2

DOE/MC/28087-3596

Integrated Seismic Study of Naturally Fractured Tight Gas Reservoirs

TECHNICAL PROGRESS REPORT
for the Period: 7/1/93 - 9/31/93

Report Date 10/23/93

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

Department of Geophysics
Stanford University
Stanford, California 94305-2215

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Se

This was the eighth quarter of the contract. During this quarter we (1) continued the large task of processing the seismic data, (2) collected additional geological information to aid in the interpretation, and (3) continued integrating regional structural information and fracture trends with our observations of structure in the study area.

Review of Study Area; Available Seismic and Well Information

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.

Structural Trends, Rotation Analysis Results, and Fractures

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 the seismic lines 1 and 3. At the start of the project, Amoco's geologist 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 at least qualitatively consistent with this.

The results of rotation analysis of the multicomponent seismic data (discussed in the next section) are marked by arrows designating the fast and slow shear wave polarization directions. Typical analyses suggest that if the seismic anisotropy is related to fractures, then the fractures are trending parallel to the fast axis (which, if fact is roughly parallel to the flexure axis); a conjugate set of fractures is also possible, perpendicular to the main set,

but it would be expected (from the typical seismic interpretation) to be less intense. We find the trend of the seismically-inferred primary set of fractures to be fairly consistent over the study area. However there is an anomalous zone trending roughly east-west, shown by the darker shaded region, where the rotation analysis is anomalous and poorly defined, possibly indicating additional fractures superimposed at a different orientation. The northeast end of line 4 shows an anomalous orientation, which is consistent with orientations determined from fracture identification logs from the Apache #36-1 State well. The trends from this well are approximately N50°E for the Frontier formation, and N30°W for a group of fractures within the Niobrara. As stated in previous reports, northwest-trending fractures were found by Lewis *et al.* (1991, Geophysics) for the Niobrara at Silo Field in southeastern Wyoming. Laubach (1992, GRI Tight Gas Sands Report), in a study of the Green River Basin and Moxa Arch area of southwestern Wyoming, noted that Cretaceous and younger deformation has produced north-, northeast- and east-trending fractures in the foreland basins. This latter trend is approximately in agreement with that found in the rotation analysis. However, further work is necessary to reconcile the results from the seismic and those from the well logs, and to interpret the meaning of the interesting "anomalous" (shaded) area.

Figure 2 shows a preliminary structure map on the top of the Niobrara shale. The crest of a structural high appears to be centered just to the southeast of the intersection of lines 2 and 3 at this level, and slightly farther west at the Frontier level. The central high, around the well labeled "Energetics Sims," also corresponds roughly to the area between the two zones of differing fracture orientation. Thus, the axis of the proposed anticlinal feature at this level may mark a shift in fracture orientation with respect to the structure. The next step will be to relate the structural information to the seismic data (both arrival time and amplitude variation), in order to analyze the significance of this observation.

Data Processing

The four-component shear-wave data of the four survey lines, totaling 30 miles, are of very high quality. Exceptions are the southernmost 3 miles of line 1 and southernmost 2 miles of line 3, where there are high curvatures and steep dips.

Assuming the survey area is azimuthally anisotropic (due to vertical fractures, for example), we can find the symmetry axes by linearly combining the four-component shear-wave data to minimize the cross-talk between perpendicularly polarized sources and receivers. The idea is that when the source is polarized in the same direction as one of the

symmetry axes, it only generates a single of mode shear-wave, and no crosstalk will happen. We can simulate this by rotating our original dataset to align with the earth symmetry axes. This is sometimes called the Alford rotation. The basic assumptions here, in addition to azimuthal anisotropy, are that the symmetry axes stay the same at all depth, the rays travel nearly vertically, and the earth is a linear filter for this kind of experiment. These assumptions may not be strictly true, but the results of performing Alford rotation indicate that they are good approximations.

Under a rotation of angle θ , the resulting matrix of traces, v , can be computed from the original data in terms of

$$v = R \begin{pmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{pmatrix} R^T$$

$$= \begin{pmatrix} u_{11}\cos^2\theta + u_{22}\sin^2\theta + u_{12}\cos^2\theta - u_{21}\sin^2\theta - & \\ 0.5\sin 2\theta(u_{12}+u_{21}) & 0.5\sin 2\theta(u_{11}-u_{22}) \\ u_{21}\cos^2\theta - u_{12}\sin^2\theta - & u_{22}\cos^2\theta + u_{11}\sin^2\theta - \\ 0.5\sin 2\theta(u_{11}-u_{22}) & 0.5\sin 2\theta(u_{12}+u_{21}) \end{pmatrix}$$

where u_{11} , u_{12} , u_{21} , u_{22} are the recorded seismic traces and

$$R = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

is the rotation matrix.

Figure 3 shows a sample of the stacked four-component data before and after the rotation. Notice that the crosstalk drops below the noise level after proper rotation. When the events are strong, the rotation angle can be determined within $\pm 5^\circ$.

Figure 4 shows an example of shear-wave mistie between inline-inline and crossline-crossline events after the optimum rotation. There is no observable travel time difference between certain corresponding shallow events, but at greater depth, the mistie is quite large. This indicates that the main sources of anisotropy are in deep layers.

In some places, the crosstalk won't vanish for any rotation angle. In fact the events seem to be balanced so perfectly that their relative strength doesn't change much for different rotation angles. We believe that this is caused by either a variable fracture orientation with depth, or a superimposed set of fractures that distorts the symmetry of the material. We have observed several such anomalous zones as mentioned in the previous section.

It is very interesting to see that there is a strong correlation between reflected P-wave amplitude and such shear-wave anomalous zones. Figure 5 shows a P-wave true amplitude stack section. The amplitude of the marked event decreases dramatically within the anomalous zone. We are in the process of modeling the various causes of P-wave amplitude anomalies: pore fluid changes, fractures, porosity changes, etc.

Plans for Next Quarter

We will continue to process and analyze 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. This will include noise rejection studies, true amplitude processing, surface consistent amplitude analyses, and forward modeling of travel time and amplitude effects.

DOE Fractured Reservoir Project - Base Map

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: Preliminary structure map on the top of the Niobrara shale. Contour interval is 50 ft, except in steeply dipping areas (southwest part of the map) near the flexure, where the contour interval is 100 ft. Structure is based primarily upon 13 well log tops, with some integration with seismic in the steeply dipping areas and to the southeast.

Figure 3a: Four-component shear-wave stack sections at the same CDP locations before performing the Alford rotation.

Figure 3b: Four-component shear-wave stack sections at the same CDP locations after performing the Alford rotation.

Figure 4: An example of shear-wave mistie after the coordinate rotation. The left 50 traces are from inline-inline stack and the right from crossline-crossline stack. The CDP numbers are continuous from left to right.

Figure 5: P-wave true amplitude stack section. On the left side (in the shear-wave anomalous zone) the marked event is hardly observable, but on the right side (outside the shear-wave anomalous zone) the same event is very strong.

END

**DATE
FILMED**

2/25/94