured media and 7.Final-field validation experiments in fractured gas reservoirs. For the purposes here we will group the above efforts into three broad categories: 1. Modeling and theory of seismic wave propagation in complex media, 2. Improved field measurements and 3. Interpretation processing and integration

In many different applications of seismic imaging the scientific community has addressed all of these elements individually. The success of the characterization effort in seismic imaging will rely to some extent on the effective integration of a concerted development efforts in each of these individual areas. The result we hope will be, on the whole, a substantial advance in subsurface elastic-wave seismic imaging which will increase the efficiency of exploration for and monitoring of geothermal resources.

Modeling and theory of seismic wave propagation in complex media

Present methodologies for modeling and extracting fracture properties from seismic data utilize effective media approximations in which fracture systems are represented by their zero-frequency anisotropic elastic moduli. Equivalent anisotropic properties may be useful for predicting fractured-related AVO and shear wave splitting when fractures are aligned, many wavelengths in planar extent, and closely-spaced relative to the seismic wavelength. However, the primary limitation of the equivalent fracture anisotropy approach is that it does not include wave phenomena such as diffractions off fracture tips, generation of fracture interface waves, fracture head waves, and fracture channel waves. These wave phenomena are potentially more sensitive to fracture properties and geometry. In addition, methods of analyses that utilize these waves may offer higher resolution methods for extracting fracture properties from surface, VSP, and crosswell seismic measurements.

Shown in Figure 12 is an example of how modeling can provide valuable information by showing what one would expect from a surface reflection source in a fractured geology. Figure 12 shows the wave field from a point source (left hand side of Figure 12) as it propagates through the model on the right. This model contains both large fractures (meant to model through going faults) and small fractures (simulate a fractured layer). This model is a 2-D model but capability now exists to model in 3-D. Prior to a few years ago this type of capability was not available. Improved theory and numerical modeling as well as parallel processing has now made it possible to model realistic fracture and fault heterogeneity for practical scale geothermal cases. The important thing to note about this particular result is that in addition to the reflections off of the layers, the faults and fractures cause just as large or larger effect. It was always assumed that heterogeneity or fracturing caused the "no record" sections seen in many geothermal cases where reflection was applied. Modeling now makes it possible to quantify the effect as well as design better field surveys.

To advance the effort as well as taylor for geothermal cases the following efforts need to be addressed:

1. Extend to elastic solution for variation of fracture properties
(a) Stiffness (include filling of fracture air, fluid, chemical interactions etc.)
(b) Dimensions vs. wavelength
(c) Multiple fracture interaction

2. The explanation of amplitude and frequency variation: i.e. frequency dependent (AVO-AVA) as a function of azimuth for:
(a) Single fracture (P&S)
(b) Multiple fracture (P&S)

As can be seen form the example in Figure 12 fractures cause many horizontally propagation waves which must be measured and used in improved imaging. This also should be a thrust in the field measurements in addition to the modeling.

Improved field measurements:

The examples give to this point have been from surface reflection studies. If wells are available an important component should be VSP (3-C and 9-C) to aid in the analysis of the surface data and in some cases replace the surface work. To demonstrate the utility of the methods refer to Figures 13 and 14. This is actual data from the same area as shown in the surface reflection examples (San Juan). Figure 13 is the P-wave data and Figure 14 is thew S-wave data. The survey was a limited offset study using three component geophones and three component sources (9-C). The data have been rotated and separated into P-and S-wave components. The data are still being processed, but it is clear that many different arrivals are in both the P-wave and S-wave data (indicating complexity and fracture content) (note that the time scales are different). Both upward and downward data are present as well as normal reflection from the different horizons. VSP also improves the resolution because of the higher frequency content (surface attenuation is reduced) as well as giving a direct validation of the reflector.

Higher resolution yet are single well methods (Majer et al 1997) which are now just being developed for the petroleum industry. In this technique a source and multiple receivers are placed in the same borehole. The source is activated as the string of source and receivers moves up the borehole. The resolution as well as depth penetration depends on the source and receiver spacing in addition to the source used. Figure 15 is a schematic of the method. This method relies on energy being reflected back from the formation into the borehole. It is being proposed for use in the oil industry for identifying the distance to layers above and below a horizontal well, imaging salt dome edges from wells outside of the salt dome, but the most important application that would apply to the geothermal case would be mapping fractures in addition to mapping fractures which are parallel or nearly parallel to the well which are drilling targets. A few permeable fractures can result in large production. If a well misses the fracture by a few 10's of metes the well can be a dry" hole. If one knew while drilling that a fracture was near by, or a leg could be drilled off of the well to make it much more productive then drilling could be much more cost effective. In essence the single well method is a deep penetration well log. Most well logs are for measuring properties at most a meter or two away from the well. Single well methods are being developed for applications from 10's to 100's of meters away from the well.

Last but not least are the crosswell methods. If several wells are available a source and a receiver can be put in the wells to image between the wells. Tomography as well as very high reflection imaging can be performed. Frequency content of up to several kilohertz can now be achieved, resulting in meter scale resolution. Several contractors are offering this service for both P-wave and S-wave imaging. As in the case of many borehole methods developed in the petroleum industry the limitation for geothermal applications in maximum temperature. The upper limit is now 200 C, with many tools only 125C. The holes can be cooled in some cases, and as the techniques are developed the speed of the work will increase, making it practical to cool the hole for the day required to run the survey. In the case of the single well, less than a day is required.

Therefore the potential field components are:

1. Surface studies
(a) Reflection seismic. AVO, AVA, vs. frequency content with P&S wave, 2-D and 3-D
(b) Refraction studies
(c) Tomographic (surface to surface)

2. VSP
(a) Multicompact sources to 3-components receivers in fractured media for same contribution as 1(a)

3. Borehole to borehole
(a) P&S wave sources for tomography
(b) Guided wave
(c) Continuity logging
(d) Reflection imaging using AVA, AVO, vs. frequency

4. Single well studies using both P&S wave for imaging fracture to properties
(a) CDP imaging
(b) Refraction tomography
(c) Guided wave

The anticipated sequence would be to perform initial VSP and single well experiments in an existing well that was sited using surface seismic. The data would be collected according to initial modeling of a range of anticipated fracture geometries. Single well would be performed in the same well to obtain higher resolution images. If possible (wells close enough) crosswell would be performed to obtain tomographic and higher resolution reflection to compare with surface seismic. Both P- and S-wave borehole sources would be used.

Interpretation, processing and integration

The objective of the interpretation and processing should be to derive images that are indicative of the fracture and fault characteristics, as well as define the lithology. Each method (surface seismic, VSP, crosswell, single well) has a different image produced at different scales. The hypothesis that higher resolution is necessary to define the important (permeable) fractures is based upon the different images produced. A second hypothesis is that there is information in. This activity should also include design of the surface seismic to be collected. Processing can be performed on all data types, surface, crosswell, VSP and single well. Any VSP and single data would will be processed for fracture anisotropy and fracture reflectivity. If crosswell data are acquired possible processing will be tomographic images as well as Vp/Vs images, S-fast/S-slow, P-wave reflectivity, S-wave reflectivity, guided waves, scattering effects. An example of imaging fractures is given in t 16. Given the model in Figure 12 can one obtain the reverse image if the data is available? This figure shows that it is possible to reverse image the structure and fractures given the data.

In terms of interpretation this links with the modeling but it will also be necessary to perform forward modeling to separate matrix effects, lithologic effects (layering) and heterogeneity (i.e. lenses, channel sands, etc.) from fracture effects. Until data are acquired and examined it is difficult to predict the exact sequence but some possible approaches are:

A. Simulation of Fractured Media
1. 3-D elastic pseudo-spectral code for fractured media
(a) Include domain decomposition
(b) Generalized geometry
(c) Generalized fracture fillings

2. Examine AVA, AVO, and fracture splitting

B. Propagation Code for Fractured Media
1. Kenneth method
2. Global matrix method

C. 3-D Boundary Element Codes for Finite Fractures or 3-D

D. 3-D Ray Tracing for Layered/Heterogenous Fractured Media With Laterally VaryingProperties

E. AVO and AVA Analysis for Fracture Identification

F. 3-D Tomography in Fractured Media (will come from Improved Ray Tracing in Fractured Media)

G Differential Frequency Shift Analysis (Harmonic Distortion Map for Mapping Fracture Properties)

Two additional methods have been proposed to tackle the problem of fracture estimation (1) random media theory to estimate the characteristic spacing between clusters of fractures, and (2) multi-component attributes such as converted-wave AVO to characterize the fractures and their fluid-content.

1 Estimation of Characteristic Fracture Spacing

Typically, individual fractures are too small to be detected with a seismic experiment. Instead of trying to detect the fractures individually, one can settle for a stochastic description of the fractures. A first stochastic parameter of interest is the fracture density. The next parameter of interest is the average spacing between clusters of fractures. The fractured material is described as a random media with a particular spatial correlation length which may be below the probing seismic wavelength.

Based on the Born approximation, a method has been developed (Virginia Tech) to estimate the spatial autocorrelation from seismic experiments. Although the method can estimate the true correlation function, a more robust approach is to use an inversion scheme to fit, e.g., a Gaussian auto-correlation function to the seismic data. These model functions contain parameters such as fracture density, orientation, and, for perpendicular directions, characteristic distances between sets of fractures.

So far, the scheme has been developed for scalar input-data only. However, an extension to multi-component data is straightforward. Furthermore, the method is independent of the geometry of the seismic experiment providing its input-data.

2 Multicomponent Wavefield Attributes

Multicomponent data is very expensive to collect. However, it is rarely used for more than estimating shear-wave anisotropy. Instead, one could use this data to better characterize the reservoir, i.e. the fractures. For example, the traditional P-wave AVO attributes can be extended to the converted waves. New attributes, e.g. ratios between frequency content of different phases, can be built. All these attributes need to be understood in terms of tight gas sands to be of interpretational value.

Summary

During the last ten to fifteen years modern seismic methods have been sparsely applied in geothermal areas. This has been partly due to the expense of such methods as full 3-D seismic, a lack of understanding of how to apply the methods, as well as a lack of “critical mass” in the application of the methods. It has become clear that over this time period, driven by oil and gas problems, many different techniques have been developed that if not directly applicable, could be modified and applied to geothermal environments with great benefit. The challenge at this point is not a lack of methods but which techniques should be applied and how much one needs to modify the current methods.

In terms of a path forward a logical sequence of activities would be as follows:

1. Sensitivity analysis of the different methods in typical geothermal areas

This activity would include taking a suite of geothermal geologic condition and modeling the effect of various different factors to determine which seismic methods would be the most appropriate. This would be using both discrete and equivalent media approaches. Modeled would be the elastic 3-D response at a variety of frequencies and geometries of data acquisition using P-wave, S-wave single component and multi-component recording. Capability now exits to perform these calculations with many of theoretical responses predicted. The result of this activity would be various designs of possible field acquisition geometries and costs as a function of information gained.

Data acquisition

A variety of methods (surface and borehole) now exist to apply. In most instances surface reflection would be the choice where no boreholes are available. The most likely in exploration and are early drilling

1. Surface studies
(a) Reflection seismic. AVO, AVA, vs. frequency content with P&S wave, 2-D and 3-D
(b) Tomographic (surface to surface)

2. VSP
(a) Multicompact sources to 3-components receivers in complex media for same contribution as 1(a)

The Borehole to borehole and single well would be included in later phases of development and in-fill drilling i.e.

(a) P&S wave sources for tomography
(b) Guided wave
(c) Continuity logging
(d) Reflection imaging using AVA, AVO, vs. frequency

Single well studies using both P&S wave for imaging fracture to properties
(a) CDP imaging
(b) Refraction tomography
(c) Guided wave

Processing, interpretation and integration

The final goal of the seismic work is not to provide images of the subsurface, that is an intermediate goal. The objective is to integrate the work such that an accurate estimation of the flow and transport properties can be derived in order site wells and optimize production This will require an integrated effort of a variety of seismic methods over a variety of scales. A wide range of different analysis approaches are available, but the focus should be on methods that discriminate between matrix heterogeneity and fracture heterogeneity. As was observed in the oil and gas industry, one can now apply single component and multi-component measurements to determine anisotropy and infer fracture directions. What is needed is further quantification of the subsurface properties, for example while fracture direction is useful, one wants to know the fracture fillings, (gas or water) connectivity, and density.

As stated above the different elements include

1. Application and integration of theory of seismic wave propagation in complex media (i.e. discretely faulted and fractured media, extreme heterogeneity, layering, etc) 2. Improved modeling and interpretation, 3. Data acquisition, field methods and equipment, 4. Processing, i.e., three-dimensional background structure estimation, 5. Interactive and manipulative data presentation with in-field smart acquisition/processing/display systems, 6. Reservoir modeling of flow and transport in fractured media and 7.Final-field validation experiments in fractured gas reservoirs.

This may seem like a tall order but with an integrated effort much progress can be made.

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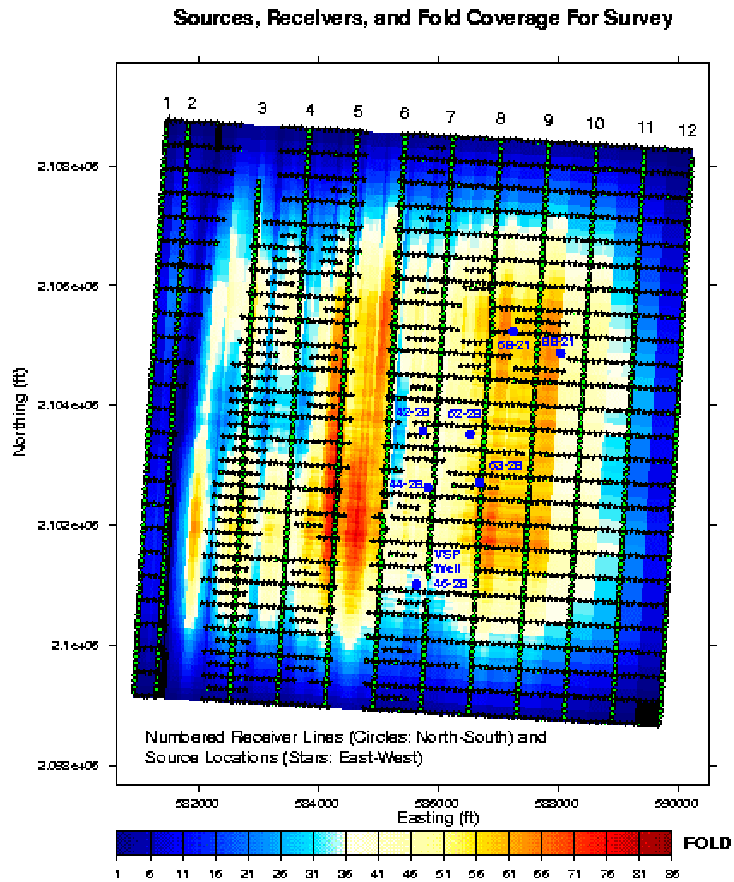

Figure 1 Source and receiver pattern for Rye Patch Survey

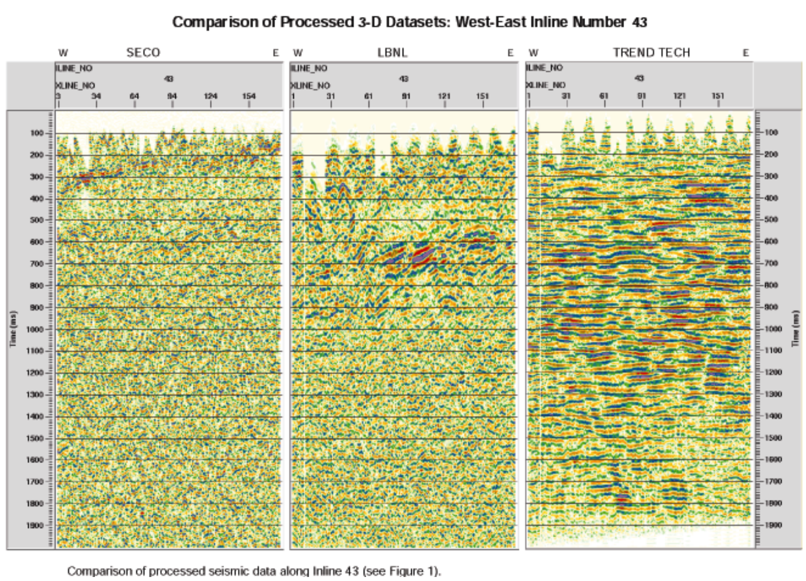

Figure 2 Data from 3-D Rye Patch survey processed in three different manners, velocity analysis by acquisition contractor, LBNL detailed processing by LBNL, and “standard” processing by commercial processing firm.

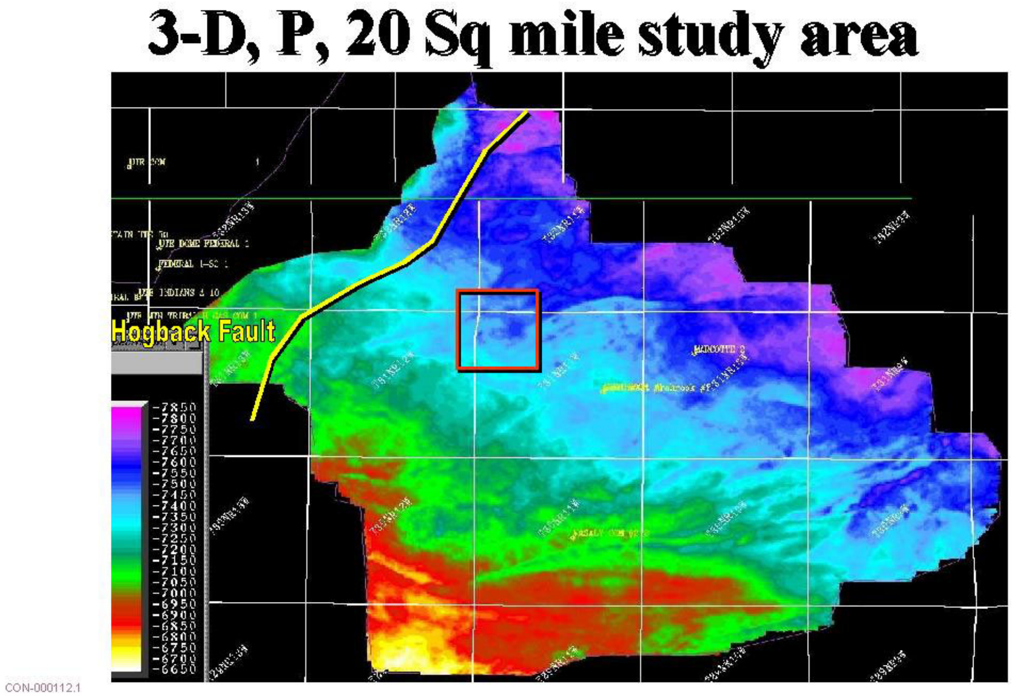

Figure 3 San Juan 3-D survey and 20 square mile study area (red box).

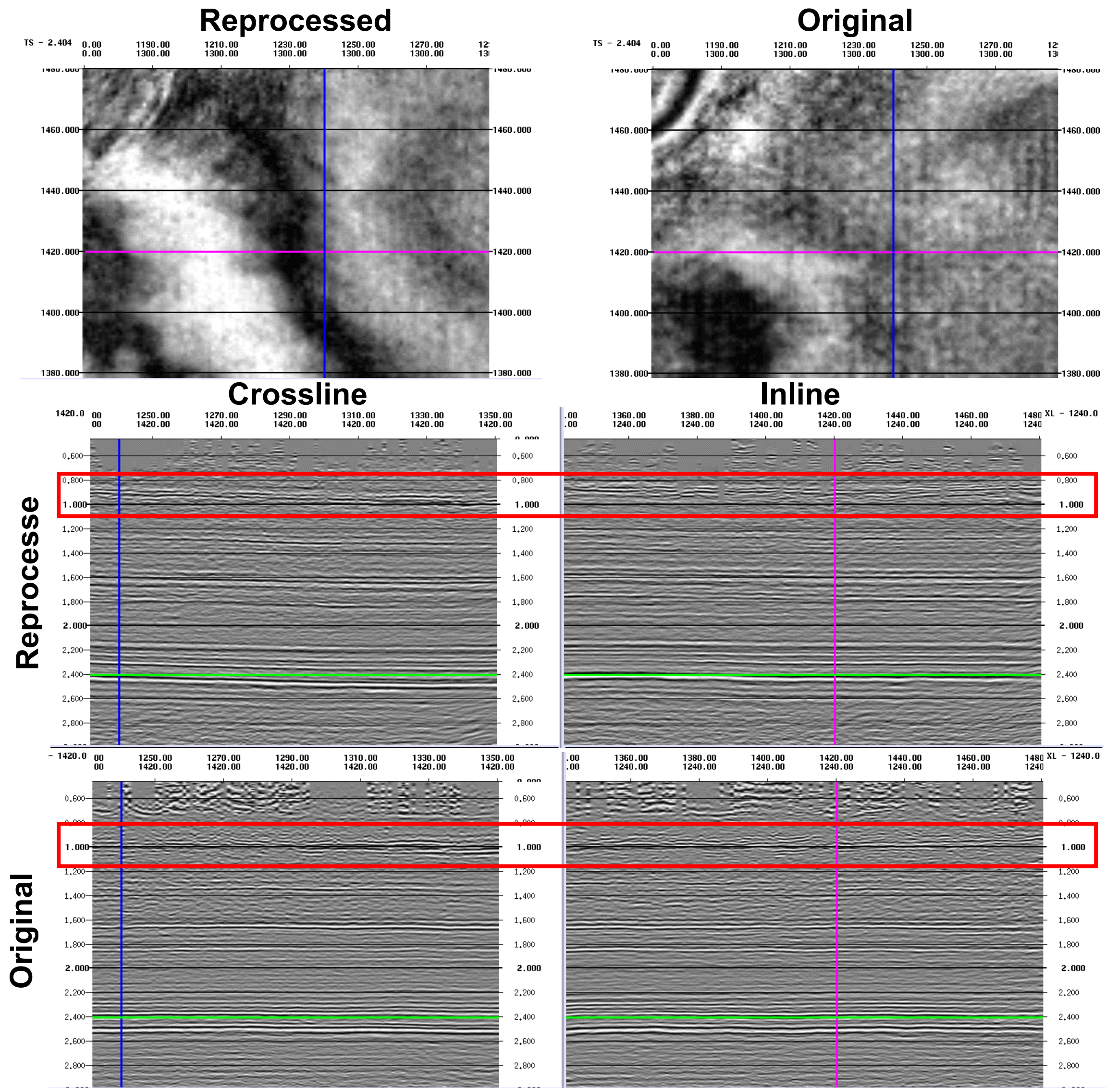

Figure 4 Before and after reprocessing of data in San Juan.

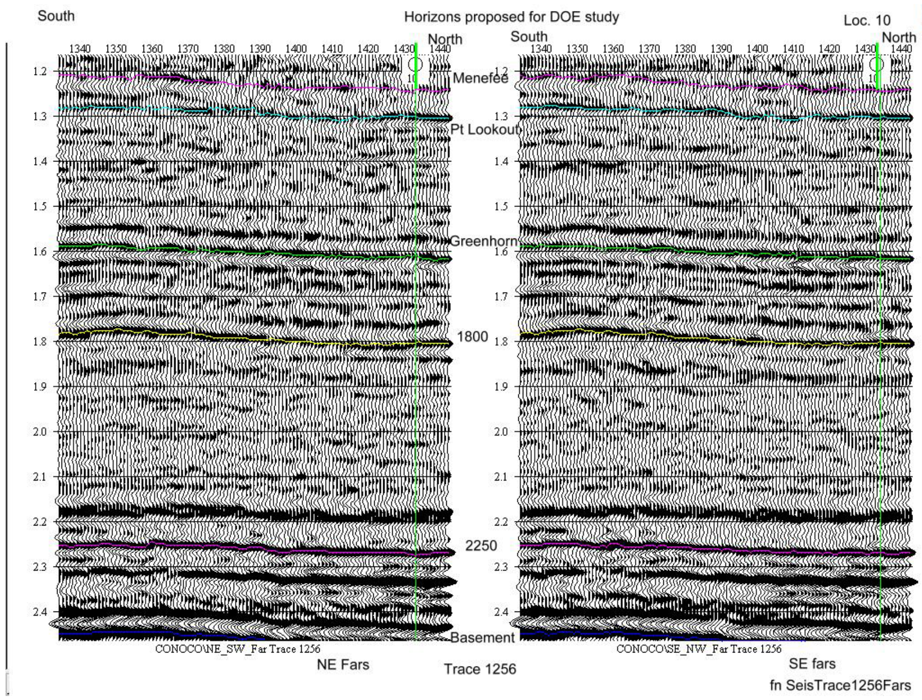

Figure 5 Example of seismic data and horizons from San Juan study.

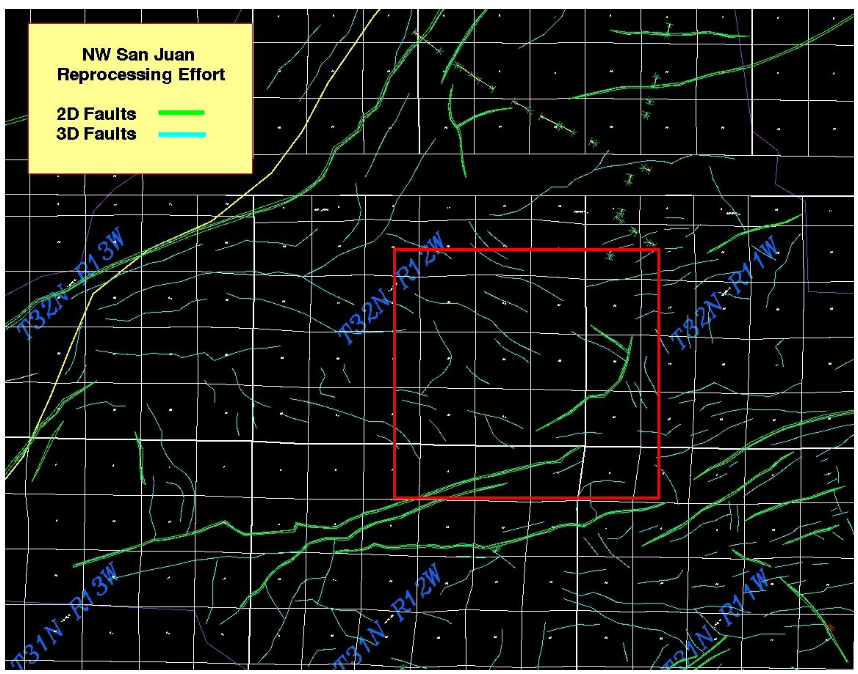

Figure 6 Faults picked from 2-D data (green) and 3-D data (blue).

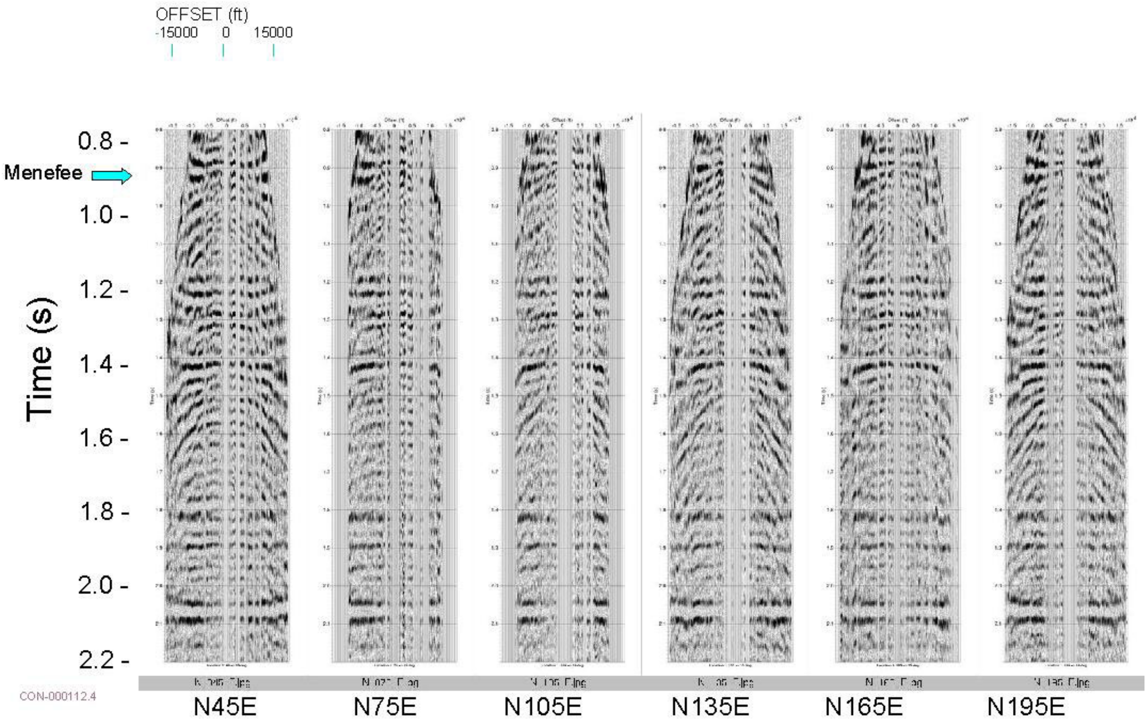

Figure 7 Data used in Azimuth analyses of Amplitude and velocity variation on Figure 8.

Picked time and Amplitude - Azimuth and Offset

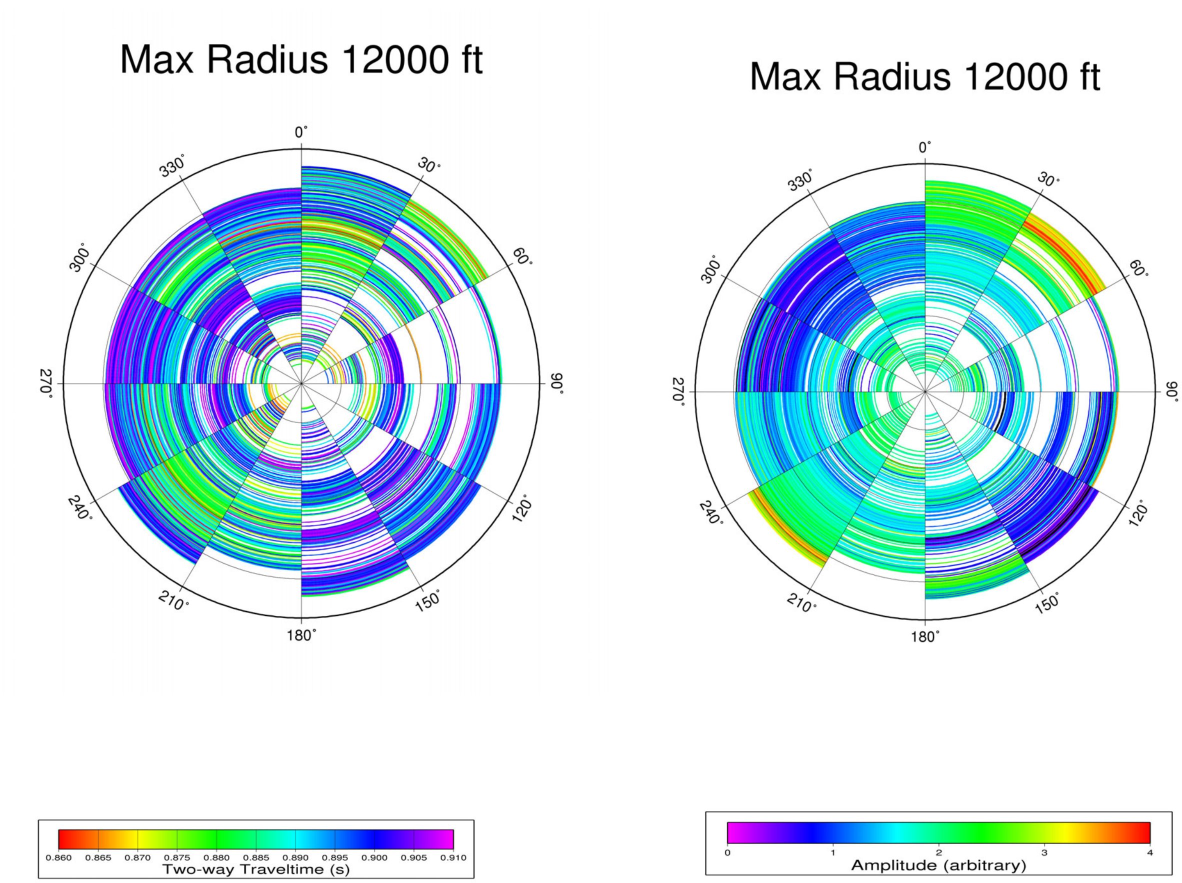

Figure 8 Examples of Amplitude-Azimuth anisotropy analysis and Velocity-Azimuth.

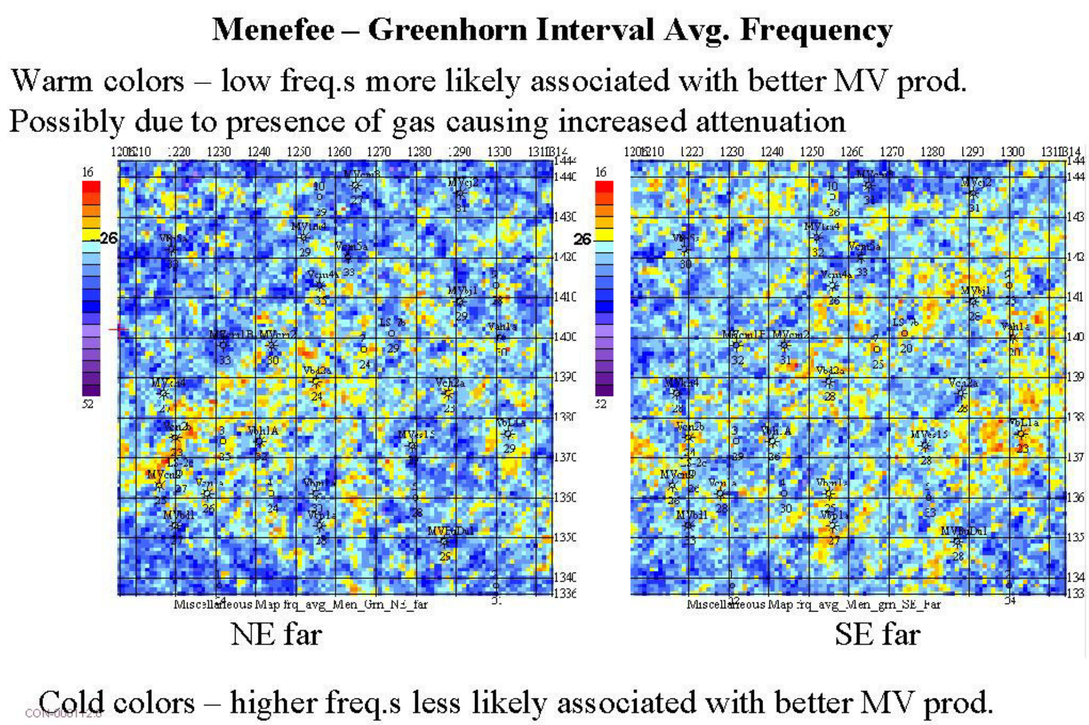

Figure 9 Frequency analysis for selected interval in San Juan study.

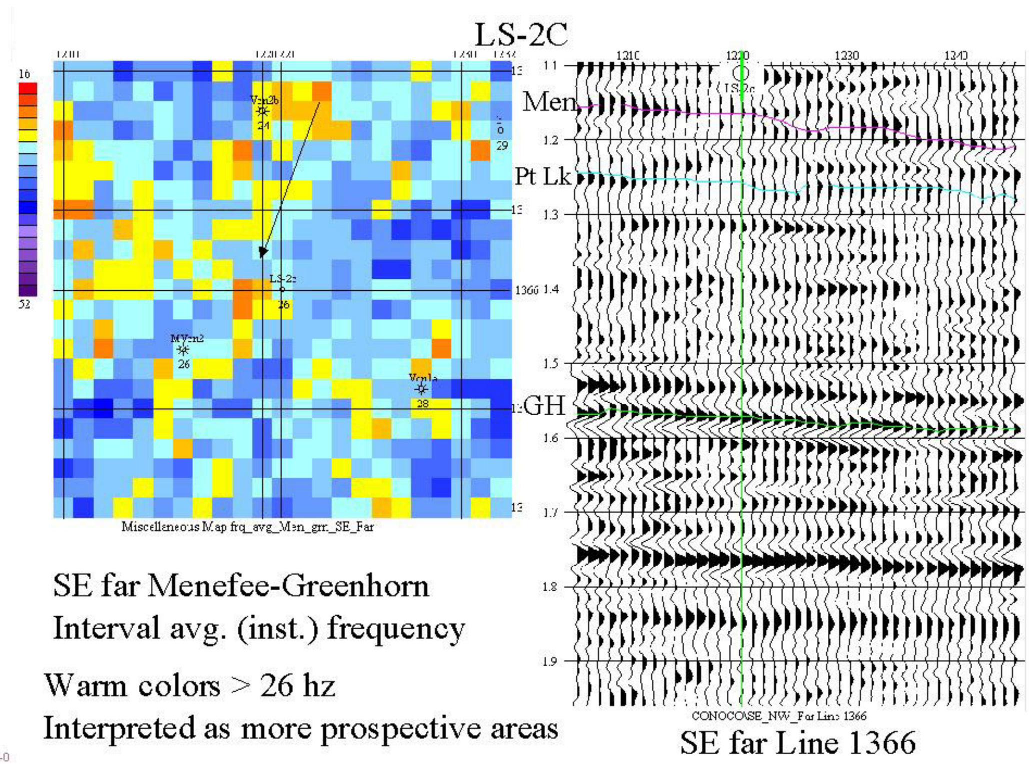

Figure 10 Detail of frequency analysis in Figure 9 for data at potential well site LS-2C.

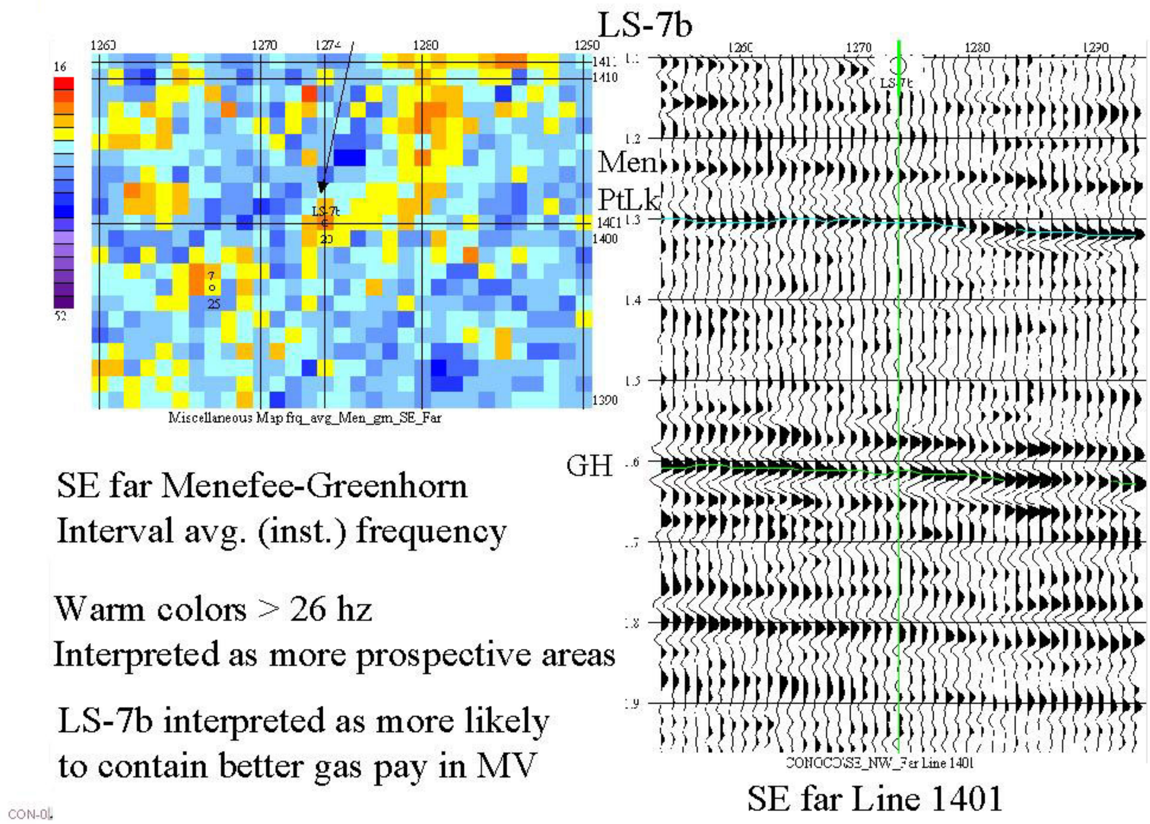

Figure 11 Detail of frequency analysis in Figure 9 for data at potential well site LS-7b.

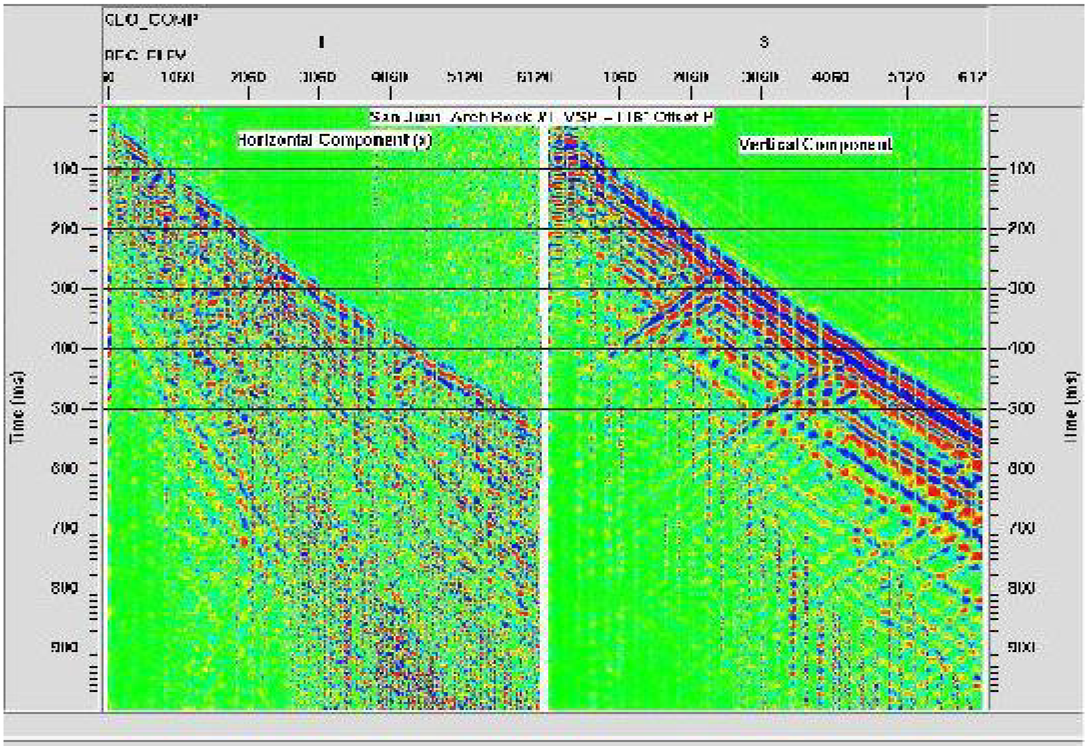

Figure 12 Portion of 9-C VSP data, P-wave.

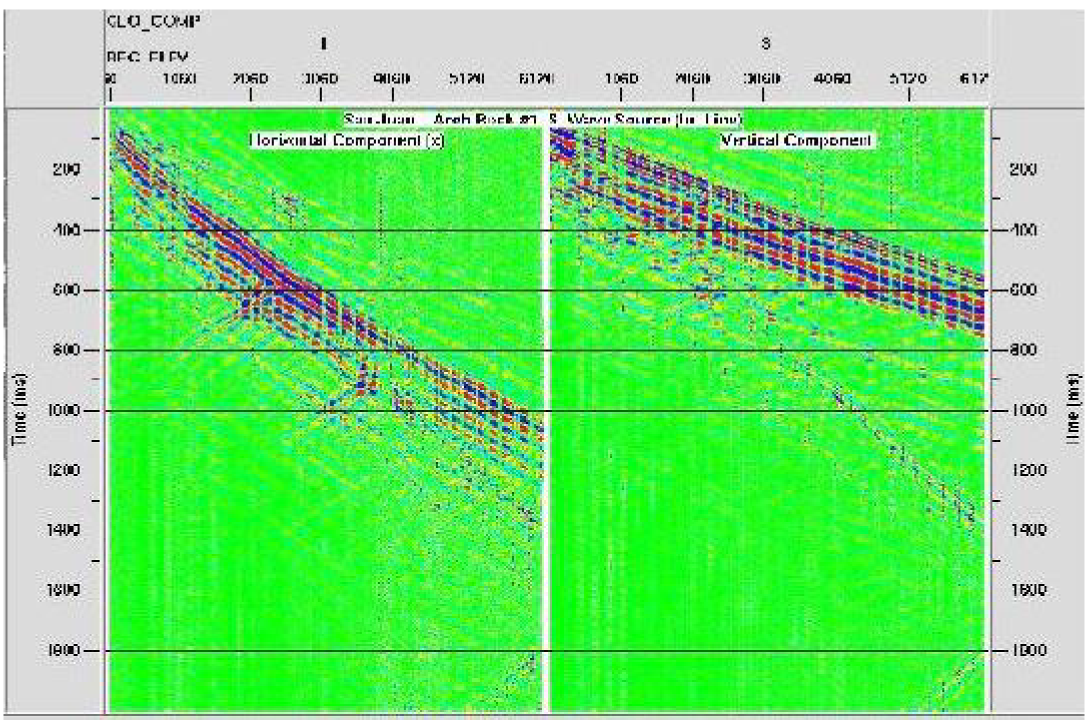

Figure 13 Portion of 9-C VSP data, S-wave.

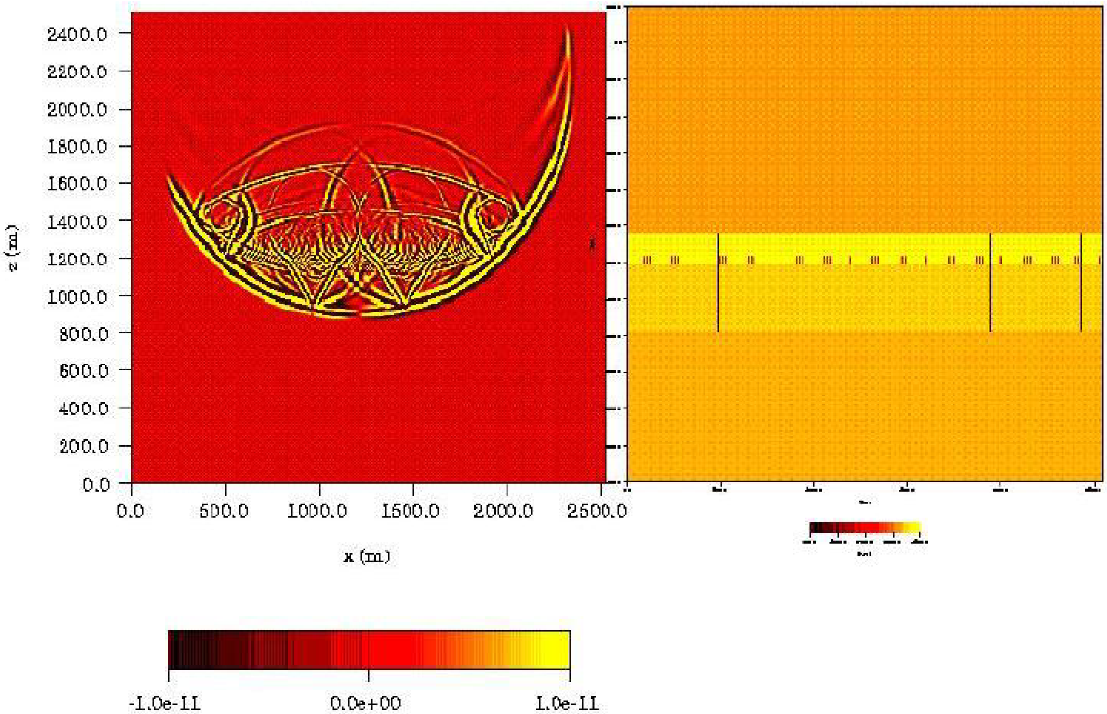

Figure 14 Model results from finite element discrete fracture approach and fracture model. Model is large fracture (faults) and fracture layer.

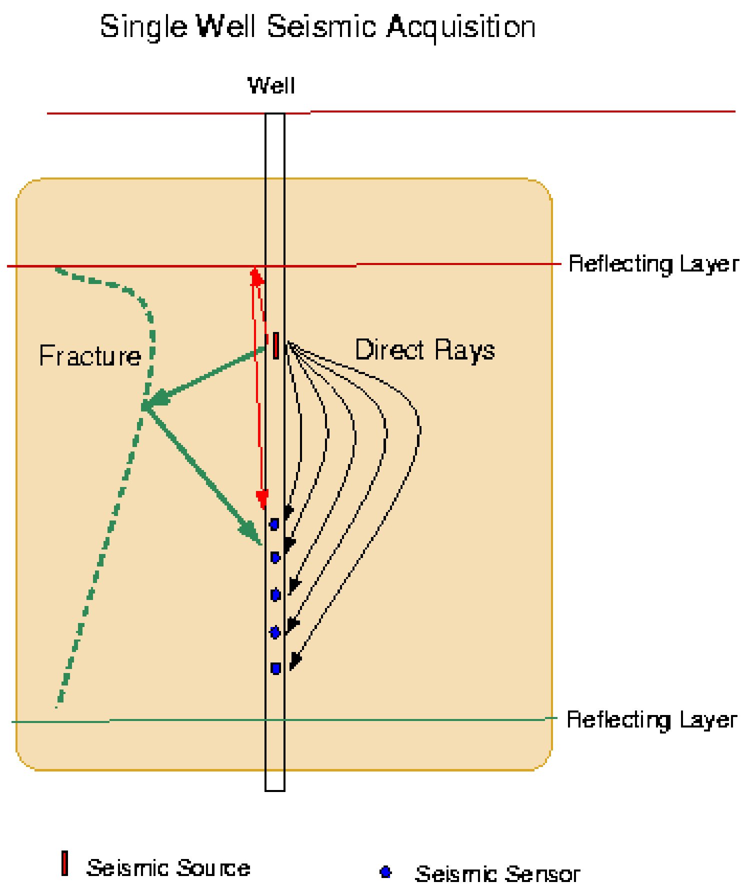

Figure 15 Concept of single well seismic source and receiving on same hole for time 3-D CDP imaging.

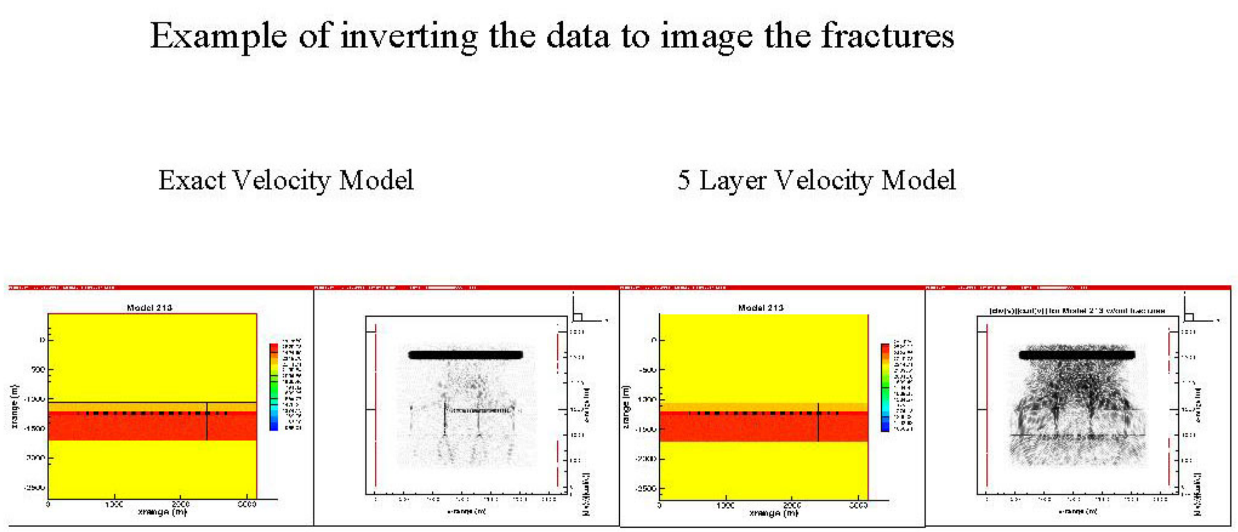

Figure 16 Imaging of fractures using data generated by model in Figure 14.