A Three-Dimensional Geometric Model of the Bayou Choctaw Salt Dome, Southern Louisiana, Using 3-D Seismic Data

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ABSTRACT

The United States Strategic Petroleum Reserve Project has conducted a geological study of the Bayou Choctaw salt dome (and SPR site) using three-dimensional seismic data, which has been reprocessed to emphasize features in the vertical interval of principal interest for underground storage. This is believed to be the first openly published study of an onshore Gulf Coast salt dome using such 3-D data. The margin of the salt stock, as mapped using data with a spatial resolution on the order of 100 ft, exhibits vastly more small scale complexity, both vertically and horizontally, than is typically of published representations of salt domes. Features on the salt flanks my be classed as flutes, outward bulges, and downward tapering wedtges. Although the different types of features are somewhat gradational with one another, they reasonably be interpreted in terms of emplacement of the salt diapir as a collection of individual salt spines, separated by boundary shear zones, moving somewhat independently over time. This interpretation has implications for the internal fabric of the salt mass, particularly closer to the periphery of a dome. Salt fabric, in turn, has implications for the leaching and operation of underground storage caverns.

INTRODUCTION

Salt domes in the onshore Gulf of Mexico region have been intensely prospected for hydrocarbons since the early part of the Twentieth Century. A significant number of these same domes have also been explored and developed for sulphur extraction and — more recently — for underground storage of various hydrocarbons and products. However, the vast majority of onshore salt dome exploration was conducted without the benefit of modern three-dimensional seismic data. Consequently, the geometry of most salt domes is known only in somewhat generalized form.

The United States Strategic Petroleum Reserve (SPR) Project, which operates underground crude-oil storage facilities in four salt domes in Texas and Louisiana (fig. 1), has licensed a 1994 commercial 3-D seismic survey over the Bayou Choctaw salt dome and SPR site. These data have been reprocessed using current technology to emphasize the more shallow portions (above ~8,000 ft) of the Bayou Choctaw salt diapir. Interpretation of the reprocessed data reveals a visualization of domal geometry that is substantially different from the conventional portrayal of a salt stock. The geometry is far more complex in detail than classical understanding, and it is likely that the various observable geometric features are genetically related to the internal structure of the salt.

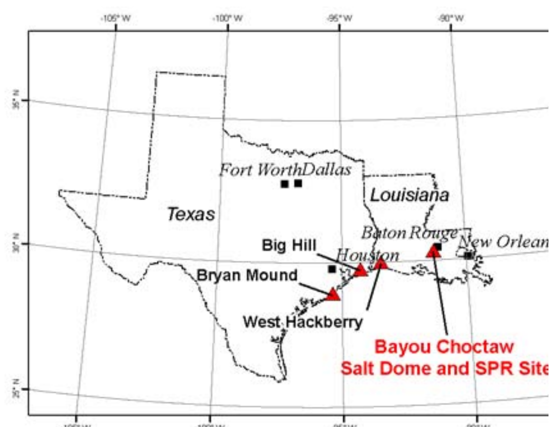

Figure 1. Index map showing location of the four salt domes use by the Strategic Petroleum Reserve, and of the Bayou Choctaw salt dome in particular.

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The Bayou Choctaw Salt Dome and Strategic Petroleum Reserve Site

The Bayou Choctaw salt dome is a relatively small salt stock, somewhat less than one mile in diameter. The geology of the salt dome and surrounding sediments has been studied at some length since the mid-1070s, as part of developing the existing SPR storage facilities (e.g., Hogan et al., 1980, Neal et al., 1993). More recently, two of us (Karl Looff and Chris Rautman) reviewed and reinterpreted the then-available information, and presented a revised characterization model of the Bayou Choctaw salt dome (Rautman, 2005). This model also incorporated a significant amount of general understanding of salt dome geology, which had been developed in the decade-plus since the study of Neal and others (1993).

This prior geologic characterization work has been based solely on information obtained from oil & gas exploration and/or production wells; storage-cavern wells are also included. Although there are some 325 wells located on the dome, or within a distance of approximately one to one-and-a-half miles of the salt flank, there is a relatively small number of actual penetrations of the salt margin, itself. Furthermore, even a large number of well intercepts of salt provide only “one-dimensional information” on the shape of the salt stock. Everything between well control points is “interpretation”.

The last reinterpretation of the Bayou Choctaw salt dome (Rautman, 2005) extended, to some degree, the amount of information available from the extant well records, by making extensive use of indirect data. Whereas an actual intercept of salt in well constitutes direct data, indirect information consists of (admittedly) somewhat less definitive indications of the presence/absence or depth to salt than an actual salt intercept. However, as direct data may be quite sparse at a salt dome, given that the purpose of petroleum exploration is ***not*** to drill salt, indirect data may contain large amounts of useful information.

An obvious types of indirect data are “permissive” indicators such as the total depth of a well not intersecting salt, although it was located over the general outline of the salt crest. Looff and Rautman also attempted, in some cases, to view historical drilling from the likely perspective of the original operator, using the total depth of the well, the maximum depth of geophysical logging, and completion records, in an effort to determine the approximate position of the salt contact with respect to the well.

The 3-D Seismic Survey

The three-dimensional seismic survey over the Bayou Choctaw salt dome used in this study was shot originally in 1994. The objective of the original processing appears to have been deep petroleum targets in upturned sediments along the flanks of the salt dome, probably at depths exceeding 12,000–15,000 ft. This translates to roughly 2.5 to 3 seconds, two-way travel time. The original data extend to 4 seconds, two-way travel time.

We determined that our study of the Bayou Choctaw dome would require only a portion of the nearly 40 total square miles of seismic data. However, we did ensure that the offsets available to us were long enough to provide adequate illumination of the steeply plunging salt flanks to the depths of interest for underground storage. The full extent of the 3-D survey is indicated on the map in figure 2, as is the area of the subset of the data licensed by Sandia National Laboratories.

The licensed portion of the 3-D seismic data were reprocessed using pre-stack Kirchhoff time migration. We used an overall processing flow which has been demonstrated to produce good imaging of the shallower portions of salt domes, and which has been used for 2-D seismic profiles in characterization of a number of domes for underground storage purposes. Resolution is excellent throughout the nominal storage cavern interval at Bayou Choctaw, from roughly 2,000 to 4,500 ft in depth. For comparative purposes, 5,000 ft equals about 1.4 seconds. The portion of the seismic data above 300 msec, two-way travel time, is of very poor quality. This interval, however, is mostly caprock, and there are adequate well penetrations of the caprock for SPR purposes.

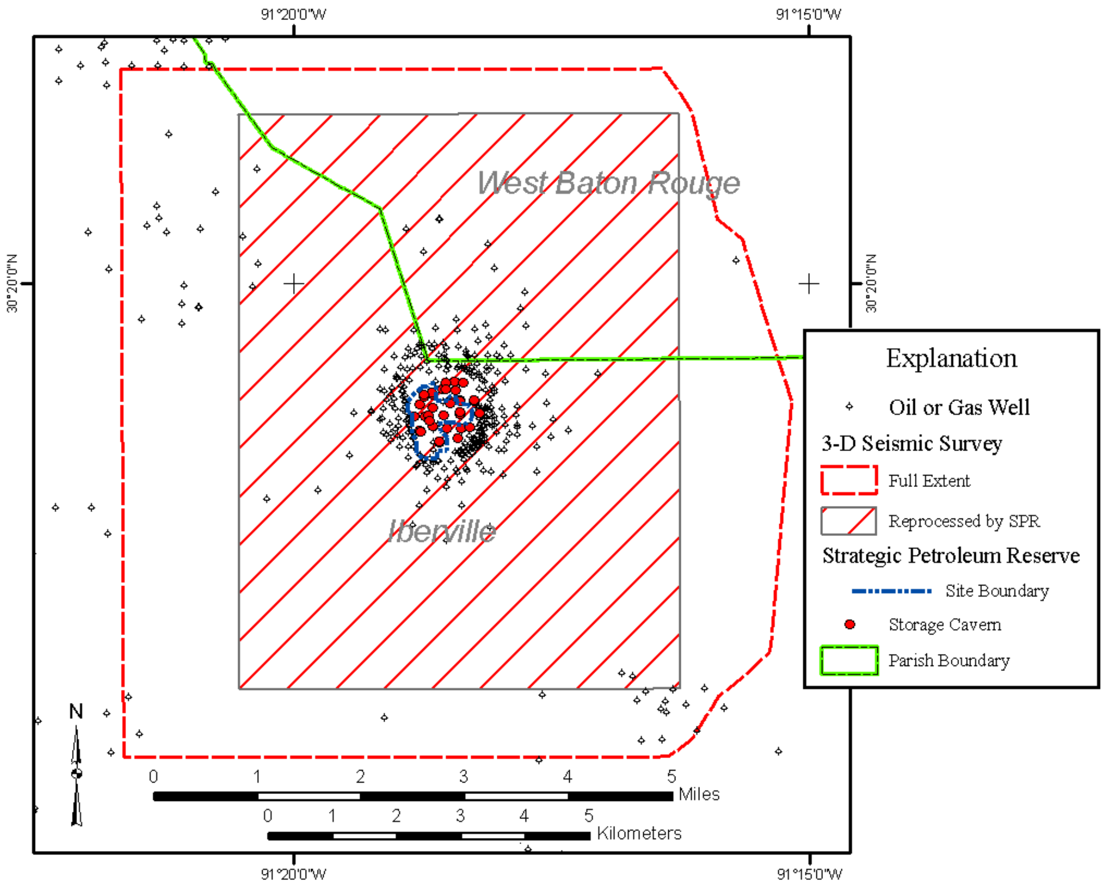

Figure 2. Index map showing the location of the Bayou Choctaw salt dome in relationship to the extents of the 3-D seismic data.

Interpretive and Modeling Process

Licensing restrictions associated with the proprietary 3-D seismic data set impose limits on the extent of the actual seismic data, and the manner of its presentation that may be published in an open report, such as this. Therefore, the images of the seisimic data presented below have been "sanitized" by removal of their spatial identification and shotpoint markings.

Overview of the Bayou Choctaw Seismic Data

Prior to beginning a detailed description of the interpretive and modeling process for the Bayou Choctaw study, it is instructive to step back and examine the Bayou Choctaw salt stock in its local sedimentary environment. Figure 3 presents two seismic profiles of the Bayou Choctaw dome. The vertical profiles pass through the approximate center of the salt mass, and they illustrate a number of features that are important in understanding any salt diapir. Note that the horizontal scale of the seismic images has been compressed very significantly. The entire width of the profiles is about four miles, whereas the vertical extent is somewhat under 15,000 ft.

The Bayou Choctaw salt diapir appears as a relatively slender, vertical feature, which gives the impression of having moved more or less straight upward. Note that the layered sediments outside the dome are much more steeply inclined at depth than they are at shallower elevations. This style of deformation is consistent with continuing uplift of the salt — or progressive sedimentary downbuilding — during deposition

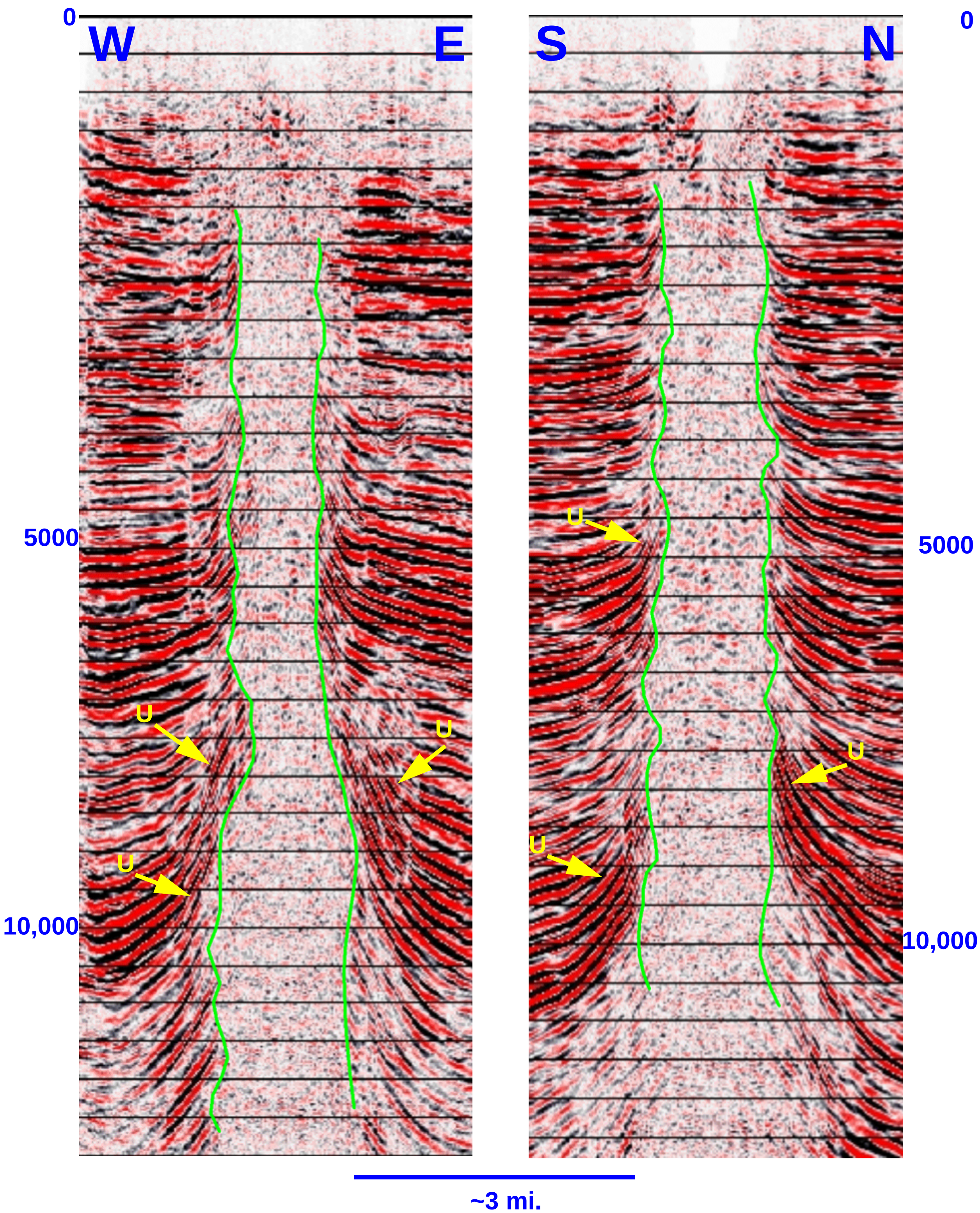

Figure 3. Horizontally compressed, deep 2-D vertical profiles through the approximate center of the Bayou Choctaw salt dome. (a) west to east; (b) south to north. Horizontal lines are 100 msec timing lines. Numbers indicate approximate depth, in feet. "**U**" – obvious unconformities.

of the surrounding sediments. Emplacement of the Bayou Choctaw salt dome clearly took place over a long period of time.

There are also a number of unconformities present in the section on these two profiles, most of which are positioned close to, or up against, the salt margin. A the more obvious unconformities have been indicated on the figure. The compressed horizontal scale of figure 3 makes it relatively east to identify the unconformities, where thick intervals of layered reflectors thin and or pinch-outt. Unconformities directly related to the salt flank provide evidence that the top of salt, at time, was above or very close to the sediment-water interface, and thereby the salt mass affected deposition. Although we have not mapped the surrounding sediments at this time, it seems likely that certain stratigraphic intervals thin towards the salt dome from all sides, indicating an influence of the dome on sedimentation even without actual erosion.

A very prominent feature of the salt diapir, in this horizontally compressed presentation, is the decidedly irregular lateral contact with the enclosing sediments. We will expand significantly upon this observation later in the report. Although the overall form of the salt is relatively streamlined. there are a number of very distinct outward bulges of varying horizontal and vertical extent. Clearly, the salt has moved *outward*, in addition to upward, at certain times. It appears that episodes of largely outward movement were then followed at a later time by more vertically directed upward motion. Although one may argue the precise positioning of the salt flank in some of these intervals, the nature of reflector terminations over the entire vertical interval presented in the figure leaves little question that the lateral bulges are real geologic features.

Interpretation in 2-D

The several past site characterization activities at Bayou Choctaw have provided a reasonably detailed context in which to interpret and model the 3-D seismic information. The interpretation of the Bayou Choctaw salt stock by Looff and Rautman had been converted to a three-dimensional visualization model (Rautman, 2005). This digital representation of the salt dome served as a starting point for interpretation of the much more extensive seismic information.

Displaying and interpreting three-dimensional seismic data is normally accomplished using sophisticated computer workstations designed for that purpose. Sandia did not have ready and ongoing access to such a workstation, with the result that we adopted a mixed 2-D/3-D manual interpretive process. Following completion of the geophysical reprocessing, a digital representation of the earlier visualization model was imported into a geophysical workstation at the vendor’s office, and superimposed electronically upon the processed data. Two-dimensional seismic profiles were then extracted from the seismic volume in both the inline and crossline directions (essentially east-west and north-south). Additional 2-D profiles were also extracted in the 45-degree directions. The various 2-D profiles were then plotted in hardcopy, and the salt margin was interpreted manually, using a set of criteria specific to this data set, and which “evolved” significantly over time.

Figures 5 and 6 present representative east-west and north-south seismic profiles of the Bayou Choctaw salt dome, Although we cannot indicate the precise locations of these profiles, they pass generally through the center of the salt dome in the two directions. Both uninterpreted and interpreted versions of the profiles are presented

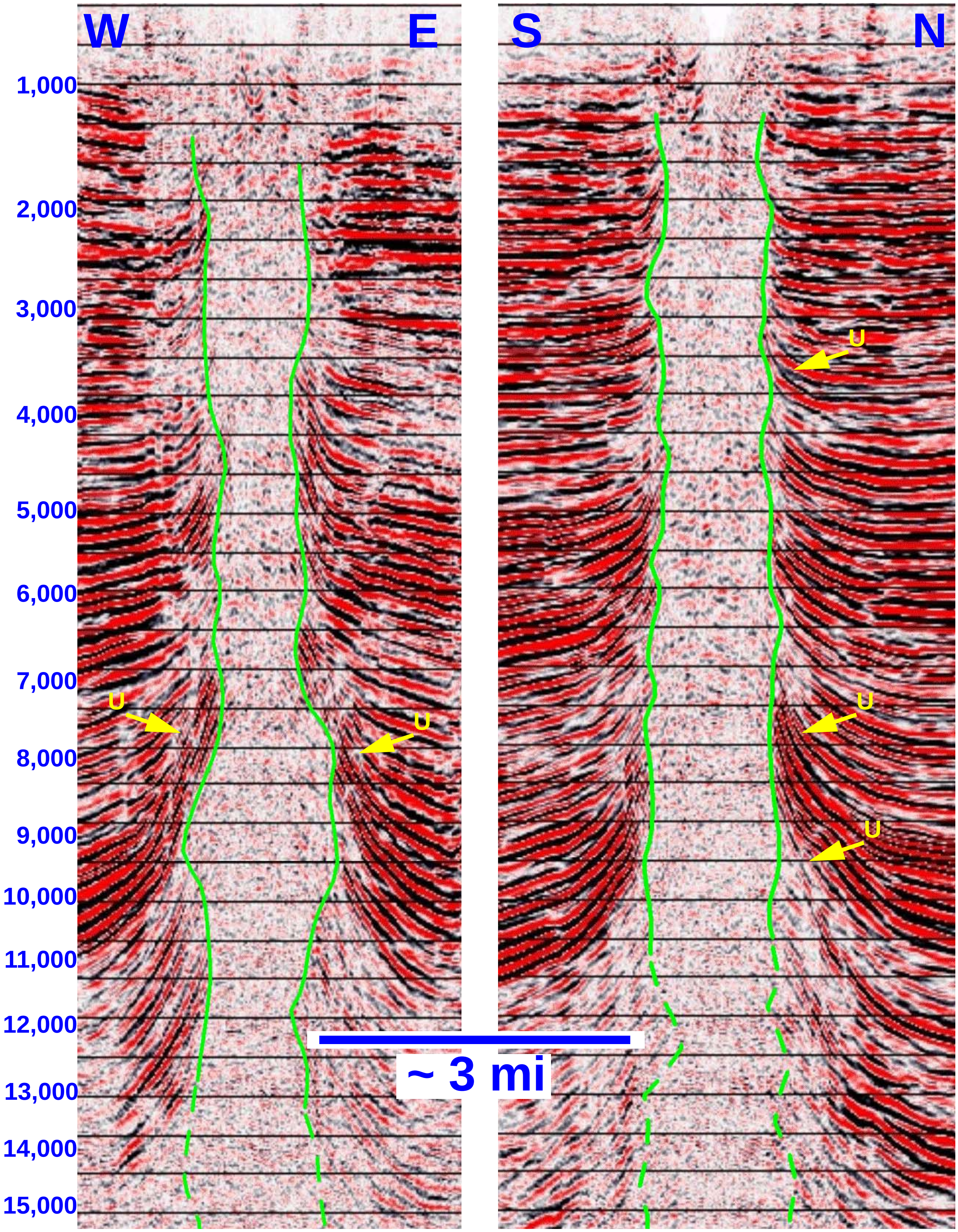

Figure 4. Horizontally compressed, deep 2-D vertical profiles through the approximate center of the Bayou Choctaw salt dome. (a) west to east; (b) south to north. Horizontal lines are 100 msec timing lines. Numbers indicate approximate depth, in feet. "**U**" – obvious unconformities.

Interpretation of 2-D Vertical Profiles

The overall position of the salt stock is clearly indicated by termination of the turned sedimentary reflectors surrounding the dome. However, interpreting the precise location of the salt flank becomes somewhat more difficult. Table 1 presents a list of the criteria used to pick the salt margin, in their approximate order of priority. As indicated, truncation of reflectors is only one of many criteria that we applied, in order to produce a consistent salt interpretation using 2-D profiles in multiple directions.

Table 1: Criteria used to interpret the salt margin

Priority (Approx.)	Criterion
1	Truncation of reflectors
2	Nearby well control, if it can be projected to the profile with confidence
3	Roll-over of upward-inclined reflectors
4	Position with respect to previously interpreted salt margin
5	Marked change in character of a group of reflectors
6	Any break in slope of a set of reflectors
7	Vertical interpolation between more-obvious salt-margin indicators
8	2-D horizontal reconciliation with other profiles

The north-south profile in figure 5 probably represents one of the most straightforward interpretations. In almost every instance, the margin of the salt could be picked — and reconciled with picks on other profiles — using criteria 1 and 3 from the table. Terminations and roll-over of reflectors are well developed, except in the shallowest portions of the profile, 1,000 ft and above. Here the interpretation is based principally upon the structure contour map of the top of salt developed previously and reported by Rautman (2005).

The east-west profile, shown in figure 6, represents a somewhat more complicated case for interpretation. In many locations, the margin of the salt dome is clearly indicated by truncation of upturned sedimentary reflectors. The eastern flank of the dome, at a depth of roughly 4,000 ft, is a good example. Likewise, reflector roll-over provides an apparently precise salt-sediment contact on the western flank, somewhat above a depth of 2,000 ft.

However, the margin of the salt dome is not so clearly delineated — on this profile, at least — in a number of other positions. Note, for example, the apparent inward continuation of a group of reflectors on the western flank, at depths of 4,500–5,000 ft. These reflections clearly appear to be present within the salt margin, as interpreted. However, moving the contact inward, to the “more obvious” termination of this group of reflectors, creates severe difficulties in interpreting the margin on adjoining profiles in different directions.

Another example involves the eastern flank of the dome at depths of 1,000 to nearly 3,000 ft. The best terminations of the strongest reflectors are positioned substantially east of the interpreted margin. What is not shown, on this particular figure, is that only a few hundred feet to the south of this 2-D seismic profile, there are two or three wells which provide definitive control on the position of the salt flank, down to a depth nearly 5,000 ft. It simply is not possible to consider 2-D profiles in isolation from one another, or from other types of constraining information.

Single-time Structure Contour Maps

The manual interpretation methodology involved identifying the apparent salt-margin seismic pick at even 100-msec travel-time intervals, and then plotting the *x-y* spatial position of this contact on a map. Repeating this process on each of the profiles in each of the four directions should, therefore, represent a time-based structure contour on the salt margin. Repeating the process at other 100-msec times should then allow creation of a fully 3-D representation of the salt stock by stacking the resulting contour maps in time sequence.

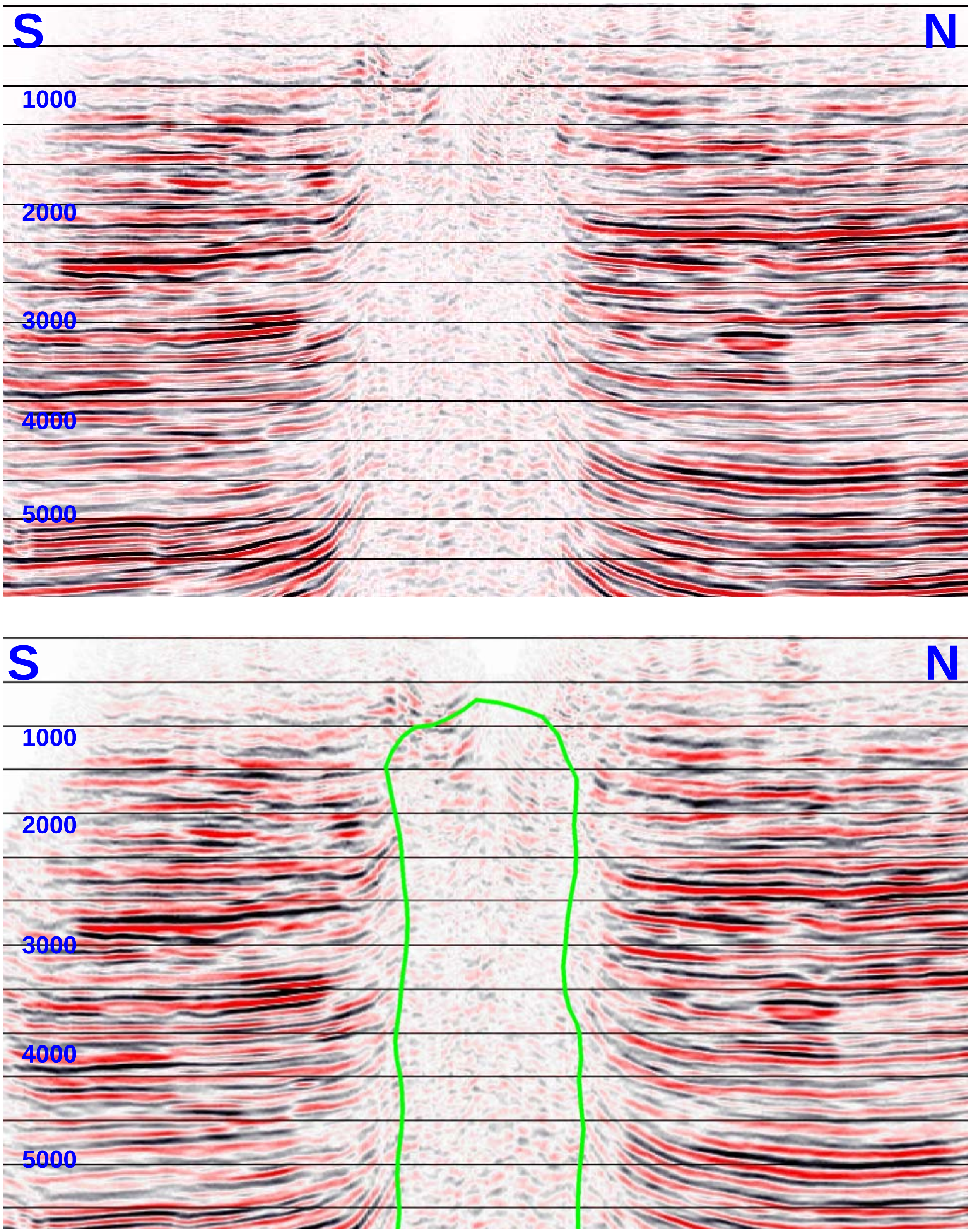

Figure 5. South-to-north 2-D seismic profile through the approximate center of the Bayou Choctaw salt dome, extracted from the 3-D seismic volume. (a) Uninterpreted; (b) interpreted. Horizontal lines are 100 msec timing lines. Numbers indicate approximate depth, in feet.

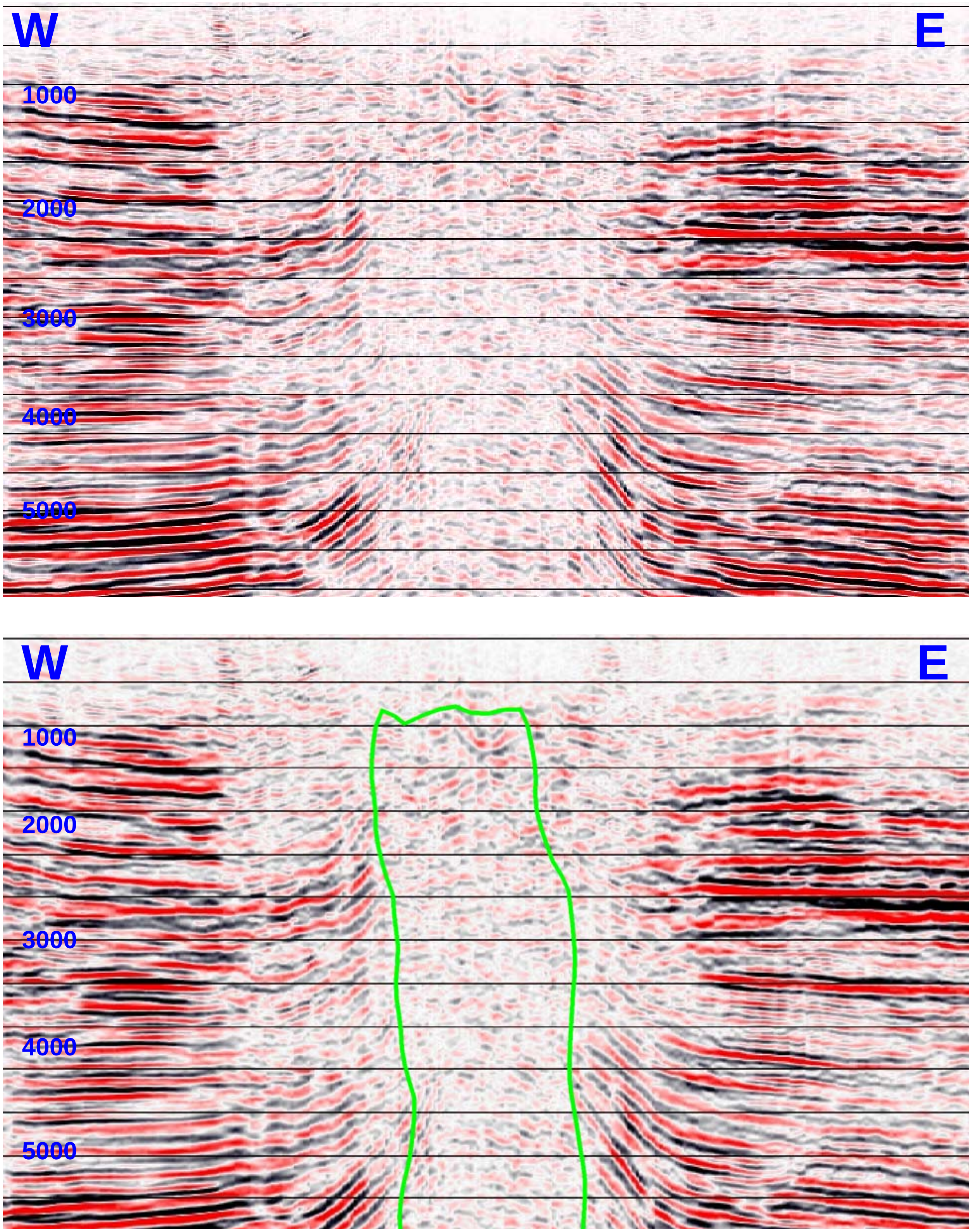

Figure 6. West-to-east 2-D seismic profile through the approximate center of the Bayou Choctaw salt dome, extracted from the 3-D seismic volume. (a) Uninterpreted; (b) interpreted. Horizontal lines are 100 msec timing lines. Numbers indicate approximate depth, in feet.

The final structure contour at a given two-way travel time became, of necessity, a best-fit compromise among the four potential sets of 2-D profiles. In general, interpretations derived from the inline and crossline profiles were easier to reconcile than the initially inferred contacts on the northwest-southeast and southwest-northeast 45-degree profiles. Figure 7 shows individual time-based structure contour maps for two of the fourteen mapped 100-msec time slices. To aid in the interpretation and understanding of the structure contour maps, the figures also indicate the 100-msec time contours immediately above and below the contour of interest.

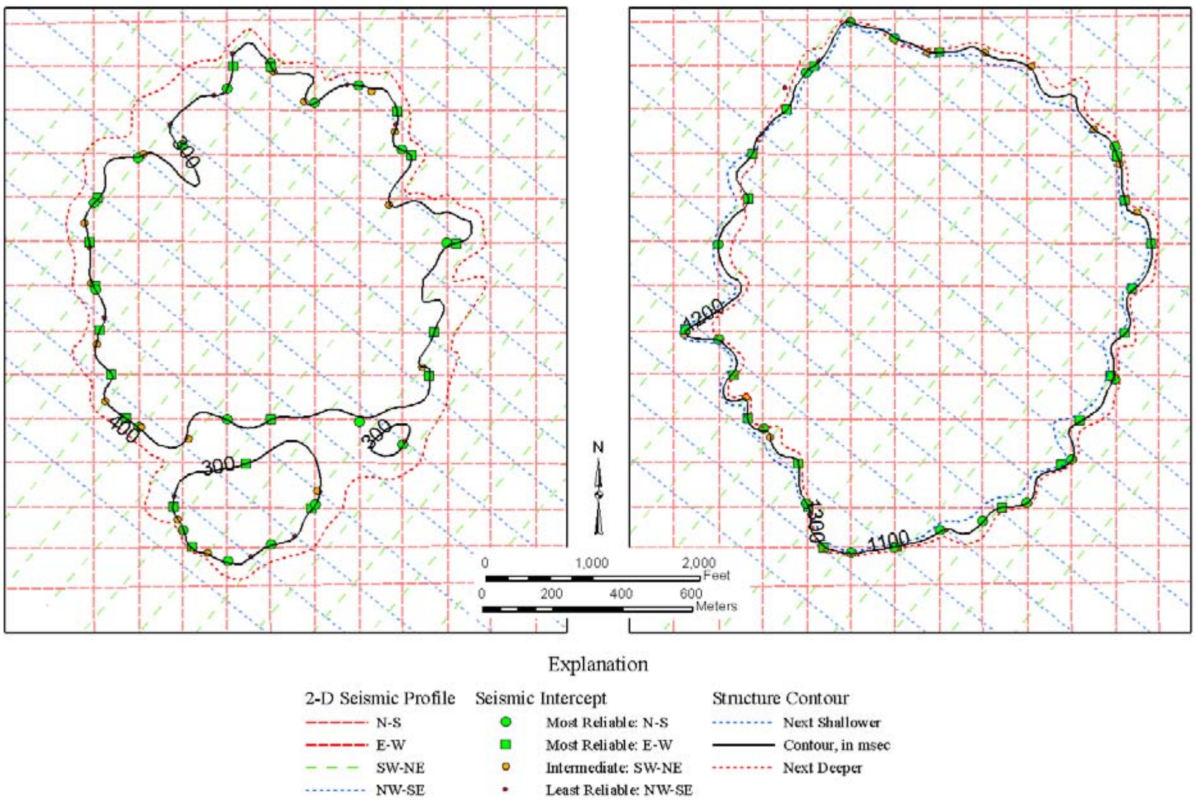

Figure 7. Individual time-based structure contour map of the Bayou Choctaw salt dome at a two-way travel time of 300 msec, showing control points identified using 3-D seismic data.

Note that we have identified separately three groups of salt picks. The large symbols, shown in green in figure 7, are thought to be the most reliable picks, as these were identified on either the east-west (green squares) or north-south (green circles) 2-D profiles (inline, and crossline respectively). The smaller orange circles and the yet-smaller red circles represent the picks of the salt margin on the southwest-to-northeast and northwest-to-southeast profiles, respectively.

Note that even after adjusting the apparent salt boundary picks at each 100-msec interval back and forth to accommodate this type of mapping interpretation in the horizontal plane, there is a great deal of "character" — salients and reentrants — to the outline of the salt dome at each two-way travel time. This appears to be one of the revelations of the Bayou Choctaw 3-D seismic study — an onshore Gulf Coast salt stock is by no means a simple, smooth-sided domal feature. Previous open-literature studies of similar salt stocks, based upon well data only, or even upon a small number of 2-D seismic lines, are not really capable of revealing continuous detail on the order of ~100 ft in all three dimensions.

Integration in 3-D

A major objective of this entire study is the creation of a fully three-dimensional model of the Bayou Choctaw salt dome, for use in ongoing studies of the Bayou Choctaw SPR site. This section describes the modeling techniques used to generate such a 3-D model, using both the interpreted 2-D vertical profiles and the 2-D single contour maps.

The interpreted salt margin, as revealed both on the vertical seismic profiles and on the horizontal structure-contour maps, forms the basis of a true three-dimensional model of the Bayou Choctaw salt dome. These several interpreted "lines" have been digitized, and each digitized point assigned a set of coordinates in three-dimensional space. There are also a modest number of well intercepts of the salt margin, not only over the crest of the salt stock, but also intercepts deeper on the salt flank. Figure 8 presents two views of the salt picks generated in this manner. Taken collectively as points, these data aggregate nearly 43,000 *x-y-z* triplets, each one of which presumably lies on the salt margin.

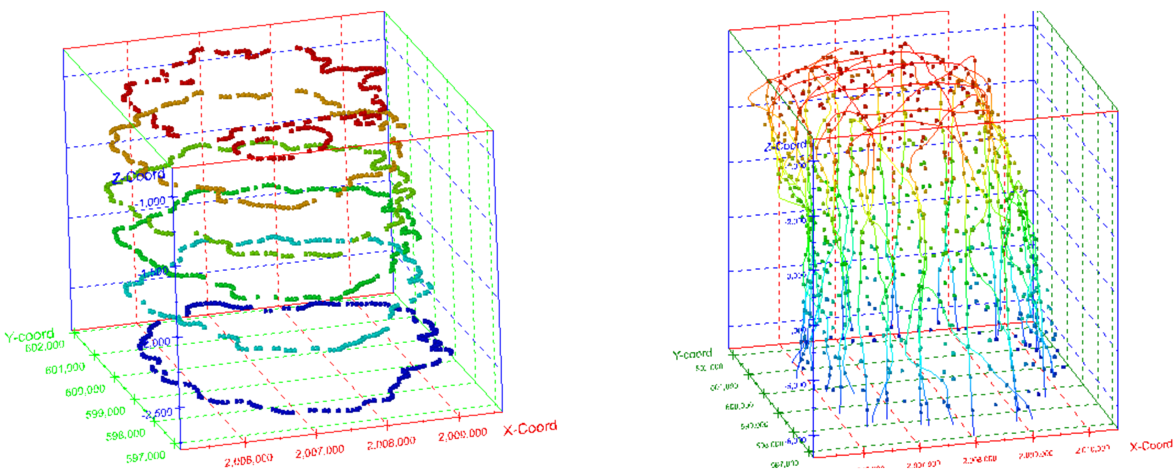

Figure 8. Three-dimensional perspective views of the mapped picks on the salt margin, mapped into 3-D computer space. (a) points corresponding to a sequence of 2-D horizontal structure contour maps; (b) points corresponding to a set of 2-D vertical profiles in multiple orientations (emphasized by lines).

Figure 8(a) presents the only the points belonging to a subset of the 14 structure contour maps. Each point on a single contour is positioned at the same time/depth, as represented by a single color. The contour-like nature of the points is quite evident. Figure 8(b), represents points from a subset of the digitized vertical profiles. There are actually many more points in the full set of interpretations than shown on these two illustrations.

The details of the modeling process used to turn the collection of 43,000-odd points into a three-dimensional model for visualization are beyond the scope of this paper. It may be summarized as generating a densely-spaced 3-D "block" model of the overall volume enclosing the salt stock, and using a variant of the geostatistical interpolation algorithm, kriging, to estimate the "distance" of each individual block from the nearest digitized point on the salt margin. Distances outside the salt (away from the centroid of the volume) are defined as positive and distances inside the salt are defined negative. The 3-D block model is then subset at "zero distance", and the result is a meshed surface representing the salt flank.

GEOMETRY OF THE BAYOU CHOCTAW SALT DOME

Figures 9 and 10 present a set of computer-generated perspective views of the modeled salt flank. The views include four different azimuths around the compass, as well as two different elevations. Figure 11 presents the final structure contour map for the Bayou Choctaw salt dome. The seismic-based 3-D model strongly resembles the earlier 3-D models of the Bayou Choctaw salt dome, as indicated by the comparisons in figure 12. As would be expected, the overall size and shape of the dome in the various models are quite similar. However, the model based upon the 3-D seismic data contains far more detail than the two earlier drill-hole-only based models. This increase in resolution is entirely in keeping with the vast increase in the amount of information contained in a 3-D seismic survey.

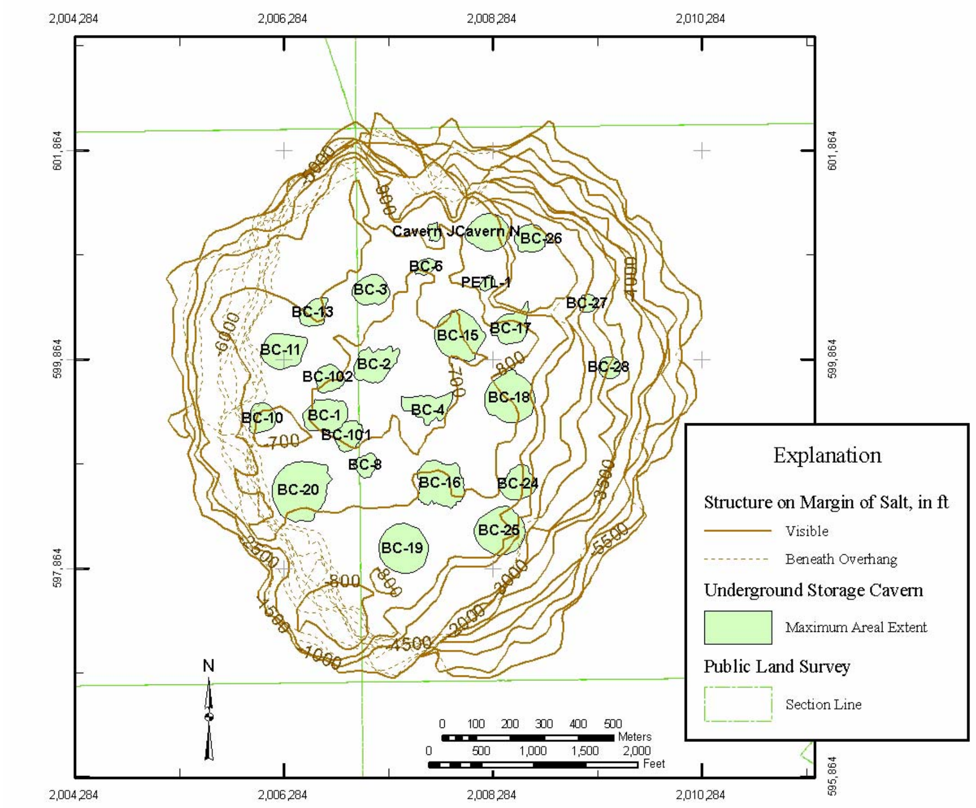

Figure 11. Structure contour map on the margin of salt at the Bayou Choctaw salt dome, Louisiana.

Comparison of Old and New Models

Figure 12 presents a side-by-side comparison of the new three-dimensional model with the two historical models. The view is from a generally southwesterly direction, and from a low elevation. These images illustrate the major differences between these representations of the Bayou Choctaw dome.

The most obvious difference among the three models is that there is a progressive decrease in the geometric simplicity of the modeled salt mass, and a corresponding increase in the amount of apparent detail. The original site characterization model (Hogan et al., 1980, as visualized by Rautman and Stein, 2004), in figure 12(a), shows the salt as not much more than a slightly distorted cylindrical form. This type of representation is fairly typical of many published (non-computer) models of salt domes; e.g., Halbouty (1979). Of course, a relatively simple geometric shape is a perfectly reasonable manner of representing a dozen or so actual salt intercepts in wells of varying depths. The model is also satisfactory and sufficient for some purposes.

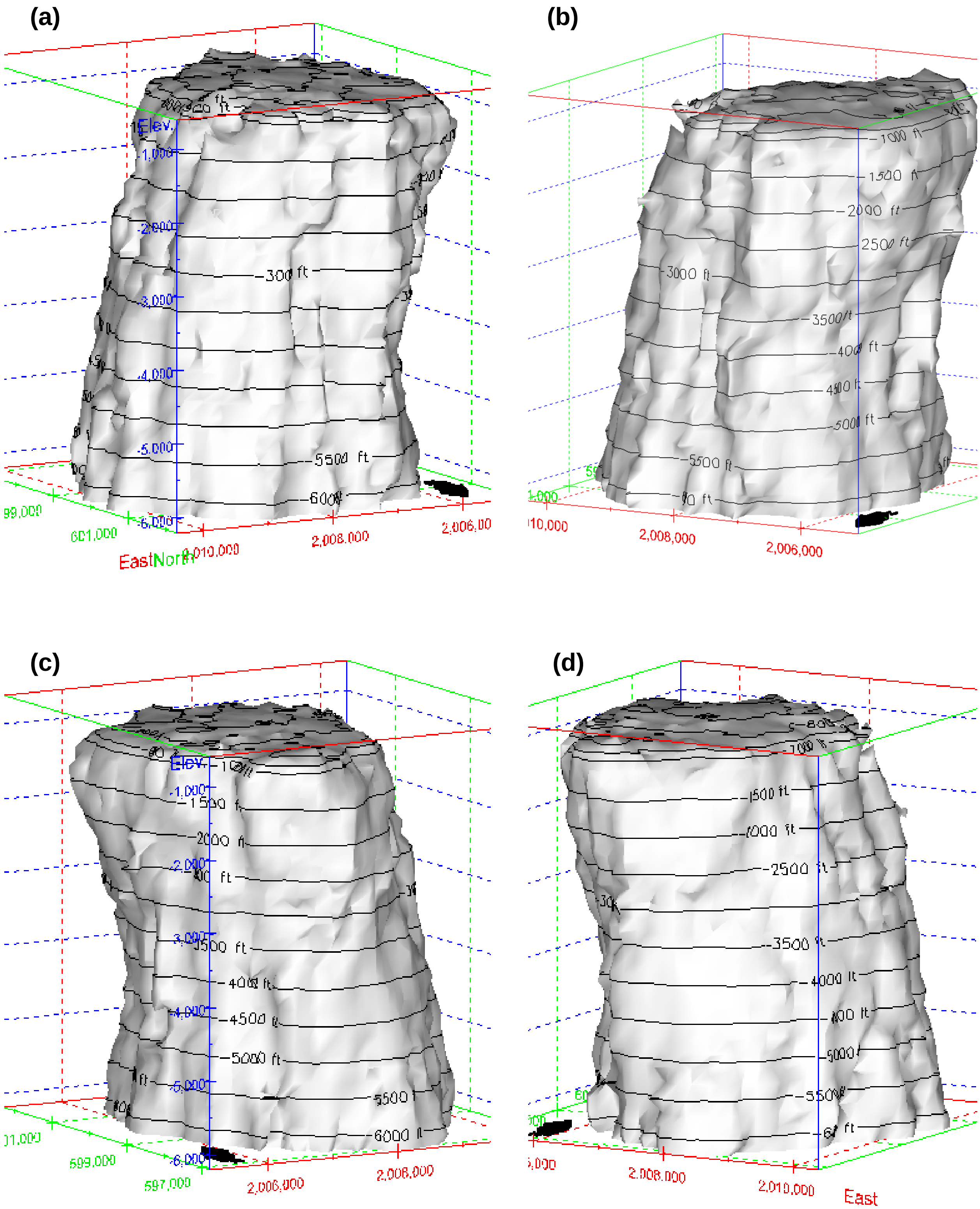

Figure 9. Low-angle perspective views of the three-dimensional model of the Bayou Choctaw salt dome, incorporating interpretation of the 3-D seismic survey. View from (a) azimuth 210°, elevation 10°; (b) azimuth 150°, elevation 10°; (c) azimuth 30°, elevation 10°; (d) azimuth 330°, elevation 10°.

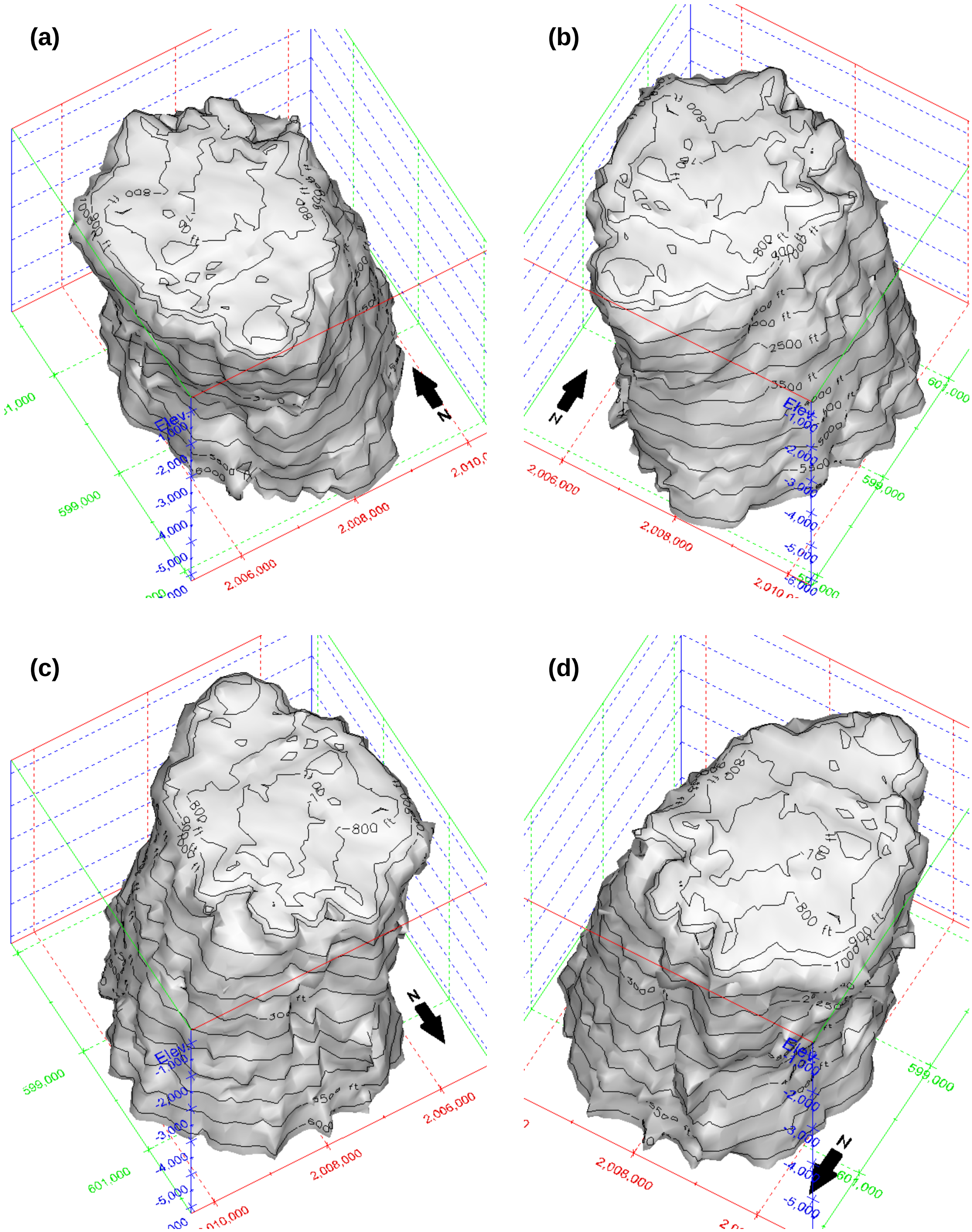

Figure 10. High-angle perspective views of the three-dimensional model of the Bayou Choctaw salt dome , incorporating interpretation of the 3-D seismic survey. View from (a) azimuth 210°, elevation 60°; (b) azimuth 150°, elevation 60°; (c) azimuth 30°, elevation 60°; (d) azimuth 330°, elevation 60°.

The somewhat more complex model, illustrated in figure 12(b), contains two types of additional information over the original site characterization model (Rautman, 1995). First, a significant amount of indirect well data has been incorporated, in addition to the actual salt intercepts that appear to have been the main basis for the previous model. Second, the interpretive task of how to interpolate the salt margin among the somewhat larger number of data points, both direct and indirect, was guided by the increased understanding of salt emplacement, developed in the quarter century following the work of Hogan and others.

There are several important structural features to be recognized in this model. First, the top-of-salt surface, on the crest of the dome, has been represented as a number of low-relief structural culminations. These are each inferred to represent the positions of individual salt spines, which together comprise the overall salt stock. The level of detail is guided largely by the additional well control that is available for the top-of-caprock surface (Rautman, 2005).

The second major difference between the models of figures 12(a) and 12(b) is that the overall salt flanks are represented as a sequence of horizontally undulating “waves”, instead of a smoothly curving cylindrical surface. This interpretive addition derives, again, from the newer understanding of salt dome emplacement by individual, quasi-independently moving spines, and also by incorporation of information from a number of indirect data points. If one attempts to infer why a particular well was terminated at a given depth, it sometimes makes more sense to push in or pull out the structure contours in a particular region. A full discussion of the subtleties of interpreting indirect, or “soft” data, is beyond the scope of this paper.

Finally, figure 12(c) compares the current geometric model of the Bayou Choctaw salt dome, based upon the three-dimensional seismic data, with the two earlier ones. The complexity of the outer margin of the salt is very much greater than that inferable from only point-type well information. The volumetric nature of the seismic information allows the identification and representation of much smaller-scale protrusions and undulations on the salt surface.

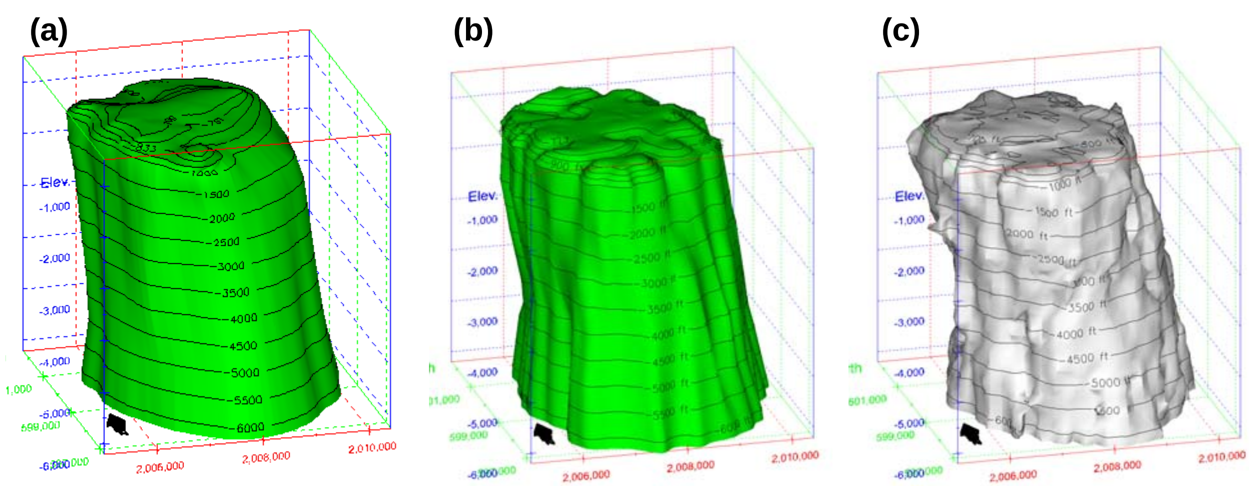

Figure 12. Side-by-side comparison of three-dimensional computer models of the Bayou Choctaw salt dome, showing evolution of modeling, and understanding of salt geometry over time. (a) Site characterization model of Hogan et al., 1980; (b) revised 3-D model of the Bayou Choctaw salt dome (Rautman, 2005); (c) new 3-D model of the Bayou Choctaw salt dome, using 3-D seismic interpretation. Views are identical from azimuth 195°, elevation 20°.

A more detailed examination of the specific differences between the latest model, (fig. 12(c)) with the earlier version (fig. 12(b)) has been conducted (Rautman and others, 2009). Again, the details are beyond the scope of this paper. However, we may summarize these differences as entirely consistent with the increased quantity and decreased spatial scale of the data. We have identified that the well-known overhang of the uppermost portion of the Bayou Choctaw dome is even more extensive than understood previously (see fig. 9). The known overhang on the western side of the dome is now modeled as more extensive, and the extent of overhang has been interpreted as extending into previously unrecognized regions on both the southern and northwestern flanks. The changes to the geometric configuration of the outward-plunging eastern flank of the salt stock are much smaller. This greater degree of similarity results, in no small part, from the more intense historical drilling activity in this eastern area, as well as from the absence of the confounding influence of structural overhang.

Interpretation of Internal Salt Structure from the New Geometry of the Dome

The most obvious differences, in detail, between the previous and new geometric representations, is that the new model of the salt margin is particularly “lumpy”. The revised salt flanks exhibit a great deal more texture, with small protuberances here and there, and small-scale reentrants elsewhere. In fact, for one accustomed to viewing typical structure contour maps with smooth contours, or smooth-sided two-dimensional cross sections of salt domes, the amount of surface variability in the new model is virtually “shocking”, at first glance. This is definitely *not* the classical representation of a salt dome, such as those provided by Halbouty (1979).

It is now generally recognized that salt domes are emplaced in a somewhat piecemeal manner, and in stages. Emplacement involves slow upward movement of the salt, differential down-building of sediments around the salt, or both. The process involves some number of separate masses of salt, termed spines, which move quasi-independently of one another. Individual spines are originally separated from one another by boundary shear zones (BSZs), which represent regions of significant differential movement. Much of this understanding was derives from work by Kupfer (1990), who mapped internal structures and rock salt with differing properties in the workings of salt mines.

Although most of the movement along boundary shear zones is purely ductile in nature, dilation of the salt within and adjacent to boundary shear zones almost certainly occurs as well. The presence of very large individual halite crystals, many times the width of a core segment, argues strongly for crystal growth essentially into open space. Pockets of pressurized brine and/or methane are well known from drilling within salt domes. Looff and others (this volume) provide significant expansion of this topic.

Movement of the salt in any particular spine need not be purely vertical. Mapping of salt fabric within mine workings indicates a wide variety of structural orientations. Accordingly, the inference is that salt spines may move vertically, obliquely. or even near horizontally. Mushroom-shaped salt stocks have been described by Halbouty (1979) and many other sources (e.g., Jackson et al., 1990), so the general form produced by lateral movement has been known for decades.

The significantly increased geometric variability and “texture” of the 3-D seismic model of the Bayou Choctaw salt dome, as presented in figures 9 and 10, is compatible with the increased understanding of salt dome emplacement mechanisms and internal structure. Although direct observation of the salt is here restricted to that forming the outer margin of the stock, the features and processes interpreted are very likely to apply — to a greater or lesser extent — to the internal portions of a salt dome.

For purposes of discussion, we may define three more-or-less distinguishable classes of features along the flanks of the modeled Bayou Choctaw salt stock. These are (1) flutes (and associated reentrants), (2) outward bulges, and (3) downward-tapering wedges. In light of the newness of the application of three-dimensional seismic to the understanding of salt domes, we should probably also define a fourth class, modeling artifacts, which is only partially separable from the former three.

Flutes and Reentrants

Fluting is a term that has been used to describe the wavy pattern that is often displayed by depth contours on the salt flank. These typical are presented as plan-view features, and the waviness is prominently displayed in the time contours of figure 7 (and 8(a)). These "waves" tend to be continuous vertically over some interval. The three-dimensional form is thus one of a sequence of more-or-less rounded grooves running down the flanks of the diapir. This geometric configuration is easily identifiable in several of the different parts of figures 9 and 10, and has been described previously by Rautman (2005); see also figure 12(b).

Reference to parts (a) and (b) of figure 9 reveals another attribute of this fluting: that a flute need not extend throughout the entire vertical extent of the diapir. Any individual *flute* (meaning the outward-extending feature) may disappear into the main mass of salt in either an upward or downward direction, or both. Flutes may also be inclined at an angle to the vertical along the flank of a dome.

For example in figure 9(b), a relatively prominent flute extends upward from the base of the model to a subsea elevation of approximately –3,000 ft. The termination of this flute is essentially directly under the –3,000-ft contour label. Figure 13(a) presents an enlarged visualization image of this particular flute and its flanking reentrants. An example of a flute which terminates in both vertical directions is highlighted in figure 13(b). This flute is also visible, in its broader context, in figure 9(b), immediately to the right of the labels for the 4,000- and 4,500-ft structure contour lines.

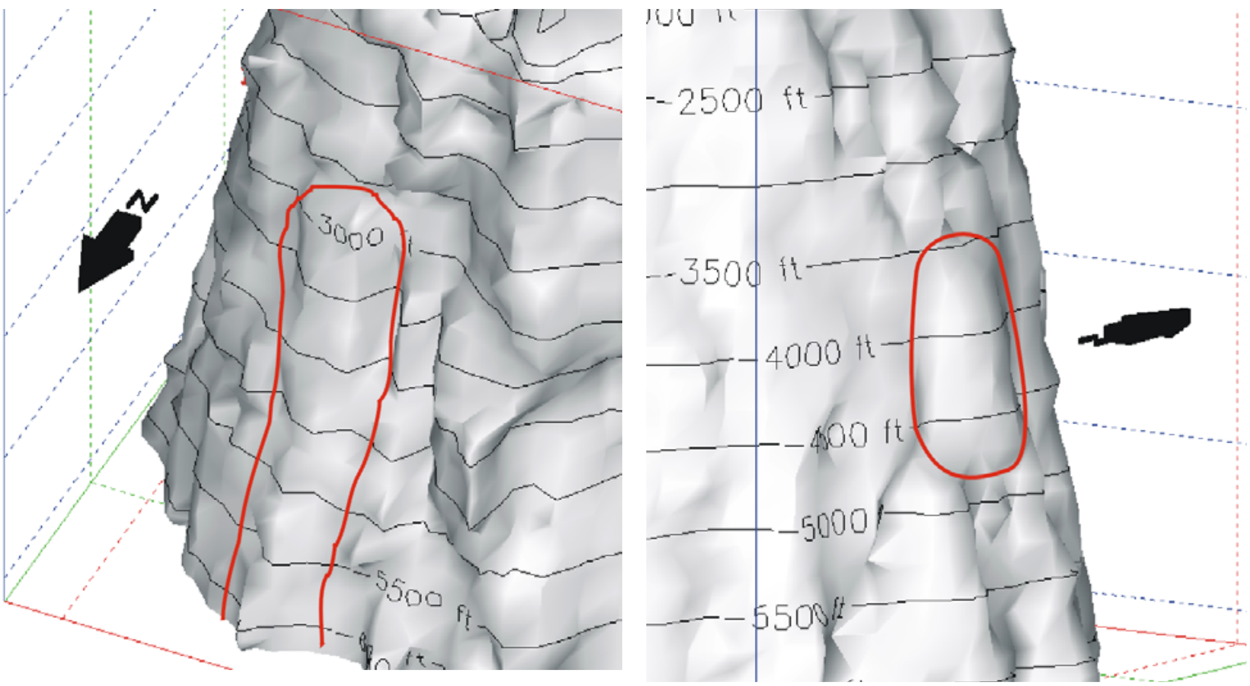

Figure 13. (a) Example of a vertically extensive flute, terminating upward. Figure 14. Termination is at a subsea elevation of approximately –3,000 ft. View is from azimuth 335°, elevation 40°. (b) Example of a flute terminating both upward and downward. View is from azimuth 145°, elevation 10°.

This discussion of fluting thus far has been purely descriptive. Moving beyond mere observation of what is visible, both on maps and in the three-dimensional visualizations, it is appropriate to speculate about the origin of these features. Current understanding of salt domes involves the movement of quasi-independent masses of salt, known as spines. Spines are taken as separated by boundary shear zones, along which differential movement is accommodated.

Flutes, therefore, may be interpreted as the external expression of individual salt spines, which are located sufficiently close to the flank of the dome that they protrude from the overall “circular” dome outline. The reentrant portions of the contour lines, or the grooves, themselves, appear to relate to the external expression of boundary shear zones. If flutes truly are the expression of salt spines near the edge of a dome, it would appear that the longevity of the activity that formed the flute shown in figure 13(b) was significantly less than that which formed the flute illustrated in figure 13.

Outward Bulges

Outward bulges are protrusions — admittedly somewhat gradational in form with flutes — which are somewhat different in interpreted origin. At a minimum, given that all salt domes are presumably the result of movements of multiple salt-spines, the implications of these features is somewhat different.

Salt diapirs in the Gulf Coast region are usually assumed to move upward and outward, as the surrounding strata continue to subside around them. The formation of a salt dome thus represents some combination of active upward salt intrusion and passive sedimentary downbuilding. To the extent that salt is moving actively upward, the relatively plastic salt will tend to follow a path of least resistance within the surrounding strata. Such paths of least resistance typically would exist at shallow depths, where the sediments are still essentially unconsolidated. Consolidation of Gulf Coast sediments invariably increases with increasing burial, thereby increasing resistance to outward movement of salt. An outward bulge is then most logically formed — initially — close to the then-top of the salt diapir. The presence of thick, rigid caprock overlying a salt dome may also contribute to a preferred outward direction of salt movement.

Figure 15 presents a fairly obvious example of an outward bulge located near the very top of the Bayou Choctaw salt dome. The highlighted region, immediately to the right of the north arrow, extends to a depth of no more than about 1,000 ft below sea level. The addition of colored elevation values to the visualization serves to emphasize the western edge/reentrant of this feature, as well as the shallow extent.

The presence of such outward bulges along the *deeper* flanks of a salt dome, therefore, logically suggests that these features formed as various types of salt overhang at some earlier time. The implication is that if the salt within the bulge was moving actively outward, the enclosing sediments must have been relatively weak, and thus near the top of the salt stock at that time.

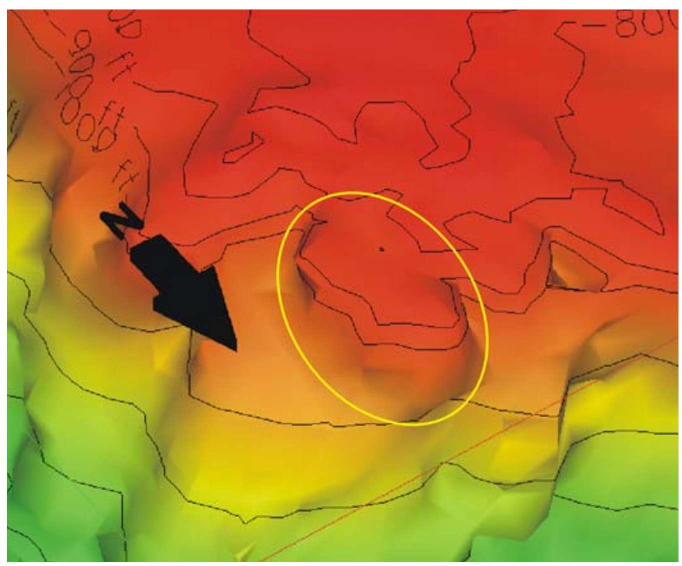

Figure 15. Example of an outward bulge near the crest of the Bayou Choctaw salt dome. Colors represent subsea elevation, from shallow (red) to deeper (green). View is from azimuth 35°, elevation 50°.

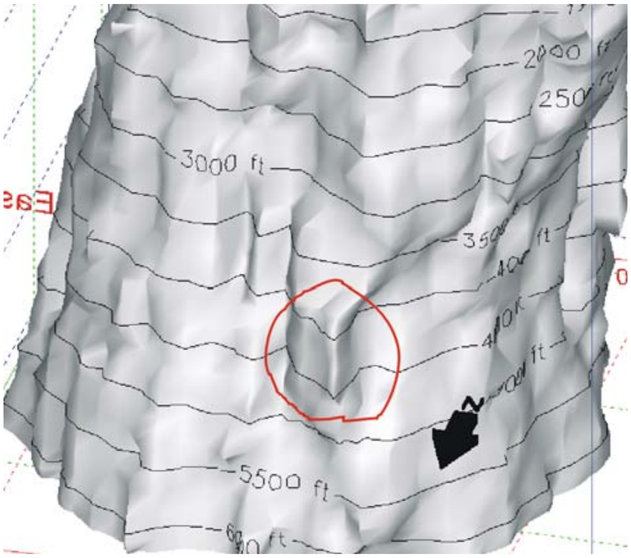

Figure 16. Example of an outward bulge on the side of the Bayou Choctaw salt dome at a depth of approximately 4,000 ft. View is from azimuth 345°, elevation 30°.

Figure 16 presents an example of a more deeply buried, presumably now-inactive outward bulge, positioned at an elevation of approximately 4,000 to 4,500 ft, subsea. As comparison of figures 16 and 13(b) makes clear, the distinction between a buried “outward bulge” and a “flute” of short vertical extent is probably somewhat academic.

Following our line of reasoning suggests that outward bulges develop initially at shallow depths of burial. As sedimentation continues surrounding the salt diapir, the position of initial break-out will be buried, progressively, to some greater or lesser extent. If salt continues to move upward for an extended period of time, the outward bulge may extend over a significant vertical interval, thereby forming a flute. The vertical extent of the resulting flute is a function both of how long a particular near-edge salt spine remained active and of the rate of subsidence and exterior sedimentation.

That outward-bulges of salt actually were formed near the top of the dome is supported by the fact that some of these features may be associated with unconformities in the sediments outside the dome. Were the salt actively moving upward at a particular time near the depositional surface, it would likely form a topographic, or more likely submarine, high of some lateral extent. Laterally extensive (“regional”) sedimentation in the presence of such an elevated sea-floor or ground surface would result in thinning or actual erosion of the contemporaneous sediments (Rautman et al., 2005).

A number of unconformities in the near-dome sediments are identifiable on many of the 2-D vertical seismic profiles presented earlier in this report. (e.g., figs.5 and 6). We have not yet attempted to correlate these unconformities with geometric features of the salt flank.

Downward-tapering Wedges

The third identifiable class of features observable on the salt flank of the Bayou Choctaw dome are *downward-tapering “wedges”*. Again, the distinction between these various types of features is somewhat subjective. However, we believe that the distinctions are valid, if perhaps gradational.

It has been known for some time that salt — all else being equal — will tend to move upward (and outward) along the upthrown sides of faults. For example, the Big Hill salt dome (and SPR site), Texas, is associated with a substantial northeasterly trending regional fault (Dollison, 1965; Geomap, 2002). Additionally, salt domes inevitably are associated with extensional faulting, whether caused by active uplift of the diapir or by passive downbuilding of sediments. The extensional environment, coupled with any zone of weakness/offset within the sediments, will operate together to form a path of least resistance. Although circumferential faults are present at some salt domes, the dominant type of faulting is most likely radial in nature.

Under the assumption that different faults form, or become active, at different times in the geologic history of a particular salt dome, the movement of salt would likely be initiated early in the history of the fault, and continue for some time thereafter. The result, after some indefinite period, would most likely be a downward-tapering wedge-like body of salt at an appropriate location on the salt flank.

The wedge would be small in lateral extent at the time/depth of initial formation, and expand upward and outward while active salt movement took place. The upper width of the wedge may correspond, more or less directly, with the length of time that a particular salt spine remained active. Additionally, if the "root" of such a salt spine is later cut off by movement of a newer spine, the wedge may be truncated, and now preserved only at some depth along the present-day geometric flank of the dome. Identifying the age of adjacent sediments associated with the breakout of the wedge and/or its upper termination would allow documentation of the timing and duration of (more) active salt movement.

Figure 17 shows a particularly well-developed downward-tapering wedge. This visualization is from a viewer perspective somewhat in between the views of figures 9 and 10, parts (a) in both. The wedge begins somewhere below an elevation of –4,000 ft, and extends to the top of the domal crest. The overall width increases toward the top of the dome.

This particular wedge would appear to be associated with a currently active salt spine. Note that there is a high spot on the crest of the salt dome, directly above this feature. This small region of higher-than-average-elevation salt crest is defined by a closed contour. Closure of the contours on the crest of the dome is quite evident in the higher-elevation view of figure 9(a).

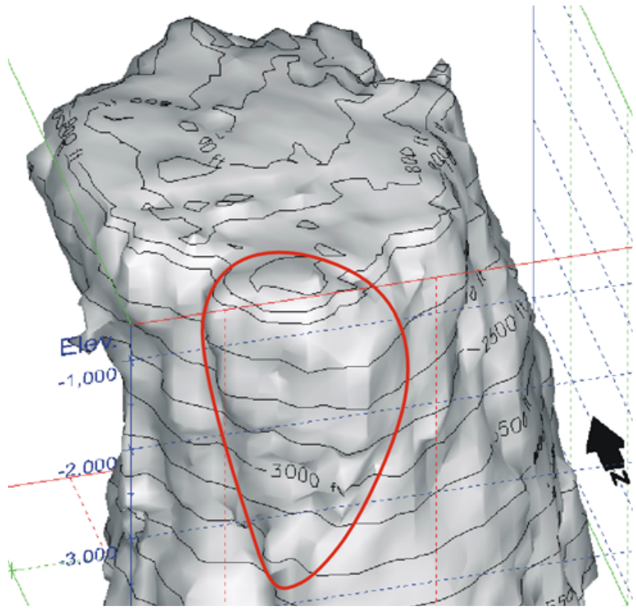

Figure 17. Example of a downward-tapering wedge affecting a portion of the Bayou Choctaw salt dome. View is from azimuth 195°, elevation 35°.

Modeling Artifacts

There is little question that *some* of the protuberances and recesses on the surface of the Bayou Choctaw salt model are nothing more than modeling artifacts. For example, consider figure 9, part (b). In figure 9(b), there is a very sharp, small-radius protuberance on the left-hand side of the image, immediately below the –2,000-ft structure contour. In figure 10(b), this same feature is visible from another angle on the left-hand side of the image, also just below the –2,000-ft contour line.

These artifacts most likely originate, at least in part, from the "discrete" nature of the modeling process. The geostatistical interpolation algorithm, which was applied to the "distance from salt" measurements described previously, and which was then contoured in three dimensions at zero distance to produce the models in figures 9 and 10, produces a discretized representation of the salt and its surrounding region. The scale of discretization, in such cases, is well known to produce 'blocky" results. Decreasing the three-dimensional block size can alleviate some of this artificially induced irregularity. However, improved spatial resolution comes at the cost of computational times that scale as the cube of the number of blocks in each dimension.

Implications for Underground Storage

Internal Fabric of the Salt

If the degree of surface variability exhibited by the revised model of the Bayou Choctaw salt dome is even reasonably realistic, then it would appear that a great many more salt spines may have been involved in emplacement of this dome than might typically be assumed. Not all of the "many" spines suggested by the numerous protuberances, outward bulges, and flutes visible in figures 9 and 10 need to have been active at any one time. Nor would many of these spines even need to have been active for a particularly long time. Nonetheless, the existence of numerous, partially independent salt masses moving collectively can easily be visualized conceptually as giving rise to the type of complex geometry evident in the current reinterpretation.

Consider a prototypical outward bulge. The rubric under consideration here states that these form, at shallow depths of burial, by *lateral movement* of salt away from the preexisting salt margin. Any structural fabric within the salt, such as insoluble inclusions (clay, anhydrite) or elongated salt crystals (including any potash salts present), will therefore most likely be oriented at a relatively high angle to the nominally vertical axis of a salt diapir. Salt fabric is known to influence the leaching of solution-mined cavities, creating significantly irregular geometry in some instances.

If the salt associated with an outward bulge continues moving for some meaningful length of time, the bulge may transition to a flute-like structure. The lowest part of the resulting flute will probably preserve any quasi-horizontal fabric associated with the original bulge. However, fabric higher along the flute would most likely be oriented more vertically, in concordance with the presumed upward direction of salt flowage.

We have noted previously (e.g., fig. 13) that outward bulges and flutes may terminate upward. The implication is that the salt within such structures is no longer actively moving, at least compared with other parts of the dome. Inactive masses of salt simply will simply be carried downward (i.e., buried) to greater depths by continuing salt rise and/or downbuilding of the salt diapir. Preservation of such "old" salt overhangs at depth implies that the outer surface of the salt in that portion of the dome has been inactive or passive during subsequent burial. However, whatever *fabric* was formed during active movement of the bulge/flute/downward-tapering wedge will be preserved — to a greater or lesser extent within that portion of the salt mass. This includes volumes in which the fabric is oriented in significantly different directions than the vertical.

Another significant implication of the genetic rubric suggested by the new model of the Bayou Choctaw salt dome is inactivation of early moving salt (either outward or upward) through truncation, or short-circuiting, by younger salt movement. The locus of such younger salt movement may be related to formation of a new outward bulge (and subsequent flute?) by new outward-directed flowage. This would most likely apply near the depositional interface.

In the former instance, the salt mass thus short-circuited may remain on the periphery of the salt dome, and be identified easily using the techniques described in this report. However, in the latter case, whatever anomalous fabric formed by lateral or oblique movement will be obscured by the more recently formed salt mass now on the flank of the dome. One can conceive of this process being repeated many times over the evolution of a given Gulf Coast salt dome, which could lead to very complex patterns of internal fabric. "Encouragement" of salt breakout in both internal and external positions, with respect to previous directions of salt flow, by faults (as described above for the Big Hill salt dome, Texas) may complicate further the internal structure of a salt diapir.

Alternatively, it seems perhaps more plausible that the locus of such younger salt movement may be most likely to be at some distance *inward, toward* the center of the overall salt dome. Among other reasons may be that the salt is more likely to be hotter, in the central parts of a diapir, than adjacent to "cold" sediments on the flanks. Central, rather than peripheral, upwelling of salt would appear to be required by the presence of structural culmination on the salt-caprock interface, as observed at some domes. Thick sequences of caprock lithologies, in the interior portions of domes, also suggest greater than average upwelling and dissolution of salt in these locations (Martinez, 1980).

These thoughts are, in fact, somewhat speculative at this time. More work with three-dimensional seismic data will be required before these sorts of interpretations can move into mainstream thinking, regarding the origin of salt domes. However, if the concept of outward formation of bulges and flutes, followed by internal short-circuiting by younger salt movement, is correct, there are implications for underground storage.

Under this particular hypothesis, salt fabric is likely to be more complex — and oriented at high angles to the vertical axis of the dome — near the periphery of the salt stock. Salt within the central portion is likely (a) to be more massive, and (b) to exhibit a more vertically oriented fabric. That the latter proposition is true is supported by the fact that many storage and brining caverns, which — overall — tend to be located away from the salt edge, generally do not exhibit severe operating problems. The converse also seems to be true, supporting the former proposition.

One example of immediate relevance is Bayou Choctaw cavern 20. While the initial positioning of the well for this cavern within XXX ft of the outside of the dome probably did not help matters, this cavern does seem to have leached preferentially toward the salt flank. In addition to the outward-directed greater extent of leaching of cavern 20, note that the extent of the cavern in the southeasterly direction appears to terminate along a southwest-to-northeast linear trend. It would appear that this portion of cavern 20 intersected a likely boundary shear zone bordering salt of differing solubility.

Another example may be cavern 14 at the LOOP (**L**ouisiana **O**ffshore **O**il **P**ort) storage site at the Clovelly salt dome, Louisiana. Here, even though the cavern appeared to be positioned well within the overall salt stock, the cavern lost integrity and was abandoned (McCauley et al., 1998). This cavern is associated by a high-angle planar feature (McCauley et al., 1998, fig. 5), which almost certainly represents the intersection of the cavern with a boundary shear zone. This feature is found at the same depth interval at which the integrity of the cavern appears to have been compromised.

Looff and others (this volume), present a somewhat different example. In their figures 6 and 7, cavern 108 at the Big Hill Strategic Petroleum Reserve site, which is positioned nearly in the center of the Big Hill salt dome, exhibits essentially vertical “wings” on an otherwise well-formed circular cavern. Looff and others interpret BH-108 as affected by preferential leaching along a northeast-trending zone of more soluble salt, probably within or adjacent to a boundary shear zone. These authors also present a sonar image of a geometrically complex cavern at the Spindletop (Texas) salt dome (their fig. 8). This cavern may best be interpreted as intersecting three (3) separate salt spines separated by two boundary shear zones.

CONCLUSIONS

Three-dimensional seismic data from the area containing and surrounding the Bayou Choctaw salt dome allow imaging and interpreting geometric details of the salt flank, which are at least an order of magnitude finer in scale than that which is possible using well data alone. Conversion of the salt margin interpreted on vertical seismic profiles to structure-contour maps, and then to a three-dimensional computer model produces visualizations that are unlike any known published salt interpretation. Although a number of uncertainty considerations that affect the data have been identified, the sheer volume of information provided by the 3-D seismic survey, and the continuity of that data on a scale of ~100 ft, suggest that much of the fine-scale geometric detail visible on the flanks of the Bayou Choctaw salt dome is real.

The margin of the Bayou Choctaw salt dome is characterized by numerous protrusions and reentrants in all three directions. These features may be classified, according to a somewhat gradational or overlapping scheme into (1) outward bulges, (2) flutes and associated reentrants, and (3) downward-tapering wedges. All three versions of these surface features are interpreted as reflecting various types — or degrees of expression — of individual salt spines, which have moved actively in various spatial locations and for varying periods of time.

Logical arguments, based upon the geometry, and upon what appear to be the most likely origins of these features, suggest that 3-D seismic data may be used to help map the internal fabric of at least parts of a salt diapir. The implication of a preliminary assessment of salt fabric for the Bayou Choctaw salt stock is that the internal structure of this dome, and of Gulf Coast salt domes more generally, may be much more complex than suspected heretofore.

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REFERENCES

Dollison, R.S., 1965. *Big Hill field, Jefferson County, Texas.* Transactions Gulf Coast Assoc. of Geol. Soc., vol. 15, p. 25–35.

Geomap, 2004. 2004 edition, *Executive reference map 312, northeast Texas Gulf Coast.* Geomap Company, Houston Texas. Scale 1:32,000.

Halbouty, M.T., 1979. *Salt domes: Gulf region, United States and Mexic*o. Houston: Gulf Publishing Co., 561 p.

Hogan, R.G. (ed.), 1981. *Strategic Petroleum Reserve (SPR) geological site characterization report: Bayou Choctaw salt dome.* Sandia Report SAND80-7140, Sandia National Laboratories, Albuquerque, N.Mex.

Jackson, M.P.A., Cornelius, R.R., Craig, C.H., Gansser, A., Stöcklin, J, and Talbot, C.J., 1990. *Salt diapirs of the Great Kavir, Central Iran.* Geol. Soc. America Memoir 177, 139 p.

Martinez, J.D., 1980. *Salt dome caprock: a record of the geologic processes*. Fifth International Symposium on Salt, Northern Ohio Geological Society, Cleveland, O., vol. 1, p. 143–151.

McCauley, T.V., Ratigan, J.L., Sydansk, R.D., and Wilson, S.D., 1998. *Characterization of the brine loss zone and development of a polymer gel plugging agent to repair Louisiana Offshore Oil Port (LOOP) Cavern 14.* Fall 1998 Meeting, Solution Mining Research Institute, Clarks Summit, Penn., p. 391-406.

Neal, J.T., Magorian, T.R., Byrne, K.O., and Denzler, S., 1993. *Strategic Petroleum Reserve (SPR) additional geological site characterization studies: Bayou Choctaw salt dome, Louisiana.* Sandia Report SAND92-2284, Sandia National Laboratories, Albuquerque, N.Mex.

Rautman, C.A., 2005. *Milestone letter report "describing the revised and updated model of the top-of-caprock and top-of-salt surfaces" at the Bayou Choctaw salt dome.* Memorandum report from C.A. Rautman to Wayne Elias, SPR PMO, New Orleans La., dated December 15, 2005.16 p.

Rautman, C.A., and Stein, J.S., 2004. *Conversion of the Bayou Choctaw geological site characterization report to a three-dimensional model.* Sandia Report SAND2003-3300, Sandia National Laboratories, Albuquerque, N.Mex., 52 p.

Rautman, C.A., Looff, K.M., Stein, J.S., and Snider, A.C., 2005. *An updated three-dimensional geologic-genetic model of the Big Hill salt dome and Strategic Petroleum Reserve site.* Solution Mining Research Institute, Spring 2005 meeting, Syracuse NY. Solution Mining Research Institute, Clarks Summit, Penn.