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Integrated Seismic Study of Naturally Fractured Tight Gas Reservoirs

TECHNICAL PROGRESS REPORT
for the Period: 10/1/93 - 12/31/93

Report Date 1/29/94

DOE Contract: DE-AC21-91MC28087
Principal Investigator: Dr. Gary Mavko
Co-PI: Dr. Amos Nur

Department of Geophysics
Stanford University
Stanford, California 94305-2215

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This was the ninth quarter of the contract. During this quarter we (1) continued processing the seismic data, (2) collected additional logs to aid in the interpretation, and (3) began 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.

During this quarter, we obtained additional well log data from Arco Oil and Gas. We are attempting to relate this data to the other wells already in our inventory, and to incorporate this information into the final interpretation.

Figure 1 shows the project basemap, with the locations of the four multicomponent lines, and several wells labeled for reference. On this map are superimposed several features. A thin line trending southeast from the western edge of the project marks the beginnings of a steep flexure, beyond which the beds ramp up sharply to the southwest. The flexure marks the southwest edge of the Powder River Basin and can be seen clearly on seismic lines 1 and 3. Amoco's geologist has speculated that at least some of the fracture sets in the area should trend parallel with the flexure axis, roughly corresponding to the maximum curvature of the beds. We are finding seismic anomalies that are consistent with this.

As stated in the previous quarterly report, 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. However there is an anomalous zone trending roughly east-west, shown by the darker shaded region (Figure 1), where the rotation analysis is poorly defined, possibly indicating additional fractures superimposed at a different orientation. A change in apparent rotation angle is also

observed to the east, on line 4 and on the logs for the Apache well. The relationships between these trends and fracture identification logs were discussed in the previous report.

P-wave Amplitudes - Post Stack

P-wave amplitudes from the Niobrara and Frontier show several interesting variations along the lines. Thus far, we have extracted amplitudes from edited, true-amplitude sections for the Niobrara, Frontier and a reflector located at a shallower level. (In this case, "true amplitude" means that we have processed the data using (1) spherical divergence amplitude correction, (2) no AGC, and (3) careful hand editing to remove noisy traces.) The shallow reflector has a fairly constant amplitude throughout the survey, so we use it as a "reference" trace to normalize the Niobrara and Frontier reflections. This is an approximate and heuristic surface consistent correction. We have also reprocessed all of the P-wave lines with a true surface consistent analysis to find and correct for the spatially variable source strength and receiver coupling.

Figures 2 and 3 show smoothed, "normalized" amplitudes for the Niobrara and Frontier reflections for lines 2 and 3. These were produced by picking the maximum amplitudes within a specified window on the full stack, with a 9-trace mix applied. Next, the picks were smoothed over a 25-CDP range and scaled by dividing by the amplitude of a shallow event at approximately 2100 ms. The normalized Niobrara (Figure 2) in particular, ties very well at the intersection of the two lines. The Niobrara reflector also has an anomalously high amplitude with respect to the rest of the line in the zone marked "anomalous rotation" which corresponds to the dark shaded region on the map (Figure 1). The normalized Frontier ties somewhat less well, and shows high amplitudes only for Line 2 in the "anomalous rotation" zone.

Since the northwest-oriented fracture trend, discussed in previous reports, is nearly parallel to Line 2, these fractures would not likely be detectable on this line. The anomalously high amplitude may indicate some change in this orientation, or possibly the presence of an additional, superimposed fracture set with an orientation more favorable for detection. Structurally, the area in the vicinity of line 2 between lines 3 and 4 is apparently at the crest of an anticlinal feature at the Niobrara level. The changing structural attitude in this area may also mark a change in fracture pattern and/or spacing. Further analysis is needed to justify these speculations.

P-wave Amplitudes - PreStack

Figure 4 shows reflector amplitudes of all traces, pre-stack for line 4. The amplitudes were obtained after carefully editing the noisy traces and then making a surface consistent amplitude analysis on an event at 2.5 seconds (two-way travel time), to remove the source and receiver variability. In the figure, blue is low amplitude and red is high amplitude (a range of 1:10). In this type of plot, vertical lines correspond to all of the traces have the same receiver; horizontal lines correspond to all of the traces in a common shot gather; lines trending 45° from lower left to upper right correspond to all traces having the same offset; and lines trending 45° from upper left to lower right correspond to CDP gathers. Several dominant AVO trends are readily apparent. At the lower left, the reflectivities are relatively high at all offsets, without a significant AVO trend. Next to this is a band of low amplitude CDPs, again without a significant AVO trend. Farther to the right is a band of traces with high amplitude near offsets, and a strong decrease with offset. These last two bands correspond to regions with two strikingly different shear wave rotations. If significant, this could be a P-wave signature of the fracture variation.

Figure 5 shows theoretical modeling of P-wave reflectivity. The upper layer is isotropic, and the lower layer is weakly azimuthally anisotropic. The vertical axis is reflectivity and the horizontal axis is angle of incidence (approximately the offset). Each curve shows the AVO trend for a different angle between the source-receiver line, and the material symmetry plane (fracture orientation). This shows a large variation with fracture orientation, even though the anisotropy is very small (4%). We are in the process of comparing the patterns in Figure 5 with the spatially variable reflectivities in Figure 4.

Plans for Next Quarter

We will continue to process, analyze, and model the seismic data, and to compare our interpretations with information from logs. We will be looking more closely at the P-wave data for reflectivity and AVO anomalies that correlate with the fracture occurrence.

Figure 1: Basemap showing locations of the survey lines, labeled Lines 1-4, and several wells (small circles). Also shown are fracture orientation determinations from rotation analysis (labeled by fast and slow directions) and from log results for the Apache State well. Shaded area represents region of anomalous rotation analysis results.

Figure 2: Normalized amplitude of Niobrara reflection, Lines 2 and 3, showing apparent amplitude increase in anomalous rotation zone.

Figure 3: Normalized amplitude of Frontier reflection, Lines 2 and 3, showing a pronounced amplitude decrease near the Energetics Sims well (see basemap, Figure 1).

Figure 4: Prestack reflector amplitudes of event at 2.5 seconds on line 4.

Figure 5. Theoretical amplitude variation with offset for an isotropic layer over an azimuthally anisotropic layer, with different angles between the source-receiver line and the symmetry plane.

DOE Fractured Reservoir Project - Base Map

Norm. Ampl. Niobrara (peak), Line2, 25-trace smooth, Full stk

Norm. Ampl. Niobrara (peak), Line3, 25-trace smooth, Full stk

Normalized Ampl. 1st Frontier, Line2, 25-trace smooth, Full stk

LINE 2, CDP 2450

LINE 2, CDP 2850

Normalized Ampl. 1st Frontier, Line3, 25-trace smooth, Full stk

LINE 3, CDP 2450

SW ↗

Line 4: Surface-consistent RMS Amplitude (event at 2.5 seconds)

P-wave Reflectivity vs Angle of Incidence

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