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SEDIMENTARY ROCK IN EAST TEXAS

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Microearthquakes induced by a hydraulic injection in sedimentary rock, East Texas

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Summary

In October, 1993, ARCO carried out a hydraulic injection near Beaumont, TX, into an unconsolidated sand, the Frio Formation. Fluid was injected into a 55m long zone at a depth of 1350 m. Four separate injections were done during 5 days. A total of more than 2.1 million gallons of bentonite slurry was injected, along with more than 3 million pounds of sand. Downhole fluid injection pressures ranged between about 3,000 and 3,500 psi.

Induced microearthquakes were monitored by a set of 25 geophone packages situated in each of two monitoring well. More than 2,400 microearthquakes were recorded during the injection, although most were too small to locate reliably using arrival times. A total of 54 microearthquakes were selected for detailed study. They were precisely located using arrival times of P and S phases from both of the monitoring boreholes. These locations are distributed non-uniformly, with a cluster near the injection borehole, a linear distribution about 200 m from the injection borehole, and a relatively quiet zone in between. The large vertical extent of the geophone packages allowed an inversion of the arrival times for transverse isotropic elastic parameters, which yielded Vp anisotropy of about -13% and Vs of about -2%. Since these anisotropy values indicate that the vertical Vp and Vs are larger than the horizontal, they are surprising for this well bedded formation.

Single-event focal mechanisms could be determined for 47 of the microearthquakes, and all are shear slip type. They show a large range of mechanisms, ranging from normal to reverse slip. Normal or oblique-normal slip predominant, though, with T (tensional) axes generally nearly horizontal and approximately N-S.

Introduction

A demonstration of a solid-waste injection was done in Jasper County, Texas, near Beaumont, in October, 1993. This involved one injection borehole (FTD-2) and two boreholes (FTD-1 and FTD-3) for microseismicity monitoring. Figure 1 shows a perspective view of the wellbores. More than 2.1 million gallons of a bentonite slurry was injected into a 55 m perforated interval at a depth of about 1350 m. Along with the fluid, more than 3,000,000 lb. of sand was injected. There were four separate injection cycles that extended over 5 days. Bottom hole injection pressures ranged from about 3,000 to 3,500 psi, with the injection well shut-in between injection cycles. The maximum injection rate was about 13.5 bbl/min. during the last injection cycle.

Figure 1. Perspective view of the boreholes, with depth range of monitoring geophones and injection shown.

Induced microseismicity was monitored by a suite of 25 three-component geophone packages in each of the two nearby monitoring boreholes (see also the paper by Withers and Rieven, in this volume). The geophone packages were positioned at 30 foot intervals. The extensive geophone coverage was important to satisfy one of the objectives of the injection, which was to determine the vertical extent of the fracturing. The total number of geophone channels that could be recorded was 96, so all three geophone components were recorded from alternate geophone packages, and only the vertical geophone components were recorded from the other packages.

The large range of depths covered by the geophone packages makes it possible to analyze the microearthquakes in detail. The large number of microearthquakes that were recorded (more than 2,400) made it impossible to study all of them carefully. Microearthquakes were selected for study if they were large enough to be recorded clearly above the background noise level. Generally the microearthquakes had large S arrivals that were easily identified at many geophones. The P arrivals were generally much smaller, however. Events that were selected had several reliable S picks from each monitor borehole, and at least one reliable P pick from each borehole. A total of 54 microearthquakes were selected for detailed study.

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Induced Microearthquakes and Locations

Both P and S arrival times for the 54 selected microearthquake were picked from as many of the geophone packages as was possible. To make the picking easier and more reliable, the seismograms from the three component packages were rotated into Longitudinal-Radial-Transverse components.

The orientations (azimuths) of the horizontal components of each geophone package had to be determined to be able to rotate the seismograms. Several primacord shots were set off at different depths within the injection borehole and were recorded by various 96 trace subsets of the geophone components. The seismograms from those explosions were used to determine the orientations of the geophone packages, as well as an initial velocity structure. For the packages that recorded multiple shots, the differences in orientations from the shots was about 5 degrees or less. After making initial arrival time picks, tentative event hypocenters were determined and then used for a final rotation of the seismograms into P, SH and SV components. Improved arrival times for P, SH and SV were then picked from the rotated seismograms. These were used to calculate hypocenters with the initial, homogeneous, isotropic velocity structure, and are shown in Figure 2. The velocities used (v_p of 2.47 m/ms and V_s of 1.12 m/ms) were chosen from travel times from the shots, and agree with those estimated from the velocity logs.

The epicenters define three separate groups: near the injection, far from the injection (more than 100 m) and between the near and far groups. Interestingly, all the epicenters lie to the SW of the injection borehole, on the same side as the monitoring instruments. Analysis of a fuller event set from this experiment (Withers and Rieven, this volume) shows a similar picture, even though they made a careful search for events that might have been located to the other side of the injection borehole.

The epicentral distribution that Withers and Rieven (this volume) found is from many more earthquakes and differs somewhat from what is shown in Figure 2. Their epicenters extend about 170 m farther to the SW (along a trend of N120°W) than what is shown in Figure 2. In addition, they found a N10°E striking trend of epicenters that extended about 120 m from the injection borehole. Apparently none of the events in that trend passed the event selection criteria for this study.

In depth view (Figure 2), the hypocenters are confined to a narrow range of depths - 1360 to 1390 m, with those in the far cluster confined to a zone only 10 m thick. All events occurred within the Lower Frio formation, which contained the injection interval, and most are toward the deeper side of the formation. None were located near the

top of the Lower Frio formation, which was an important conclusion for the injection experiment.

Figure 2. Plot of selected microearthquake locations calculated with the initial isotropic homogeneous velocity structure. Top: epicentral view. Bottom: depth section, looking North.

Considering the three-dimensional distribution of the hypocenters, those in the far cluster define a fairly narrow tube of events that approximately aligns with the injection borehole. Considering the trend of those far events and the position of the injection borehole, we would estimate a fracture elongation direction of about N120°W degrees, which suggests that the minimum principle stress is oriented about NNW-SSE.

Events in the middle group are sparse and only roughly align with the trend of the events in the far zone. It appears that the continuity of the fluid pathways may be disrupted in the area of the middle zone. Yet the unconsolidated character of the Frio formation, suggests that there are unlikely to be features in it that would be profound enough to significantly alter or disrupt fluid pathways. Thus, the apparent disruption of the event distribution seen in the middle group events is an enigma.

Inversion for Transverse Isotropy

The Frio formation is a well-bedded formation that is nearly horizontal-layered in the area of the injection. The large depth range of the monitoring geophones provided ray paths that sampled a large range of vertical angles. Those two factors suggested that the data set was well suited to study transverse isotropy.

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Transverse isotropy (TI), or hexagonal symmetry, is the simplest form of anisotropy that has general applicability in geophysics. It is characterized by two orthogonal directions of uniformity (usually taken as horizontal) and a third direction, typically vertical, which has different elastic parameters.

Following the derivations of Thomsen (1986) and Banik (1987) we simultaneously inverted for the 5 independent elastic moduli, C11, C13, C33, C44, and C66, and revised earthquake hypocenters. The seismic velocities and anisotropy values could then be derived from the elastic moduli. Although not solved for by the inversion, the bulk density affects the resulting elastic moduli, and is also needed to derive velocities from the moduli. Densities from the well logs averaged about 2.15 to 2.20 g/cc, and we chose two densities: 2.1 g/cc as a lower bound, 2.5 g/cc as an upper bound, and present the results for the density of 2.1 g/cc below. The elastic moduli were slightly different when the density of 2.5 g/cc was used, but the derived velocities and anisotropies were nearly identical to those from the 2.1 g/cc inversion.

Table I. Parameters Calculated from Inversion, density of 2.1 g/cc.

Parameter	All Events (54)	Far Zone (28)	Near Zone (17)
γ (S anisot.)	-0.02	-0.03	-0.02
ϵ (P anisot.)	-0.14	-0.14	-0.13
δ (med. anisot.)	-0.12	-0.11	-0.12
V_{ps} (m/ms)	2.41	2.39	2.42
V_{sz} (m/ms)	1.02	1.02	1.02
Poisson Ratio _z	0.39	0.39	0.39

The revised hypocenters obtained from the simultaneous inversion are shown in Figure 3. The epicenter view (top) shows a distinctly different trend for the far zone events compared to the isotropic velocity structure. Those far zone events trend nearly EW in Figure 3, compared to more NE-SW with the isotropic velocity structure. Thus, the trend of the far-zone epicenters in Figure 3 no longer aligns toward the injection borehole, but rather is notably oblique to it. The near injection epicenters are shifted slightly to the SW in Figure 3 compared to Figure 2. Finally, the middle zone events are very close to the line of symmetry between boreholes FTD-1 and FTD-3.

The overall root-mean square travel time residual for the simultaneous inversion (2.58 ms) is distinctly lower than the RMS of the isotropic locations (3.60 ms), which suggests that the TI inversion has fit the travel time data somewhat better than the isotropic velocities did.

Looking at the hypocenters in depth view (bottom of Figure 3), the depth range of the far zone events is even smaller (perhaps only 10 m) than for the hypocenters in

Figure 2. The combined near and middle zone hypocenters appear to progress to systematically greater depths with increasing distance from the injection borehole, and those two zones appear continuous in this depth view. Compare that to the obvious discontinuity seen in the epicentral view of Figure 3. The deepening to the SW seen in the near and middle zone events truncates near the position of borehole FTD-3, where the far zone events show only a very slight deepening to the W.

Figure 3. Microearthquake locations obtained by the simultaneous inversion for transverse isotropic (TI) moduli and earthquake hypocenters. Top: epicentral view. Bottom: depth section, looking North.

Earthquake Mechanisms and Stresses

A total of 47 of the 54 selected microearthquakes showed sufficient clear and consistent first motions to allow determining single-event focal mechanisms. A summary of the mechanisms for the far and near injection zone events is shown in Figure 4. The first conclusion we draw from these mechanisms is that the larger microearthquakes resulted from shear displacement along slip planes, rather than purely tensile opening of fractures.

There is considerable scatter among individual mechanisms, but the T ("tensional") axes for the near injection zone events are generally nearly horizontal and

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trend to the SE, perpendicular to the general trend of the fracture extension inferred from the seismicity of Figure 2. The P axes of the near injection events are more spread out, but approximately define a NE-SW trending swath of varying plunge, that would imply that the maximum principle stress is nearly vertical and is thus consistent with opening of NE-SW trending near-vertical fractures.

Figure 4. Plots of P, T axes for events in the far (left) and near (right) clusters of seismicity

The mechanisms of the far zone events are even more scattered than those of the near zone. Both the P and T axes plunge fairly steeply, about 30 to 60 degrees, and define an approximate cone (seen as a circle in Figure 4). T and P axes are intermingled within this conical distribution, suggesting that the magnitudes of the principle stresses may be similar.

Overall, there is a predominance of normal to oblique normal slip, which is consistent with the normal faulting stress state in the Gulf Coast region summarized by Zoback and Zoback (1980). In spite of the predominance of normal or oblique normal slip, there is a tremendous range of different slip types, from pure normal, to oblique normal, to nearly pure reverse slip. That large range of slip types also suggests that the magnitudes of the principle stresses may not be similar.

Conclusions

Extensive monitoring for induced microearthquakes during a hydraulic injection in the sedimentary Frio formation of east Texas produced a large, high quality data set. This injection demonstrated that fluid injection into even unconsolidated sediments can produce microseismicity. Although most of the induced microearthquakes were small, many were large enough to be well recorded at both monitoring boreholes.

These well-recorded microearthquakes show two different spatial characters. Events near the injection borehole have epicenters that are scattered. Events far from the borehole have epicenters that align NE-SW or E-W, depending on the velocity structure used to locate them. Between the near and far zones lies a poorly defined middle zone, in

which there were few well-recorded events. The relatively nonseismic behavior in the middle zone compared to the other two zones suggests that the middle zone represents a discontinuity in the Frio Formation, although no obvious discontinuity has yet been identified from logs or nearby seismic reflection profiles.

The large depth extent of the monitoring geophone packages allowed inverting for anisotropic elastic moduli, under the assumption that the sediments satisfied transverse isotropy. A simultaneous inversion for transverse isotropic elastic moduli and revised earthquake hypocenters produced surprising results. First, the P wave anisotropy (-13%) far exceeds the S wave anisotropy (-2%), and second, both the P wave velocity and the S wave velocity are higher for vertical propagation, compared to horizontal propagation.

Single-event focal mechanisms were determined for most of the studied events, and show that the largest of the induced microearthquakes resulted from shear slip, rather than tensile opening. There is considerable diversity of mechanism orientation and slip type. Since the Frio Formation that was injected is unconsolidated and therefore is not likely to contain well-developed slip surfaces, we expected to find much less diversity in the mechanisms.

Additional analysis of the seismicity data from this hydraulic injection is aimed at trying to extract more information about the fluid flow paths by analysis of secondary arrivals in the coda of the direct P and S waves. If successful, that analysis may allow identification of individual fluid flow pathways within the fracture system.

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References

- Banik, N.C., "An effective anisotropy parameter in transversely isotropic media", *Geophysics*, 52, 1654-1664, 1987.
- Tomsen, L., "Weak elastic anisotropy", *Geophysics*, 51, 1954-1966, 1986.
- Zoback, M.L., and M. Zoback, "State of stress in the conterminous United States", *J. Geophys. Res.*, 85, 6113-6156, 1980.