Fracture Patterns within Mudstones on the Flanks of a Salt Dome: Syneresis or Slumping?

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ABSTRACT

Mud-prone facies within the Upper Oligocene and Lower Miocene strata on the flanks of the complexly faulted Vinton Dome Field in the northwest Gulf of Mexico show fine-scale, sub-seismic polygonal fracture patterns, averaging 200 ft (approximately 60 m) in diameter. These facies may relate to gravitational slumping away from the salt dome or to dewatering during compaction. Similar dewatered polygons have been identified in mudstones in 3D seismic surveys from the Miocene aged strata in the North Sea and from Cretaceous strata in Alberta but have never been described from the Gulf of Mexico. Well control and modern seismic attribute analyses reveal the relationship between the depositional environment, structural patterns, and salt tectonics. The dome is characterized by a counter-regional fault and three peripheral fault sets, each having a different outline and basis for its formation. The structural setting of the Miocene shelf is the result of the hereditary Upper Oligocene structural design and substantial evolution of sediment dispersal. Salt movement set the stage for thinning and thickening of the Chattian (28.5 to 23.8 Ma) strata creating unconformities and onlap against the salt plug, whereas the overlying Aquitanian (23.8 to 20.52 Ma) strata is generally characterized by major syn-depositional faults. Different lithologies are characterized by non-rigid polygons, suggesting rheological control on fracture density. Homogeneous polygonal features and fracture intensity support a strong link between the major faults and smaller-scale polygonal faults. Fracture systems could be open, healed, or partly open, but significant structural complexity of the shales might affect seal integrity.

INTRODUCTION

Fault compartmentalization and seal integrity are key issues in predicting the effect of shales in reservoir productivity. Seismic attribute technology has the potential to identify small or subtle structural and stratigraphic features, such as polygonal fractures, that may affect seal competency. This study tested the applicability of these volumetric seismic attributes on deltaic-shelfal Aquitanian and Chattian strata constrained by biostratigraphic data. We used seismic, attributes, biostratigraphic, and a variety of well and engineering data to identify fault compartments, polygonal fractures, deformation structures, depositional systems tracts, facies migration and stacking patterns, and their relationships to salt tectonism. This study focuses on the major structural and depositional pattern of the Upper Oligocene to the Lower Miocene strata at Vinton Dome and highlights small-scale polygonal fractures that are revealed by curvature attributes.

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STUDY AREA

The Vinton Dome is located on the northern Gulf of Mexico shelf in the Calcasieu Parish in southwestern Louisiana (Fig. 1). It is generally characterized by salt intrusion and related faulting. The dome contains a core of massive cap rock, rock salt, gypsum, and anhydrite, in succession, with the cap rock extending over the rock salt (Thompson and Eichelberger, 1928). The Upper Oligocene to Lower Miocene strata is primarily characterized by intercalated layers of sandstones and shale and minor layers of carbonates at the *Heterostegina texana* zone. Based on well log and biostratigraphic analysis, the depositional environments are broadly fluvial-deltaic and consistently lie in a relatively shallow marine, inner shelf environment. The Early Miocene has been characterized as a time of substantial evolution in sediment dispersal in the northern Gulf of Mexico (Edwards, 1994; Fillon and Lawless, 1999, 2000; Galloway et al., 2000) and high sediment influx to the top of the Anahuac shale.

The Upper and Lower Aquitanian sandstones consist of shoreline facies and stacked, upward-fining fluvial deposits in the northern edge of the dome, whereas the south to northwest parts are characterized by unconformities. Thinning of the Upper Oligocene strata is associated with the salt body and several units appear to onlap toward the center of the dome. This configuration suggests a period of active salt movement (Fig. 2). Relatively constant stratal thickness is observed in the Aquitanian strata, except for onlap of the strata against the salt body at the center of the dome.

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STRUCTURE

The Vinton Dome salt boundaries are circular to ellipsoidal in plan view (Fig. 3). The piercement point of the salt is circular while the diapir becomes more ellipsoidal with depth. The salt is not detached from the underlying salt body (Fig. 4). Strata thin near the flanks of the salt and thicken towards the edge of the dome. The thickening at the periphery of the dome is attributed to slumping and syn-depositional thickening. Strata are asymmetrical on opposite sides of the salt, largely caused by salt tectonics and displacement by a counter regional fault. The dip of beds ranges from 85° near the margin of the salt to near-horizontal at the periphery of the study area. The structure is characterized by a multistyle fault pattern, i.e., a combination of single offset and offset radial fault pattern (Fails, 1990) (Fig. 3). The master fault is counter-regional, dips inland to the north, lies in a northeast-southwest transverse direction, and subdivides the dome into approximately two equal parts. The fault trends parallel to the ellipsoidal direction of the salt, and its length is almost the diagonal of the dome. It strikes N75°E, with dip of 45° and throw of approximately 1400 ft (427 m).

Peripheral fault sets in the dome are normal and consist of divergent, en echelon, and parallel fault patterns. The northeast faults splay in one of the direction of the salt's ellipsoidal axis. They strike between N5°W and N80°E, and dip between 45° and 60° with throws ranging from 7 ft (2 m) to 175 ft (53 m). These faults are generally shallower than the southeast faults. The southeast faults are parallel almost in an *en-echelon* pattern while the northeast faults are divergent with their tips converging toward the center of the dome. Faults strike N5°W to N40°W and throws range from 65 ft (20 m) to 445 ft (136 m). The west faults are positioned closely to the northwest and west of the master fault, in the western ellipsoidal direction of the salt. They are relatively short, parallel, and appear to be complimentary to the master fault.

Intrinsic factors, such as the shape of salt bodies and regional stress, significantly influence fault patterns during periods of doming (Parker and McDowell, 1955; Hughes, 1960; and Withjack and Scheiner, 1982). The experimental and analytical models illustrating elliptical and circular domes (Withjack and Scheiner, 1982) show that normal faults on elliptical domes form on the crest which roughly parallel the long axes, but splay outward toward the ends of the long axes near the peripheries, whereas circular domes exhibit more radial faulting. These models also show that regional extension is usually perpendicular to the direction of normal faults. This pattern is observed on Vinton Dome with divergent faults on the northeast toward the elliptical direction of the salt only, but the other parts of the dome with associated circular salt direction do not have divergent faults. The northeast faults splay in the direction of the salt's ellipsoidal axis and were perhaps caused by regional extension and differential loading of sediments during doming. The southeast faults on the dome were perhaps linked to salt flowage and early deformation in the area which may cause varying rates of deposition in the fault blocks (Hughes, 1968).

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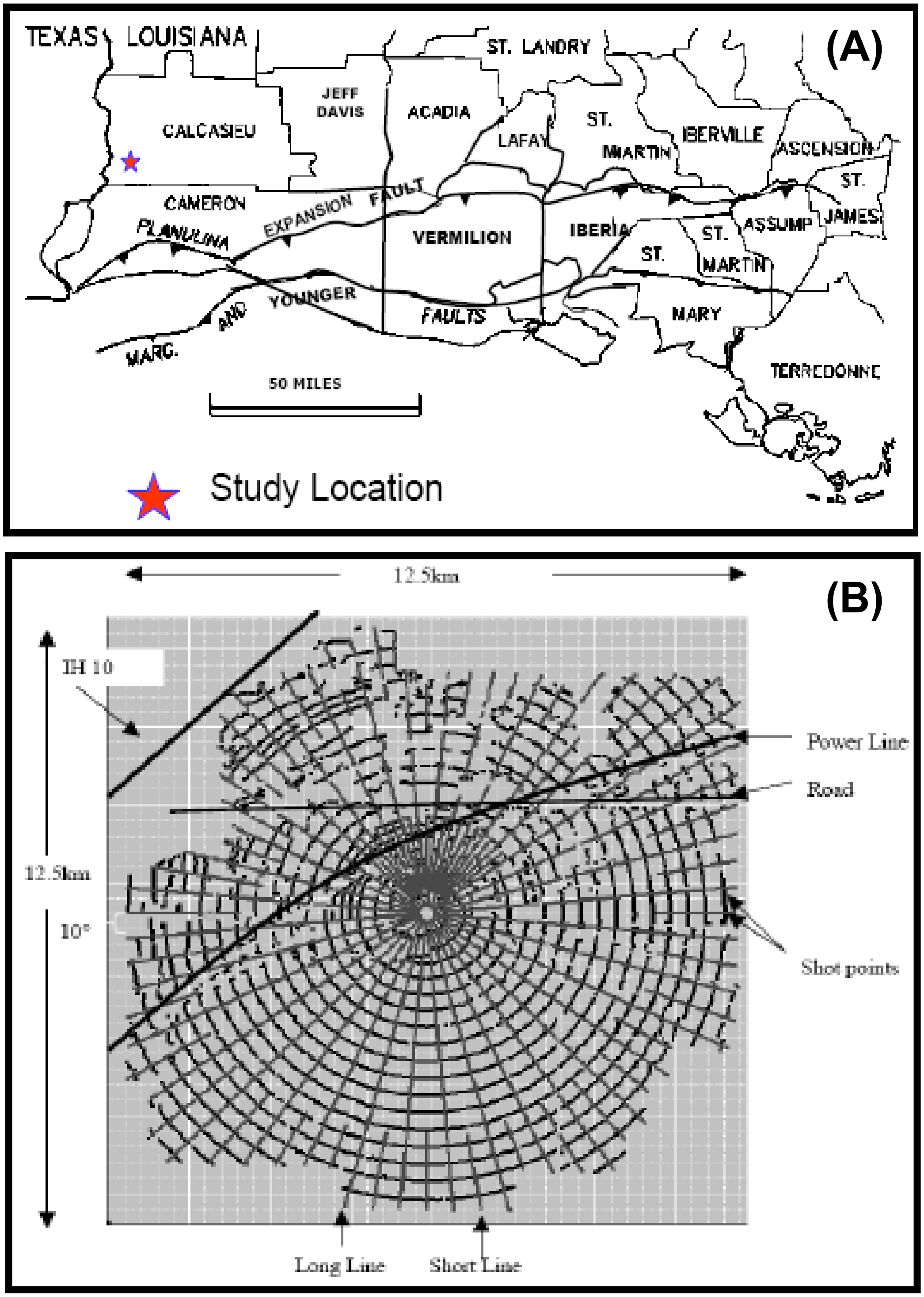

Figure 1. (A) Vinton Dome location, northwest Gulf of Mexico, Southwest, Louisiana (modified after Edwards, 1994). (B) Acquisition pattern of the Vinton Dome area (Constance et al., 1999, reproduced with permission of the Society of Exploration Geophysicists).

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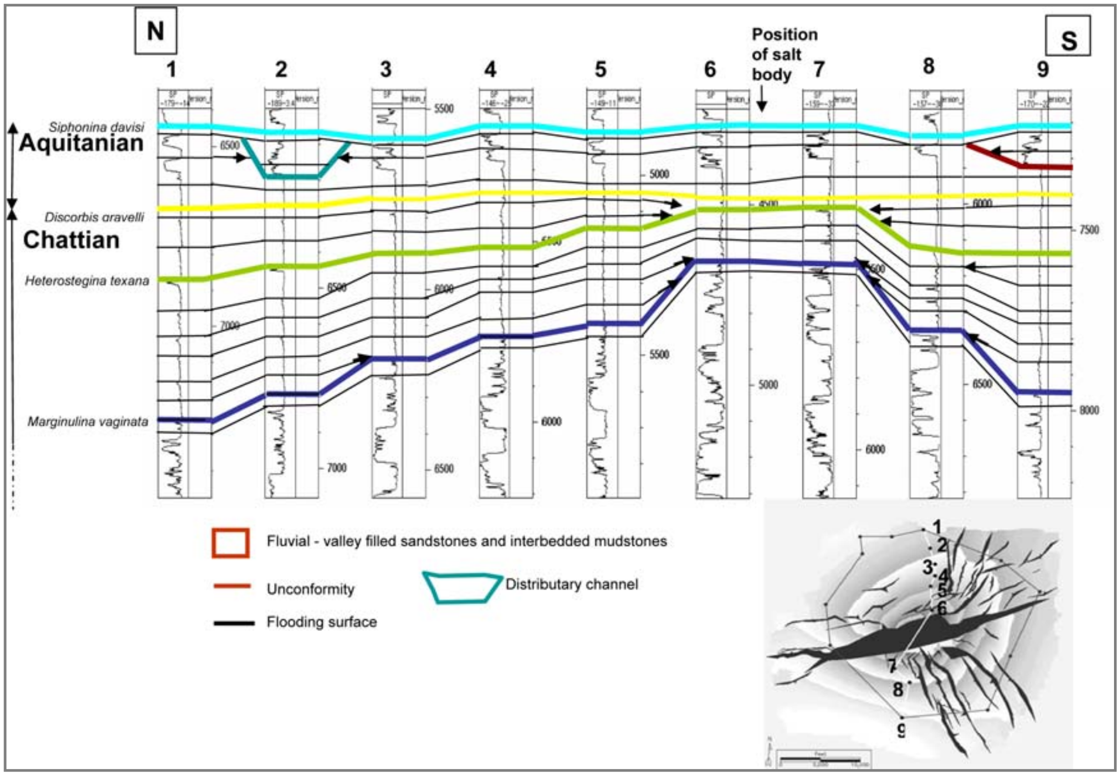

Figure 2. Well correlation of SP logs in the north-south longitudinal cross section, Vinton Dome. (Log data courtesy of OPEX – Output Exploration Company.)

SEISMIC ATTRIBUTES

The dip and azimuth maps of the Upper Oligocene and Lower Miocene horizons indicate consistency in their structural pattern and tilt (Fig. 5) and show a perfect match between the attribute maps and the time structure maps. The strata dip away from the salt and were domed by the effect of upward movement of the salt (Fig. 6).

POLYGONAL FRACTURES

Curvature images provide detailed information in structural and stratigraphic interpretation and are particularly useful in mapping faults. The negative curvature, however, measures negative bending of a surface (Roberts, 2001; Chopra and Marfurt, 2006, in press) and emphasizes synclinal features such as faults, fractures, joints, and channel axes. Negative curvature maps of the Vinton Dome Field show mosaic patterns on all horizons (Fig. 7). The multi-directional polygonal features exist in the deep marine sediments, as well as on the shelf and in the shore zones, with an average diameter of 200 ft (approximately 60 m). They are consistent throughout the entire survey from the *Marginulina vaginata* section in the deepest marine and throughout the entire Miocene section. These maps show a broadly radiating direction that matches the overall structure. Polygonal fracture patterns vary in shape, size, and position. The *Heterostegina texana* horizon displays more radial and linear faulting than the other horizons, which display more robust polygons. The *Siphonina davisi* and *Discorbis gravelli* horizons mark shale tops while the *Marginulina vaginata* horizon marks a sand top, but the *Heterostegina texana* section is a carbonate zone (Krutack and Beron, 1990). The importance of a different lithology and sediment loading of the area during the *Heterostegina texana* time may significantly contribute to increased salt movement and consequent slumping of sediments which may be responsible for its increased linear and radial pattern of polygonal faulting. The *Siphonina davisi* and *Discorbis gravelli* horizons display no significant change

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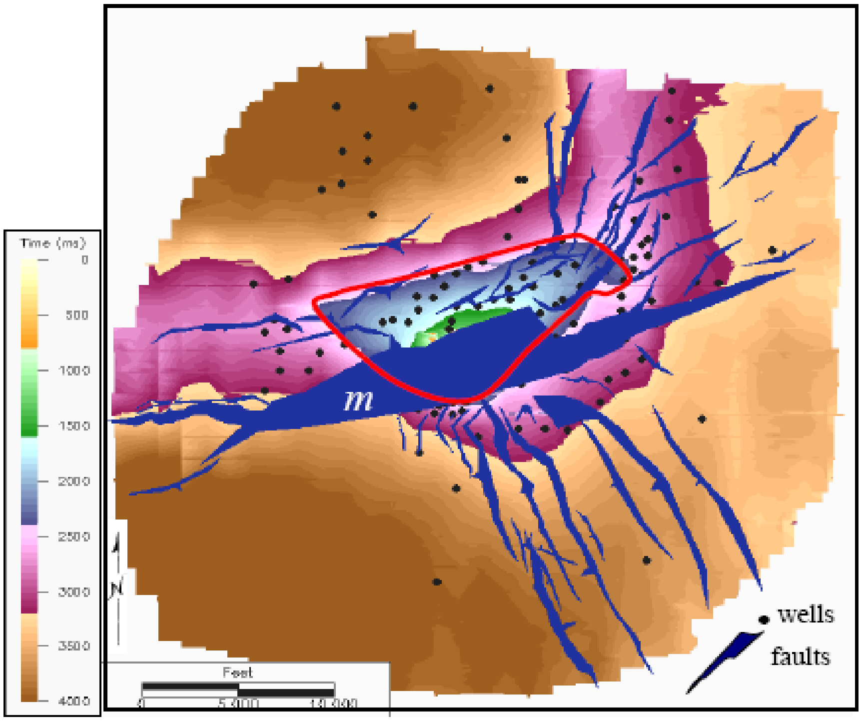

Figure 3. Time map of top of Vinton salt. Red line indicates Early Miocene salt boundary. Aquitanian faults are overlaid on the salt map.

in polygonal faulting, perhaps due to their closeness in time (approximately 50 ms), but reveal change in major faults. These horizons differ considerably from the *Heterostegina texana* and the *Marginulina vaginata* horizons, which are farther apart in time (a difference of 100 ms and 250 ms respectively from *Siphonina davisi*).

FRACTURE INTERPRETATION

Consistent polygonal features from deep marine horizons to shallow shelf horizons (750 ms – 2200 ms) (Fig. 8), and high dip of beds in the Vinton area strongly suggest fracturing of strata as a result of the upward thrust of the salt plug. This is indicated by the broad match between the structural style of the major faults and the smaller-scale polygons. The non-stationary polygons and the differences in fracturing intensity between the different lithologies (e.g., *Heterostegina texana* carbonate versus *Marginulina vaginata* shales) suggests a rheological control on fracture density. The lack of change in fracture intensity as a function of overall structural dip suggests that slumping is not a significant mechanism for generating the fractures and supports a strong link between the major faults and development of smaller scale faulting.

Syneresis is another means by which polygonal faults form. This process, however, has been associated with very fine sediments, such as silty mudstones and claystones, that are found in slope or basin floor depositional environments (Lovell, 1990; Joy, 1993; Dewhurst et al., 1999). The continuous presence of the fracture sets throughout the Upper Oligocene and Miocene sections in Vinton Dome is found in clastic progradational sequences, as well as marine sequences. A combination of many processes could also be responsible for the formation of the Vinton Dome polygonal fractures. The configuration used for Vinton 3D seismic acquisition was a circle and spoke pattern (Fig. 1B). This may likely introduce some noise of equal pattern to the seismic data. The noise may be interpreted as acquisition or processing footprints. Ideally, the Vinton Dome polygonal features would benefit from calibration with image logs, given that the patterns are partially variable despite the presence of strong structural deformation.

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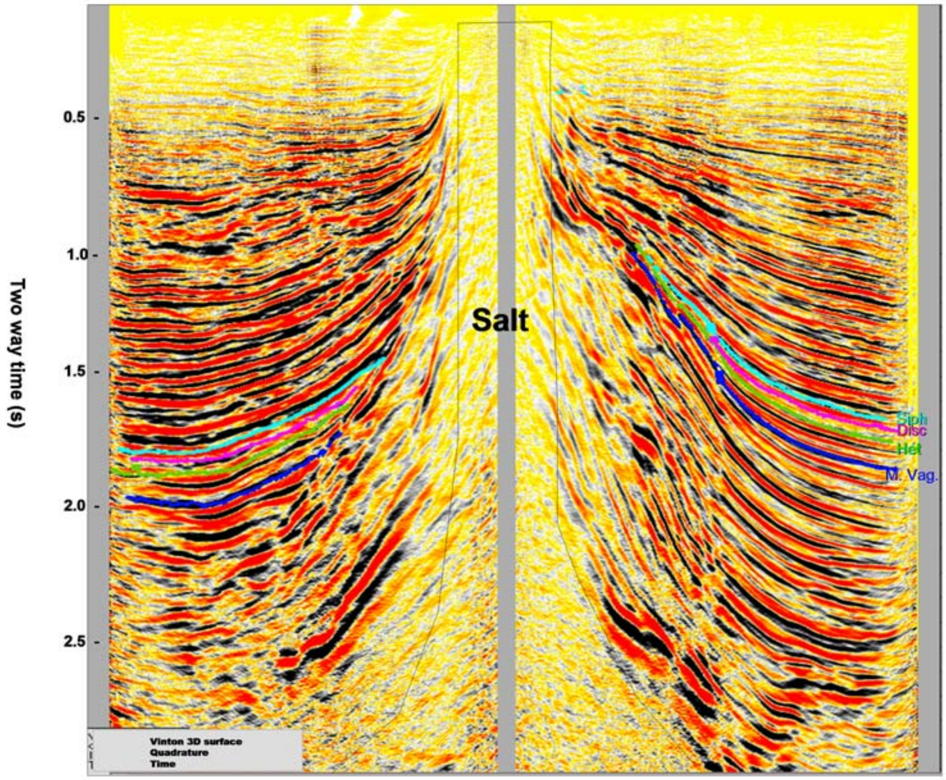

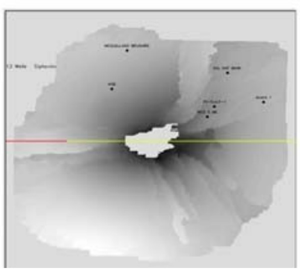

Figure 4. Time-depth map on Middle Miocene reflector, showing inline location (Seismic data courtesy of OPEX – Output Exploration Company). M. Vag. (*Marginulina vaginata*); Het (*Heterostegina texana*); Disc (*Discorbis gravelli*); and Siph (*Siphonina davisi*).

OTHER EXAMPLES OF POLYGONAL FAULT SYSTEMS

In the North Sea Basin, overpressured Lower Cenozoic mud rock sequences exhibit polygonal features. These features are unrecognizable in conventional 3D seismic and amplitude time slices but are revealed in coherence slices. Polygonal features can be formed by episodic hydro-fracturing of basin-wide over-pressured compartments or syneresis (Haskell et al., 1999, (Fig. 9); Dewhurst et al., 1999, (Fig. 10)), and Alberta Basin Oligocene strata (Chopra and Marfurt, 2006, in press (Fig. 11)). These features are associated with slumps and dewatering structures, which may indicate geologic hazards.

CONCLUSIONS

Vinton salt shape largely controlled the structural pattern in the Late Oligocene to Early Miocene. The dome shows a complex structural style that consists of a counter-regional fault, three peripheral fault sets, and small sub-seismic scale polygonal fault system in the entire dome. This is the first documentation of fine scale polygonal faults in the Gulf of Mexico Basin. Similar polygonal faults in the North Sea and Alberta Basins have been

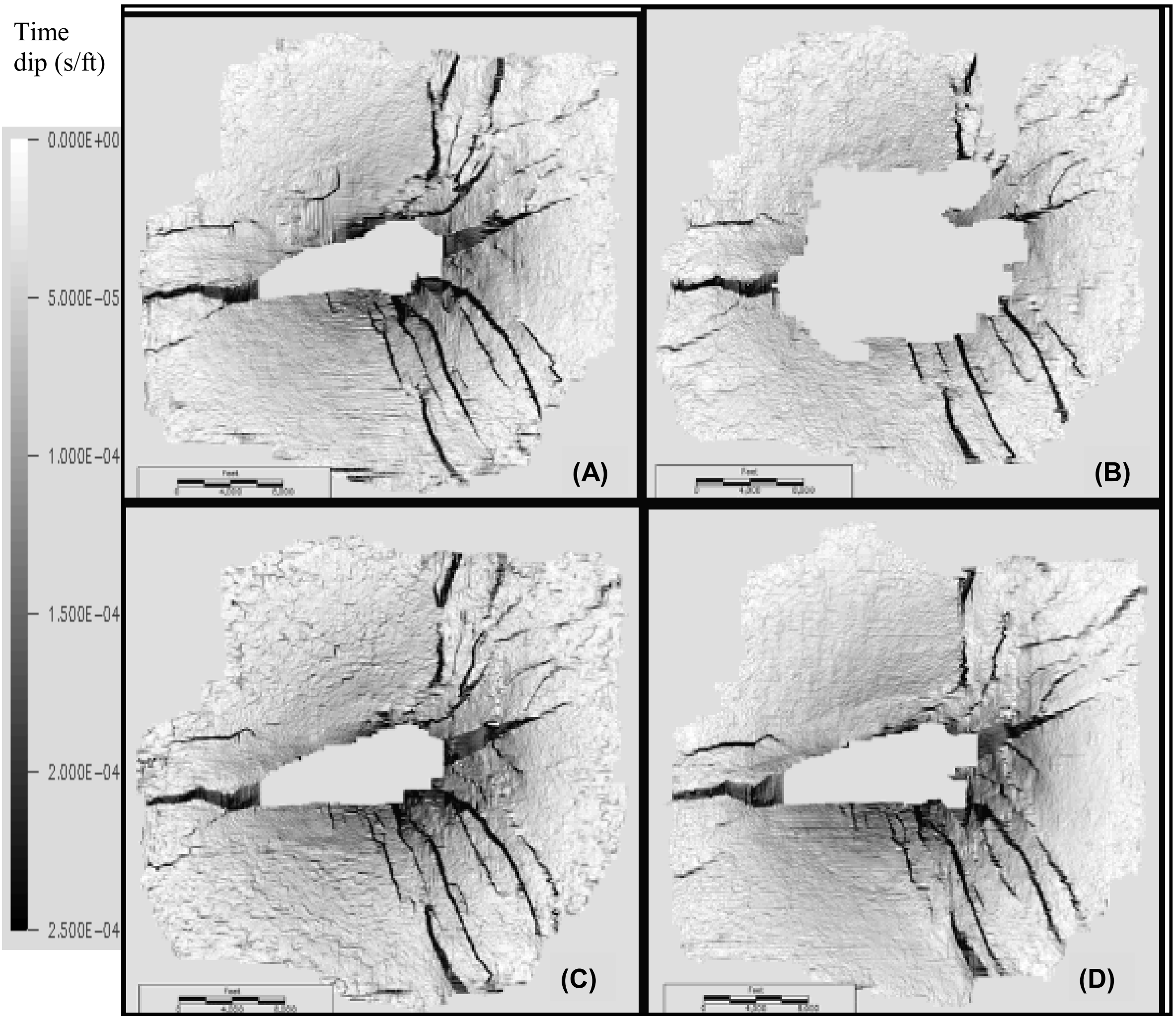

Figure 5. Basemap profile showing time dip (s/ft) of faults in Lower Miocene to Upper Oligocene horizons. (A) *Siphonina davisi*; (B) Top Anahuac (*Discorbis gravelli*); (C) *Heterostegina texana*; and (D) *Marginulina vaginata*. These are computed in a window of 20 ms. Darker grays correspond to steeper dips.

interpreted to be formed by dewatering processes. The similarity of polygonal faulting in Vinton Dome in the Gulf of Mexico suggests similar mechanisms and deformation by salt movement. Fracture systems could be open, healed, or remain partly open. Our study documents polygonal fault systems in the Gulf of Mexico Basin and suggests significant structural complexity of the shales, which might affect seal integrity.

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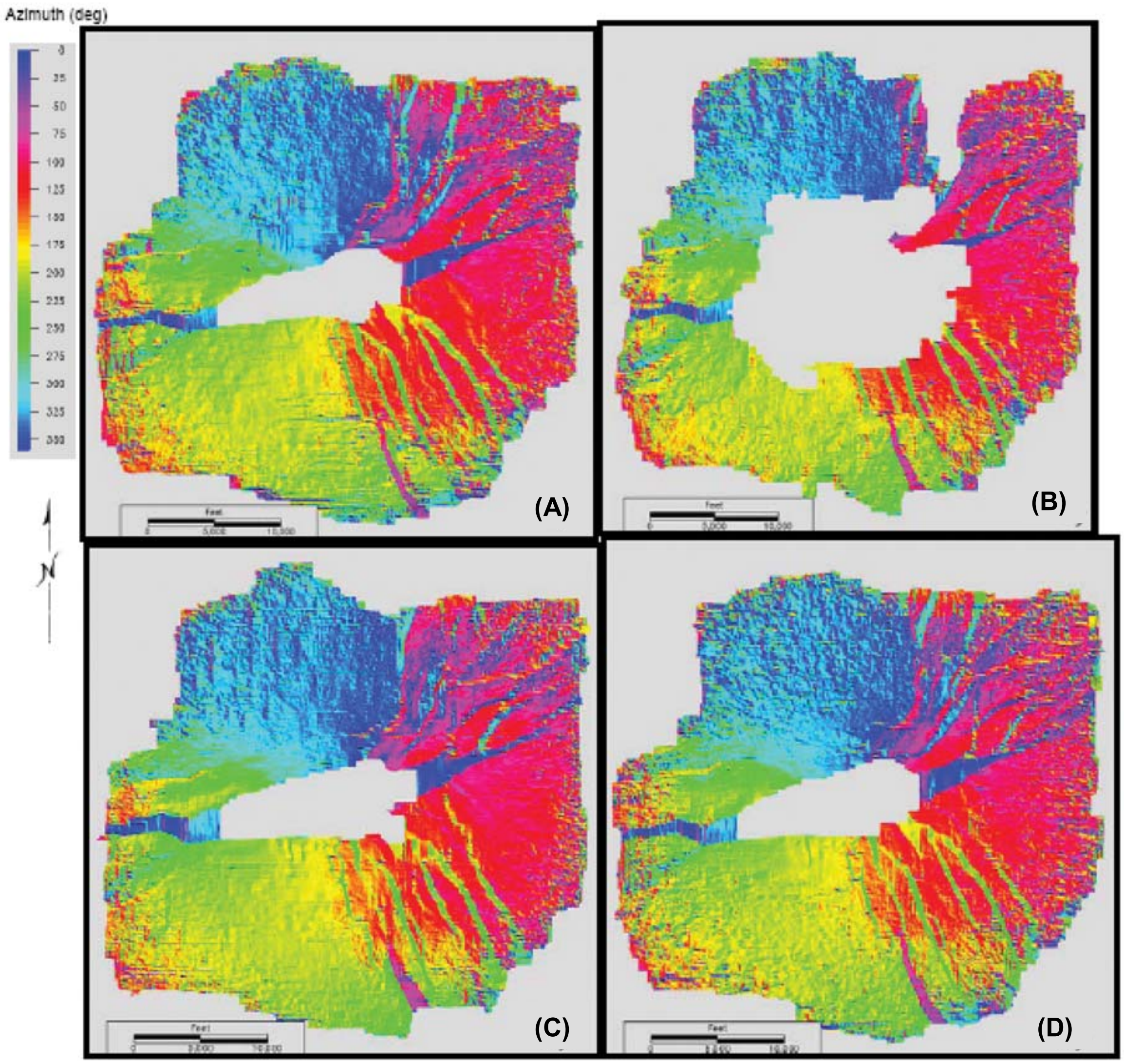

Figure 6. Basemap profile showing dip azimuth (in degrees) of faults in Lower Miocene and Upper Oligocene horizons: (A) *Siphonina davisi*; (B) Top Anahuac (*Discorbis gravelli*); (C) *Heterostegina texana*; and (D) *Marginulina vaginata*.

REFERENCES CITED

Chopra, S., and K. J. Marfurt, 2006, Seismic attribute mapping of structure and stratigraphy: Society of Exploration Geophysicists, Tulsa, Oklahoma, 268 p.

Chopra, S., and K. J. Marfurt, in press, Seismic attributes for prospect identification and reservoir characterization: Society of Exploration Geophysicists, Tulsa, Oklahoma.

Constance, P. E., M. B. Holland, S. L. Roche, P. Bicquart, B.Bryans, S. Gelinsky, J. G. Ralph, and R. I. Bloor, 1999, Simultaneous acquisition of 3D surface seismic data and 3C, 3D VSP data: 69th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts, p. 104-107.

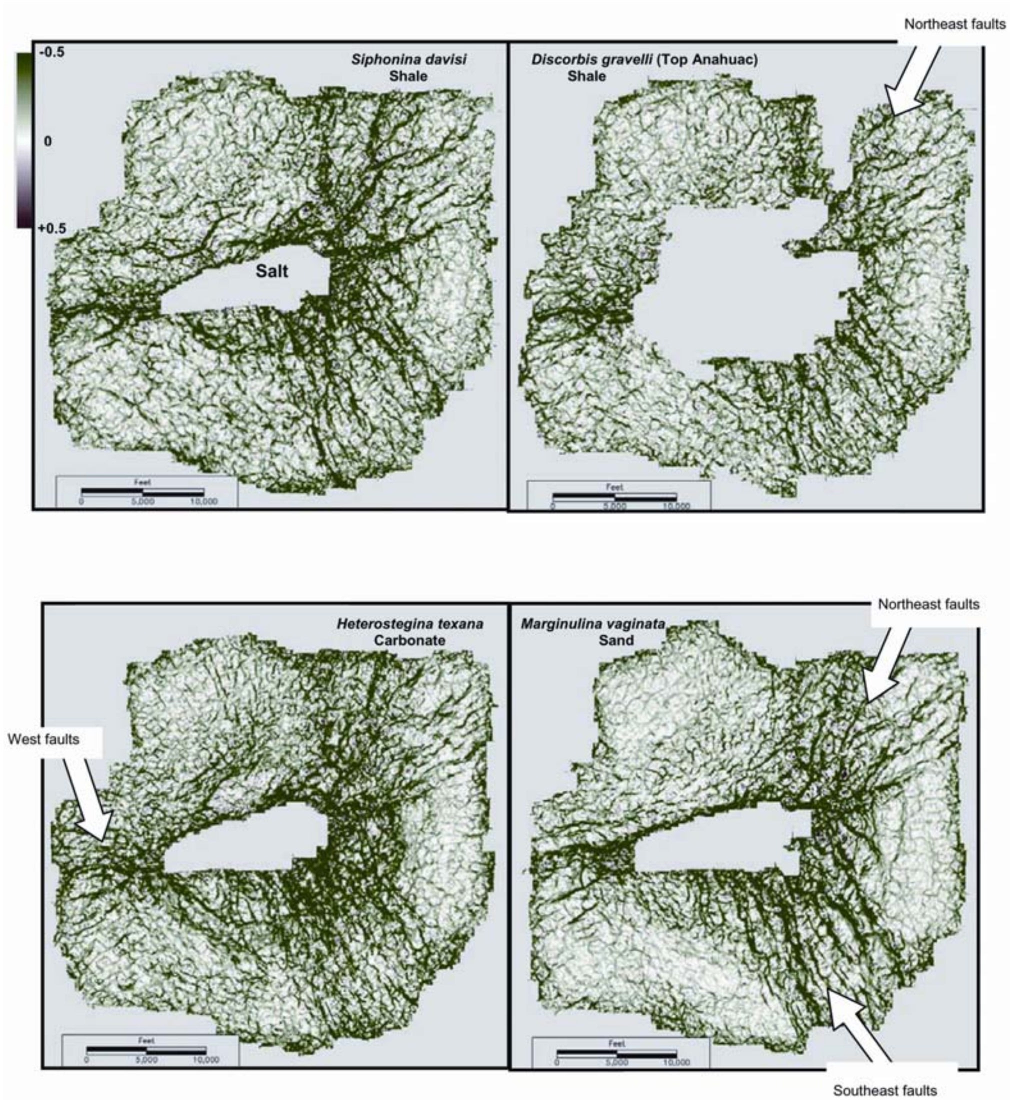

Figure 7. Most negative curvature maps of Lower Miocene and Upper Oligocene horizons. Higher resolution Lower Miocene map is placed in the Appendix A.

Dewhurst, D. N., J. A. Cartwright, and L. Lonergan, 1999, The development of polygonal fault systems by syneresis of colloidal sediments: Marine and Petroleum Geology, v. 16, p. 793-810.

Edwards, M. B., 1994, Enhancing sandstone reservoir prediction by mapping erosion surfaces, Lower Miocene deltas, southwest Louisiana, Gulf Coast Basin: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 205-215.

Fails, T. G., 1990, Variation in salt dome faulting, Coastal Salt Basin: Gulf Coast Association of Geological Societies Transactions, v. 40, p. 181-193.

Fillon, R. H., and P. N. Lawless, 1999, Paleocene – Lower Miocene sequences in the northern Gulf, progradational slope salt-basin deposition and diminishing slope-bypass deposition in the deep basin: Gulf Coast Association of Geological Societies Transactions, v. 49, p. 224-241.

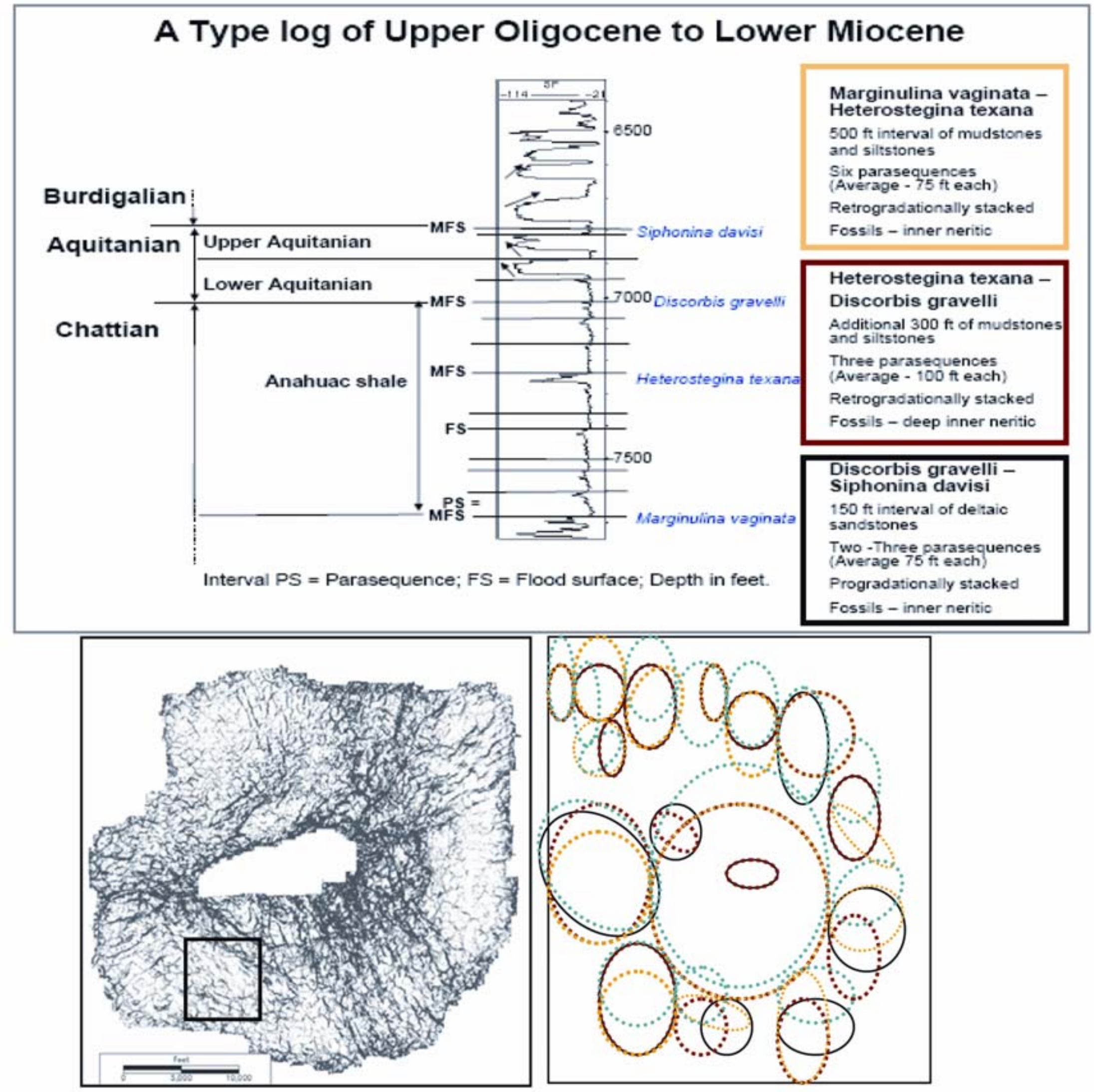

Figure 8. Colored ovals represent the general positions and sizes of selected fault polygons within the black square on the dome. Change in color represents different horizons. *Siphonina davisi* – Black; Top Anahuac – Red; *Heterostegina texana* – Yellow; *Marginulina vaginata* – pale blue. Mapping shows that polygons are non-stationary and do not necessarily occupy the same position between stratigraphic levels, especially those farther apart.

Fillon, R. H., and P. N. Lawless, 2000, Lower Miocene – Early Pliocene deposystems in the Gulf of Mexico, regional sequence relationships: Gulf Coast Association of Geological Societies Transactions, v. 50, p. 411-428.

Galloway, W. E., P. Ganey-Curry, X. Li, and R. T. Buffler, 2000, Cenozoic depositional evolution of the Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 84, p. 1743-1774.

Haskell, N., S. Nissen, and M. Hughes, 1999, Delineation of geologic drilling hazards using 3-D seismic attributes: The Leading Edge, v. 18, p. 373-382.

Hughes, D. J., 1968, ERRATA salt tectonics as related to several Smackover fields along the northeast rim of the Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions, v. 18, p. 320-330.

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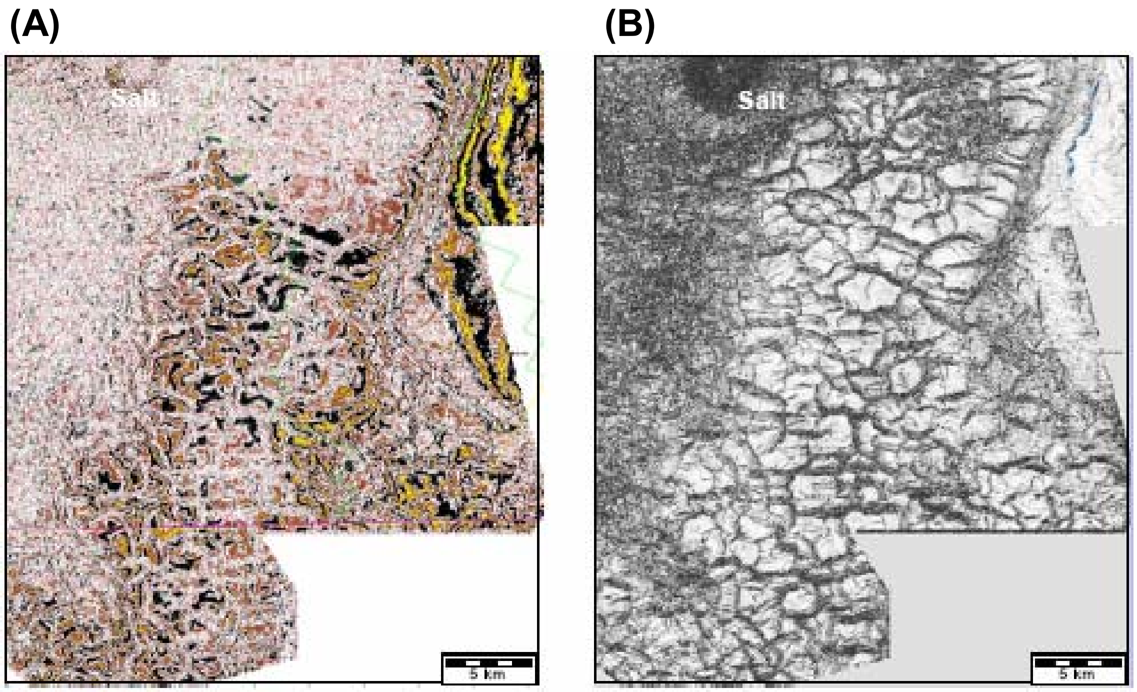

Figure 9. (A) Time slice and (B) coherency slice at 2800 ms showing polygonal faults caused by dewatering of overpressured shales in the Lower Miocene, Valhalla area, North Sea. Polygon size is approximately 1-3 km (from Haskell et al., 1999, reproduced with permission of the Society of Exploration Geophysicists).

Krutack, P. R., and P. Beron, 1990, Heterostegina zone—A shallow Anahuac (Late Oligocene – Early Miocene) oil frontier in southern Louisiana and Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 40, p. 397-409.

Lovell, J. P. B., 1990, Cenozoic, *in* Glennie, K. W., ed., An introduction to the petroleum geology of the North Sea: Blackwell Scientific Publications, Oxford, U.K., p. 273-293.

Parker, T. J., and A. N. McDowell, 1955, Model studies of salt dome tectonics: American Association of Petroleum Geologists Bulletin, v. 39, p. 2384-2470.

Roberts, A., 2001, Curvature attributes and their application to 3D interpreted horizons: First Break, v. 19, p. 85-100.

Thompson, S. A., and O. H. Eichelberger, 1928, Vinton Salt Dome, Calcasieu Parish, Louisiana: American Association of Petroleum Geologists Bulletin, v. 12, p. 385-394.

Withjack, M. O., and C. Scheiner, 1982, Fault patterns associated with domes—An experimental and analytical study: American Association of Petroleum Geologists Bulletin, v. 66, p. 302-316.

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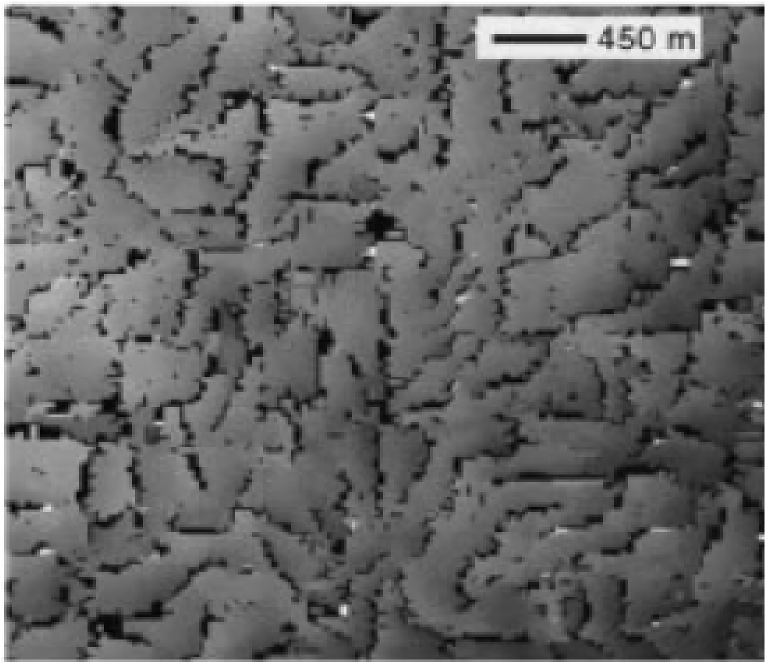

Figure 10. Horizon slice of Lower Miocene, North Sea Basin, showing polygonal faults caused by syneresis. Polygon sizes are 200-500 m. Time contours 1.18 s (white), and 1.29 s (Dark gray) (from Dewhurst et al., 1999, reproduced with permission of Elsevier on behalf of the Marine and Petroleum Geology Society).

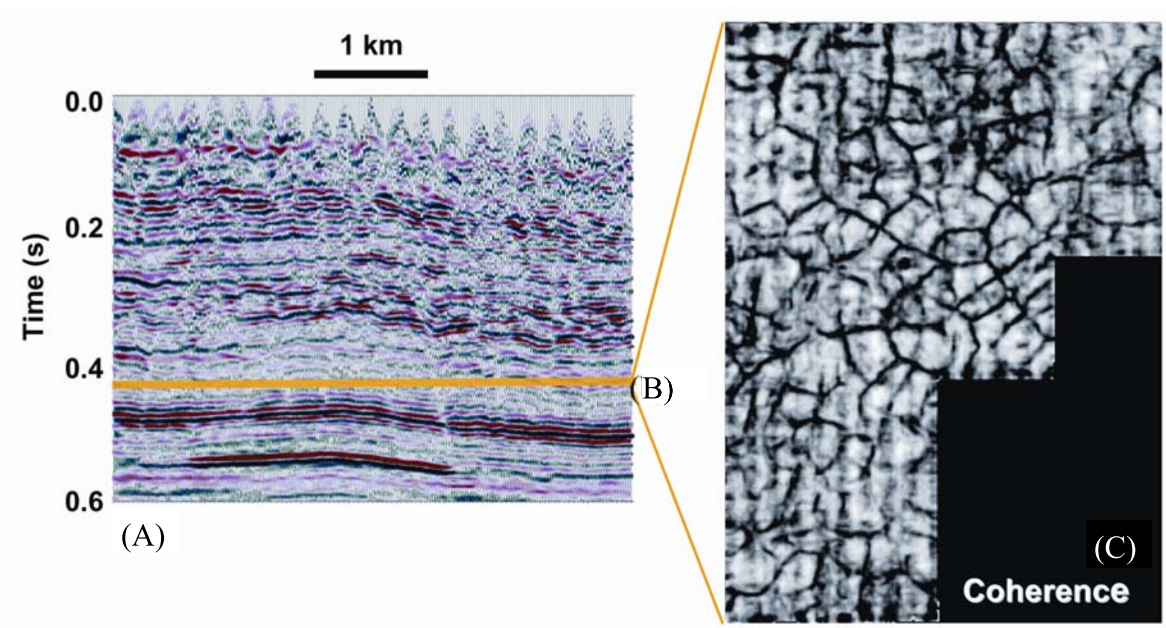

Figure 11. Shale dewatering features exhibited in coherence volume from a survey in Alberta, Canada. A vertical slice through seismic data is indicated by (A). Position of time slice at *t* = 0.420 s is indicated by (B). A slice at the "B" position from a coherence volume is indicated by (C), which shows polygonal fault patterns, delineating cells 1–5 km in diameter (from Chopra and Marfurt, 2006, reproduced with permission of the Society of Exploration Geophysicists).

APPENDIX

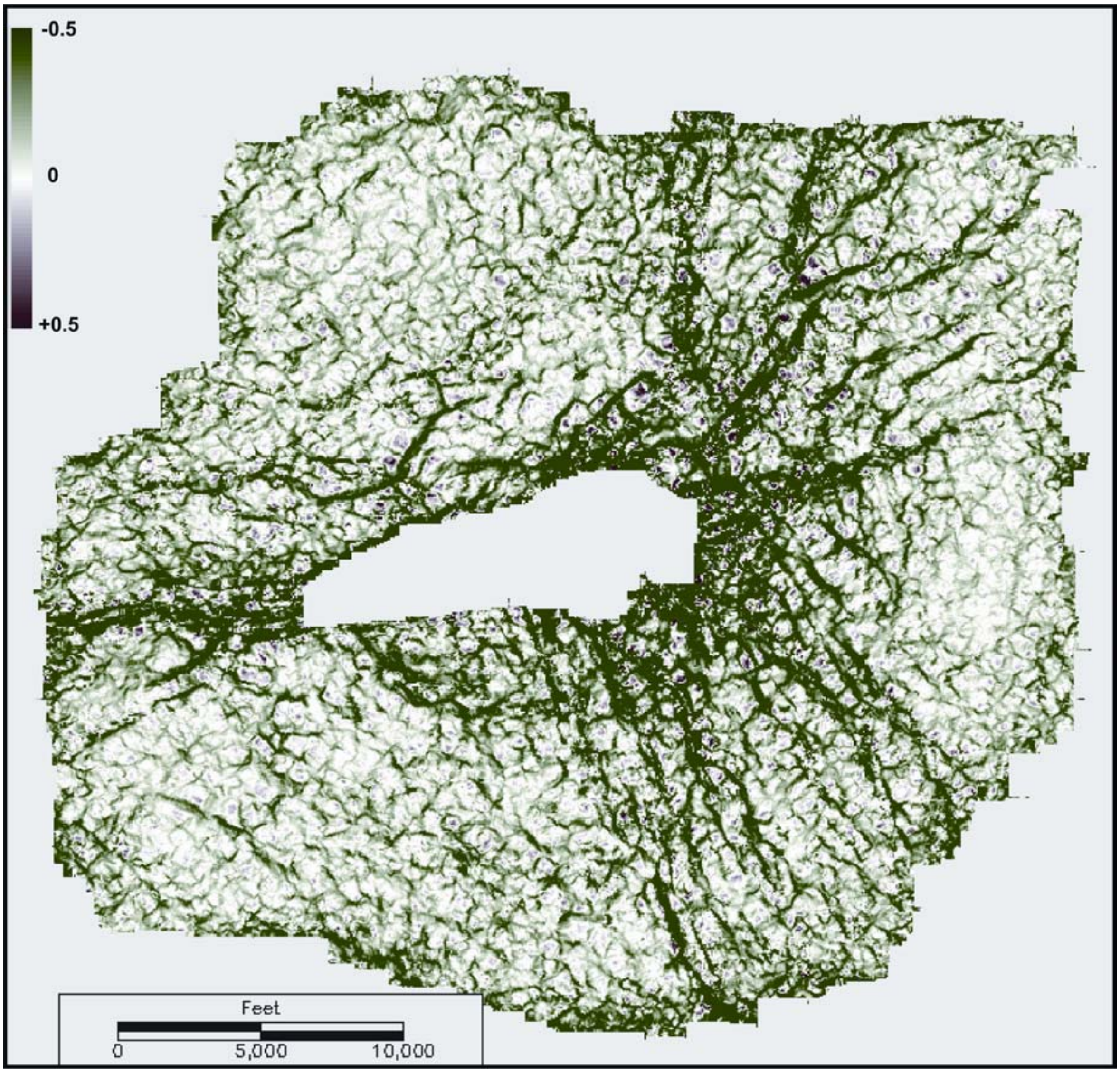

Figure A-1. Most negative curvature map of *Siphonina davisi* zone.

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