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THE APPLICATION OF VERTICAL SEISMIC PROFILING AND CROSS-HOLE TOMOGRAPHIC IMAGING FOR FRACTURE CHARACTERIZATION AT YUCCA MOUNTAIN

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ABSTRACT

In order to obtain the necessary characterization for the storage of nuclear waste, much higher resolution of the features likely to affect the transport of radionuclides will be required than is normally achieved in conventional surface seismic reflection used in the exploration and characterization of petroleum and geothermal resources. At the Department of Energy's (DOE) Yucca Mountain site in Nevada fractures will play an important role in the transport of water. Because fractures represent a significant mechanical anomaly seismic methods using are being investigated as a means to image and characterize the subsurface. Because of inherent limitations in applying the seismic methods solely from the surface, state-of-the-art borehole methods are being investigated to provide high resolution definition within the repository block. Therefore, Vertical Seismic Profiling (VSP) and cross-hole methods are being developed to obtain maximum resolution of the features that will possibly affect the transport of fluids. Presented here will be the methods being developed, the strategy being pursued, and the rational for using VSP and crosshole methods at Yucca Mountain. The approach is intended to be an integrated method involving improvements in data acquisition, processing, and interpretation as well as improvements in the fundamental understanding of seismic wave propagation in fractured rock. The scales of application range from a few meters to over a kilometer.

INTRODUCTION - The Need for Better Subsurface Imaging:

The scales of application at Yucca Mountain for the seismic imaging techniques may range from a few meters in the case of detailed property mapping around canisters to several kilometers in mapping subsurface properties beneath the repository. In the standards set out by the EPA and NRC (USDOE, 1988), it is obvious that the low level of uncertainty for waste containment will rely on high-resolution characterization of the features that control the ground water flow, such as porosity, water content, and fractures.[1] In addition, monitoring capability will be required during the entire repository lifetime.

Outstanding Difficulties:

In the earth we are dealing with complex structures. At Yucca Mountain we have partially saturated volcanic 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 shear wave, which does not exist in fluids. However, this complication also presents an opportunity in that the highest resolution images must be constructed using the information contained in the shear and converted waves, along with the compressional waves.

Imaging Yucca Mountain will involve a wide range of scales and distances. The frequencies and wavelengths required will vary 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 canister regions, 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. 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. The main objective of the subject work is to extend the resolution of the seismic imaging methods proposed for application, i.e., VSP and crosshole techniques in order to resolve in as much detail the structural characteristics that may affect the transport of fluids within the repository block.

Present Capabilities:

The greatest effort by far in imaging the solid earth using seismic techniques has been exerted by the petroleum industry. Billions of dollars have been spent in developing and applying the surface seismic reflection profiling method and the more recently developed techniques for Vertical Seismic Profiling. The image resolution of these 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, the heterogeneous surface weathered layer, often tens of meters thick, severely limits the high frequency content and the coherence of the signal that is input through the ground. 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 wavefield with a vertical array in the borehole, so that upgoing and downgoing waves can be identified and separated. Another limitation of the surface-based techniques is the inability to surround the target with sources and receivers, as is done in the case of medical tomographic imaging. Given these fundamental problems, enhanced resolution in surface reflection work has come mainly from improved signal processing techniques and data acquisition methods. This is image enhancement, and it does not address fundamental impediments to finer scale resolution.

An approach that does address the fundamental imaging limitations is one which incorporates properties of the secondary (S) and the converted waves (P to S, S to P) that are generated in the earth. This approach is particularly well suited for VSP 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 common, particularly in defining anisotropy and fracture content of rock. Fracture detection using P- and S-waves with VSP methods is increasingly demonstrating that the full potential of VSP requires 3-component data.[2,3] 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.[4] Crampin also stresses the importance of 3-component data in VSP work.[5,6,7,8,9]

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.[10,11,12] 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. This approach, if successful, is particularly well suited to the Yucca Mountain case because it is exactly this phenomenon that exists at Yucca Mountain, i.e., discrete discontinuities, fractures, in a matrix. At scales of VSP application the main features that will be detected are major discrete features such as large joints and fracture systems.

Beyond VSP lies the emerging crosshole technique. It offers the most promising approach for increasing resolution significantly. The advantages gained by placing the source in a borehole are the additional spatial coverage obtained for image construction as well as the elimination of the attenuating surface layer from the source receiver path. Figure 1 illustrates the potential application of VSP at Yucca Mountain. Shown in Figure 2 is the assumed application scale within the repository for cross hole methods. However, either method can be used at many scales, assuming the availability of boreholes. Figure 2 shows planned cross-hole investigations for detailed characterization between the underground excavations.

POTENTIAL MEANS OF RESOLUTION ENHANCEMENT

Improved seismic imaging technology can result from three different efforts; collecting better data, better processing, and better interpretation. Better data will come with improved sources which enhance bandwidth and amplitude of the signals. The development of a downhole seismic shear wave source for use in a crosshole environment is an example. Others include phased arrays of sources and/or multicomponent sources that can be focused in controlled directions.

The object of any processing sequence is an image representative 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 beamforming or multi-spectral image display, and easy manipulation of the data. Improved algorithms are needed for fast 3-D interactive waveform modeling and efficient displays. A major obstacle to rapid advancement of seismic imaging is the lack of real-time processing and manipulation in the field of borehole tomographic imaging data.

Discussed here will be several approachs to imaging earth structure by using tomographic methods, which we believe to represent the most likely means of achieving the significant improvement in resolution called for in the characterization of Yucca Mountain. A means to "tune"

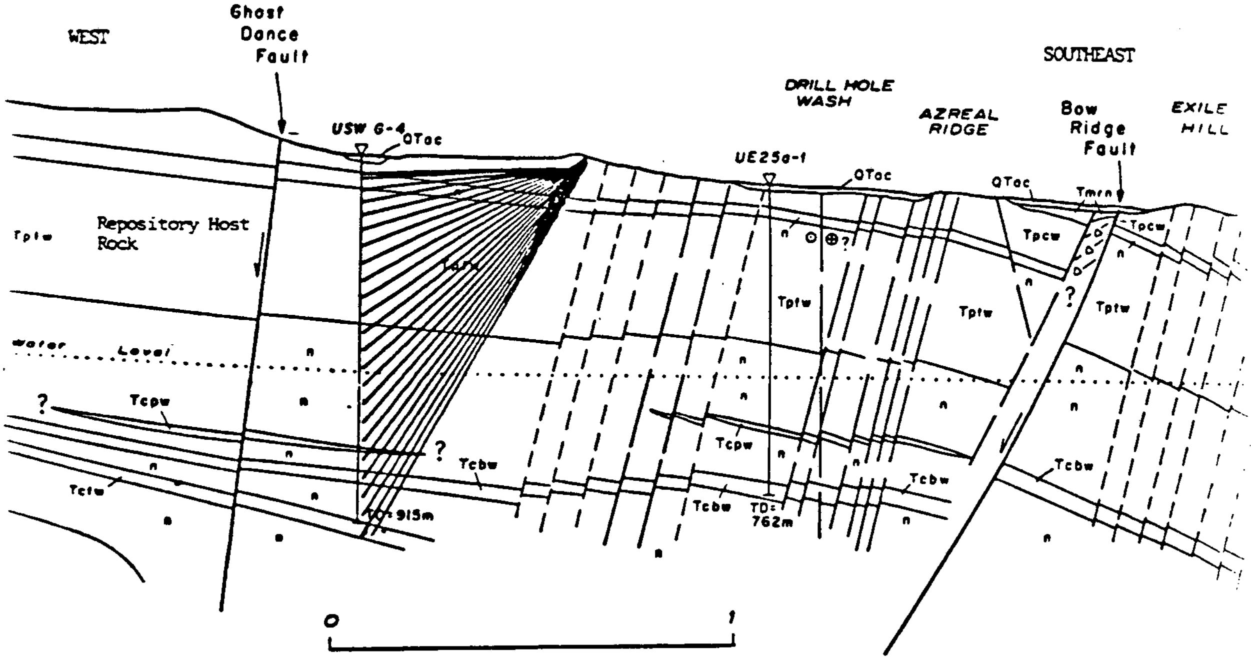

Figure 1. The anticipated geometry and scale of application for VSP work at Yucca Mountain, cross section is from Scott and Bonk.[33]

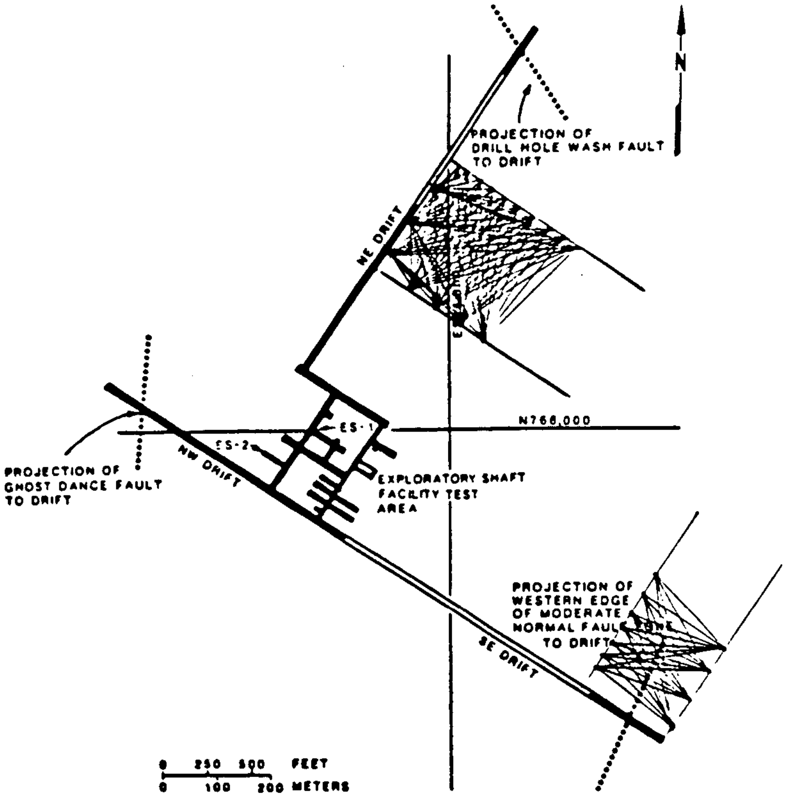

Figure 2. An example of the anticipated application for cross hole seismic work at the repository horizon.

the image interactively in the field through customized processing and data acquisition may be necessary to approach an order of magnitude increment improvement in resolution over the conventional surface reflection and VSP methods in a reasonable time. This capability allows hand-on processing and technique development. It will not be as simple as in the medical or marine applications, given the heterogeneity and complexity of the earth at a wide range of scales. However, rapid advance will come only through a balanced program of in-field application and processing of the resulting data. The greatest present need is to acquire the data in order to assess the proper approach and application of seismic imaging methods.

Tomographic Imaging:

With the advancement of medical transmission tomography applications spread quickly to geophysics, spawning work in seismic ray transmission tomography.[13,14,15] Diffraction tomography in acoustic media and electromagnetic ray tomography in a electrically resistive media have followed.[16,17,18] Elastic and electromagnetic tomography are two primary areas of research in the earth sciences as well as in the medical sciences. Experience in VSP, microearthquake studies and tomographic surveys has led us to conclude that a significant advance in imaging technology must combine new data manipulation capabilities and tomographic imaging methods, using new borehole sources and receivers that are being developed for the toxic waste and resource exploration applications.[19,20,3,21,22,23] Diffraction and transmission ray tomography for seismic applications each have distinct advantages, and we believe the optimal approach in a particular application will always be a combined use of these techniques. This is an important point to stress, usually only one or the other approach is used, and rarely both done together.

Transmission Ray Tomography:

Transmission tomography uses only the travel times and amplitudes of P- and S-waves, which are inverted for medium slowness and attenuation. The usual method of inversion is some form of iterative algebraic reconstruction algorithm, based on a back-projection method. The section of earth to be imaged is divided into many pixels of constant physical properties. As the waves pass through each of the pixels, amplitudes and velocities are dependent on the pixel properties and we assume that the contribution of each pixel can be deduced by back-projecting the rays. It follows that a data set consisting of many rays crossing at all angles may be back-projected to yield an estimate of the distribution of velocities in each pixel needed to produce the observed travel times. The attenuation properties of each pixel may be determined in a similar manner, using the amplitude information.

In general, the method of processing is based on the relation between propagation velocity and the total travel time, or between attenuation characteristics and received amplitude. For a particular ray path in the u-v plane, the relation for total travel time is

$$t_k = \int_{R_k} \frac{ds}{\phi(u,v)} \tag{1}$$

where $\phi(u,v)$ is the velocity of the medium, s is the ray segment, and the integration is along a particular ray path R_k. The amplitude A_k at the receiver is related to the attenuation field, $\alpha(u,v)$ through the equation

$$A_k = A_0 \exp(-\int_{R_k} \alpha(u,v)ds) \tag{2}$$

where $\alpha(u,v) = \dfrac{\pi f}{\phi(u,v)Q}$ and Q is dependent on (u,v). A_k has been corrected for the radiation pattern, geometric spreading, and instrument response. $\alpha(u,v)$, as determined from this model, will be an effect of apparent attenuation, consisting of intrinsic dissipation described in equation (2) plus elastic scattering. The projection is then defined as

$$P_k = \ln\frac{A_k}{A_0} = -\int_{R_k} \alpha(u,v)ds \tag{3}$$

where A_0 is the source amplitude.

The general form of the integral equation for time or amplitude is written:

$$y_k = \int_{R_k} x(u,v)ds \tag{4}$$

with y_k, $k = 1,2, \cdots, N$ representing the measured travel time or amplitude for N paths, and x representing the slowness or attenuation operator. After discretizing the field, the line integral becomes a finite sum and the problem may be described by a set of linear equations

$$y_k = \sum_{i=1}^{I} \Delta a_{ki} x_i \qquad k = 1,2, \cdots, N \tag{5}$$

where Δa_{ki} is the length of ray k which penetrates pixel i, I is the total number of pixels, and x_i is the property of pixel i. This is a classical matrix problem which may in principle be inverted using a variety of methods. However, the size and sparseness of the matrix, the conditioning of the problem, and the inconsistencies of the equations due to measurement errors usually render most classical methods of inversion ineffective. Algebraic reconstruction techniques (ART), developed for this problem work well only in media that have small contrasts. These techniques are iterative in nature, where one equation, i.e., one ray, is analyzed at a time and the pixel values are continually updated. A simple example of an ART algorithm is the basic back-projection

$$x_i^{q+1} = x_i^q + \frac{\Delta y_k^q}{L_k} \qquad k = 1,2,\cdots,N \tag{6}$$

where Δy_k^q is the residual travel time (observed minus the calculated value) for the q^{th} iteration and L_k is the length of ray k.

ART algorithms give exact solutions if the ray coverage is adequate, the ray lengths consistent, the ray paths determined exactly, and with no measurement errors. This is never the case. Ray coverage is usually 3-sided at best, with the bounds determined by the rectangular area defined by the boreholes and the surface, and with the surface measurements often of much poorer quality than borehole data. This geometry results in incomplete coverage and ray lengths. True ray paths are curved, and they may be determined iteratively along with the pixel values, but a straight ray path is usually assumed. Measurement errors remain a source of inversion uncertainty. Increased resolution will come primarily through the elimination of inversion artifacts such as smearing, and from the use of more realistic 3-D ray paths. Smearing is caused by a number of problems, including inadequate angular coverage and sampling, assuming straight rays (or any improper ray paths), and travel time and station location errors.

For the past several years, as part of the DOE Nuclear Waste Program, we have been performing tomographic imaging at controlled small-scale field sites. An example of this work is shown in Figure 3. The images shown are results of four-sided transmission tomography in a highly anisotropic fractured rock. The imaging was carried out with P- and S-wave sources and 3-component receivers. The data were collected with a PC-based acquisition system. The figure illustrates the results of improvements in the source and in the processing systems. Figure 3b is a combined amplitude-velocity tomograph of the 10-meter by 21-meter region in Figure 3a. Figure 3c is the P-wave velocity tomogram of the same region. This figure shows the importance of interpreting the full wave form data as well as the first arrival data. The dark regions in 3b indicate the highly attenuating, low velocity regions, where the dark regions in Figure 3c show the low velocity regions only. Such complicating effects as anisotropy, curved rays, and algorithm stability are all being addressed with this work.

Diffraction Tomography:

To date the applications of full-waveform diffraction tomography are not as extensive as for ray tomography, but the potential developments may prove as valuable as ray tomography. In diffraction tomography less spatial coverage of sources and receivers is needed to obtain resolution equivalent to ray tomography, because reflected and scattered waves are used in forming the image.

To demonstrate the basic principles of full-waveform diffraction tomography, consider a simple two-dimensional case, as in Figure 3a. The background medium is assumed to be a homogeneous acoustic medium, with two-dimensional velocity inhomogeneities (diffracters) embedded in it. An acoustic line pressure source, perpendicular to the page in Figure 3a, is harmonic in time and is operated at a fixed audio frequency. Under these conditions the acoustic field satisfies the scalar wave equation. A relation between the secondary acoustic field and the velocity to be imaged can be deduced from the integral formulation

$$U^s(\mathbf{r}_r,\mathbf{r}_s) = -\int k_0^2\, O(\mathbf{r})\, U(\mathbf{r},\mathbf{r}_s)\, G(\mathbf{r}_r,\mathbf{r})\, dxdz\ , \tag{7}$$

where $U^s(\mathbf{r}_r,\mathbf{r}_s)$ is the secondary acoustic field at $\mathbf{r}_r$ due to a source at $\mathbf{r}_s$; $U(\mathbf{r},\mathbf{r}_s)$ is the total acoustic field; and $G(\mathbf{r}_r,\mathbf{r})$ is the two-dimensional Green's function. The object function $O(\mathbf{r})$ is defined as $1-k^2(\mathbf{r})/k_0^2$. Here, $k(\mathbf{r}) = \omega/c(\mathbf{r})$ and $k_0 = \omega/c_0$ in the acoustic case, with ω denoting angular frequency, and $c(\mathbf{r})$ velocity. c_0 is the background velocity, and k_0 is the background wavenumber, which are used as reference.

To simplify this nonlinear equation, a weak-scattering Born approximation, $U(\mathbf{r},\mathbf{r}_s) = G(\mathbf{r},\mathbf{r}_s)$, is employed to linearize equation (7).

$$U^s(\mathbf{r}_r,\mathbf{r}_s) = -\int k_0^2\, O(\mathbf{r})\, G(\mathbf{r},\mathbf{r}_s)\, G(\mathbf{r}_r,\mathbf{r})\, dxdz\ . \tag{8}$$

Taking Fourier transforms along the source and receiver lines respectively for the geometry shown in Figure 3a, equation (8) becomes

$$V^s(k_r,k_s) = \int O(\mathbf{r}) \exp[-i(\gamma_s-\gamma_r)x - i(k_s+k_r)z]\, dxdz, \tag{9}$$

where V^s is the filtered secondary responses in wavenumber domain. k_s and k_r are the Fourier domain wavenumbers along source and receiver lines; and

$$\gamma_s^2 = k_0^2 - k_s^2; \qquad \gamma_r^2 = k_0^2 - k_r^2. \tag{10}$$

Where we use the real wavenumber k_0^2. Note that in the seismic application, γ_s and γ_r are real numbers as long as k_0 is real and k_s and k_r are smaller than k_0. Letting

$$\gamma_s - \gamma_r = k_x\ ; \qquad k_s + k_r = k_z, \tag{11}$$

equation (9) shows that the object function $O(\mathbf{r})$ can be derived by performing a double inverse Fourier transform on both sides of equation (9).

Obtaining the object function is the solution of the inverse problem, and is our ultimate aim. It is also important to note that the model medium constructed for this

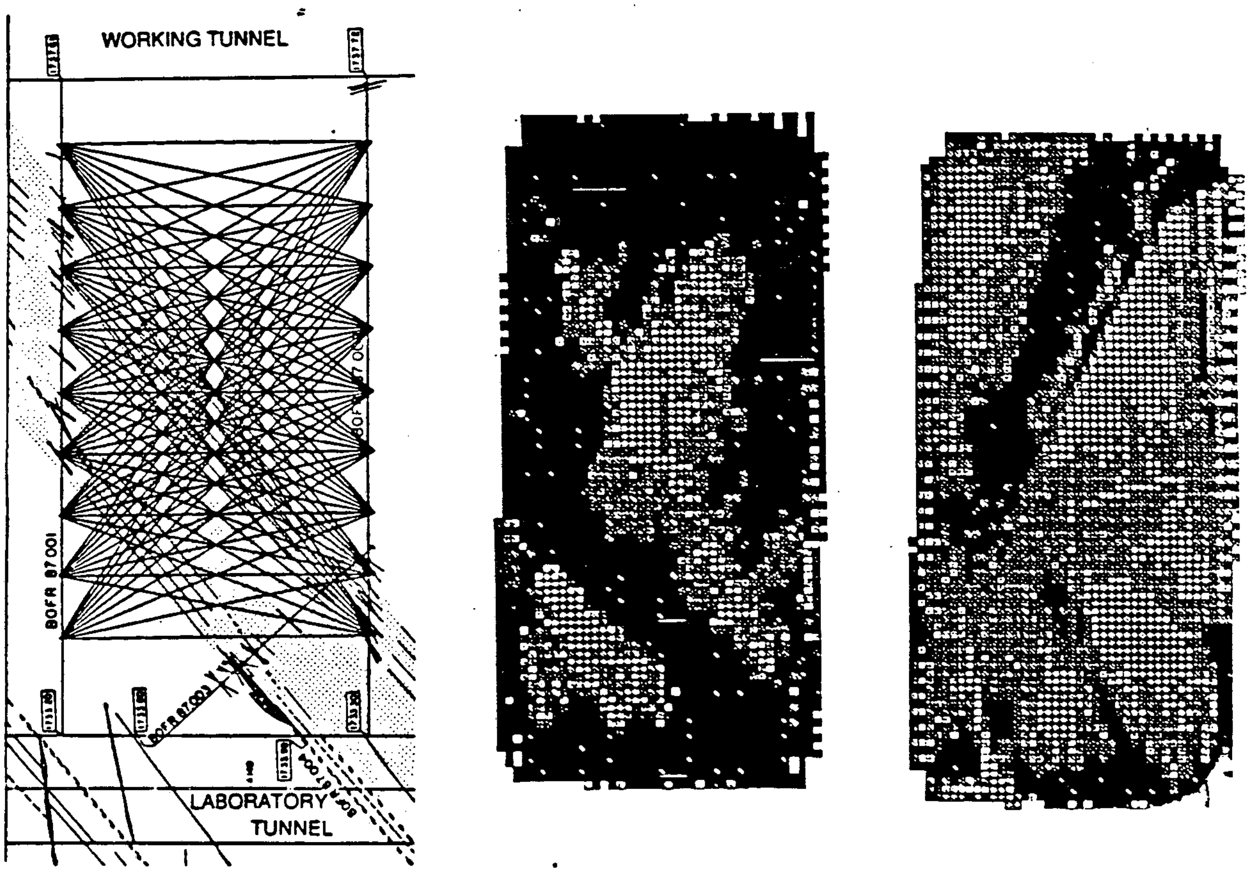

Figure 3. (A.) Plan view of a seismic cross hole test area in a fractured rock, the area is 10 meters by 21 meters. Shown also are the projections of fracture patterns and significant geologic structures. (B.) A tomographic image of the zone in Figure A using four sided ray transmission techniques on the P-wave first arrival time. Effects of attenuation are also included. (C.) A tomographic image of the zone in Figure A also using four sided ray transmission tomography, but eliminating attenuation effects.

theory may not be the actual medium which we want to image. For example, attenuation has not been included, and the Born approximation utilized may be inappropriate for a high contrast medium. These problems can be overcome by the development of new data processing schemes and the improvement of theory if necessary.

Given complete definition in the wavenumber domain, the transform of the object function can be determined exactly, and the inversion yields the unique object function. Because we do not have perfect spatial coverage it is not possible to obtain complete wave number definition. In addition, sources and receivers are discrete in the transform direction, thus producing discrete samples of the object function in the transform domain. Finally more importantly the maximum coverage we can obtain is determined by a circle of radius $2k_0$. This means that as the data frequency content increases, the inversion will be sharper due to the higher wavenumbers in the object function's transform. Given these limitations there is still a distinct advantage over transmission tomography, in that in most cases in real applications the access to any rock volume will be limited to at most three sides. Although the usable frequency band is constrained by spatial aliasing considerations and by the source function, all else being equal, diffraction tomography still produces sharper images given the same spatial coverage. Also, inversions at different frequencies could be done and averaged in order to increase coverage in the transform domain.

An example of the application is given in Figure 4. In Figure 4a a model is given, with the synthetic imaging of this model by two sided coverage given in Figure 4b. In this example the fracture zone was assumed to be a fracture zone in a 2-D medium. The inversion was done at 25 frequencies from 2440 to 5490 Hz with 122 Hz intervals, and the results averaged. The background velo-

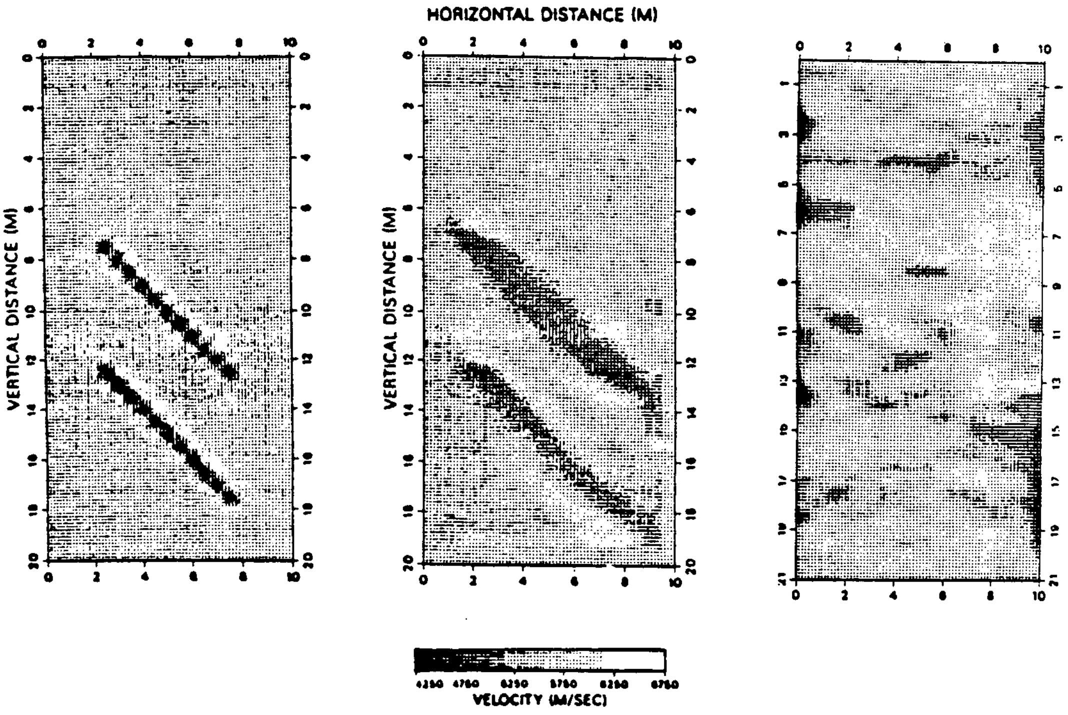

Figure 4. (A.) A model of the fracture zones in Figure 3a. (B.) The result of performing two sided diffraction tomography on the model in Figure 4a. (C.) The result of performing two sided diffraction tomography on the actual data used in Figure 3.

city is 5500 m/sec, the inhomogeneity 4500 m/sec. 40 sources and 40 receivers are used with 0.5 m separation. The area between the boreholes is discretized into 20 by 40 pixels. For the acoustic case the method outlined in the previous section can be carried out exactly. The inversion in Figure 4b was done by back-propagating the recorded waves into their correct locations.[24,25] In general, the linear system of equations formulated is similar in concept to that used in ray tomography, except that now a full matrix is required to describe the process. Therefore, the equations can be solved using a constrained least-squares method which is introduced to ensure the stability.[26]

Figure 4c shows an actual field example using the data from the application mentioned in Figure 3. To obtain this inversion the data are heavily processed in order to obtain the scattered field, remove the attenuation effects, deconvolve the the source wavelet, and correct for 3-D effects. This inversion is done using the quadratic programming method rather than the back propagation method. It is useful to compare the results of Figure 4c to Figures 3b and 3c, i.e., the inversions obtained using four-sided coverage for the ray transmission case. As can be seen, the results from the diffraction tomography inversion, 4c, match the ray tomography results, 3b and 3c, only slightly, However, the significant features do show up in the diffraction case, even though the coverage is two sided for the diffraction case versus four sided for the ray transmission case. A reason for the lack of better resolution for the diffraction case, using real data, may be that the algorithms applied in this case were developed for the 2-D acoustic case, where we are really dealing with a 3-D elastic case in rock. Currently we are developing algorithms for the elastic case. Another reason is that the method also uses the Born approximation which requires weak scattering.

Making use of synthetic simulations, we have investigated this type of solution rather extensively and have developed an understanding of how the results are influenced by various factors such as geometry, noise, separation of primary waves, and free surface effects. The results of these simulations have all been quite positive, leading to the general conclusion that basic diffraction tomography is a powerful robust method, however, questions regarding the practical implementation of the method in a field situation still remain.

TASKS TOWARDS IMAGE IMPROVEMENT

While we have not previously had the impetus to integrate the best and most promising points of a broad program into a concentrated effort for improved imaging, this current emphasis at Yucca Mountain has made clear the need for such integration in addressing the stated goals. The somewhat independent elements which collectively span the needs for improved imaging technology include:

1. Data Acquisition.
2. High-precision P- and S-wave travel-time measurement and data management.
3. Three-dimensional background structure estimation.
4. Transmission- and diffraction-tomographic imaging algorithm optimization.
5. Interactive and manipulative data presentation with In-field 'smart' acquisition/processing/display systems.

In many differerent applications of seismic imaging we have 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 at Yucca Mountain.

Data Acquisition:

The first step in any imaging project is to understand the target and the medium in which the target resides. Modeling, code and algorithm development can be done prior to field activities with values obtained from well logs, core, etc., however, one must at some point take the methods to the field and assess their applicability and determine the most effective path of action. The most immediate requirement in this application is to obatin a state-of-the-art data set from the environment in which the method is to be applied, i.e., Yucca Mountain. Only armed with these data can one pursue the most effective program in seismic imaging at Yucca Mountain.

High-Resolution Timing:

Transmission ray tomography relies heavily upon accurately measured travel-times of P- and S-waves and the efficient management of large sets of data. Aware of the importance of accurate timing, we have developed two complimentary routine analyses. First, an efficient cross-correlation/cross-spectral procedure was implemented to analyze relative travel time changes between multiples of seismic events within similar source regions. The method is also applicable to the controlled-source vibrator data, cross-hole tomographic data, or any pair of similar waveforms. The slope of the coherency phase spectrum gives the delay between the waveforms.[27,28] The width of the coherent frequency band is a systematic function of event-pair spatial separation, ranging for P-waves from about 100 Hz for 10-20 m separation to about 50 Hz for separations of the order of 100 m. S-wave coherency is about 80 Hz at 10-20 m separation. This represents more than an order of magnitude improvement. These results present a consistent and persuasive argument for the claim that the coherency phase timing method is routinely producing reliable times with precision about 1/10 of the sampling interval. The remarkable improvement obtained in these source image point locations depended also on the velocity model used in the inversion, in this case a fully 3-D distribution, determined from the same data, as discussed next.

Estimating the Three-Dimensional Velocity Distribution:

Improved resolution in imaging 3-D heterogeneous subsurface structure is a key step in determining the initial, or background starting model in tomography. The 3-D ray-tracing algorithms are being modified and optimized for use in borehole-borehole and surface-borehole tomographic applications, and velocity distribution inversion routines are being incorporated into a scheme for estimating the model background. Again, recent advances in high-resolution earthquake research may point the way for cross-hole tomography. In our work we have developed an effective method, based on the simultaneous earthquake location and three-dimensional velocity inversion algorithm proposed by Thurber.[29] Since a very important part in any velocity inversion code is the calculation of the travel times (forward problem), we tested several ray tracers and we finally implemented Thurber's code with the Sine-wave Distortion of Circular Ray-paths (SDCR) method proposed by Protheroetal.[30] When the code was tested against a 3-D ray tracer written solving the Eikonal equation, we found that for most ray paths, the accuracy of the computed travel times is a fraction of a millisecond. After extensive testing, we have recently started the joint inversion for both P and S velocity structure and for hypocenters, adopting some damping to smooth the resulting model. The results as applied to ray tomography are very promising, as the method may truly enhance resolution at Yucca Mountain.

TOMOGRAPHIC IMAGING OPTIMIZATION:

Transmission:

The primary area of work has been improving the means by which the seismic energy is approximated by a raypath. We are pursuing a statistical approach to estimate the raypath by using a weighted average of several different raypaths. A method we are investigating for this purpose is expectation maximization (EM). This is an iterative method used to compute a maximum likelihood estimate where the observations can be viewed as an incomplete data set. The second area of work in transmission tomography is in algorithm development using the method of regularization due to Tikhonov and Arsenin.[31] Our initial focus is on developing improved penalty functions to restrain smearing in the image corners, and to incorporate realistic structure into the slowness pattern. Regularization chooses the estimate $\hat{S}$ which minimizes a weighted sum of two functions.

$$L(S) + xJ(S)$$

where L(S) is a likelihood type function and J(S) is a penalty function. In the case of seismic tomography, S is a matrix of slowness values, L(S) could be a sum of error terms, and a typical J(S) would be a measure of the difference between adjacent slowness pixels. Various other measures can also be used, or even a combination. For example, S-wave data could be used to constrain the solution.

Diffraction:

A considerable amount of developmental and experimental work is necessary to modify and tune the basic (2-D acoustic) diffraction tomography method so that it works well in practical 3-D heterogeneous field situations. The extension of the basic method to the case where the source and receiver are points rather than lines (3-D versus 2-D) has just been carried out. The extension to the elastic case will be more difficult and is being addressed. One approach is to process the data in such a way as to achieve a partial separation between P- and S-waves, and then apply the acoustic method to the separated data sets. The case of a strongly inhomogeneous background will also require work. In principle, there is no problem calculating the Green's functions for such a medium, but the computational time can increase dramatically and the associated expense can make the method impractical for routine application. Other approaches to this particular problem are also being investigated. The algorithms must now be tested on real data sets to determine their applicability and improvements necessary for usefulness. Another approach is to use the available migration software to migrate the data as is commonly done with surface reflection data, however, a large amount of programming is necessary to convert these programs for cross-well use. A recent method of initially doing a ray tomography inversion to obtain the slow variation in the medium followed by a diffraction tomography inversion to improve the resolution is being considered.

Expert Systems in Seismic Processing:

In order to process and analyze the data in a timely and efficient manner we are also in the process of coupling the processing and collection tasks with an expert system. This has proved fruitful in a variety of earth science applications already.[32] In general, expert systems are designed for ten basic tasks; interpretation, debugging, repair, prediction, diagnosis, design, planning, monitoring, instruction, and control. The features to be used primarily in this project will be the interpretation, debugging, prediction, monitoring and control. The interpretation feature is often used to examine incoming data and to arrive at a decision. Such application would include time picking, but also such features as pattern recognition and image enhancement would also use this feature. The debugging feature would be used to test various inversion algorithms as well as to "debug" such parameters as array dimensions, source polarization, etc. The diagnosis and monitoring would be very advantageous for tracking the performance of the various hardware and software components. This again, would provide information for optimizing the imaging system. Last but not least, the control aspect would be used for such features as regulating complex processes within the system, an example would be CPU time devoted to a particular task, or the display of processed images. Currently we are incorporating recent seismological developments in precision phase timing, 3-D ray-tracing and velocity estimation into the design of a compact field tomography development system (≈ 20 MIP capability), along with improved and tested transmission- and diffraction-tomographic imaging algorithms, and featuring an interactive image display system allowing the user to manipulate the data processing under 'quick-look' conditions for image improvement. The system will involve 'expert systems' operational control insofar as beneficial. The system will be field-tested initially at our cross-well test facility, and subsequently used at Yucca Mountain.

SUMMARY

The ultimate goal of this project is to provide state-of-the-art capability for high resolution tomographic imaging. Our experience has shown us that successful seismic imaging is a result of trial and error and application of proper techniques. If it were possible to make this a real time experience, then it may be possible to realize a great improvement in resolution. Our approach is an integrated system that is intended to be an extension of our laboratory computational and theoretical capabilities operating in the environment of eventual application. The effort is a balanced program between theoretical and mathematical improvements in the fundamental processing algorithms, and the implementation on field computer. We believe that this is the most cost effective and realistic approach to carry out seismic imaging techniques for the application at Yucca Mountain.

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REFERENCES

1. USDOE, "Site Characterization Plan Overview, Yucca Mt. Site, Nevada Research and Development Area, Nevada," USDOE, Office of Civilian Radioactive Waste Management, 164 pp. (1988).

2. R. R. STEWART, R. M. TURPENING and M. N. TOKSOZ, "Study of a Subsurface Fracture Zone by Vertical Seismic Profiling," *Geophys. Res. Lett., 8,* pp. 1132-1135 (1981).

3. E. L. MAJER, T. V. MCEVILLY, F. S. EASTWOOD and L. R. MYER, "Fracture Detection Using P- and S-Wave VSP's at The Geysers Geothermal Field," *Geophysics, 53(1),* pp. 76-84 (1988a).

4. J. DOUMA, "Crack-Induced Anisotropy and its Effect on Vertical Seismic Profiling," Ph.D thesis, Inst. of Earth Sciences, U. of Utrecht, The Netherlands (1988).

5. S. CRAMPIN, "Seismic-Wave Propagation through a Cracked Solid: Polarization as a Possible Dilatancy Diagnostic," *Geophys. J. Roy. Astron. Soc., 53,* pp. 467-496 (1978).

6. S. CRAMPIN, "A Review of Wave Motion in Anisotropic and Cracked Elastic-Media," *Wave Motion, 3,* pp. 343-391 (1981).

7. S. CRAMPIN, "Effective Anisotropic Propagation through a Cracked Solid," In Crampin, S., Hipkin, R.G., and Chesnokov, E.M., eds., Proc. of the First Internat. Workshop on Seismic Anisotropy, *Geophys. J. Roy. Astron. Soc., 76,* pp. 135-145 (1984a).

8. S. CRAMPIN, "Anisotropy in Exploration Seismics," *First Break, 2,* pp. 19-21 (1984b).

9. S. CRAMPIN, "Evaluation of Anisotropy by Shear Wave Splitting," *Geophysics, 50(1),* pp. 142-152 (1985).

10. L. R. MYER, D. L. HOPKINS and N. G. W. Cook, "Effects of an Interface in Partial Contact on Attenuation of Acoustic Waves," *Geophysics,* in press (1989).

11. M. SCHOENBERG, "Elastic Wave Behavior Across Linear Slip Interfaces," *J. Acoust. Soc. Am., 68(5),* pp. 1516-1521 (1980).

12. M. SCHOENBERG, "Reflection of Elastic Waves from Periodically Stratified Media with Interfacial Slip," *Geophys. Prosp., 31,* pp. 265-292 (1983).

13. M. SLANEY and A. C. KAK, "Imaging with Diffraction Tomography," School of Electrical Engineering, Purdue University, Report TR-EE 85-5, 211 p. (1985).

14. R. H. HUESMAN, G. T. GULLBERG, W. L. GREENBERG, T. F. BUDINGER, "Users Manual: Donner Algorithms for Reconstruction Tomography," Lawrence Berkeley Laboratory, University of California, Report PUB-214, 285 p. (1977).

15. R. M. MERSEREAU and A. OPPENHEIM, "Digital Reconstruction of Multidimensional Signals from their Projections," *Proceedings of the IEEE, 62(10),* p. 1319-1338 (1974).

16. J. E. PETERSON, Jr., "The Application of Algebraic Reconstruction Techniques to Geophysical Problems," Ph.D thesis, University of California, 188 p. (1986).

17. P. BOIS, M. LAPORTE, M. LAVERGNE and G. THOMS, "Well to Well Seismic Measurements," *Geophysics, 37,* p. 471-480 (1972).

18. K. A. DINES and R. J. LYTLE, "Computerized Geophysical Tomography," *Proceedings of the IEEE, 67(7),* p. 1065-1073 (1979).

19. T. M. DALEY, T. V. MCEVILLY and E. L. MAJER, "Analysis of P- and S-Wave Data from the Salton Sea Scientific Drilling Project," *Jour. of Geophys. Res., 93(b11),* pp. 13025-13036 (1988).

20. T. M. DALEY, T. V. MCEVILLY and E. L. MAJER, "Multiply Polarized Shear-Wave VSP's from the Cajon Pass Drill-Hole," *Geophy. Research Letters, 15(9),* pp. 1001-1004 (1988).

21. E. L. MAJER, J. E. PETERSON, T. V. MCEVILLY, L. R. MYER, P. BLUMLING and G. SATTLE, "VSP/Tomographic Imaging for for Fracture Detection and Characterization," *Earthquake Notes, 59(1),* pp. 41 (1988b).

22. E. L. MAJER, J. E. PETERSON, L. R. MYER and P. BLUMLING, "Crosshole Seismic Measurements for Fracture Characterization," *EOS, Abs. AGU Annual Fall Meeting, 69(64),* (1988c).

23. W. FOXALL and T. V. MCEVILLY, "The Microearthquake Process as seen in High Resolution with the Parkfield Network," *Seismol. Res. L., 59(1),* (1988).

24. A. J. DEVANEY, "Geophysical Diffraction Tomography," *IEEE Transactions on Geoscience and Remote Sensing, GE-22(1),* p. 3-13 (1984).

25. R. WU and M. N. TOKSOZ, "Diffraction Tomography and Multisource Holography Applied to Seismic Imaging," *Geophysics, 52(1),* p. 11-25 (1987).

26. C. L. LAWSON and R. J. HANSON, *Solving Least Squares Problems,* Prentice-Hall, Chpt. 23 (1974).

27. G. POUPINET, W. L. ELLSWORTH and J. FRECHET, "Monitoring Velocity Variations in the Crust using Earthquake Doublets: An Application to the Calaveras Fault, California," *Journ. Geophys. Res., 89,* pp. 5719-5731 (1984).

28. J. J. FREMONT and S. MALONE, "High Precision Relative Locations of Earthquakes at Mount St. Helens, Washington," *Journ. Geophys. Res., 92,* pp. 10223-10236 (1987).

29. C. H. THURBER, "Earthquake Locations and Three-Dimensional Crustal Structure in the Coyote Lake

Area, Central California," *Journ. Geophys. Res., 88,* 8226-8236 (1983).

30. W. A. PROTHERO, W. J. TAYLOR and J. A. EICKEMEYER, "A Fast, Two-Point, Three-Dimensional Raytracing Algorithm using a Simple Step Search Method," *Bull. Seism. Soc. Amer., 78,* pp. 1190-1198 (1988).

31. A. TIKHONAV and V. ARSENIN, *Solutions of Ill-Posed Problems.* Wiley Press, New York, New York (1977).

32. B. M. MILLER, "Future Applications of Expert Systems for the Evaluation of Energy Resources," *Jour. Pet. Tech.*, pp. 348-352, March (1988).

33. R. B. J. SCOTT, "Preliminary Geologic Map of Yucca Mountain Nye County, Nevada with Geologic Cross Sections," "USGS Open File Report" 84-494, 9 pp. (1984).