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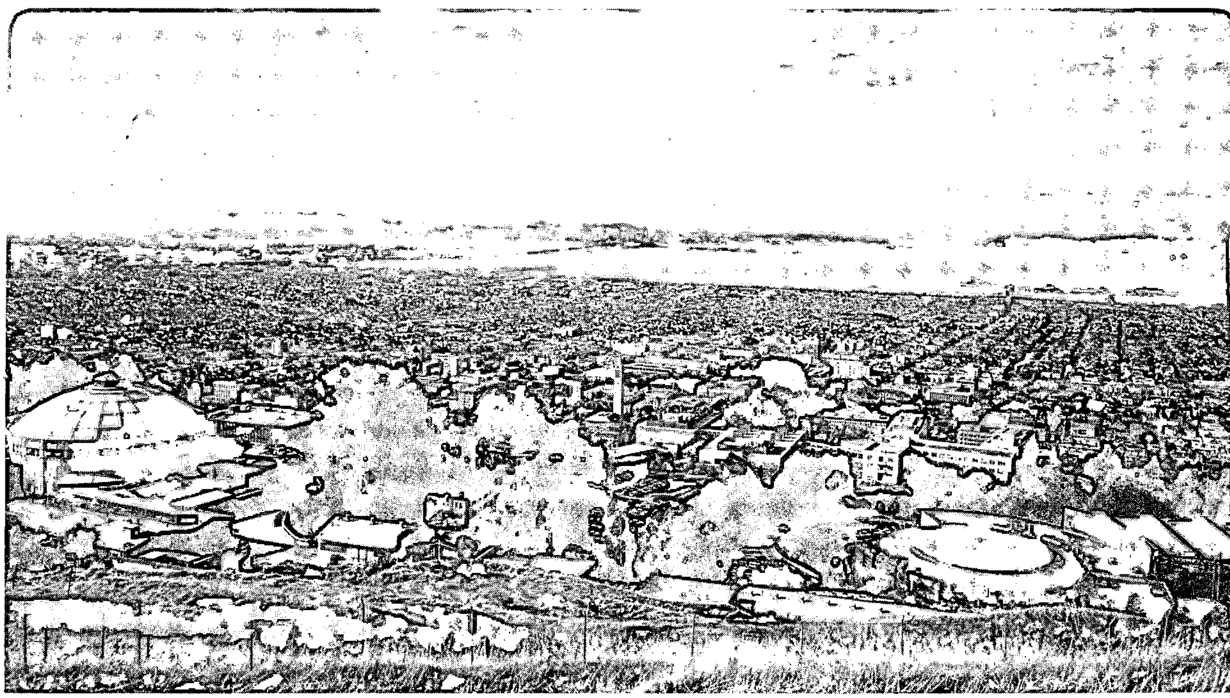

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Crosswell Tomography

Transmission Tomography

Crosswell transmission tomography is becoming a commonly used tool for seismic modeling. The basic idea is to back project a set of many rays to yield an estimate of the distribution of velocities needed to produce the observed travel times (Peterson, 1986; Dines and Lytle, 1979). This is done by minimizing the difference between the observed and calculated travel times, usually through an iterative process based on a least squares inversion.

One difficulty with iterative inversions is knowing when to stop the process. Iterative inversions are performed primarily because of the tremendous size of the matrix involved, but also because the assumptions used and the measurement errors make an exact solution uninformative. The iterative procedure enables one to stop the inversion process some time before the exact solution is approached. However, some criteria needs to be developed to adequately determine the proper stopping point. We have been developing an objective technique to find a stopping time. A statistical method called cross-validation is used to find a stopping point which we expect will minimize prediction error and prevent overfitting to a specific data set of travel times. The idea is to divide the rays randomly into n sets, then build a series of submodels by leaving out one of the sets while using all the others. The RMS residual of each submodel is calculated for each iteration. At first, the prediction RMS for the excluded rays will go down as the model improves. At some iteration the prediction error, or RMS, for the excluded rays will begin to increase. This happens because the iterative algorithm begins to overfit the model to the specific set of rays used. The iteration with the minimum predicted RMS is found for each submodel. We expect that the mean iteration at which the minimum predicted RMS occurs to be the best stopping time for the model built using the entire data set.

The existence of background anisotropy can also produce large errors in the results. This is due to the fact that the sampled area can have a range of velocities depending on the angle of incidence of the ray. Unless a complete angular coverage of rays is present for all sampled regions, it is impossible to produce an adequate inversion that includes anisotropy. The way in which we rectify this problem is to first determine the background anisotropy, then remove it from the travel times before they are inverted (Johnson and Peterson, 1986). The P-wave anisotropy may be approximately represented as

$$V_p^2 = A + B\sin(2\phi) + C\cos(2\phi) + D\sin(4\phi) + E\cos(4\phi)$$

where ϕ is the angle of direction of propagation. A function of this form is fitted to the data represented as ϕ vs average velocity. The coefficients A, B, C, D and E represent the strength of the anisotropy. The background anisotropy can be determined in the laboratory from rock samples, from the travel time data itself, or from a separate experiment in the same anisotropic rock which is relatively free of fractures or other anomalous zones. This method will not, of course, give a solution for changes in anisotropy, but has given adequate solutions in our field tests.

Diffraction Tomography

The applications of full-waveform diffraction tomography has not been as extensive as transmission tomography, but the potential developments may prove valuable. In diffraction tomography less spatial coverage of sources and receivers are needed to obtain resolution equivalent to transmission tomography, because scattered waves at various angles are used in forming the image. The basic idea of diffraction tomography is to back propagate the scattered wavefield in order to reconstruct the velocity perturbation causing the scattering.

Making use of finite difference synthetic simulations, we have investigated this method rather extensively and have further developed the method in order to be applicable to field data. These developments include the application of two and a half dimensional (2.5-D) corrections to our field data. The inversion is done using two separate methods: The first is the conventional back projection method (Devaney, 1984; Wu and Toksoz, 1987) and the second is a quadratic programming method with constraints. The Born approximation is utilized for linearization (rather than the Rytov) since this approximation is quite accurate in representing fractured media. The inversion methods have been tested on 2-D pseudo spectral finite difference forward data and on 2.5-D Born forward data together with the 2.5-D corrections.

Grimsel Test Site - A Case Study

During the past three years we have carried out experiments at the Grimsel rock laboratory in the Swiss Alps in cooperation with the Swiss cooperative for the storage of nuclear waste (NAGRA). In one area of the laboratory two parallel drifts and two parallel boreholes form a 10 by 21 meter region. This region was chosen so that a mylonitic fracture zone crosses this region at a strike of about 45 degrees. The primary objective of this study was to gather high quality P- and S-wave data across the fracture zone to determine the seismic visibility of the fractures. Seismic sources were placed at 0.5 meter intervals in the boreholes and at 0.5 meter intervals in shallow holes drilled into the drift wall. A three component accelerometer package was recorded at corresponding locations to give complete four-sided coverage. Three experiments were performed in this region, one each in 1987, 1988 and 1989. The results of the 1987 and 1988 experiments will be presented along with preliminary results of the 1989 experiment.

The travel times were picked by eye on the component with the strongest P-wave motion using an interactive picking routine. A total of 4004 values were produced. These values were inverted using an algebraic reconstruction technique with a pixel array of 44 by 88. The stopping criterion which we developed performed well and also showed the stability of this particular data set. This produces a pixel size of 0.25 meters which is the resolution we expect given the wavelength of 0.7 meters and station spacing of 0.5 meters. These inversions were performed without the anisotropy corrections, but these results proved inadequate.

Previous experience has shown that the Grimsel granite is highly anisotropic (~10%). The method outlined above was used to remove the background anisotropy and another inversion performed using the same input parameters. These results were quite different and proved more stable. The improvement is more marked when just the borehole to borehole times are inverted.

The results from the 1987 (Figure 1) and 1988 (Figure 2) inversions show many similar features and many unexpected differences. Most of these differences are attributable to the different source strengths. The fracture zone is visible in both results, but is dominated by tunnel affects in 1987 and by a large anomalous zone which does not correspond to any feature seen in the drifts or boreholes. These results have increased our understanding of the practical aspects of a tomographic survey.

The full waveform methods were also applied to these data sets. For practical implementation, only the borehole to borehole waveforms were used in the inversions. A background attenuation value is estimated for the region using a simple statistical approach. Estimates are the wavelet are found by a common source gather, common receiver gather and average of all traces. The data are inverted after the background attenuation is corrected for, the incident field removed, the data reconvolved and the 2-D corrections applied. Results of the back propagation and quadratic programming inversions (Figure 3) show features corresponding to fracture zones in the core samples and anomalous zones in the transmission tomograms.

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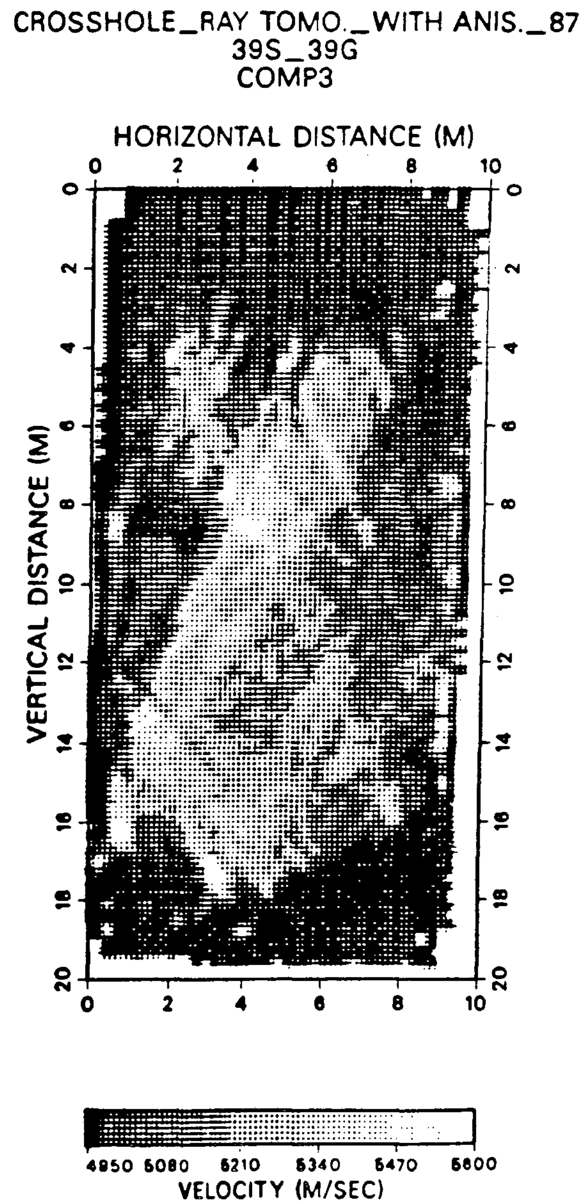

Figure 1. Tomographic image of the 1987 survey after anisotropy corrections.

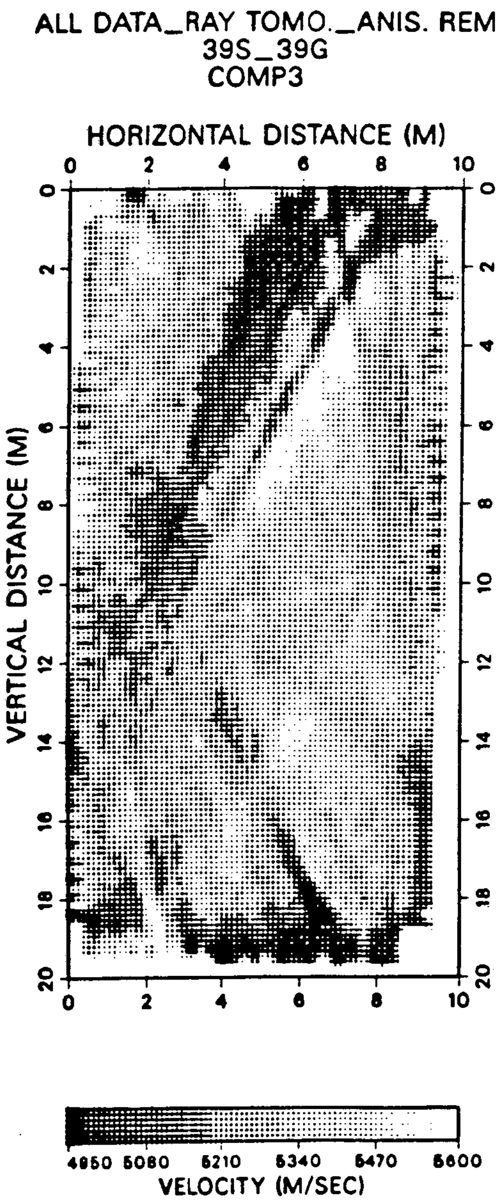

Figure 2. Tomographic image of the 1988 survey after anisotropy corrections.

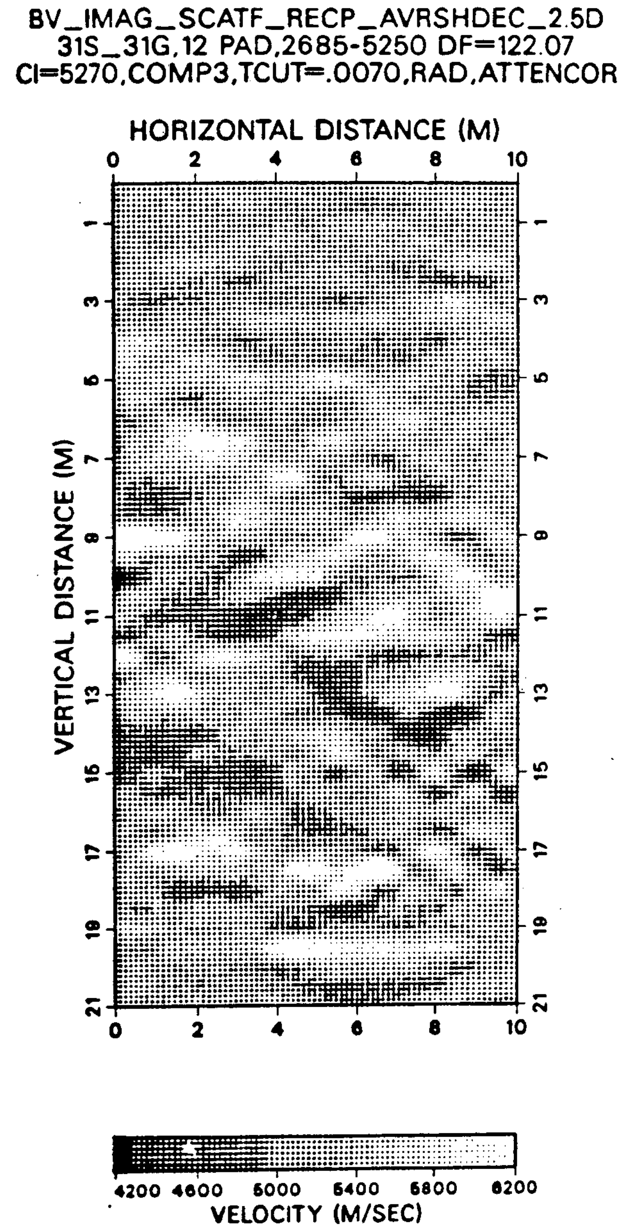

Figure 3. Tomographic image of the 1988 survey using full wave diffraction tomography.

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