The effects of base-salt relief on salt flow and suprasalt deformation patterns — Part 2: Application to the eastern Gulf of Mexico

Tim P. Dooley¹ and Michael R. Hudec¹

Abstract

In the eastern Gulf of Mexico, the pattern of early stage salt flow is complicated by basement topography consisting of a series of plunging arches that trend obliquely to the early flow direction. Seismic lines downdip of the Florida Middle Ground Arch reveal a puzzling array of structures. Sections trending roughly north–south (parallel to the regional dip) document predominantly extensional structures; however, east–west sections reveal shortening structures. Both sets of structures occur well updip of the downdip salt pinchout. We designed a physical-modeling study to investigate these puzzling relationships. Models presented in Part 1 of this paper indicate that localized shortening and extension can occur as salt passes over simple base-salt steps. Physical models were run with complex salt isopachs featuring plunging arches oblique to dip and salt flow. Models reveal the formation of shortening belts as the salt and its thin prekinematic overburden are translated across the arches. The complex salt isopachs deflect salt flow to produce convergent and divergent flow, which, along with flow-velocity gradients, results in the rotation of early formed thrust belts. Rotations of up to 70° were recorded in the most complex model, resulting in transported fold belts with trends that were close to dip parallel, similar to those observed on seismic data from the eastern Gulf of Mexico. Additional zones of shortening are found in and around complex salt pinchouts in the updip zones of the gravity-gliding system. The dynamic nature of these salt-related tectonic systems can result in the downdip translation of fold belts far from the basement topography over which they were created.

Introduction

As documented by the companion paper, Dooley et al. (2017), salt-flow patterns can be perturbed by base-salt relief. Examples of this type of topography include fault steps that localize deposition of thick salt or basement arches that produce complex salt isopachs. Subsalt topography can impart a degree of radial gliding during early stage salt tectonics, such as that in the Campos Basin (Cobbold and Szatzmari, 1991). Suprasalt deformation patterns can be influenced by a residual topography imparted by extensional faulting during rifting (e.g., Gaultier et al., 1993).

More recently, Pilcher et al. (2014) document radial gliding from a portion of the eastern Gulf of Mexico (Figure 1). In this region of the gulf, a series of basement arches and associated base-salt relief has had a strong influence on the early stage (Upper Jurassic to Early Cretaceous) rafting and associated deformation patterns (Figure 2). The Jurassic Louann Salt is continuous from the Apalachicola Embayment over the Florida Middle Ground Arch system and then into the main salt basin (Figure 3). In parts of this region, seismic data often paint a confusing pattern: Extensional structures dominate in the north–south dip direction as expected (Figures 3 and 4a); however, in strike sections (east–west lines), deep shortening structures involving the Upper Jurassic Norphlet and Smackover Formations are observed overlain and surrounded by extensional features (Figure 4b). The geometry and evolution of these rafts are very relevant to the petroleum system in the northeastern Gulf of Mexico because the eolian sandstones of the Norphlet Formation and the lime mudstones of the Smackover Formation are an important reservoir and source rock, respectively (Pilcher et al., 2014).

¹The University of Texas at Austin, Bureau of Economic Geology, Jackson School of Geosciences, Austin, Texas, USA. E-mail: tim.dooley@beg.utexas.edu; michael.hudec@beg.utexas.edu.

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In this paper, we address three pertinent questions about these shortening structures: (1) How did they form, and why are they surrounded, overlain, and dissected by extensional structures? (2) Why are the shortening structures located so far updip from the typical compressional toe regime, in which shortening in gravity-driven systems is typically observed? (3) Why are the structures best seen in east–west-trending sections, thus oriented subparallel to the dominant salt-flow direction?

**Figure 1.** Bathymetric map of the northeastern Gulf of Mexico. Data are from the GeoMapApp and the Global Multi-Resolution Topography (GMRT) synthesis.

**Figure 2.** Structural features and depth-to-basement map of a portion of the northeastern Gulf of Mexico. Location of map is illustrated in Figure 1. Redrawn and modified from Mancini et al. (2001). Length of lines indicating the approximate locations of Figure 4a and 4b are not to scale.

**Figure 3.** Northeast–southwest-trending seismic section from the Pensacola Arch through the Apalachicola Embayment and across the Southern Platform-Middle Ground Arch. Note that a continuous salt layer or salt weld connects the Apalachicola embayment to the rest of the central Louann Salt Basin. The diagram is modified from Hudec et al. (2013). Seismic data are courtesy of Spectrum. An approximate location of the seismic line is illustrated in Figure 2.
To address these questions, physical models are used to explore the role that base-salt relief plays in deformation patterns in strata overlying the salt layer in time and space. In our companion paper (Dooley et al., 2017), we explored the role of simple base-salt steps on the localization of extensional and contractional structures in strata overlying salt. When salt carrying a thin overburden passes over a high block, shortening structures form parallel to the boundaries of the block near its updip edge and adjacent to its downdip edge (Figures 5 and 6). In this paper, we expand on the work presented by Dooley et al. (2017) to include models with more complex salt isopachs that thin onto plunging basement highs, similar to the base-salt relief in the eastern Gulf of Mexico.

**Methodology**

As in our companion paper, we simulated rock salt using ductile silicone and simulated its siliciclastic overburden using brittle, dry, granular materials. The silicone is a near-Newtonian viscous polydimethylsiloxane, a long-chain polymer with a density of 950–980 kg m$^{-3}$ and a dynamic shear viscosity of $2.5 \times 10^4$ Pa s at a strain rate of $3 \times 10^{-1}$ s$^-1$ (Weijermars, 1986; Weijermars et al., 1993). Prekinematic and synkinematic strata were composed of a mixture of silica and clay.

**Figure 4.** (a) Interpreted seismic line showing dominantly extensional structures viewed in north–south-trending dip lines. Seismic data are from Pilcher et al. (2014). (b) Interpreted east–west seismic line illustrating deep shortening structures just above the base salt. The shallow/younger parts of the section are extensional. The vertical exaggeration = 3.5:1. Interpretation is courtesy of Steve Ehlinger, Noble Energy. Seismic data are courtesy of WesternGeco Multiclient and appeared originally in Smith (2015). The approximate locations of seismic data are shown in Figure 2.

**Figure 5.** Summary diagram illustrating the effects of a subsalt high block on salt flow and cover deformation based on data in Dooley et al. (2017; their model 7). (a) Streamlines converge as the salt thins onto the subsalt high block. This large change in salt thickness (high $T/t$ ratio) creates a major flux mismatch between the thick and thin salt regions due to basal drag, resulting in initial contractional thickening of the salt. (b) Overhead view of the model illustrating this process. (c) As the salt thickens above the base-salt high, the effects of basal drag are partially mitigated, resulting in accelerated flow and extension.
sand (bulk density of 1700 kg m$^{-3}$; grain size of 300 μm; internal coefficient of friction, $\mu = 0.55$–0.65; see material properties studies in, e.g., McClay, 1990; Krantz, 1991; Schellart, 2000) and hollow ceramic microspheres to achieve a density equal to that of our model salt (bulk density of 600 kg m$^{-3}$, grain size of 90 μm, and typical $\mu = 0.45$; Rossi and Storti, 2003). This was done to avoid complexities introduced by the foundering of the brittle overburden.

The setup for the three models — models 10, 11, and 12 — presented in this study is illustrated in Figure 7a–7c, respectively. These models differ from those of our companion paper (Dooley et al., 2017) by their more complex salt. Model 10 consisted of a simple plunging
high block oriented 60° oblique to the dip direction. The salt thickness increased from 3 mm in the south to 20 mm in the north (Figure 7a). Model 11 consisted of two plunging arches oriented approximately 50° oblique to the dip direction (Figure 7b). Our model salt (silicone) thins from 12 mm thick off the arches to zero directly over the updip part of the arch to form a complex salt pinchout geometry. Model 12 consisted of a single plunging arch oriented 40° oblique to the dip direction (Figure 7c). In this case, the model salt thinned from a maximum of 15 mm to zero in a complex pinchout along the arch. In models 11 and 12, thick polymer/salt in an embayment was partly surrounded in the dip direction by thinner polymer/salt across the plunging arch system. In all models, the subsalt topography was built by sculpting wet sand. Once the topography was built, the salt analog (silicone) was emplaced and allowed to settle. A thin (5 mm thick) prekinematic layer with a unique color was placed on top of the salt analog, and the model was tilted to 3° to initiate deformation. As in part 1 of this paper, we chose to minimize the effects of gravity spreading and focus on gliding, mixing the silica sand and ceramic beads such that their density was equal to that of our model salt.

Computer-controlled digital cameras recorded the evolution of the obliquely lit upper surface of the models at set time intervals. A 3D digital image correlation (DIC) system, consisting of a pair of high-resolution charge-coupled devices and associated software, tracked the surface-strain history, subsidence, and uplift values, as well as displacement vectors for the prekinematic layer and for each subsequent synkinematic layer added to the model. For more details on DIC monitoring techniques, see Adam et al. (2005).

**Figure 8.** Early stage topographic evolution of model 10. The data were generated by DIC software from high-resolution stereo imagery. (a) Topography after 3.5 h. A high and a low formed above the updip and downdip edges of the high block. The high corresponds to compressional thickening of salt due to the low flux through the high block. The low is an extensional monocline. (b) Topography after 12 h. The zone of thickened polymer above the plunging high collapses under extension as the flow velocity increases. The low downdip of the high block is a compressional hinge. (c) Topography after 20 h. Extension now dominates throughout the zone updip of the high block. Extensional graben formed on top of the high were translated into the compressional hinge and inverted to form a fold belt that is subparallel, at this time, to the plunging high.
The base of the deformation rig was transparent to allow us to monitor deformation of the prekinematic layer even after burial by synkinematic strata in models 12 and 13. The prekinematic layer was viewed from below through the transparent silicone of the model salt layer. Models with synkinematic sedimentation were wetted with a gelatin solution to allow sectioning. Coregistered digital photographs of the closely spaced serial sections (≤ 3.5 mm apart) yielded a 3D voxel model of orthogonal cross sections and depth slices. Inlines (parallel to the regional dip direction) are sliced and photographed cross sections, whereas crosslines and depth slices are virtual sections constructed from the voxel model; as a result, the crossline and depth-slice images are not as high resolution as those derived directly from photographed inlines.

**Effects of salt thickness — Flow across a plunging high block**

Model 10 investigated the effects of a simple plunging ridge on salt flow (Figure 7a). Tilting the deformation rig to 3° initiated deformation. Figure 8 illustrates the early-stage topographic evolution of model 1. After 3.5 h, a block-parallel structural high formed above the updip end of the ridge. A structural low formed just downdip of the edge of the ridge (Figure 8a). The topographic high formed because of compression and thickening as more salt was fed onto the high block than

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**Figure 9.** (a) Overhead view of model 10 after 22 h of deformation. Extension dominates in the region updip of the subsalt high as well as across the high block itself. Extensional graben were inverted to form fold belts immediately downdip of the high block (approximately 30° from the north). At this stage, these folds had orientations that were subparallel to the plunging high. (b) Overhead view of model 10 after 71 h of gravity-driven deformation. Major extension is seen throughout most of the model, with significant separation of raft blocks. The raft blocks also record significant clockwise rotation, as do the folds that formed in the compressional hinge. Early formed folds with initial orientations 30° clockwise of N now display orientations of up to 57° from the north. (c) Overhead view of model 10 at 36 h with superposed streamlines. The streamlines illustrate a component of northward flow on the updip side of the plunging high and southward flow as the model salt and its overburden crosses the high block. The flow is greatly perturbed above the thinner salt. (d) Velocity map of model 10 at 36 h. The velocity gradient (faster above thick salt) drove the rotation of the fold belts as they were translated downdip.
could be accommodated — a result of inhibited flow across the subsalt high block, similar to that seen in Figure 5. The low was the downdip portion of an extensional monocline similar to that seen in Figure 6. Eventually, this early high became thick enough to partly overcome the effects of basal drag and collapsed under extension as salt-flow velocity accelerated (Figure 8b). The topographic hinge continued to develop just downdip of the subsalt high block (Figure 8b). With continued deformation, extension dominated throughout the zone updip of the high block (Figures 8c and 9a). Extensional graben that passed through the downdip compressional hinge were inverted to form a fold belt that was initially subparallel to the plunging high (Figures 8c and 9a).

After 71 h, major extension was seen throughout most of the model, with significant separation of raft blocks (Figure 9b). Raft blocks also recorded significant clockwise rotation, as do the folds that originally formed in the compressional hinge. The earliest formed folds recorded clockwise rotations of up to 20° (Figure 9b). Streamlines from an earlier stage of the model illustrate a component of northward flow on the updip side of the plunging high and southward flow across the high block (Figure 9c). The flow is greatly perturbed above areas of thinner salt. The associated velocity gradient (faster above thick salt), recorded in the DIC data, drove the rotations of the fold belts and the raft blocks as these structures were translated downdip (Figure 9d). Note that the fold belts, heavily dissected by extension, were translated far downdip from where they formed, blurring the spatial link between their present location and their cause of formation (Figure 9b).

Complex salt isopachs — Flow across basement arches

Model 10 illustrates that subsalt topography can have a profound influence on salt flow and the structures formed in the suprasalt overburden. It also shows that variations in salt thickness can drive significant rotations within the overburdens because of velocity gradients. Models 11 and 12 expand on the findings of model 10 with setups that contain elements of base-salt relief, similar to those present in the eastern Gulf of Mexico, which are likely to have significantly impacted early stage salt flow (Figure 7b and 7c).
Figure 10a shows an overhead view of model 11 39 h into the experiment. The white model surface is the first synkinematic layer deposited above the prekinematic overburden. Deformation is dominated by extension, with associated reactive diapirs in the embayment, adjacent to the salt pinchout and downdip of the basement arches. However, minor shortening structures are seen in which the prekinematic layer pokes through the synkinematic layer in the form of anticlines, along the arch and at the downdip edges of the arches. Shortening strains from just before the addition of this first synkinematic layer are illustrated in Figure 11a. Shortening is concentrated against the complex updip pinchout that flanks the embayment, along the arch, and near the toe of the arch (Figure 11a). The minor folds seen in the earlier stage of the model were significantly amplified and rotated counterclockwise in the north and clockwise in the south. Shortening strains are recorded along the plunging arches and out into thicker salt as these structures were translated and rotated (Figure 11b). Views of the underside of the model illustrate the folds forming at the toe of the plunging arches and their

![Figure 11](image)

**Figure 11.** DIC imagery showing shortening strains in model 11. (a) Shortening strains in the prekinematic overburden after 25 h runtime. Shortening is concentrated against the complex updip pinchout in the embayment, along the arch, and near the toe of the arch. Note the diffuse shortening zone between the seaward edges of the arch network. (b) Shortening strains after 50 h runtime and the addition of the first synkinematic layer (see the overhead view in Figure 10b). On both plunging arches, a zone of shortening runs down the plunge of the arch and out into a thicker mobile layer downdip of the arch network as these structures were translated and rotated. A zone of diffuse shortening links the two main shortening trends.

![Figure 12](image)

**Figure 12.** (a-c) Views looking up through the transparent model salt layer at the underside of the prekinematic layer (orange) in model 11 reveal the rotation of the fold belts once they are translated past the nose of the arches. A total of 56° counterclockwise rotation is recorded for the northern folds (c). This is in addition to the rotations observed on the surface views before they were translated off the arch system and visible from below.
gradual rotation as they are translated downdip (Figure 12). A total of 56° counterclockwise rotation was recorded for the northern folds (Figure 12c).

DIC data from model 11 (Figure 13) reveal similar but more complex patterns of topography, flow direction, and velocity gradients than those seen in model 10. Tracking northward and southward flow reveals that convergent flow dominates updip of the arches, thickening salt in the embayment, whereas divergent flow dominates downdip of the arches, resulting in rotational strains (Figure 13b). Figure 13c illustrates that dip-parallel displacements were at their maximum in the center of the model, where there was a narrow gap in the arch system and where the salt was thickened by the convergent flow shown in Figure 13b. The shear couples associated with this velocity gradient drove significant rotation of the fold belts (Figures 10–12).

Model 12 tested whether shortening structures would form in the suprasalt section moving over a single plunging arch (Figure 7c). An overhead view and DIC map indicating shortening strains is shown in Figure 14. As shown in model 11, a proximal fold belt formed adjacent to the complex salt pinchout, and a zone of arch-parallel folds formed above the plunging arch before being translated further downdip (Figure 14a and 14b). An underside view of model 12 reveals a series of fold belts downdip of the nose of the subsalt arch (Figure 14c).

Figure 13. DIC data from model 11 from the end of the first synkinematic layer (50 h runtime). (a) The change in relief illustrates the extensional subsidence within the embayment. The local lows immediately downdip of the arch are due to the higher flux of thicker salt pulling away from the noses of the arch systems. (b) Image showing northward (warmer colors) and southward (cooler colors) motions. A convergent flow dominates updip of the arches, thickening salt in the embayment, whereas a divergent flow dominates downdip of the arches, resulting in rotational strains. (c) Dip-parallel displacements show a maximum in the center of the model, where there is a narrow gap in the arch system and where the salt is being thickened by the convergent flow shown in (b). The shear associated with this velocity gradient also drives rotation.
Complex salt isopachs — Cross-section description

Dip sections through model 11 reveal a deformation style dominated by extension (Figure 15). However, shortening structures are seen in various locations. A section that cuts through the updip breakaway and lateral salt pinchout reveals extension dominating updip and downdip of this pinchout, whereas the crest of the arch and pinchout reveals significant shortening structures (Figure 15b). Moving further south in the model, the structures appear to be predominantly extensional (Figure 15d; similar to the style seen in Figure 3), but detailed views reveal oblique sections through the translated fold belts downdip of the arch, as well as a squeezed diapir and partially inverted graben above the arch system (Figure 15f and 15g). This diapir originally formed in the extensional zone updip of the arch system, but it is not clear whether it was shortened because it climbed up on the arch or because it approached the downdip side of the arch. However, a partial section through an updip part of the southern arch reveals a shortened diapir (Figure 15h). In this case, shortening was clearly related to basal drag or buttressing by the arch (Figure 15h). In the center of

Figure 14. (a) Overhead view of the deformed surface of the first synkinematic sediment layer of model 12 after 50 h model runtime. As in model 11, we see a proximal fold belt adjacent to the complex salt pinchout and a zone of arch-parallel folds that formed above the plunging arch before being translated off the arch into thicker salt. Note the major extension above the thicker salt in the embayment in the south and the closely spaced faulting above thin salt on the pinchout ramps. (b) DIC data showing the shortening strain from the location illustrated in (a). The proximal shortening zone is very well-developed against the pinchout. The more distal shortening is not as strong but extends along part of the arch in a diffuse manner. (c) Underside view of model 12, looking up onto the prekinematic granular layer. The location is illustrated in (a). G1 is the graben seen in the overhead view in (a), where the overburden was extensively thinned. The more updip fold belt is the one imaged in (a and b) as it traversed off the nose of the subsalt arch. An older, translated, and rotated fold belt, visible downdip, formed in the same location as the more updip fold belt before the addition of the first synkinematic layer.
the model, major raft development occurred in this region of continuous thick salt through the gap between the subsalt arches (Figure 15e). Closely spaced faults characterize deformation above the pinchout ramp where the salt thins, forming a series of prerafts until thicker salt is reached where major rafting occurred (Figure 15e).

Figure 16a illustrates stacked virtual depth slabs through the reconstructed 3D volume of model 11. In the shallower depth slab, structures appear to be entirely extensional; however, dip lines reveal squeezed diapirs in the proximal domain and low-amplitude folds further down slope. The lower slab illustrates the final orientation of the deep, translated, and rotated fold belts (Figure 16a), which are flanked by major reactive diapirs in the central part of the model. A detailed view of a dip section illustrates that late-stage shortening above the oblique arch was accommodated by squeezing of reactive diapirs, resulting in partial inversion of an extensional graben (Figure 16b). Because of the significant rotations of the early-formed fold belts, shortening structures are best seen in virtual strike lines from the model 3D volume (Figure 16c). In this example, deep thrusting of a fold places our prekinematic strata (Norphlet equivalent) above the first synkinematic layer (Figure 16c), similar to structures seen in the east-west seismic data from the eastern Gulf of Mexico (Figure 4b).

**Figure 15.** (a) Overhead view of the top of synkinematic layer 4 in model 11 at the end of the experiment, showing locations of sections in (b-e). (b) Cross section through the model that cuts across the subsalt arch and lateral salt pinchout. Extension dominates updip and downdip of the pinchout. A series of shortening structures are present on the crest of the arch. (c) Section further south illustrating dominant extension deformation and the formation of a series of rafts of prekinematic strata (orange) in the updip domain. (d) Moving further south, the degree of rafting increases. Note that the extensional graben rise up as they traverse up and across the basement arch system. (e) Section from the center of the model illustrates major raft development in this region of continuous thick salt through the gap between the subsalt arches. Closely spaced faults characterize deformation above the pinchout ramp where the salt thins. (f) Detailed view of a portion of the section in (c), illustrating a translated and buried inactive fold downdip of the arch and a squeezed diapir/inverted graben system on the downdip flank of the arch. As the overburden thickened and strengthened, the mild shortening was focused on diapirs. (g) Detail of the section shown in (d), illustrating the translated northern fold-thrust belt far downdip from the basement arch where it formed. (h) Partial section through the southern arch system showing a squeezed reactive diapir. Shortening here is attributed to buttressing by the updip edge of the arch system.
Conclusion

Part 1 of this paper demonstrates that extensional diapirs and compressional fold belts can be initiated anywhere on a slope as salt accelerates and decelerates when flowing across base-salt relief; thus, structural evolution is likely to be more complex than a simple extension-translation-shortening model commonly invoked for gravity-driven deformation above mobile substrates. The three physical models presented in this paper possessed more complex, plunging, base-salt relief and complex salt isopachs, resulting in far-more-variable salt flow, similar to what we suspect occurred during early stage rafting of the Norphlet and Smackover Formations in the northeastern Gulf of Mexico.

Despite the additional complexities, the basic principles outlined in the simple models of our companion study (Figures 5 and 6) also remain valid in these more complicated geologic scenarios. Fold belts formed as the salt and its thin overburden flowed across the plunging base-salt arches. Early-formed fold belts were enhanced, and later-formed extensional grabens were inverted because they flowed off the highs through contractional hinges into regions of thicker salt downdip. The models may explain how and why similar structures seen in 3D seismic data from the northeastern Gulf of Mexico formed above autochthonous salt so far from the toe-of-salt zone typically associated with shortening in gravity-driven systems. Additional zones of shortening in our models formed in and around com-
plex updip salt pinchouts associated with base-salt relief, generating unexpected updip-pinchout-proximal fold and thrust belts.

The fold belts are surrounded, overlain, and dissected by extensional structures because their formation is spatially limited to the base-salt relief that produces shortening strains; once transported away from this localized shortening zone, the overburden is free to extend as the salt flows downslope at variable rates. In addition, fold-thrust structures only form when the overburden is thin enough to fail under the typically low shortening strains produced by base-salt relief (Figures 10 and 12). As the system evolves and the overburden thickens and strengthens, local shortening is cryptic, typically accommodated by layer-parallel shortening or by squeezing of preexisting diapirs, as observed in our model 11 (Figures 15 and 16).

The more complex salt isopachs in the physical models presented in this study have a fundamental impact on salt flow, producing flow directions that deviate from dip-parallel and velocity gradients across the model. These velocity gradients are the driving force behind the extreme rotations of early-formed shortening structures so that their trend is almost dip parallel (Figure 16), similar to the situation seen in seismic data from the northeastern Gulf of Mexico (Figure 4b). Continued downdip translation obscures the relationship between such structures and the base-salt relief that caused their formation. In addition, weak zones such as diapirs are likely to be rejuvenated under extension and contraction if they encounter additional base-salt relief downslope.

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Tim P. Dooley received a B.Sc. (1988) from Trinity College Dublin and a Ph.D. (1994) from the University of London. He spent the next nine years with the Fault Dynamics Research Group at Royal Holloway University of London. He has conducted experiments studying structural processes since 1988. He joined the Applied Geodynamics Laboratory (AGL), a research group focused on salt tectonics, at the University of Texas at Austin in 2003, where he managed the physical modeling laboratories. His current research interests include the growth, advance, and coalescence of salt sheets; salt-stock canopy systems; strike-slip deformation above salt; the effects of shortening on salt diapirs and minibasins; and the effects of base-salt relief on salt flow and suprasalt deformation patterns. He is a corecipient of AAPG’s Braunstein award.

Michael R. Hudec a Ph.D. (1990) from the University of Wyoming. He joined the Bureau of Economic Geology in 2000, where he directed the Applied Geodynamics Laboratory consortium. His current research interests include the evolution of salt basins and seismic interpretation of salt structures. He is a recipient or corecipient of AAPG’s Matson, Braunstein, and Levorsen awards.