

*Structure architecture interpretation of the middle Frio Formation using 3D seismic attributes and well logs: an example from the Texas Gulf Coast of the United States*

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The introduction of 3D seismic techniques three decades ago greatly enhanced our ability to image complex subsurface structure and stratigraphy in petroleum provinces around the world. 3D seismic provides an efficient tool in the recognition and recovery of reserves in both the new and mature oil fields (Nestvold, 1996). 3D seismic helps reduce dry-hole risk resulting in better well placement. 3D seismic can also add reserves in mature producing fields such as Stratton and Agua Dulce fields in the Texas Gulf Coast of the United States.

While the success of 3D seismic data as an exploration and development tool has been demonstrated many times, it is important to continue documenting this success in different geologic terranes. Therefore, the objective of this work is to show how 3D seismic data acquired in the Texas Gulf Coast sedimentary basin results in better subsurface structural images that were impossible to fully interpret from 2D seismic data and well logs.

Integrated approaches that use high quality data sets have a great promise for better reservoir development and exploitation especially in mature fields such as Stratton and Agua Dulce in south Texas. In the Stratton and Agua Dulce field area (Figure 1), two 3D seismic surveys resulted in imaging previously undefined small-scale faults at the middle Frio level that may have resulted in more reservoir compartmentalization. Previous analysis of well logs and 2D seismic sections in the Wardner lease of Stratton field indicate that faults die out at the lower Frio stratigraphic level and rarely extend upward into the middle Frio; the amount

of fault throw is usually small and fault block rotation is minimal (Levey et al., 1993, Figure 2). We will use our 3D seismic surveys to validate this earlier interpretation.

The Oligocene middle Frio Formation is a major hydrocarbon producer in the Gulf Coast of the United States. At Stratton field, the middle Frio Formation consists of multiple vertically-stacked reservoir sequences. The target stratigraphic interval for investigation is the basal part of the middle Frio Formation (BMF) interval between the G2 (top lower Frio) and the F11 horizons (Figure 3). The structural setting of the middle Frio Formation in the study area is represented by growth faults and associated rollover anticlines.

The complex internal architecture of the middle Frio fluvial reservoirs along with the structure complexity caused by growth faults may result in bypassed reservoirs or compartments that have potential reserve growth. Previous studies by Levey, et al.(1993) showed that untapped and incompletely drained reserves were encountered in the middle Frio reservoirs. Such results inspire the use of 3D seismic to search for additional by-passed gas resources in the BMF interval in the Stratton field area.

We used two post-stack final-time-migration 3D seismic surveys to develop a detailed structure architecture interpretation of the middle Frio (Figure 1). The first survey is a 90 mi<sup>2</sup> (235 km<sup>2</sup>) 3D data set provided by Anadarko Petroleum Corporation which was original shot in 1993 by Union Pacific Resources (UPR) Company and processed by Western Geophysical. The second is a 7.6 mi<sup>2</sup> (20 km<sup>2</sup>) public domain 3D seismic survey acquired in 1992 by the State of Texas Bureau of Economic Geology (BEG) at the University of Texas at Austin and processed by Mercury International Technology Company in Tulsa, Oklahoma. This latter 'public domain' survey is readily accessible through the BEG and has been the subject of dozens of published geophysics and geology papers. It is our hope that by presenting this smaller BEG survey in the context of the larger UPR survey, that we might inspire others to further refine the interpretation of the smaller BEG survey.

## **INTERPRETATION OF THE MIDDLE FRIO STRUCTURE ARCHITECTURE**

We used the vertical seismic profile (VSP) (Figure 4) acquired by the BEG at the Wardner 175 well in Stratton field to directly tie the seismic data to the geologic horizons. The Wardner 175 well with the VSP lies in the heart of the BEG survey and on the southern border of the UPR survey. The two 3D seismic surveys (BEG and UPR) used in the interpretation partially overlap in the northern Stratton field area (Figure 1).

**Major and Subsidiary Faults: Syndepositional or Post-Depositional?** The geological cross section (Figure 5a) illustrates the change in thickness of the interval between the marker top E41 horizon (MTE41) and the marker top lower Frio horizon (G2) in both the hanging wall and footwall sides of the Agua Dulce (AD) fault. Note the change in thickness of the BMF interval in the hanging wall side at different locations relative to the AD fault. The coincident arbitrary seismic line (Figure 5b) also illustrates that the AD fault has significant control over total thickness variation at different locations with respect to the fault.

Our BMF isochron maps indicate a thick sediment section that was deposited in a time when structurally low areas provided greater accommodation space. The thin sediment section was deposited in a time when structurally high areas resulted in little to no deposition of sediments corresponding to significantly smaller accommodation space. The F11-F39 vertical section (Figure 5) and isochron map (Figure 6) generated using both seismic and well log data show thickening between reflectors on the hanging wall side of the AD fault, suggesting that the fault was syndepositional.

To test whether or not the synthetic and antithetic faults associated with the major growth faults were active during deposition we constructed two geological cross sections along with the coincident arbitrary seismic lines (Figures 7 and 8). Correlating the middle

Frio horizons (Figure 7a) indicates that the gross thickness of the interval between the marker top E41 horizon (MTE41) and the marker base F39 horizon (MBF39) is thicker by 126 ft (38 m) in the hanging wall of the antithetic fault than in the footwall block. In Figure 8a the gross thickness of the interval between the top F11 and the base F39 in well Gruene 9 in the hanging wall block of the synthetic fault B is 44 ft (13 m) thicker than the same interval in well Gruene 21 located in the footwall block. These two examples indicate that the synthetic and antithetic faults associated with the major AD growth fault are not just accommodation faults but they are syndepositional faults that cut through the BMF interval (the interval between G2 and F11).

Further investigation is needed to determine if these secondary faults are conduits or seals to the migrating hydrocarbons in the Stratton and Agua Dulce fields. The middle Frio Formation is composed of fluvial deposits in the form of point bar and crevasse splay sandstones isolated within floodplain mudstones and siltstones. This heterogeneity makes it possible that even a small amount of vertical fault offsets will juxtapose low-permeability floodplain deposits against permeable sandstone reservoir rocks. Therefore, small vertical offsets along these faults may form lateral flow barriers. Another way in which these synthetic and antithetic faults may compartmentalize the middle Frio reservoirs is by providing seals which follow the fault as gouge or cemented breccias which formed along fault planes due to mechanical breakdown of rock during fault movement. Therefore the secondary faults interpreted from the 3D seismic data sets (Figures 5-8) may impact the lateral continuity and result in more compartmentalization of the middle Frio meandering fluvial sandstone reservoirs. Coupled with an appropriate depositional model, mapping the structural and stratigraphic complexity with the aid of the 3D seismic data of the BMF interval can help better image and develop fluvial reservoirs in the Stratton and Agua Dulce fields' area and in the Texas Gulf Coast at large.

**Structure framework.** While the previously constructed structure maps on top of shallower middle Frio horizons -- based on well data only -- clearly showed the AD fault, the more subtle synthetic and antithetic faults were not recognized. Figure 9 is a structure contour map showing Yang's (1998) structure configuration of the F11 horizon in Stratton field. Other than the major AD fault, there is only one minor fault mapped in the southeast corner of the map. Figure 10 is a two-way time structure map constructed for the same F11 horizon in the Stratton and Agua Dulce fields' area from the BEG and the UPR 3D seismic surveys. This map shows two major faults bounding the western side of the image area and several subtle faults that were not shown before, at the F11 stratigraphic level and scattered at different parts of the rollover anticlinal structure in the hanging wall side of the AD fault. Figure 11 is a 3D view of the F11 horizon mapped from the BEG 3D seismic survey. Note that the surface irregularities in the rollover anticline reflect the locations of subtle faults in the hanging wall of the AD fault. At the deeper horizons of the middle Frio Formation (such as the F39 horizon shown in Figures 7b and 8b) the hanging wall deformation is more pronounced than at shallower horizons. Based on seismic data only, the structure of the F39 horizon exhibits rollover amplitudes (structural closures) that range from 150 ft (46 m) to 700 ft (213 m). At the shallower F11 stratigraphic level, the rollover amplitudes decrease and range from 50 ft (15 m) to 500 ft (152 m).

**Nature of the growth faults.** 3D seismic data volumes provide detailed information on the imaged subsurface rock volume. In the vertical sections it gives the best view of structure style and picking of events across the faults. In the horizontal sections it aids in accurate delineation of fault blocks and thus results in accurate well placement. As shown from the previous maps and cross sections (Figures 5-11), the major growth faults affect the BMF interval and younger sediments. The nature of the subsidiary synthetic and antithetic faults is

estimated by looking at several vertical seismic lines from both the UPR and the BEG 3D seismic surveys. The seismic crossline in Figure 12a illustrates that the BMF interval is deformed by the subsidiary faults on the hanging wall side of the AD fault and is accommodated mainly by synthetic faulting. The difference between the level of details in this 3D seismic crossline and that presented by Levey et al., (1993) (Figure 2) is dramatic. Recognizing such details from regional 2D seismic sections and well data alone is not possible. This comparison clearly illustrates the power of 3D seismic volumes over 2D seismic grids. The deformation is more pronounced in the area closer to the AD growth fault. Approximately, 1.5-mile (2.4-km) distant from the trace of the AD fault in the down-basin direction, we note an average of five secondary faults that affect the stratigraphic units of the BMF interval (F39-F11), with the deeper horizons (e.g. F39) being more deformed than the shallower horizons (e.g. F11). The vertical seismic section shown in Figure 12b illustrates the deformation of the deeper middle Frio in the footwall side of the AD fault. It shows that antithetic faulting accommodates the AD fault footwall deformation, the opposite case of the hanging wall deformation, and is more intense in the northern part of the UPR 3D seismic volume (southern Agua Dulce field area) than in the southern part (northern Stratton field area). Note the difference between the structure details which appear in this seismic line and that presented by Levey et al., (1993) (Figure 2). Several synthetic and antithetic faults affect the deeper middle Frio interval (G2-E41) and younger horizons. The coherence slices shown in Figure 13 indicate that the studied BMF interval is clearly affected at different stratigraphic levels by several growth faults that occur in different parts of the image area. Figure 14 shows maximum positive and maximum negative curvature attributes that also indicate that the BMF interval is deformed by many faults. These faults are assumed to result in more compartmentalization of the fluvial channels embedded in the studied BMF stratigraphic interval.

**Fault offsets.** The vertical displacements of the major and subsidiary growth faults mapped in the study area were measured from both vertical seismic sections (inlines and crosslines) and well log cross sections. Based on observations made from the two-3D seismic volumes, it was found that the amount of fault throws of major and minor faults vary from line to line in the seismic surveys and increases in the northern part of the UPR 3D seismic survey in the Agua Dulce field area. The amount of vertical separation of the AD growth fault increases with depth and ranges between 850 ft (259 m) to 1600 ft (488 m). For the subsidiary synthetic and antithetic faults, vertical displacements range from 15 ft (5 m) to 145 ft (44 m). These subtle small-throw faults can be a significant part in the creation of multiple reservoir compartments within the middle Frio Formation.

**Structure Architecture Model for the Middle Frio Formation.** One of the objectives of this study is to test the hypothesis of whether or not synthetic and antithetic faults cut through the middle Frio Formation in the area of the Stratton-Agua Dulce fields. Investigating the BMF interval (G2-F11) from the available two 3D seismic data volumes and well log data (Figures 5-14) shows that the studied middle Frio horizons (e.g. F11 and F39) become segmented or compartmentalized by the effect of the subsidiary synthetic and antithetic faults associated with the major growth faults.

Based on these findings, we propose a new structural architecture model (Figure 15) for the BMF interval. In this model, the interval between F11 and G2 has been broken into several compartments by major and secondary growth faults. At about 2.75-mile (4.5-km) distance from the trace of the AD growth fault, the BMF horizons split into several reservoir compartments due to, on average, seven synthetic and antithetic faults cutting through this interval. Movements along these individual faults may result in several compartmentalized

traps rather than one undeformed larger rollover anticlinal trap. In the footwall block of the AD fault, antithetic faults are common and displace the BMF and younger horizons.

In the middle Frio Formation at Stratton field, Kerr and Jirik (1990) and Yang (1998) recognized two architectural end members: the concentrated and the dispersed sandstone bodies. These architectural styles were noted on the hanging wall side of the AD growth fault. Figure 16 is a robust rollover anticline from Stratton field that shows that shows good examples of the concentrated and the dispersed facies architectural styles. In this interval, and based on well data and 2D seismic data (Levey et al. 1993) the structure attitude is mostly affected by the master growth faults while all the antithetic and synthetic faults are diminished. This facies architectural model proposed by Kerr and Jirik (1990) and Yang (1998) did not account for the effect of the secondary faults on the architecture of the middle Frio strata. This model can be modified to include the effects of the major and subsidiary faults together on the middle Frio interval as presented by this study (Figure 17). In addition, syndepositional movements of these growth faults may result in the creation of more accommodation space and in the avulsion of the BMF fluvial channel belts. Thus, in order for more development of the middle Frio reservoirs in the Stratton-Agua Dulce area and in the Texas Gulf Coast basin as well, the structural and the facies architectural models (Figures 15 and 17) presented by this study should be taken into consideration.

## **CONCLUSION**

In this paper, an example from the Texas Gulf Coast of the United States showed that information extracted from two 3D seismic data volumes resulted in the enhancement and more understanding of the structural styles and architecture and in accurate delineation of

reservoir blocks in the area of study. The results of this work promise for more development opportunities in the Stratton-Agua Dulce area in the FR-4 (Frio gas play) in south Texas. At Stratton and Agua Dulce fields in south Texas new structural and facies architectural models proposed and show that the Vicksburg and AD faults and numerous subsidiary synthetic and antithetic faults are syndepositional and cut through the BMF and younger horizons. These faults affect the architecture of the sandstone bodies stacked in these intervals.

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**Suggested Readings.** “The impact of 3D seismic data on exploration, field development, and production. *In*: Weimer, P., and Davis, T.L., 1996, Applications of 3D seismic data to exploration and production. AAPG Studies in Geology, No. 42 and SEG Geophysical Developments series No. 5, AAPG/SEG, Tulsa, p. 1-8” (by Nestvold, 1996); “Structural Geology”. W.H. Freeman and Company, USA, P. 74-88” (by Twiss, R. and Moores, E., 1992). “Interpretation of Three-Dimensional Seismic Data, AAPG Memoir 42, Fifth Edition, p.55-96” (By Brown, 1999).

### **TABLE OF FIGURE CAPTIONS**

Figure 1. Index map showing the location of the Stratton and Agua Dulce fields in south Texas, the location of the UPR and the BEG 3D seismic surveys, and the well in which the VSP survey was run.

Figure 2. Interpreted regional 2D seismic line passing through the Wardner lease area of Stratton field showing rotation of fault blocks in the lower Frio and Vicksburg Formations compared to the lack of faulting in the middle Frio Formation, (from Levey, et al., 1993).

Figure 3. Reference log from well Wardner 177 showing reservoir subdivisions and markers of the basal middle Frio interval (BMF) used in this study. T= top, B= base, m= marker.

Figure 4. VSP display of Wardner 175 well (Modified from Hardage, et al., 1996). Some horizons of interest: e.g. F11 and F39 are located at ~1.58 s and ~1.65 s, respectively. The peaks (black-filled to the right) are top of reservoir units.

Figure 5. (a) Geological cross section showing the disparity in thickness of the BMF interval (MTE41-MTG2) on both sides of the AD fault. The hanging wall is deformed by the rollover anticline and a set of synthetic and antithetic faults. (b) Coincident arbitrary seismic line from the UPR 3D seismic survey showing the AD listric normal fault and the associated structures. Displacement on the AD growth fault occurs during sedimentation resulting in equivalent beds being thicker in the hanging wall block than in the footwall block.

Figure 6. Isochron map extracted between F11 and F39 reflectors from the UPR 3D seismic volume. Thick isochrons (dark colors) indicate the growth of the faults.

Figure 7. (a) Well log cross section showing that the minor antithetic faults associated with the AD fault are also syndepositional (growth) faults. The growth of the fault as measured between MTE41 and MBF39 is approximately 126 ft in the hanging wall side of the fault. This growth is evident in the thickening of the individual layers such as F11 and F39. Location of the cross section is indicated in Figure 9. (b) Coincident arbitrary seismic line (from the BEG 3D seismic survey) showing the antithetic fault (AF) in Fig. 7a.

Figure 8. (a) Well log cross section showing that the subsidiary synthetic faults associated with the AD fault are syndepositional (growth) faults. The interval between F11 and F39 are thicker in the hanging wall by 44ft than in the footwall side of the synthetic fault. Location of the cross section is indicated in Figure 9. (b) Arbitrary seismic line (from the UPR 3D seismic survey) showing the synthetic fault (SF) in (a).

Figure 9. Structure contour map constructed on top of the F11 horizon in Stratton field area based on well data, showing only the AD fault and one subsidiary fault (From Yang, 1998).

Figure 10. Time structure map constructed on top of the F11 horizon from the BEG and the UPR 3D seismic surveys. Fault polygons indicate the locations of the major faults and several secondary faults. These secondary faults were not shown before (compare with Figures 2 and 9) at the F11 stratigraphic level.

Figure 11. 3D view of the F11 structure from the BEG 3D seismic survey clearly showing surface irregularities in the hanging wall rollover anticline that indicate the locations of the secondary faults associated with the major AD fault.

Figure 12. (a) Seismic crossline from the UPR 3D seismic survey showing the deformation on the hanging wall side of the AD fault. All the subsidiary faults are affecting the deeper middle Frio (G2-F11). Note the difference in structure details in this seismic line and that shown in Figure 2. (b) Another seismic crossline from the same survey showing deformation in the footwall block of the AD fault.

Figure 13. Three coherence slices near the top (a), near the middle (b) and near the bottom (c) of the BMF interval corresponding to the UPR survey showing that the whole BMF stratigraphic interval is clearly affected by many large and subtle faults.

Figure 14. Maximum positive (a), (c) and maximum negative (b), (d) curvature 3D attributes extracted near the top (a), (b) and near the bottom (c), (d) of the BMF interval. These attribute maps clearly show the locations of the faults that affect the BMF interval.

Figure 15. Structural architecture model based on seismic and geological observations showing the effects of the major and subsidiary growth faults on the deeper middle Frio succession in the Stratton and Agua Dulce fields, south Texas. The faults displace the horizons into several compartments. Deformation is more pronounced in the hanging wall sides of the growth faults. AD fault footwall deformation is common in northern Stratton field and southern Agua Dulce

Figure 16. Regional well log structural cross section showing good example of a rollover anticline developed on the hanging wall of the major Agua Dulce fault in the Stratton field area. The stacking patterns of the BMF fluvial sandstone reservoirs ranges from dispersed architecture (multiple vertically stacked sand bodies that have limited lateral continuity and

separated vertically by thick layers of floodplain mudstones) closer to the major growth fault to concentrated architecture (multiple laterally stacked sand bodies that have more lateral continuity and separated vertically by thin layers of floodplain mudstones) along the crest of the rollover anticline. Location of the cross section is indicated in Figure 9.

Figure 17. Schematic 2D facies architectural model of the BMF stratigraphic interval.

Deformation caused by growth fault (major and subsidiary) activity is one possible factor controlling the BMF fluvial architectural styles in the study area. Thickness and number of sandstone bodies increase on the hanging wall sides of the growth faults relative to the footwalls (modified from Kerr and Jirik, 1990, and Yang, 1998).



































