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VSP AND CROSS HOLE TOMOGRAPHIC IMAGING FOR FRACTURE CHARACTERIZATION

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ABSTRACT

For the past several years LBL has been carrying out experiments at various fractured rock sites to determine the fundamental nature of the propagation of seismic waves in fractured media. These experiments have been utilizing high frequency (1000 to 10000 Hz.) signals in a cross-hole configuration at scales of several tens of meters. Three component sources and receivers are used to map fracture density, and orientation. The goal of the experiments has been to relate the seismological parameters to the hydrological parameters, if possible, in order to provide a more accurate description of a starting model for hydrological characterization. The work is ultimately aimed at the characterization and monitoring of the Yucca Mountain site for the storage of nuclear waste. In addition to these controlled experiments multicomponent VSP work has been carried out at several sites to determine fracture characteristics. The results to date indicate that both P-wave and S-wave can be used to map the location of fractures. In addition, fractures that are open and conductive are much more visible to seismic waves than non-conductive fractures. The results of these tests indicate direct use in an unsaturated environment.

INTRODUCTION

The problem of adequate fracture detection and characterization is essential to the understanding of the hydrologic and geomechanical behavior of any underground nuclear waste repository. Fracture properties can be directly measured at the surface and underground openings, but because of the large variation in the geometry of fracture sets, it is unlikely that one can rely on the direct interpolation of structural information between boreholes for adequate fracture characterization. Also, although there may be many fractures, or sets of fractures, the relative geomechanical or hydrologic contribution of the fractures may widely vary. Therefore, there is a crucial need to have techniques for fracture detection and characterization between boreholes and underground workings. The problem of detection, however, is very different from characterization. Detection may only involve the confirmation of the existence of fractures. Characterization ideally would be not only be the detection of the fractures, but would also define such parameters as orientation, density, aperture, degree of connection, infilling material and ideally the hydrologic character of the fractures and fracture sets. In order to address these problems one naturally turns to geophysical or remote methods for solutions, i.e., the seismic and electrical methods. The work described here concerns seismic, hydrologic and geomechanical methods linked with the geologic description.

As applied on a large scale to a repository environment the most likely seismic method would be the multi-offset/multi-source Vertical Seismic Profiling (VSP) from the surface. On smaller scales the crosshole techniques in the underground workings will be used for detailed characterization of the rock surrounding the underground openings and canister areas. By performing a tomographic analysis of the VSP and crosshole data from multiple offsets and azimuths, it may be possible to map the fracture characteristics between the boreholes and underground workings. This information could then be used in hydrologic or geomechanical models of fracture networks to study the behavior of the rock mass. Seismic methods would then be used to provide a method for extrapolating fracture characteristics observable at the borehole walls and underground workings to the entire repository block, thus providing a more complete data set to characterize the overall hydrologic and geologic parameters.

Fracture detection using P- and S-waves in VSP studies is not a new idea.[1] Coupling effects such as matrix anisotropy and partial saturation need further investigation relative to the effect on the propagation of seismic waves. It is becoming increasingly apparent, however, that to utilize the full potential of the seismic methods, 3-component data should be acquired. Crampin has pointed out the importance of using 3-component data in VSP work, particularly for fracture detection.[2,3,4,5,6] This author and others have pointed out the phenomenon of

shear wave splitting and the anisotropy effects of SH- versus the SV-waves in addition to P- versus S-wave anisotropy.[7] In addition to Crampin's theoretical work on shear wave splitting (1978, 1985) there has been some recent laboratory and theoretical work which explains shear wave anisotropy in terms of fracture stiffness.[8,9,10] The fracture stiffness theory differs from Crampin's theory in that at a fracture, or a non-welded interface, the displacement across the surface is not required to be continuous as a seismic wave passes. The only boundary condition in the solution to the wave equation is that the stress must remain continuous across an interface. This displacement discontinuity is taken to be linearly related to the stress through the stiffness of the discontinuity.

The implication of the fracture stiffness theory is that for very thin discontinuities, for example fractures, there can be significant effect upon the propagation of a wave. Usually one thinks of seismic resolution in terms of wavelength as compared to the thickness and lateral extent of a bed or other feature. In the stiffness theory the lateral extent is still important, but if the fracture stiffness is small enough the thickness of the feature can be much less than the seismic wavelength. The effect should be even more pronounced in an unsaturated environment, such as at the DOE site at Yucca Mountain, Nevada, because the stiffness of an unsaturated fracture is less than that of a saturated fracture. Thus for any given size of fracture the lower limit of fracture detectability in an unsaturated fracture will be smaller than if the fracture is saturated. Alternatively, if the fractures are fairly uniform, it may be possible to map isolated saturated zones or perched water.

SEISMIC IMAGING EXPERIMENTS

During the past three years the USDOE, with cooperation of the Swiss cooperative for the storage of nuclear waste, NAGRA, has been carrying out experiments in a Swiss rock laboratory in the Swiss alps in a granitic rock. In this underground laboratory there is the Fracture Research Investigation area (FRI) where these experiments have been carried out. Figures 1a and 1b are schematics of the FRI zone showing the two 21 meter long, parallel boreholes 10 meters apart connecting two drifts in laboratory, the access drift (top of figure 1b.) and the laboratory tunnel. The two drifts and boreholes form a 10 by 21 meter area that can be investigated by various geometrical configurations. The FRI experiment area offers an excellent opportunity to perform calibrated experiments in a rock mass where the fracture locations and characteristics are relatively well known with the benefit of well calibrated fracture sets for study. The greatest attraction, however, is the opportunity to test the fracture stiffness and other theories at different scales. Pyrak et al. (1989) have performed laboratory experiments which have at small scales confirmed the effect of fracture stiffness.[8] The scaling of this phenomenon to

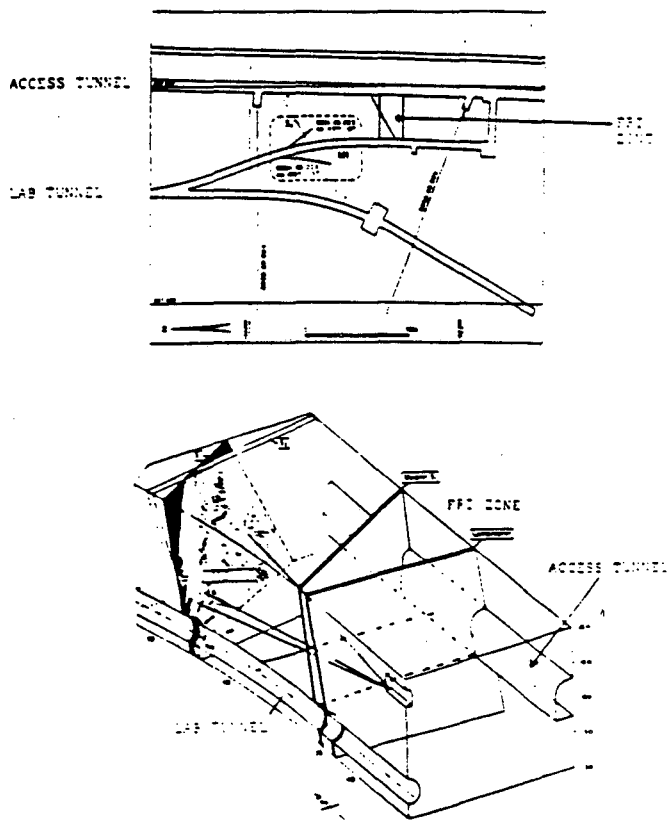

Figure 1a. Schematic of FRI zone and Swiss Test Facility.

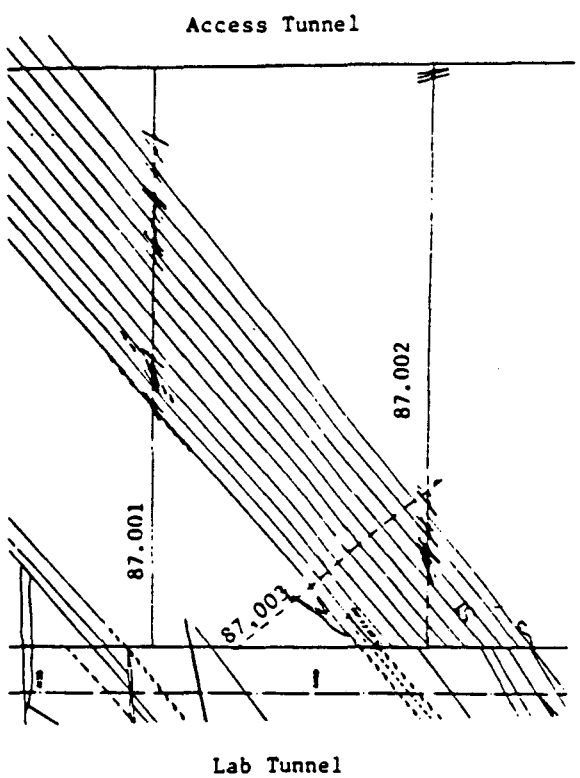

Figure 1b. Geologic plan view of FRI zone.

larger distances is yet unknown. Therefore, one of the main objectives of the FRI experiments was to observe the effect of fracture density, orientation and spacing on the propagation of the P- and S-waves. A second objective was to relate the seismic response to the hydrologic behavior of the fractures, i.e., do all fractures effect the seismic wave, or do just fluid filled, or partially saturated fractures effect the seismic waves in a measurable amount. Another objective of the study was to assess the amount of seismic data necessary to provide useful information, and how does one process these data for the maximum information in a routine fashion. These are important questions when one progresses to the point of applying these techniques on larger scales in a routine fashion.

In the FRI zone there is a mylonitic fracture zone crossing the experimental area. The boreholes were drilled to intersect this fracture zone as well as other structural features as shown in Figures 1a and 1b. Boreholes 87.001 and 87.002 are 86-mm holes drilled from the lab tunnel to the access tunnel to provide a means of performing crosshole seismic work, core of the fracture zone, and for carrying out hydrologic experiments. Borehole 87.003 is a 127-mm hole drilled through the fracture zone for obtaining large core for laboratory analysis and also for hydrologic testing. In addition to these holes, 76 shallow holes were drilled into the lab and access tunnel walls between boreholes 87.001 and 87.002 at 0.25-meter spacing to allow the placement of the seismic sources and receivers.

The concept behind the FRI seismic experiments is relatively simple. Seismic sources were placed in the holes (boreholes 87.001, 87.002, and the shallow holes in the sides of the tunnel) and activated. The data from a three component accelerometer package was recorded at 0.5-meter spacing in boreholes 87.001 and 87.002. The receiver package was also placed in the shallow holes to give complete four-sided coverage. The objective of the experiments was to gather high quality P- and S-wave data across the fracture zone to determine the seismic visibility of fractures. This controlled field data would then be compared to the laboratory results on the core and to in-situ tests of the mechanical and hydrologic behavior of the rock. Three experiments were performed in the FRI zone, one each in the summer of 1987, 1988 and 1989. Discussed here will be the results of the 1987 and 1988 experiments. The data were recorded on an in-field PC-based acquisition system. Four channels of data were acquired, the x, y and z receivers and the "trigger" signal. The sample rate was 50,000 samples/sec on each channel with 20 milliseconds of data being recorded for each channel in the 1987 experiments and 250,000 samples/second in the 1988 data. Typical travel times were less than 5 milliseconds for the P-wave and 10 milliseconds for the shear wave. Nearly 60,000 ray paths (X, Y and Z components) were collected in the FRI zone, at distances from 1/2 meter to nearly 23 meters. The peak energy transmitted in the rock was 5,000 to 10,000 Hz, thus yielding a wavelength of approximately 1 to 0.5 meter in the 5.0 km/sec velocity rock.

After acquisition the data was first demultiplexed and the traces stacked. During acquisition multiple signals were produced with the same source-receiver pairs in order to stack the data for improved signal quality. The travel times were picked by eye using an interactive picking routine. The times were picked on the component with the strongest P-wave motion. This was confirmed by rotating the data into the P-, SV- and SH-directions. The source used in 1988 was more powerful than the 1987 source so that the signal to noise ratio has dramatically improved. The repeatability of the source has resulted in more accurate travel time picks from the more consistent waveforms.

The travel time picks were initially analyzed by plotting a time-distance curve, a velocity-distance curve, and a velocity vs. incidence angle curve. These values were rechecked and shown to be acceptable picks with their anomalous values apparently due to a heavily fractured zone in this area. This is a problem in fractured zones since the initial impulse has a low amplitude, so a sufficient decrease in power can reduce the first one or two pulses to zero causing a late travel time reading. This seems to have happened in 1987 since the velocities are generally lower, especially for rays passing through the damaged zone.

The travel times were inverted using an algebraic reconstruction technique (ART). A pixel array of 44 x 88 was chosen for the tomographic inversion. This produces a pixel size of 0.25 m which is the size of the smallest anomaly we expect to see given the wavelength of 0.7 m and station spacing of 0.5 m. Previous experience has shown that for this geometry a pixel size of half the station spacing gives the optimal combination of resolution and inversion stability. The data have been inverted using pixel sizes as small as 0.1m with adequate results when the background anisotropy is removed. As expected, the results do not resolve any additional features. When an inversion is performed without the anisotropy correction or with slightly improper travel time corrections, severe smearing occurs with unreliable results. An image was produced using almost the entire 1988 data set (Figure 2). These velocity values are compared to the 1987 results (Figure 3) using the same velocity intervals (4.9 km/s to 5.4 km/s). The main features identified in the 1987 results are the low velocity zones adjacent to the tunnels, assumed to be damaged zones, and the large shear zone extending from the middle of borehole 87.001 to the access tunnel/borehole 87.002 intersection. After an initial look, and in fact after prolonged examination, the 1988 image appears to give a very different representation.

Figure 2. Tomographic image of FRI from 1988 survey, no anisotropic correction.

Figure 3. Tomographic image of FRI from 1987 survey, no anisotropic correction.

1- There is little evidence of the extensive 1987 damaged zones in the 1988 results. Also, the average velocity values in the 1988 field are higher.

2- The prominent shear zone observed in 1987 is shown as a single strong low velocity zone about two meters wide. The corresponding zone in the 1988 results consists of two or three very thin (<0.5 meters thick) zones which become discontinuous at about at four or five meters from the laboratory tunnel.

3- There appears to be an additional feature in the 1988 image whi was masked by the low velocity zone on the edges in the 1987 result. This feature extends from near the access tunnel/87.002 intersection to the middle of 87.001 and is, in fact, the dominant feature of the 1988 results. Evidence of this feature exists in the 1987 data, but is not so dominant and is obscured by the damaged zone.

The differences between the two images seem severe and will be discussed in detail later in the paper.

Previous experience has shown that the Grimsel granite is highly anisotropic (≈10%). Image improvement may be achieved by removing the background anisotropy from the travel times.[11] 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. These values may be determined in the laboratory or in the field. The laboratory values are difficult to determine and may not adequately represent the in-situ anisotropy. In the field, the same travel times gathered for the tomographic may be used to determine the coefficients or a separate test may be set up in a more homogeneous (though not more isotropic) area. At Grimsel the tomographic travel time data was initially used for this calculation, but two problems were encountered. First, the existence of a fracture zone may create an apparent anisotropy even in an isotropic medium. Second, the existence of any low velocity zone associated with the tunnels or boreholes will distort the anisotropy. The damaged zones associated with the tunnels at FRI are such that the rays with high incidence angles will always pass through this zone, while the shallow angled rays will primarily travel cross borehole, through less fractured rock. This will create a false anisotropy centered with maximum value along the horizontal (parallel to the tunnels). Therefore, removing the anisotropy in this way would not be beneficial.

These problems were overcome by taking measurements between two boreholes on either side of relatively homogeneous material 15 meters away. The boreholes are one meter apart and the geological logs show a lack of fractures or weak rock. This anisotropy survey produced a sweep of signals with an angular range from −80° to 80° from horizontal. The anisotropy coefficients calculated from these values show almost 10% rock matrix anisotropy in the direction of the main FRI fracture zone which is also the orientation of the foliation:

$$A = 25.6911;\ B = 1.57302;\ C = -0.670456;$$

$$D = 0.111240;\ E = -0.360488$$

The contribution of this anisotropy was calculated and removed from the observed travel times. This consists of calculating the difference between the travel time calcu-

lated with coefficients A-E and the travel time calculated with only coefficient A, and then subtracting this value from the measured travel time.

The corrected travel times were inverted using the same technique as applied to the the uncorrected data as well as using the same parameters. The result after applying to the 1988 data is a smoother image with the anomalous zones more distinct (Figure 4). The inversion also appears to remove some artifacts that are produced in the original inversion. The smearing seen in the upper left of Figure 2 is removed as is a strong, thin low velocity feature extending from the middle of the laboratory tunnel to the dark zone in the middle-left of the plot. The "secondary" fracture which parallels the main shear fracture in is also eliminated.

When the same anisotropy corrections are used for correcting the 1987 data, interesting changes appear (Figure 5). The most obvious change is that the shear zone is no longer a continuous feature, but instead consists of a couple of large "blobs", the largest corresponding with a similar feature seen in the 1988 results. On the other hand, the feature extending from the access tunnel to the center of 87.001 is more continuous. Also, the large low velocity feature adjacent to borehole 87.002 is more extensive.

The most obvious difference between the 1987 and 1988 results is the disappearance of the damaged zones in 1988. The data quality was much better in 1988 than 1987 for several reasons. The source was more powerful and its repeatability increased. We also stacked from 2 to

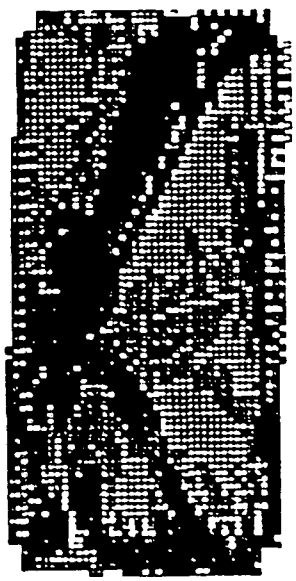

Figure 4. Tomographic image of FRI from 1988 survey after anisotropy corrections.

Figure 5. Tomographic image of FRI from 1987 survey after anisotropy corrections.

9 traces for each source receiver pair. These improvements decrease the signal to noise ratio providing better travel time picks. This is precisely the reason that the 1988 results appear different than the 1987 results. The poor data quality prevented the true travel times to be picked in 1987. In some cases the value picked was a pulse or two later than the true time. This is especially true where the attenuation is greater, e.g., the damaged zones adjacent to the tunnel, because the initial pulse or two (which are relatively small) can be completely attenuated. The entire 1987 travel time data for sources or receivers along the tunnel are probably picked consistently late, producing a velocity reconstruction which shows consistently lower velocities near the tunnels and resulting in a lower average velocity.

The second difference in the results is that the shear zone becomes discontinuous and less dominant in 1988. This result is of great interest because this is the zone that we were initially trying to image. In 1987 we had assumed that we had imaged the feature satisfactorily as a 3-meter-wide, low velocity zone. However, before the background anisotropy is removed the 1988 inversion does not show such an extensive feature, but instead one or two thinner zones which extend to about 4 meters from the laboratory tunnel. The zone continues after another meter or two as in the form of several more spherical low velocity regions. This appears similar to the image produced from the inversion of the 1987 data after the anisotropy is removed (Figure 4). To show this, the 1988 image is subtracted from the 1987 image pixel by pixel, both for the original (Figure 6) and the anisotropy corrected travel times (Figure 7). The low velocity feature is quite distinct in the uncorrected differences suggesting a real difference in the values. However, the corrected

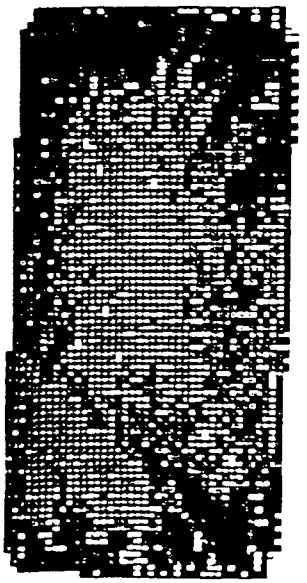

Figure 6. Difference between Figures 2 and 3.

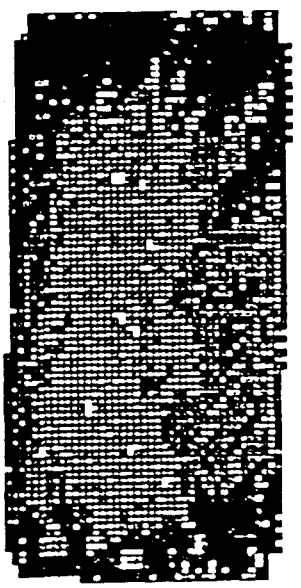

Figure 7. Difference between Figures 4 and 5.

differences are changed very little, showing that the two images are virtually the same in the shear zone area. (An inversion using the differences in travel times could not be performed because slightly different stations were used for some sweeps). These differences suggest that the 1987 low velocity zone is an artifact of the inversion process and the anisotropy, even though it is what we had hoped to see. We now believe that the shear zone either has variable stiffness or is almost transparent to seismic velocity changes at these frequencies, but is "loosened" by the drilling process near the laboratory tunnel producing lower velocities. The large low velocity features toward borehole 87.001 on strike with the shear zone are areas of greater fracturing, possibly due to intersecting fractures, or an intersecting lamprophyr.

The most unexpected result from the 1988 inversion is the low velocity feature which extends from the access tunnel-87.002 intersection to the large low velocity feature near 87.001. A strong effort was made to determine whether this is an actual zone of low velocity material or an artifact of the inversion process or some kind of field error. The 1987 result does show a hint of this feature protruding from the large low velocity zone adjacent to the access tunnel. However, it is not a dominant continuous feature. The anisotropy corrected results do show a more continuous feature, though obscured by the extensive damaged zone. Checking the difference plots again we see that in either case the differences are not significant. This indicates that the zone probably exists in the 1987 results, but is dominated by the damaged zones.

The raypaths which travel lengthwise through the zone from the access tunnel to 87.001 show some anomalous behavior which could be due to measurement error or station mislocation. An inversion excluding these was performed as a confidence test for the existence of the feature. The result shows a widening of the zone, with most other details of the image remaining intact. Since these rays are those which are most likely to artificially induce the low velocities, this result gives us more confidence in the reality of the anomaly.

The anisotropy corrected 1988 travel times produce a good image of the velocity field at FRI. Most of the features in this image correlate well with the geology logs of boreholes 87.001, 87.002, 87.003 and the access and laboratory tunnels. Figure 8 shows these logs mapped on to the velocity field image. In 87.001 the areas of greatest fracture frequency are centered at 16 meters and 10 meters from the laboratory tunnel. These are seen to correspond well with two large low velocity features. At 5 meters a hydrothermally altered zone associated with a tension fissure creates another low velocity anomaly. This tension fissure is probably associated with the lamprophyr observed in the laboratory tunnel, about two meters to the right of 87.001 which produces an extension of the low velocity zone. About a half meter to the right of this is a zone of higher (or about normal) velocities. The tunnel log shows that this appears to be due to a single fracture observed at this point. It is not known why this fracture would produce high velocities. At about two meters to the right of 87.002 the main fracture of the shear zone intersects the laboratory tunnel, corresponding to a half-meter-wide, low velocity zone. The strike of this fracture is N52E as measured off the wall which is not as steep as

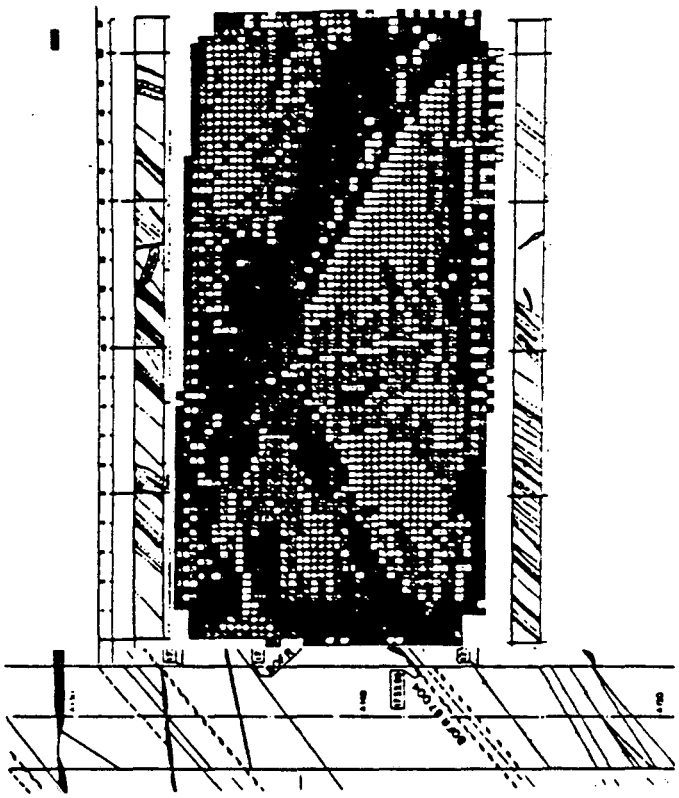

Figure 8. Core logs superimposed on 1988 results after anisotropic correction.

the image shows (N60E). It is possible that we are imaging a small lamprophyr which is observed along this fracture in boreholes 87.003 and 87.004. In borehole 87.002 the most highly fractured region occurs at 5 meters from the laboratory tunnel. A low velocity zone extends from this area toward the large low velocity region near 87.001. This region appears to be a point of intersection between several zones, including feature B. A cluster of tension fissures occur at 10 to 12 meters in 87.002. These correspond to a broad low velocity anomaly adjacent to the borehole. They do not appear to extend more than a meter or two away from the borehole.

The most dominant feature in the velocity field is the feature extending from the access tunnel to the center of 87.001. This fractured area seems to consist of subhorizontal fractures with the access tunnel logs showing a tension fracture in this same area. It is most likely that this feature is associated with a lamprophyr or an especially large tension fissure. The strike is different from the lamprophyrs in the immediate area, but lamprophyrs are not known for their consistent behavior, especially when associated with shear zones.

These results show that the imaged velocity field, and the actual velocity field can be quite different than that deduced from the geology. Unexpected zones are imaged which may be more hydrologically important than those determined from borehole and tunnel observations. At FRI it is probable that the low velocity zones are produced primarily by lamprophyrs, tension fissures and fracture intersections. The individual fractures are transparent to the seismic waves at these frequencies.

Hydrologic Analysis of FRI Experiments

At Grimsel test site, NAGRA conducted constant pressure hydraulic tests in conjunction with the seismic tests described in the previous section. In a constant pressure test, the hydraulic head in an isolated interval is kept constant and the transient flow rate is monitored. In very low permeability rocks, like the one at Grimsel test site, constant pressure is generally easier to achieve than a constant rate. It is also easier to minimize the wellbore storage effect in a constant pressure case. Moreover, because the rock near the wellbore is subjected to a constant pressure throughout the test, there is less concern about the permeability changing as a function of time. However, the permeability may change in the location away from the well as the pressure front propagates into the rock.

In these tests it is important to measure early time data as accurately as possible. Transient data reflects the change of permeability in space as a function of time. In this regard transient data is more descriptive of the rock heterogeneity than steady state data, which is influenced by the spatial arrangement of heterogeneity in an unknown way. Especially when there is a skin zone near the well, one should be able to resolve it using a set of good transient data (i.e., flow period and shut-in period).

The hydraulic tests were planned based on the 1987 tomography results (Figure 3). Packer locations are shown on Figure 9 with packer locations used in Tests A, B and C. Each test consisted of pumping water in the zone at a constant pressure and monitoring in all the other zones. Objectives of each test were: (1) to find hydraulic connection with other zones, (2) to characterize the properties of zones that are hydrologically active, and (3) to try to confirm the existence of zones about which we have only inconclusive evidence.

The purpose of Test A was to provide a hydrologic characterization of a feature which is clearly evidenced by geophysics. The packers for Zone I was placed such that they confine the fracture Zone I as tightly as possible in order to minimize wellbore storage and isolate the hydrology of the feature.

The purpose of Test B was to see if the feature IV is hydrologically significant. This test would have been conclusive if the result was positive. A negative result would have meant that the zone is not connected to anywhere being monitored. A positive test result would have

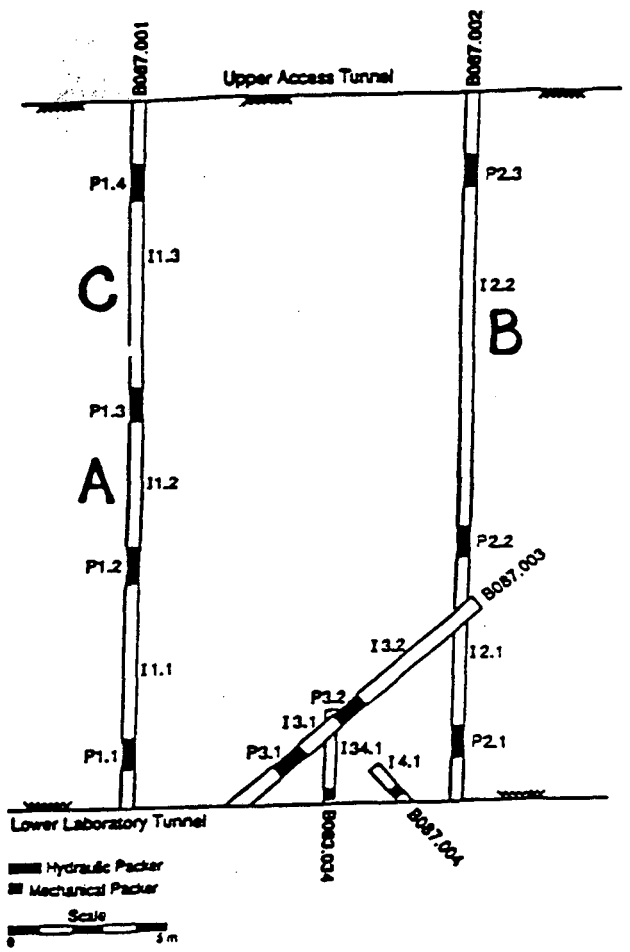

Figure 9. Packer locations used in Tests A, B and C.

been very significant because the geophysics was the only tool that could see this feature.

Test C was designed to understand the south-eastern part of the shear zone. Zone I in the north-west appeared clearly in the tomogram as extending across the tomographic plane. Zone II appeared in BOFR87.001 core and in the vicinity of the hole in the tomogram. Likewise, Zone III appeared in the BOFR87.002 and nearby in the tomogram. However, the tomogram didn't indicate that this part of the shear zone is continuous. The test was designed to see if there is continuity of if a cross-cutting feature such as IV or V might exist.

In this paper the results of Test A is closely examined. Readers interested in the details of all the test results are referred to Wyss (1988).[12]

Figure 10 shows the interference pressure transient data at various observation points in Test A. Note that the interval 3.1 responds most markedly. The pressure observed at I3.1 is significantly lower than that predicted by an analytical solution. The analytical solution assumes that the fracture is infinite, isotropic and homogeneous. Therefore, conditions must exist where one or more of the above assumptions are not appropriate. The plausible scenarios are:

(1) Skin: There is a low permeability zone around the injection well, i.e., a skin that causes the effective pressure at I1.2 to be lower.

(2) Anisotropy: The fracture is anisotropic where the maximum permeability direction is oriented vertically.

(3) Leakage: There is leakage from the fracture to the adjacent rock so that the pressure is more dispersed.

(4) Boundary Effect: The boundary effect of the laboratory tunnel is keeping the pressure stay low at I3.1.

The tests have confirmed the hydrologic significance of the fracture zone which was previously identified by the seismic tomography. It appears that the majority of the flow occurred within the relatively thin fracture zone which connects Zone I1.2 and I3.1. A weak but definite hydrologic connection between Zone I1.2 and I2.2 was also observed. The feature identified by the seismic tomography that extends diagonally from the access tunnel the BOFR87.001 may explain this hydrologic connection.

Because of the anomalous interference and flow-rate data, four different scenarios that differ from the ideal

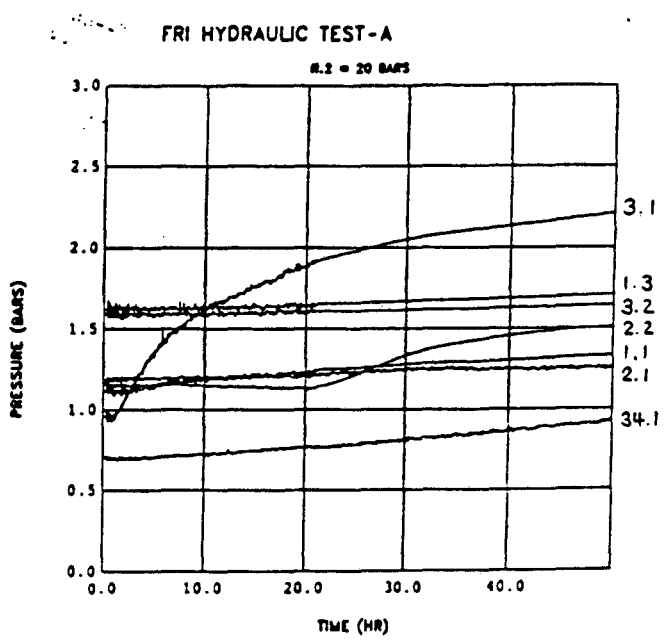

Figure 10. Interference buildup data for Test A at various observation points.

conditions were examined. They are: (1) skin, (2) anisotropy, (3) leakage, and (4) boundary effects. In the reality all of the four conditions may coexist. The most significant effect, however, seems to be the leakage into the rock.

SUMMARY

The results of the field work to date indicate that the original premise of using P- and S-waves for mapping fracture content is valid. The main fracture zone in the FRI zone was detected using P-wave tomography. The S-wave was attenuated so strongly by the fractures that given a strong enough S-wave source then one could assume that S-wave data would be even more sensitive to fracture content than P-wave data. Other low velocity zones in the FRI area were also detected, the most significant being the velocity anomalies associated with the stress relief at the tunnel walls. This work is rather conclusive in showing the difference in the damage zone between a tunnel excavated with a tunnel boring machine and a tunnel excavated by drill and blast. There were also other zones of low velocity detected in the FRI zone, most notably the low velocity zone ("dark zone") extending in along borehole 87.002 from the access tunnel approximately 8 meters. This may be due to small fractures, or as laboratory work suggests, a difference in the rock type. The core do not show significant fracturing in this zone, but the core velocities are lower for this type of rock than for the rock in the "light zone".

Future work should focus on using improved shear wave data for improving the resolution of the technique and for defining such parameters as fracture density and spacing.

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