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Integrated Seismic Study of Naturally Fractured Tight Gas Reservoirs**TECHNICAL PROGRESS REPORT****for the Period: 1/1/94 - 3/31/94****Report Date 4/29/94**

DOE Contract: DE-AC21-91MC28087
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This was the tenth quarter of the contract. During this quarter we (1) continued processing the seismic data, and (2) continued modeling some of the P-wave amplitude anomalies that we see in the data.

Review of Study Area; Structural Trends and Fractures

The study area is located at the southern end of the Powder River Basin in Converse County in east-central Wyoming. It is a low permeability fractured site, with both gas and oil present. Reservoirs are highly compartmentalized due to the low permeabilities, and fractures provide the only practical drainage paths for production. The two formations of interest are:

- The Niobrara: a fractured shale and limey shale to chalk, which is a reservoir rock, but also its own source rock.
- The Frontier: a tight sandstone lying directly below the Niobrara, brought into contact with it by an unconformity.

Figure 1 shows the project basemap, with the locations of the four multicomponent lines. As stated in previous quarterly reports, we find the trend of the seismically-inferred primary set of fractures to be fairly consistent over the study area, i.e. WNW-ESE. These are the fracture orientations inferred from analysis of shear wave splitting, and correspond to the polarization direction of the "fast" shear arrivals. There is also an anomalous zone near the intersection of lines 2 and 3, possibly indicating additional fractures superimposed at a different orientation. A change in apparent rotation angle is also observed to the east on line 4. The relationships between these trends and fracture identification logs were discussed in the previous report.

Data Processing

During these three months we finished processing on all four lines the P-to-shear converted waves, the last important part of our dataset. We also continued to clean up all of the P-to-P data so that a reasonably reliable amplitude analysis can be performed. We believe that this marks the end of the large scale seismic data processing work for this dataset. The only two components left, SV-P and SH-P, are fairly unconventional, and we see no reason that this particular kind of survey will be carried out in the future that collects only the P component data of the shear wave sources without collecting the shear

components. The information obtained from the SV/SH-P data, however, may put more constraints on our theoretical modeling to interpret the data and can be used as a source of collaboration or verification. Therefore we may process them after we finish the major part of the modeling and interpretation.

Possible evidences of anisotropy and interesting observations

The most direct evidence of P-wave anisotropy is obtained at the intersection of line 2 and line 3. At this location we have the opportunity to compare two CDP gathers (from the P-wave data) with different orientations, the CDP 1333 on line 2 and the CDP 1226 on line 3. To enhance the signal we stacked five adjacent CDP gathers centered on the intersection for each line. The result is shown in Figures 2a and 2b. The traces in these enhanced CDP gathers are filtered by a bandpass filter (10-60 Hz) and corrected for spherical divergence. No other scaling or processing is performed to preserve the amplitude.

As we can see, in the CDP of line 3 (Figure 2b), the events at 1860 msec, 2150 msec and 2600 msec are fairly strong and continuous, and their relative amplitude change is small, compared to their counterparts in the CDP gather of line 2 (Figure 2a). It is also interesting to note that the 1860 msec event is almost invisible in Figure 2a. These observations suggest that P-wave reflectivity and AVO pattern vary with orientation, which can be interpreted as evidences of anisotropy.

Similar observations can be made from the "true amplitude" P-wave stack sections of lines 2 and 3, shown in Figures 3a and 3b. The stacks are obtained by careful trace editing to get rid of the traces with erroneous amplitudes, applying a wide bandpass filter, and a geometric spreading correction. Both stacks are centered on the intersection of line 2 and 3. In addition to the difference in relative amplitudes of shallow and deep events as mentioned above, it is obvious that the event at 2.3 sec of line 3 is much stronger than that of line 2.

If vertical fractures are present, we expect that they will not affect very much the velocity of near vertically traveled P waves. They will, however, change the reflectivity pattern as observed in the P-wave stack in different azimuths by affecting the shear velocity. Since the stack is determined by the total reflected energy of all traces, natural fractures may have strong signatures in true amplitude stacks. Figure 4 shows another true amplitude stacked section of line 2. Notice the striking amplitude change of the deep events across the page and the relatively stable shallow events at 1560 msec and 1800 msec. We plan to focus our modeling activity on this region.

We want to point out that with 3D seismic data, which is becoming more and more popular nowadays, some kind of P wave signal variations with azimuth can be obtained not just at a few isolated locations and orientations as in our survey, but for almost the whole survey area and in many directions. The information can be used to identify strongly AVO anisotropic areas, and if we assume that the anisotropy is introduced by natural fractures, it can perhaps be used to quantify the fracture intensities.

P-SV/SH converted data processing

Another data type that we considering with great interest is the P-to-S converted waves. These hold great practical interest, because P-to-SV and P-to-SH data can normally be collected with relatively little additional expense beyond a conventional P-wave only survey. P-wave source to two-component converted shear wave data can be used to directly identify possible anisotropic regions. Figures 5a and 5b show the P-SV and P-SH stack sections of line 2, respectively. Notice the absence of shallow events in the P-SH section, meaning that either the shallower layers are relatively isotropic, or the principle axis of anisotropy is in the same direction as our survey line. We are inclined to the believe the first possibility, because the four-component shear wave rotation analysis shows that the principle axis of anisotropy in that area is 20° from the survey line – and this angle seems to apply to all depths. The strong localized P-SH deep events (3.3-3.5 sec) are among the first targets of our modeling and interpretation.

Plans for Next Quarter

We will continue to analyze and model the seismic data. We have found a number of spacially varying anisotropic attributes during the course of processing the data: shear wave rotation angles, shear wave splitting arrival time differences, azimuthally dependent P-wave stacking velocities, azimuthally dependent AVO patterns, spacially varying P and S-wave reflectivity. The challenge now is to find physical models of fracture occurrence that are consistent with all or most of these attributes.

Figure 1: Basemap showing locations of the survey lines, labeled Lines 1-4.

Figure 2: CDP gathers at the intersection of lines 2 and 3. (a) CDP from line 2. (b) CDP from line 3.

Figure 3: Portions of the P-wave true amplitude stacks at the intersection of lines 2 and 3. (a) Line 2. (b) Line 3.

Figure 4: Portion of P-wave stack of Line 2, showing the spatially variable reflectivity.

Figure 5. (a) P-to-SV and (b) P-to-SH stacks on Line 2.

Figure 1

Figure 2

(a)

(b)

Figure 3

(a)

(b)

Figure 4

Figure 5

(a)

(b)

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