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Conversion of the Bayou Choctaw Geological Site Characterization Report to a Three-Dimensional Model

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ABSTRACT

The geologic model implicit in the original site characterization report for the Bayou Choctaw Strategic Petroleum Reserve Site near Baton Rouge, Louisiana, has been converted to a numerical, computer-based three-dimensional model. The original site characterization model was successfully converted with minimal modifications and use of new information. The geometries of the salt diapir, selected adjacent sedimentary horizons, and a number of faults have been modeled. Models of a partial set of the several storage caverns that have been solution-mined within the salt mass are also included. Collectively, the converted model appears to be a relatively realistic representation of the geology of the Bayou Choctaw site as known from existing data. A small number of geometric inconsistencies and other problems inherent in 2-D vs. 3-D modeling have been noted. Most of the major inconsistencies involve faults inferred from drill hole data only.

Modern computer software allows visualization of the resulting site model and its component submodels with a degree of detail and flexibility that was not possible with conventional, two-dimensional and paper-based geologic maps and cross sections. The enhanced visualizations may be of particular value in conveying geologic concepts involved in the Bayou Choctaw Strategic Petroleum Reserve site to a lay audience. A Microsoft Windows™ PC-based viewer and user-manipulable model files illustrating selected features of the converted model are included in this report.

ACKNOWLEDGMENTS

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Conversion of the Bayou Choctaw Geological Site Characterization Report to a Three-Dimensional Model

INTRODUCTION

The Bayou Choctaw salt dome, located in south-central Louisiana near Baton Rouge and shown on the index map in figure 1, is one of four underground crude-oil-storage facilities operated by the United States Department of Energy Strategic Petroleum Reserve program. Sandia National Laboratories, as the geotechnical advisor to the program, conducts site-characterization investigations and other longer-term geotechnical and engineering studies in support of the program.

This report describes the conversion of existing two-dimensional geologic interpretations to numerical, fully three-dimensional geologic models of the Bayou Choctaw site. These models — because they are visual and may be examined from many angles and perspectives — are useful for quickly understanding the complex geometric relationships among the many parts of the component submodels. The intuitive, visual nature of the model representations may be particularly important when attempting to convey geologic and engineering aspects of the site to management personnel. At the same time, however, the numerical models are sufficiently precise that spatially accurate engineering or geologic drawings may be extracted from the underlying models. Additionally, the conversion process itself is important in that the degree of rigor involved in creating the numerical representation forces examination of those geometric relationships in a manner that is difficult to enforce when examining "flat," two-dimensional maps and cross sections. Geometric inconsistencies may thus be identified. Identification of inconsistent relationships and/or volumes with only minimal actual observations may form the basis for future characterization work.

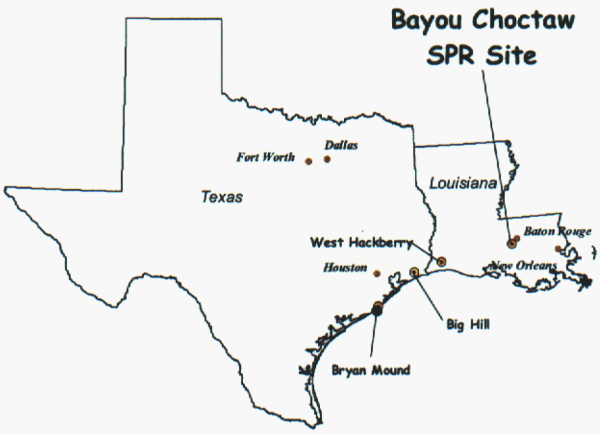

Figure 1. Index map showing the location of the Bayou Choctaw Strategic Petroleum Reserve facility and other SPR sites along the Gulf Coast of Texas and Louisiana.

BACKGROUND

The United States has pursued a national policy since approximately 1974 of implementing and maintaining a strategic petroleum reserve of crude oil for use in the event of a severe disruption of imported oil supplies. The U.S. Department of Energy (DOE) is charged with operating the Strategic Petroleum Reserve (SPR), which currently consists of four active storage sites, all located in diapiric salt domes on the Gulf Coast of Louisiana and Texas in close proximity to tanker facilities, pipelines, and refineries. The reserve currently (2003) consists of some 600 million total barrels of both sweet and sour crude oil. The oil is stored in large underground caverns leached into the main mass of the four salt domes at these sites. Some caverns were initially developed as sources of brine for chemical feedstocks and were purchased for the SPR program. Other caverns were developed by the SPR project specifically for oil storage.

Characterization of both the salt domes and the enclosing sedimentary rocks has been undertaken at episodic intervals for all sites. Initial characterization activities occurred prior to establishment of oil storage facilities, purchase of existing caverns, or development of new caverns, in order to provide a basis for site development and to ensure successful containment and ultimate recovery of the large quantities of crude oil. The initial characterization phase for the four currently active sites culminated in the late 1970s to very early 1980s, and resulted in the publication of formal site characterization reports (Hogan and others, 1980a, 1980b; Hart and Ortiz, 1981; Whiting, 1980).

Approximately ten years later, a set of "updated" site characterization studies were undertaken for each site. These updates vary in their comprehensiveness by site according to the then-current state of knowledge at each salt dome. In some cases — for example the Big Hill (Tex.) site (fig. 1) — significant new information had been developed through construction of 14 new oil-storage caverns. At other sites the "update" may have been more of a refinement of the existing state of geologic knowledge or the expansion of more operational considerations such as the potential for flooding during hurricanes or other events. These updated site characterization reports were published between 1988 and 1994 (Magorian and Neal, 1988; Magorian and others, 1991; Neal and others, 1993; Neal and others, 1994).

Conversion of Existing Report to a Three-Dimensional Model

This report is one of a series of documents that present the *conversion* of the existing site characterization models, as described in the original and/or the updated site characterization reports, to fully three-dimensional computer models of the known geology. Specifically, this report focuses on the Bayou Choctaw salt dome in south-central Louisiana, the location of which is shown in figure 1. The Bayou Choctaw salt dome is a mostly cylindrical mass of salt approximately one mile in diameter and extends to within approximately 500 ft of the present ground surface. The dome is host to six SPR oil-storage caverns, as well as a to number of caverns owned by other operators. The intent of the conversion process was to translate existing graphical, paper representations of the geology to a numerical, three-dimensional form that is amenable to state-of-the-art visualization and to direct use of that numerical representation in relevant engineering analytical studies.

The software used to support this conversion effort is ***M***ining ***V***isualization ***S***ystem[1] (MVS), a high-end geological modeling and visualization package that runs under the Microsoft Windows™ operating system, and which is produced by C Tech Development Corporation (www.ctech.com). Although the package as a whole is proprietary, the software uses a modular, open architecture and ASCII file storage, thereby allowing flexible input, output, and interfacing with external software routines of multiple types. The fundamental basis for modeling and visualization consists of finite-element-like meshes, thus rendering the software ideal for engineering use and for transfer of the models to numerical analytic codes. The package is also able to produce output as single graphical images and as PC-compatible animation (movie) formats.

In addition to these more conventional output formats, MVS is also able to write what are called 4DIM files (for ***4-D***imensional ***I***nteractive ***M***odels). 4DIM files contain one or more sets of "captured," fully three-dimensional model components that allow "interactive" viewing, such as rotations to view the model from different orientations and positions, changing the magnification to zoom in or out, panning to different portions of the model, or printing of the desired view without recourse to the full modeling program itself.

A downloadable 4DIM viewer is available over the internet in "unlicensed" format from the C Tech website. *Unlicensed*, in this context, means that the viewer will not play *all* 4DIM files, but only those that are encoded with an internal binary password. All 4DIM files produced as part of this modeling effort contain such a code, with the result that the selected 4DIM models included on the CD-R with this report are freely viewable. Refer to the discussion in Appendix A for specific step-by-step instructions for installing and running the 4DIM model player.

[1] The use of trade, product, industry or firm names is for descriptive purposes only and does not imply endorsement by Sandia National Laboratories or the U.S. government.

EXISTING DATA

Conversion of the Bayou Choctaw site characterization report involves only existing data and information. No significant new data of any type has been acquired, although we have included some existing information that was not originally included in the actual published documents (downhole cavern surveys). Accordingly, the results presented here are a more-or-less straightforward conversion of the existing paper model.

SITE CHARACTERIZATION REPORTS

The information that has been used in the conversion and modeling process for this report consists of a number of different types of data, most of which were compiled in the original site characterization report for Bayou Choctaw (Hogan and others, 1980a) and in the updated site characterization report (Neal and others, 1993). Because the vast majority of the information used in the present model-conversion exercise is from these two sources, we typically will not bother to provide specific citations as constant reference to the same source document becomes repetitive and may interfere with a clear reading of the text. Sources other than the original and updated site characterization reports will be cited as standard practice.

The site characterization reports themselves contain a number of different types of data that have been used to differing degrees and in different manners during construction of the converted models. The principal types of existing information available from the two vintages of site characterization reports consist of structure contour maps drawn on the top-of-salt surface and on various other geologic horizons, tabulations of stratigraphic "picks" of different stratigraphic horizons in oil and gas wells, a selection of geologic cross sections, and tables of stratigraphic units identified in the vicinity of the Bayou Choctaw site. Additional data regarding the subsurface configuration of the several SPR oil-storage caverns within the Bayou Choctaw salt dome have been added from downhole sonar surveys obtained on various dates.

Structure Contour Maps

Structure contour maps, which show lines of equal elevation on the top of some identifiable surface, form the principal information source from which the geology of the Bayou Choctaw salt dome and its enclosing sediments were interpreted for this model conversion. Collectively, the suite of structure contour maps presented in the original site characterization report (Hogan and others) form a "paper" model of the entire site. However, given the two-dimensional nature of paper maps, the entire model cannot easily be viewed all at once, something that modern computer-visualization software does as a matter of routine. In fact, for reasons that will be described in sections that follow, the converted geologic model of the Bayou Choctaw site is derived almost exclusively from the collection of structure contour maps. The updated site characterization report (Neal and others) does not contain a full set of revised maps (only one of the set of eight contained in the original report), with the result that we have relied most heavily upon the original report and its contained paper model.

The structure contour maps contained in the two site characterization reports were generated by hand contouring of well picks by a geologist using professional judgment. As such, there is an inevitable degree of subjectivity to these maps. Although subjectivity is neither good nor bad in and of itself, it must be considered when evaluating such maps. In fact, some subjectivity may be desirable, in that a purely mechanistic modeling approach that accepts uncritically so-called objective data may generate features of dubious geological significance. This is particularly true when working with mixed data of many sources and vintages, such as petroleum exploration well logs that date back many decades. Professional judgment and documentation of the decisions that are made in generating the model are essential.

Well Information

Both site characterization reports contain tabulated well picks for a number of sedimentary horizons and for the salt contacts in a number of oil and gas exploration and/or development wells, in addition to similar picks for a small number of other well types (cavern wells, sulphur exploratory wells, etc.). These data are presumably those used to generate the structure contour maps contained in the published site characterization reports.

Unfortunately, the utility of these existing well data is less than optimal in terms of converting the geologic model contained in the site characterization reports to a rigorous 3-D computer version. Neither of the data tabulations by Hogan and others or by Neal and others contains spatial coordinates for the well locations. Lacking the ability to plot the individual well locations and to enter the subsurface contact picks into three-dimensional space, it is virtually impossible to utilize this stratigraphic information.

Both reports contain index maps showing the locations of the well control used to produce the structure contour maps. However, there are two major problems that impede further use of the well data and these index maps in the model conversion effort.

1. The maps are presented at a relatively small scale (~1100 ft/in, or 1:13,200), and thus the size of the well markers on the printed page covers a modestly large area of real space, producing uncertainty in the actual spatial coordinates of the well. Additionally, the small scale of the maps causes well markers in regions of closely spaced hydrocarbon-development wells to overlap or to be difficult to distinguish as to which well is which. Figure 2 is a copy of the well index map from the original site characterization report and illustrates these difficulties.
2. The cross-reference scheme between the index maps and the tabulated well data is inadequate and not necessarily unique. Because of space limitations on the small scale index maps, well identifiers are necessarily abbreviated: i.e., the F(reeport Oil)-21 well or the C(arter Oil)-12. Such abbreviated identifiers ("F-21," "C-12") are in some cases non unique, leading to a modest number of wells whose true identity (and therefore locations) cannot easily be confirmed.

The base map of well locations presented by Hogan and others (their figure 2.3; our fig. 2) was digitized in an effort to resolve the location-to-data-tabulation issues by comparison to the tabulated locations of a commercially available well database (Tobin, 2001). Digitization of the small-scale index map, however, induced sufficient error into the resulting spatial positions that unique matches via coincident locations were not always possible. The commercial well data base (which uses American Petroleum Institute numbers as truly unique well identifiers) also provides the operator and lease names as additional identifying labels for potential matching with the site characterization well information. However, in many cases, the stated operators and, in some cases the leases as well, have changed over time, and thus frequently bear no relationship whatsoever to the corresponding entries in the site characterization reports. This sale-and-renaming problem is particularly troublesome for productive wells (as opposed to plugged-and-abandoned wildcat holes). These wells tend to be located immediately adjacent to the salt dome and thus highly relevant to geologic modeling for the SPR project.

It should be noted, however, that a select number of well picks for the top-of-salt surface were matched to their spatial positions, and that these picks were used in the conversion of the salt dome model. This matching was facilitated by the relatively sparse spacing of (non-cavern) wells over the crest of the Bayou Choctaw dome which limited the number of competing choices for each location. Also, most of these wells are quite old, were pure wildcats or sulphur-exploration wells, and have not been sold, transferred, or otherwise renamed.

Geologic Cross Sections

Both site characterization reports contain a number of selected cross sections through the salt dome illustrating salient points of the interpretations as selected by the authors. These profiles have been valuable auxiliary information in the model-conversion effort as confirmatory evidence. However, in common with most geologic cross sections produced in the pre-computer era, the cross sections are based on horizontal projection of individual well profiles onto a vertical plane that passes "near" the various wells portrayed on the section. Although the degree of geometric distortion induced by such projection may be less than that which results from construction of zig-zag fence diagrams passing precisely through each individual well location, the projection process nevertheless induces some amount of geometric inaccuracy. An additional problem involved in projecting off-section wells onto a line of cross section at a salt dome is that the symmetry of a diapir is nominally radial. In contrast, geologic projections

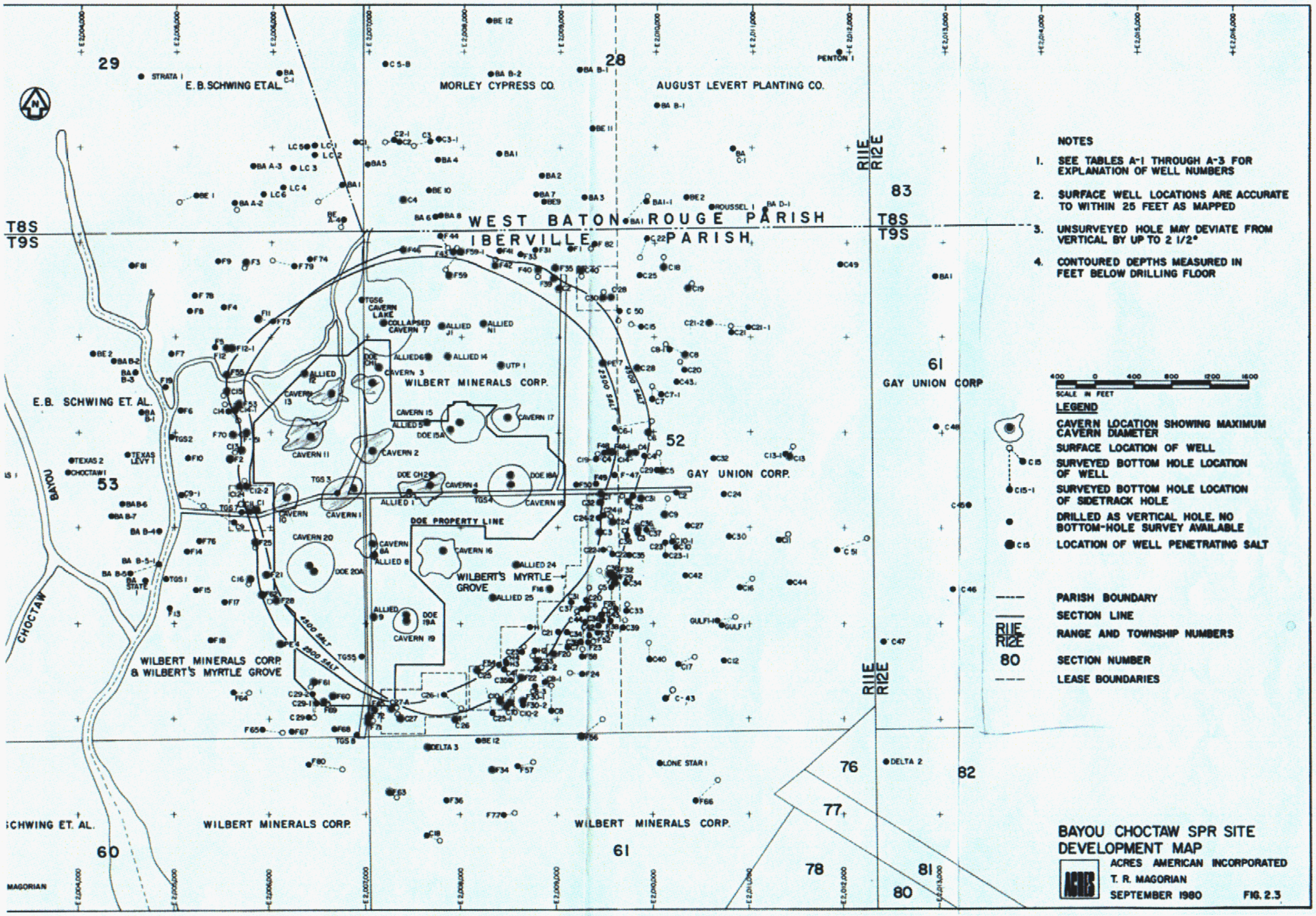

Figure 2. Reduced-scale scanned image of the well index map for the Bayou Choctaw SPR site, as presented in the original site characterization report of Hogan and others (1980a). Original map is 11x17 inches with a scale of approximately 1:13,200.

are typically (but not necessarily) constructed normal to the line of section. As the projection distance and azimuth are usually not indicated directly on the cross section, but only on the index map showing the location of the profile (if at all), the extent of geometric distortion is not typically quantifiable.

Geologic Units Identified at Bayou Choctaw

The stratigraphic section in the vicinity of the Bayou Choctaw salt dome is fairly typical of this portion of the Gulf Coast, consisting of a relatively thick sequence of alternating Miocene sands and shales overlying an Oligocene section that is generally below the depth of interest to the SPR program. The dominantly deltaic Miocene deposits are overlain by a Pliocene section of little hydrocarbon interest and which is 1000 to 2000 ft thick in the vicinity of the dome. The salt dome and its caprock are overlain by a relatively thin sequence of Pleistocene sediments.

As is typical of subsurface geology in the Gulf Coast area, many depth intervals are much more complex than the formal and quasi-formal stratigraphic nomenclature would suggest. Hydrocarbon pay zones are most typically named informally (e.g., the "'A' sand") and are likely restricted in regional extent. Biostratigraphic markers are frequently important in regional and subregional correlations.

A consequence of this complexity of detail is that only a small number of stratigraphic intervals have been distinguished for structure-contour mapping at the Bayou Choctaw site, and — in fact — the principal emphasis has been on selected "tops" of intervals, rather than on full, lithologically consistent geologic units. Although this approach provides a reasonable approximation of the geologic setting of salt domes for many purposes of the SPR program, it does pose certain limitations. For example, it is not possible to identify the specific lithology present at any given depth other than "immediately" below the indicated horizon top. The principal geologic tops reported in the original site characterization report are given in table 1. The site characterization update report does not contain an equivalent listing. Rather, the approach used in the latter report is entirely biostratraphic in nature (Neal and others, their table 1).

Cavern Sonar Surveys

The geometric configurations of underground storage caverns are determined at episodic intervals during leaching and/or ongoing cavern operations through the use of downhole sonar-surveying equipment. This equipment consists of a wireline tool that is run inside the casing and any tubing in a cavern well. The tool contains a transmitter and a primary receiver, and a secondary receiver that allows determination of the velocity of the medium immediately surrounding the tool (oil or brine). The electronics and physical design of the tool allow directional measurements using a tightly focused sonar beam and a directional receiver. Downhole rotational orientation of the tool is determined via magnetic orientation techniques.

Both site characterization reports contain a limited amount of information on the configuration of storage caverns at the Bayou Choctaw site, as this site already contained numerous caverns when acquired by the SPR program. In both cases, the information available in the published reports consists of cross-sectional views of selected caverns. A few cross-sectional comparisons of cavern profiles at different times are presented in both site characterization reports.

Availability of cavern configuration data is somewhat complicated at the Bayou Choctaw site, in that DOE shares ownership of the salt dome with the operator(s) of other storage caverns. Although some survey information is available for non-DOE-owned caverns, the timeliness and completeness of these surveys are not under DOE control. The digital sonar-survey data that are available for the Bayou Choctaw site are identified in table 2; all files originally available in digital format postdate both site characterization periods.

Conversion Methodology

A "complete" model of the Bayou Choctaw SPR site actually consists of a number of different submodels, corresponding in general to the use of a particular type of input data. Different types of geological data and the different formats in which these data are recorded require the use of different modeling approaches and mathematical algorithms. The use of a single modeling software package, however, allows the assembly of all submodel components into a unified representation for

Table 1. Geologic names and unit tops in use at Bayou Choctaw

[Modified after tables 6.1 and 6.2 of Hogan and others, 1980a. "SPR Model"–presented as structure contour maps in the Hogan report and converted as part of this modeling effort. "Tables"–presented in the tables of horizon tops in an appendix to the Hogan report]

Age	Formation	Symbol	Lithology	SPR Model	Tables	Stratigraphic Unit	Biostratigraphic Zone
Pleistocene			sand/clay				
Pliocene			sand/clay	X	X		
	Goliad		sand/shale		X		
		M	sand/shale		X		*Bulimenella*
Miocene	Fleming		shale		X		*Robulus E*
	Catahoula	A	sand	X	X	Clovelly	
		1	sand		X		
		2	sand		X		
		3	sand		X		
		4	sand	X	X	Duck Lake	*Bigenerina humblei*
		AB	shale				*Amphistegina B*
		5	sand		X	Duck Lake	
		6	sand		X		
		7	sand		X		
		8	sand	X	X	Napoleanville	*Discorbis bolivarensis*
		9	sand				
	SD		shale				*Siphonina davisi*
		10	sand				
		11	sand				
		12	sand				
		13	sand				
		14	sand				
		15	sand				
		16	sand	X	X		*Planulina palmerae*
		17	sand				
		18	sand				
Oligocene		H	limestone	X	X		*Heterostegina sp.*
		MH	sand				*Marginulina howei*
	Anahuac	A	shale				
	Frio	F	sand	X	X		
		MG	sand		X		*Miogypsinoides sp.*
		CH	sand		X		*Cibicides hazzardi*
		MT	sand				
		BM	sand		X	Hackberry	*Bolivina mexicana*
		NB	sand		X		*Nodosaria blanpiedi*
	Vicksburg		black shale				*Textularia warreni*

Table 2. Sonar cavern-survey data available in digital form

[SPR – SPR-owned cavern; *Top* and *Bottom* are depths subsea; n/a – not applicable. Files are proprietary format of Sonarwire, Inc.]

Cavern	SPR	Phase	Survey Date	Top, ft	Bottom, ft	File Name
BC-4		n/a	04-16-1997	649	1690	BC-4.cwr
			04-16-1997	682	700	UP-BC4.cwr
BC-15	X	I	06-24-1999	2565	3280	BC-15.cwr
BC-17	X	I	06-09-1999	2602	4000	BC-17.cwr
	X		07-06-1999	2602	4000	2-BC17.cwr
BC-18	X	I	10-08-1991	2172	4200	BC-18.cwr
BC-19	X	I	09-24-1996	4075	4210	BC-19.cwr
	X		06-23-1999	2600	4200	BC-19a.cwr
BC-20	X	I	11-16-2000	2422	4160	2-BC20a.cwr
	X		11-16-2000	2422	4160	2-bc20aa.cwr
	X		11-16-2000	3600	4160	2bc20ap.cwr
	X		11-16-2000	3860	3860	2-bc20au.cwr
	X		11-05-2002	2422	4165	3-BC20a.cwr
	X		11-05-2002	3600	4165	3-bc20ap.cwr
	X		11-06-2002	3860	3860	3-bc20au.cwr
BC-25		n/a	12-04-1996	2463	5698	4-UTP25.cwr
BC-101	X	II	07-25-1995	2570	4810	BC-101b.cwr
BC-102		n/a	09-22-1994	2500	5282	UTP-102a.cwr

visualization and the extraction of information for other purposes.

A Note on Coordinate Systems

Computerized geological modeling mandates the use of a standardized, numerical coordinate system. In contrast, manual "spotting" of well locations and mapping on physical paper are much less demanding in this regard, as locations are typically placed relative to land-survey section (e.g., 1250 ft from east line, 750 ft from north line) or to other well locations, and construction of the model is by hand. Computer-based modeling and visualization are based on mathematical computations, with the result that all coordinates of features to be represented must be consistent.

The vast majority of oil and gas data for the Gulf Coast have been recorded in state plane coordinates, which for this part of the state of Louisiana is the south zone of that system. The Louisiana state plane coordinate system is a Lambert conformal conic projection, in practice almost invariably referenced to the North American Datum of 1927 (NAD-27). This is the same coordinate system used historically on 7.5-minute quadrangle topographic maps published by the U.S. Geological Survey. A few recently revised 7.5-minute maps use a state plane coordinate system based on NAD-83, the North American Datum of 1983 (in addition to the secondary UTM [universal transverse mercator] grid that is presented on all USGS 7.5-minute quadrangle maps). However, virtually all historical geographic information uses the NAD-27 datum. For reference, the spatial shift between the two datums may be a much as 100-200 ft.

The site characterization reports for the Bayou Choctaw site do not state explicitly what coordinate system was being used. However, the original site characterization report does refer to the Addis, La., 7.5-minute USGS quadrangle map of 1971, which almost certainly indicates that the coordinate system is state plane, NAD-27, because the quadrangle was published prior to development of NAD-83. Additionally, the absolute magnitudes of the coordinates shown by marginal ticks on the various maps and figures correspond approximately in value to those of the Louisiana state plane coordinate system, south zone, NAD-27. Because the numerical coordinates of roughly similar positions in other systems are markedly different (by design), we have assumed that the existing coordinates at Bayou Choctaw are, in fact, state plane, NAD-27.

Generation of the Salt Dome Model

The salt model selected for conversion is the original site characterization model interpreted by Hogan and others, and it was modeled to a depth of about 9000 ft subsea. In contrast, the Bayou Choctaw salt dome was modeled only to a depth of 5000 ft subsea in the updated site characterization report. This is approximately the depth to which the SPR storage caverns extend. Although this depth is probably sufficient, strictly speaking, for many purposes for the SPR program, the greater depth is appropriate for modeling purposes, particularly because the data are readily available.

The methodology used to convert the paper site characterization model of the Bayou Choctaw salt dome margin is documented in a separate report (Rautman and Stein, 2003). The approach involves digitizing in calibrated *x*- and *y*- state plane coordinate space the various structure contours drawn of the top of salt. Each discretized contour line is assigned its relevant elevation (depth) as the (constant) *z*-coordinate value.

For the full set of digitized contours, corresponding 3-D points on successively deeper or shallower contour "rings" are connected using the external software code **`ctr2evs`** (Rautman and Stein, 2003) to form an approximation of a finite-element mesh. This process is shown conceptually in figure 3. MVS, the geologic modeling and visualization software, uses such explicit finite-element meshes, specifying the nodal coordinates and the connectivity of the various nodes, as the basis for visualization of all contained features. Thus, the model of the salt dome implied by the flat, two-dimensional structure contour map is computed externally and visualized directly by the software in three-dimensions.

Because the crest of a salt dome is essentially flat lying, in marked contrast to the steeply plunging flanks of the dome, the structure-contour representation of the top-of-salt surface is generally somewhat simplistic unless supplemental contours are provided at a closer spacing than that typically used to represent the flanks. Accordingly, the uppermost part of the Bayou Choctaw dome has

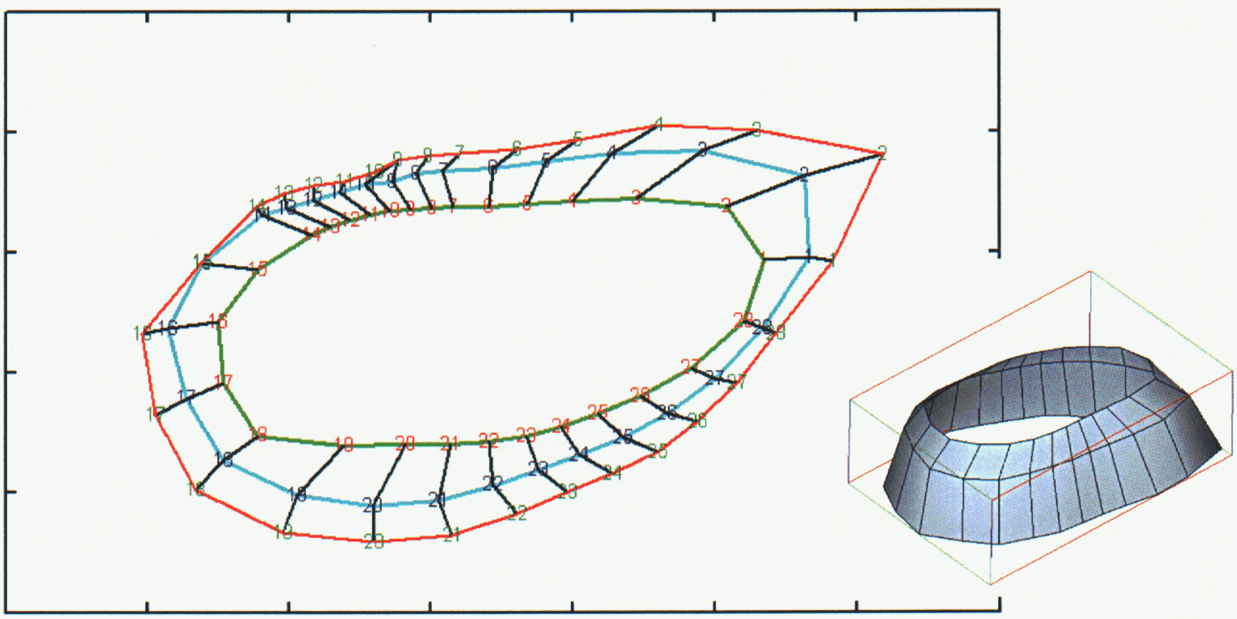

Figure 3. Conceptual representation of the process of constructing a finite-element-like mesh to represent the flanks of a salt dome from successive digitized structure contours on the top of salt. Inset: resulting 3-D mesh object.

been modeled using what well control for the top of salt could be matched to its proper spatial position. This includes principally the various cavern wells; however, a small number of other well locations were also included.

Modeling of these crestal top-of-salt picks was performed using a proprietary implementation of the geostatistical algorithm known as *kriging*. Kriging in general is merely a form of least-squares linear regression (Deutsch and Journel, 1998), in which the observed values (elevations of the top-of-salt picks) are interpolated at unsampled locations, typically onto a quasi-regularly spaced finite-element-type mesh (fig. 4), as a weighted average of the known data within a local search neighborhood. The weights applied to the observations are computed via solution of a covariance matrix that considers both the distance from each measurement location to the point being estimated and a mathematical model — the variogram — derived from all of the data, describing statistically how variable are the different measurements in space.

Within the MVS software package, kriging of geologic surfaces is implemented in the module **`Krig3D_geology`**. This module uses a proprietary "expert system" approach to compute the variogram model of the data for each geologic horizon separately, and then sequentially kriges each horizon using the appropriate variogram model and the relevant observed data. The meshes representing the two portions of the dome were then merged using the MVS module **`merge_field`** to produce a combined surface for visualization.

Generation of the Sediment Model

There are two principal methods that may be used to generate the three dimensional model of the sedimentary horizons surrounding the salt dome. The first of these is similar in some respects to the approach used to model the salt dome margin (above), and it entails digitizing the interpretive structure contour maps drawn on the top of the various surfaces that are presented in the site characterization report. The second approach involves working with the underlying stratigraphic picks for the tops of the various horizons in the various wells. This latter approach is probably more true to the original data, whereas the former approach relies heavily on the interpretation of the geologist who constructed the structure contour maps. In either event, the available data points are interpolated using kriging to produce a modeled surface.

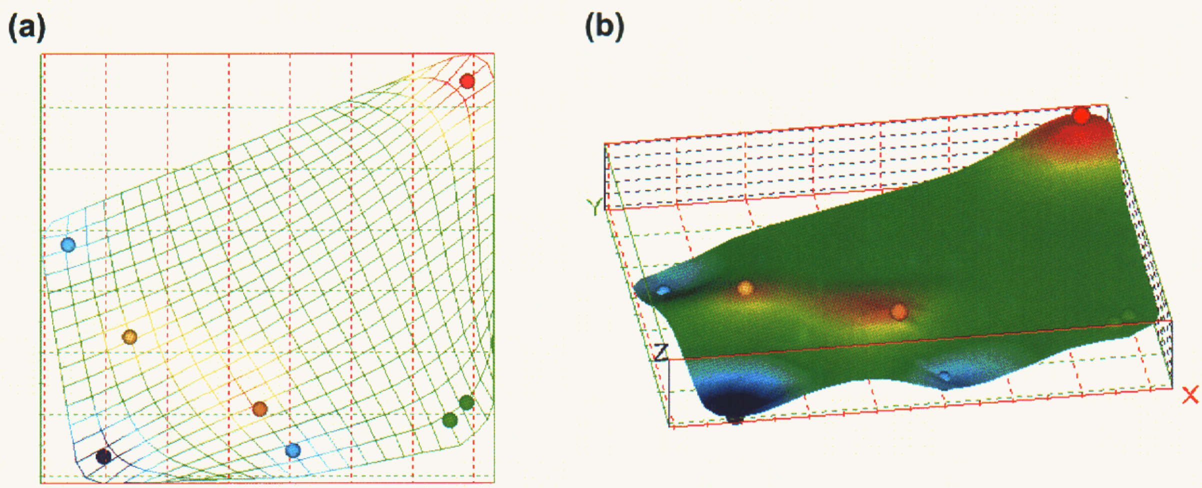

Figure 4. Conceptual representation of interpolation of scattered data points onto a finite-element-type mesh in MVS. (a) Observed data and mesh (colored by value); (b) resulting surface. No scale.

The difficulty for the Bayou Choctaw site with going back to the original stratigraphic picks is that neither of the site characterization reports contains a tabulation of well coordinates (see discussion under *Well Information* on page 11). Attempts to produce a suitable site-wide tabulation by digitizing the small-scale well-location index map contained in the original site characterization report and by use of a commercial well database were unsuccessful because of inconclusive correlations between the labeling scheme on the map and the well identifiers in the tables of stratigraphic contacts.

Consequently, the model of sedimentary horizons for the Bayou Choctaw site was generated by digitizing the available structure contour maps drawn on the tops of selected geologic horizons (table 1). Each mapped contour line was digitized at a spacing visually determined to capture the necessary details of the topology of the surface. The resulting *x-y* coordinate pairs were assigned the (constant) elevation value (*z* coordinate) appropriate to the contour in question and the *x-y-z* triples were provided to the MVS geologic modeling software module **Krig3D_Geology**, which successively processes each individual geologic horizon.

Interaction of the salt-dome model and the layered sediment model is somewhat involved. Each sedimentary horizon was modeled as a continuous surface throughout the horizontal extent of the source structure contour maps. This continuity includes generation of surface grid nodes *within* the outline of the salt mass at each relevant stratigraphic level. Because the sedimentary surface is not present within the salt dome itself by virtue of diapiric emplacement of the salt, the modeled surface in this portion of the lateral extent of the geologic horizon is completely meaningless. Nevertheless, the numerical algorithm is unconstrained at this point in the process, and thus it generates estimated elevation values by interpolation using data points located outside the dome proper.

In order to approximate the diapiric displacement of the sediments by the rising salt mass, the meshes for the full set of stratigraphic surfaces were "cut" by the finite-element mesh defining the margin of the salt dome using the MVS module **surf_cut**. In fact, **surf_cut** does no explicit cutting on its own, but rather adds a nodal data component to the meshes representing the various geologic surfaces, which indicates the distance of each grid node from the closest approach to the cutting surface (here: the salt margin model). A separate MVS module, **isovolume**, is then used to extract only those nodes of the several stratigraphic-horizon meshes that lie outside of the closed dome-margin mesh. It is these portions of the horizons that are then visualized.

Note that the model of the surface topography was also generated using **Krig3D_Geology** and the digital elevation model data points (USGS, 1998a), as the numerical difference between the surface topography and a relatively flat-lying geologic horizon is negligible. However, the model of the surface topography was generated separately from the model of the several geologic surfaces. The topography does not interact directly with the salt-dome margin, and subsetting (cutting) as described above is not applicable.

To supplement the model of surface topography and add additional realism and reference points to the final models, digital orthophotography (USGS, 1998b) was draped onto the surface DEM models. Orthophotos are high-quality (1-m resolution) aerial images from which the various distortions related to topographic relief and aircraft-camera tilt have been remove. Their geometrical accuracy is thus equivalent to a map.

Generation of the Caprock Model

The model of the caprock overlying the Bayou Choctaw salt dome was generated, in a similar manner to the sedimentary horizon models just described, using **Krig3d_Geology** applied to digitized contour data from the structure-contour and isopach maps contained in the original site characterization report. As with the sediment model, the relevant structure contour maps on the top-of-caprock and the top-of-salt surfaces were digitized in calibrated *x-y* state-plane coordinate space and converted to MVS input files. For the top-of-salt surface, the digitized contours were supplemented by well control for which spatial positions could be obtained. For the isopach map presented in the original site characterization report (their fig. 5.2), the isopach (thickness contours) were digitized instead of structure contours.

Actually, three separate models of the caprock were generated, partially as a check on the internal consistency of the various original drawings. What is here presented as the principal caprock model was generated as the difference between the top-of-caprock and the top-of-salt surfaces. Models were also generated from the digitized isopach map and this thickness model was then "hung" alternatively from the top-of caprock structure model or on the top-of-salt structure. Differences among these three representations are discussed later in this report in the section entitled *Discussion of Fault Models* on page 44.

Generation of Fault Models

A large number of faults intersect and offset the sedimentary horizons at the Bayou Choctaw site, as interpreted on the structure contour maps of the several selected horizons (table 1). Some of these faults have been included in the converted 3-D digital model (see additional discussion of faults below on page 30). The process for modeling an approximation of the faulting is as follows.

1. Digitize the fault traces in calibrated state plane coordinates, as shown on the structure-contour maps using the indicated fault-naming conventions.
2. Generate a number of equally spaced *x-y* points along each fault trace using the MVS module **`polyline_spline`**.
3. Project each of these *x-y* points onto the relevant geologic horizon generated through kriging and obtain the corresponding elevation (*z*-coordinate) using the MVS module **`geologic_surfmap`**.
4. Convert this set of *x-y-z* coordinates to a *t*riangulated-*i*rregular *n*etwork (TIN) surface mesh using the MVS module **`scat_to_tin`**.
5. Visualize the resulting TIN in association with the stratigraphic horizons.

An example of a TIN surface is presented in figure 5.

In some instances, the digitized intersections of the faults with its set of geologic surfaces at different elevations indicated a fault plane that is multi-valued in elevation. In other words, that the surface is "folded back on itself." Such multi-*z*-valued surfaces are not possible in MVS (or almost any other general geological modeling software program) and attempts by the software to fit a non-multi-*z*-valued surface to the data results in geometries that are physically absurd. However, in most situations — and, in fact, in all cases for the Bayou Choctaw domal faults — it is possible to first rotate the data points about some axis such that a rotated surface may be fitted to the points without creating impermissible geometries. MVS provides a module

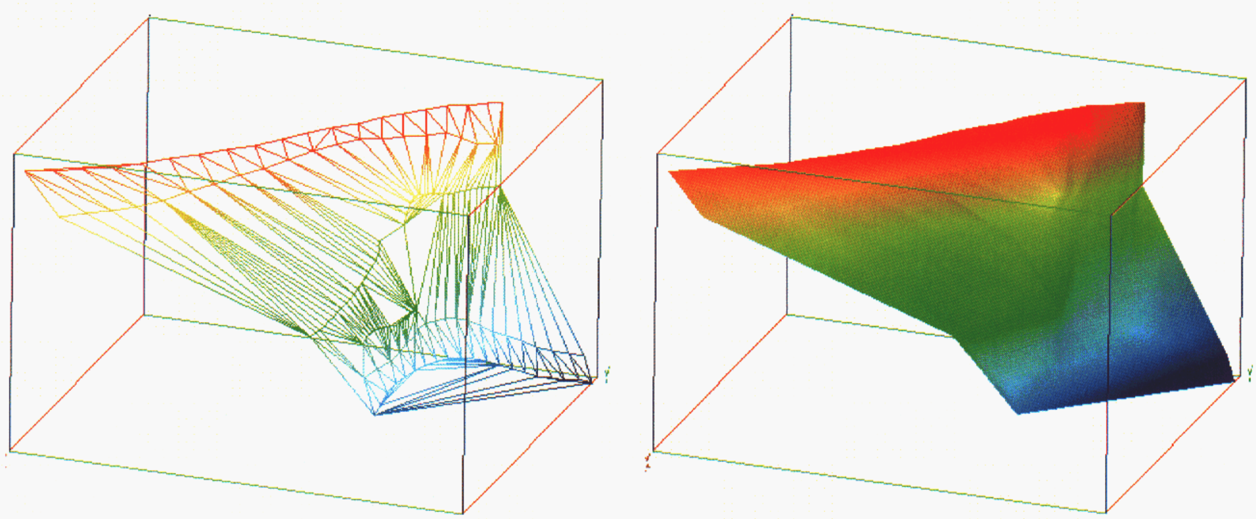

Figure 5. Example triangulated irregular network (TIN) mesh. (a) Digitized points (black) along mapped fault intersections with several stratigraphic horizons are connected by DeLauney triangles to form a triangulated network in 3-D space. (b) Resulting surface. No scale.

known as `field_math` that allows such manipulation of coordinates. Once the TIN representation of the surface has been computed in the rotated coordinate space, it is then possible to un-rotate the surface using an inverse transform and to place the now geologically reasonable representation of the fault plane in its proper spatial position.

Note that this modeling process does *not* produce actual geometric offset of the modeled sedimentary horizon, and thus the resulting models are somewhat limited in their degree of realism. However, this limitation was judged acceptable for purposes of this model conversion effort for the following reasons. (1) The various faults have relatively minimal displacement at the scale of the overall salt dome. (2) This model conversion effort is intended principally to produce visualizations to aid in the conceptual understanding of the Bayou Choctaw site. (3) The actual positions of the faults and the actual offsets along each of them are quite poorly constrained, in that the site characterization models are based only on well control, and the faults have not been imaged using high-resolution techniques such as 2-D or 3-D seismic. Accordingly, we believe that the interpretive errors in the fault descriptions are on the order of the offsets themselves, and that the limitations of this modeling approach are acceptable for the current conversion purpose.

Generation of the Cavern Models

The various sonar surveys of the storage caverns have been converted to 3-D models by computing the apparent coordinates of the reflecting surfaces around the margin of the solution cavity from the downhole measurements using simple trigonometry. The raw output from a modern sonar survey consists of a set of radial distance measurements plus the depth and beam-orientation information necessary to locate the spatial positions from which those radial measurements were obtained. The positional data comprise the depth of the sonar tool for each 360-degree sweep of the cavern, the angular inclination of the beam direction (up, down, or horizontal), and the azimuth of the sonar beam relative to north.

Because the depth, rotation, and inclination sequence is known (and constant), it is a relatively simple matter to connect the coordinates where the focused sonar beam appears to reflect from the cavern wall to form a two-dimensional surface in 3-D using quadrilateral elements. Knowledge of the surface coordinates of the well through which the survey was conducted allows conversion of the computed cavern coordinates (and surface elements) to three-dimensional real-world coordinates for merging into the visualization space of the rest of the geologic model.

It should be noted that modeling of the sonar data is conducted as though the sonar beam is essentially a line and that the reflecting surface is oriented approximately normal to the direction of travel of the sonar pulse. Although this is a necessary, and probably geologically reasonable, assumption for many caverns and at most depths, it need not apply rigorously in all circumstances. The more irregular the cavern form, the more likely it is that off-angle reflections may be mistaken for the desired cavern wall, thus distorting the modeled shape of the cavern. Interpretation of the proper reflection is performed by the sonar operator in the field during logging using professional judgment and experience. In regions of particularly complicated geometry, sonar surveys from multiple tool positions within a cavern may be helpful in identifying the best interpretation of the cavern wall.

The limitations imposed by irregular geometry are particularly relevant at Bayou Choctaw, where most of the SPR storage caverns are so-called Phase I caverns (table 2). Phase I caverns were originally leached in a relatively uncontrolled manner for chemical-feedstock brine and only later purchased by the SPR program for oil storage. Of the SPR-owned storage caverns, only cavern BC-101 at Bayou Choctaw is not a Phase I cavern. A preliminary, visual assessment of the positional accuracy of cavern margins, in Phase I caverns especially, can be performed simply by assessing which portions of a cavern model appear relatively regular in form and which are suggestive of complex geometry and rapid changes in shape with either depth or angular position. Survey precision is likely to be better in the former regions. Large regions of particularly planar boundaries may be suspect as representing sonar "shadows," rather than actual reflections. Planar boundaries that project directly toward the center point of the survey (not necessarily the same as the center of the cavern itself) are especially suspect.

RESULTS

It is virtually impossible to do complete justice to a three-dimensional geologic model in a two-dimensional report. Accordingly, 4DIM model files (see page 10), viewable using a Microsoft Windows™ personal computer, are included on CD-R media with this report. Appendix A presents installation instructions, directions for manipulating the models using the 4DIM player, and a discussion of salient features of the various 4DIM model files.

The section that follows presents highlights of the three-dimensional model that has been converted from the paper format of the original site characterization report for the Bayou Choctaw salt dome. The geometry of the dome itself is presented first, followed by description of the enclosing sediments, both the mapped stratigraphic horizons and the formed-in-place caprock. These principal features of the salt dome and its environs are displayed from a number of different vantage points or perspectives. Presentation of the overall model continues with portrayal of the geometry of the more-major faults that have been mapped cutting the sedimentary mass outside the salt dome. The section concludes with presentation of some of the storage caverns that have been constructed within the salt mass. Emphasis here is principally upon those caverns owned and operated by DOE.

SALT DOME MODEL

The geometry of the Bayou Choctaw salt dome is shown in figure 6 at 60-degree azimuthal increments, beginning from approximately south (165 degrees). The views are from 20 degrees above the horizontal. Two steeper-elevation views are shown in figure 7 (from 60 degrees above the horizon). A view from directly overhead is shown in figure 8. This interpretation of the salt dome is taken essentially as-is from the original site characterization report of Hogan and others, as the updated characterization report (Neal and others) presented a structure contour map on the top of salt only to a depth of 5000 ft.

The outline of the salt dome is generally circular in plan view and the flanks of the dome exhibit moderately pronounced overhang at depths less than about 4000 ft subsea on the western and southwestern margins. The transition from steeply dipping flanks to the relatively flat-lying dome crest occurs between depths of 1000 to 2000 ft in the eastern portion of the dome and quite abruptly at approximately 1000 ft in the west. The contours on the crest of the dome exhibit some complexity, specifically low-relief "valleys" on both the southern and northwestern portions. This geometric configuration is most obvious in the top view of figure 8. Different elevations of the dome crest in different parts of a salt dome *may* indicate the presence of separate salt spines that are undergoing differential movement. However, no significant evaluation of potential differential movement was conducted as part of this model conversion exercise.

SEDIMENT MODEL

The complete sediment model for the Bayou Choctaw site is presented in a sequence of four edge-on views from the four cardinal directions in figures 9 and 10. The selection of stratigraphic horizons, or unit tops, is that presented in the original site characterization report, and it consists in downward sequence of (1) the top of Pliocene shale, (2) the (Miocene) "A" sand, (3), the "Number 2" sand, (4) the "Number 4" sand, (5) the "Number 8" sand, (6) the "Number 16" sand, (7) the top of the *Heterostegina* limestone (Oligocene), and (8) the top of the Frio. These illustrations provide the most clear visualization of the geometry of the eight stratigraphic tops immediately adjacent to the salt dome. A set of reduced-scale visualizations, corresponding to the orientations used in figure 6 for the salt dome alone, is presented in figure 11.

The principal observation to be drawn from the various views of figures 9 through 11 is that the several sedimentary horizons mapped appear to have been dragged upward by diapiric rise of the salt mass. This is most clearly evident in the edge-on views of figures 9 and 10, which allow viewing of the surfaces close to the center of the model. Local areas of increased uplift are evident in a number of the visualizations. Some of these localized regions are almost certainly related to faulting (see discussion under *Fault Models*), as is clearly indicated on the original structure contour maps in the site characterization report.

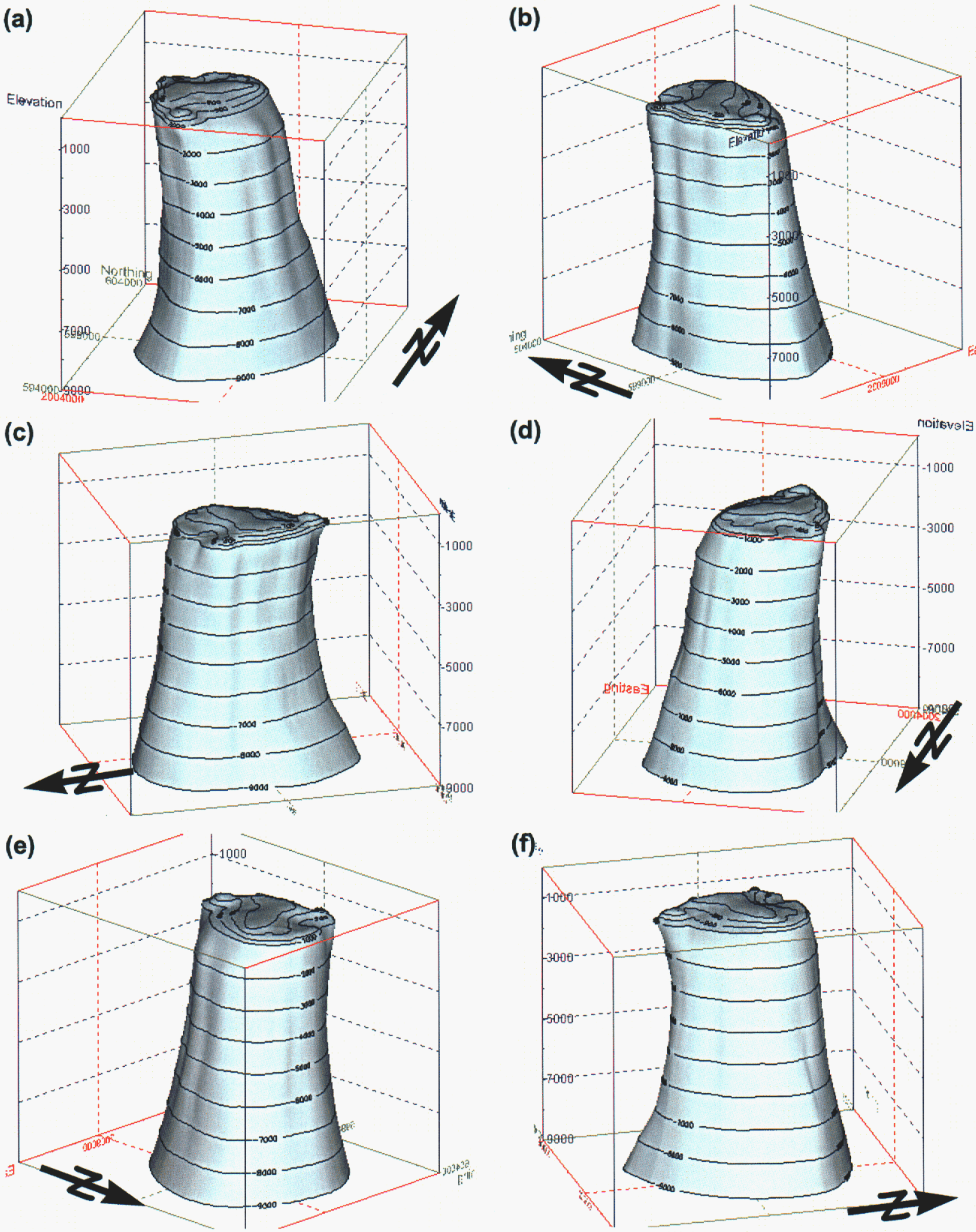

Figure 6. Geometry of the Bayou Choctaw salt dome margin. View from azimuths of (a) 165°, (b) 225°, (c) 285°, (d) 45°, (e) 105°, (f) 165°. Elevation 20° above the horizontal. Contours are elevations in feet subsea. No vertical exaggeration.

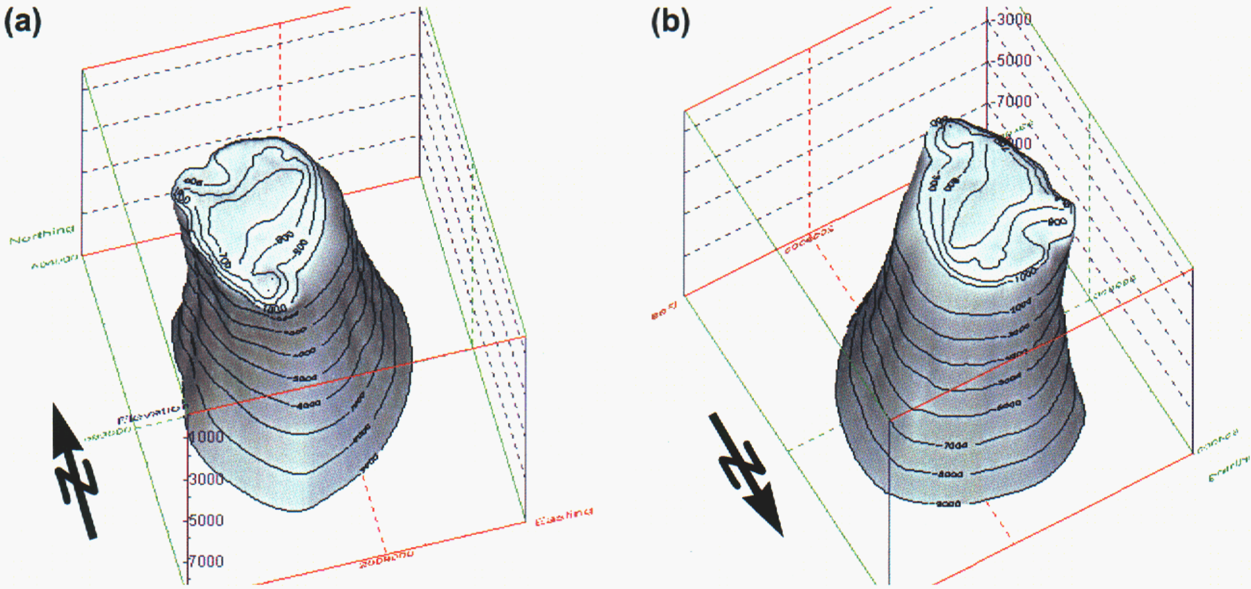

Figure 7. Geometry of the Bayou Choctaw salt dome margin showing the configuration of the crest of the dome. Views from azimuths of (a) 195° and (b) 30°. Elevation 60° above the horizontal. Contours are elevations in feet subsea. No vertical exaggeration.

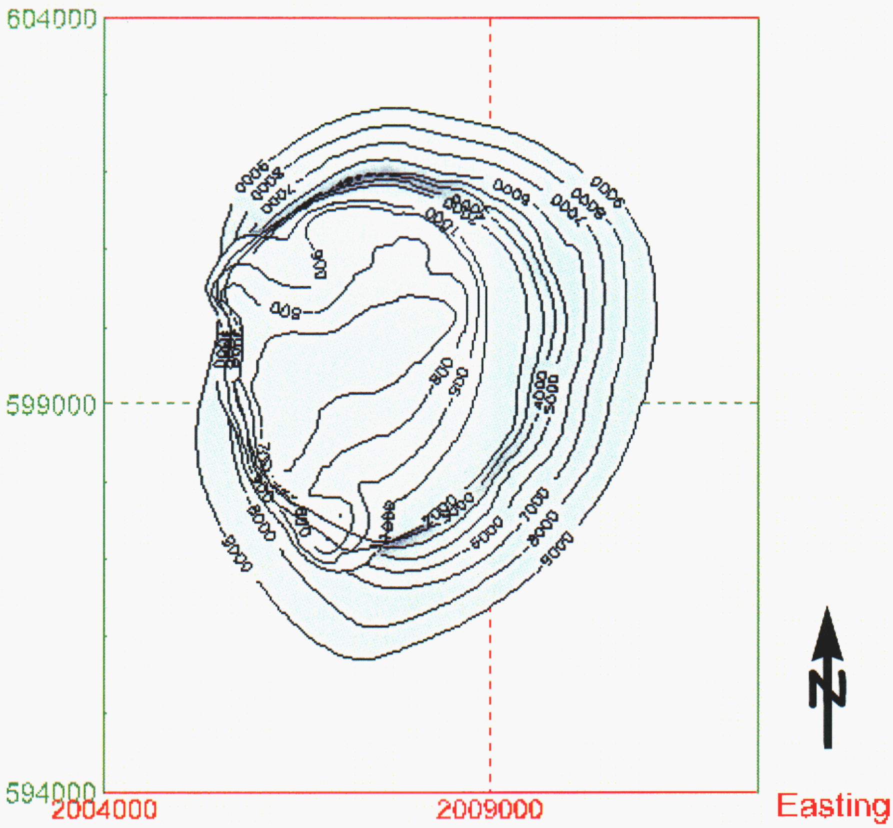

Figure 8. Geometry of the Bayou Choctaw salt dome, shown approximating a structure contour map on the top of salt. View is from directly overhead (elevation = 90°). Crossing of contour lines results from structural overhang, particularly along the western portion of the dome.

(a)

(b)

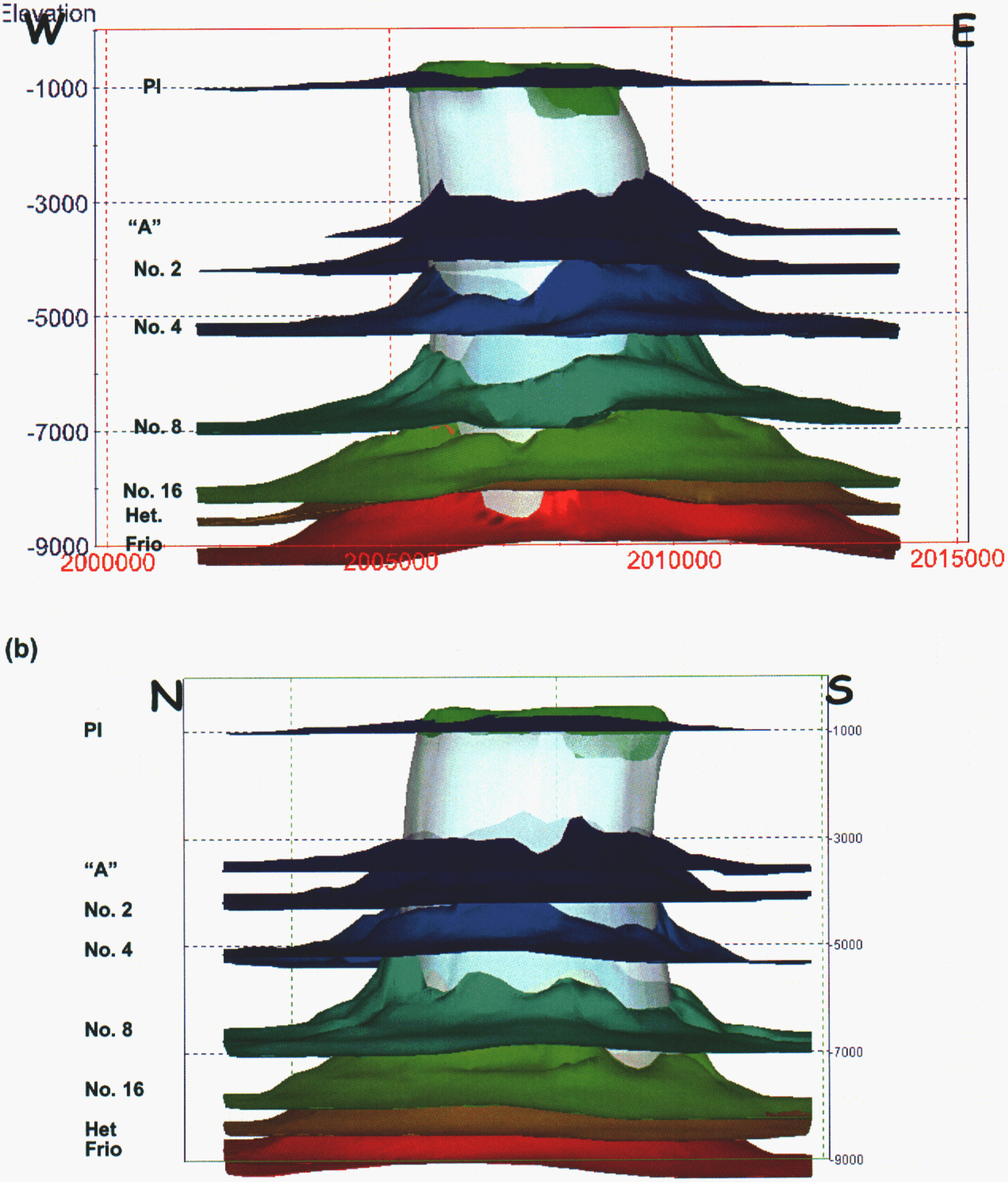

Figure 9. Two horizontal views of the Bayou Choctaw sediment and salt model from (a) the south (azimuth 180°) and (b) west (azimuth 270°). Abbreviations: Pl – top Pliocene, "A" – "A" sand, No.2 through No. 16 – No. 2 sand through No. 16 sand, Het. – Heterostegina limestone, Frio – Frio formation. No vertical exaggeration.

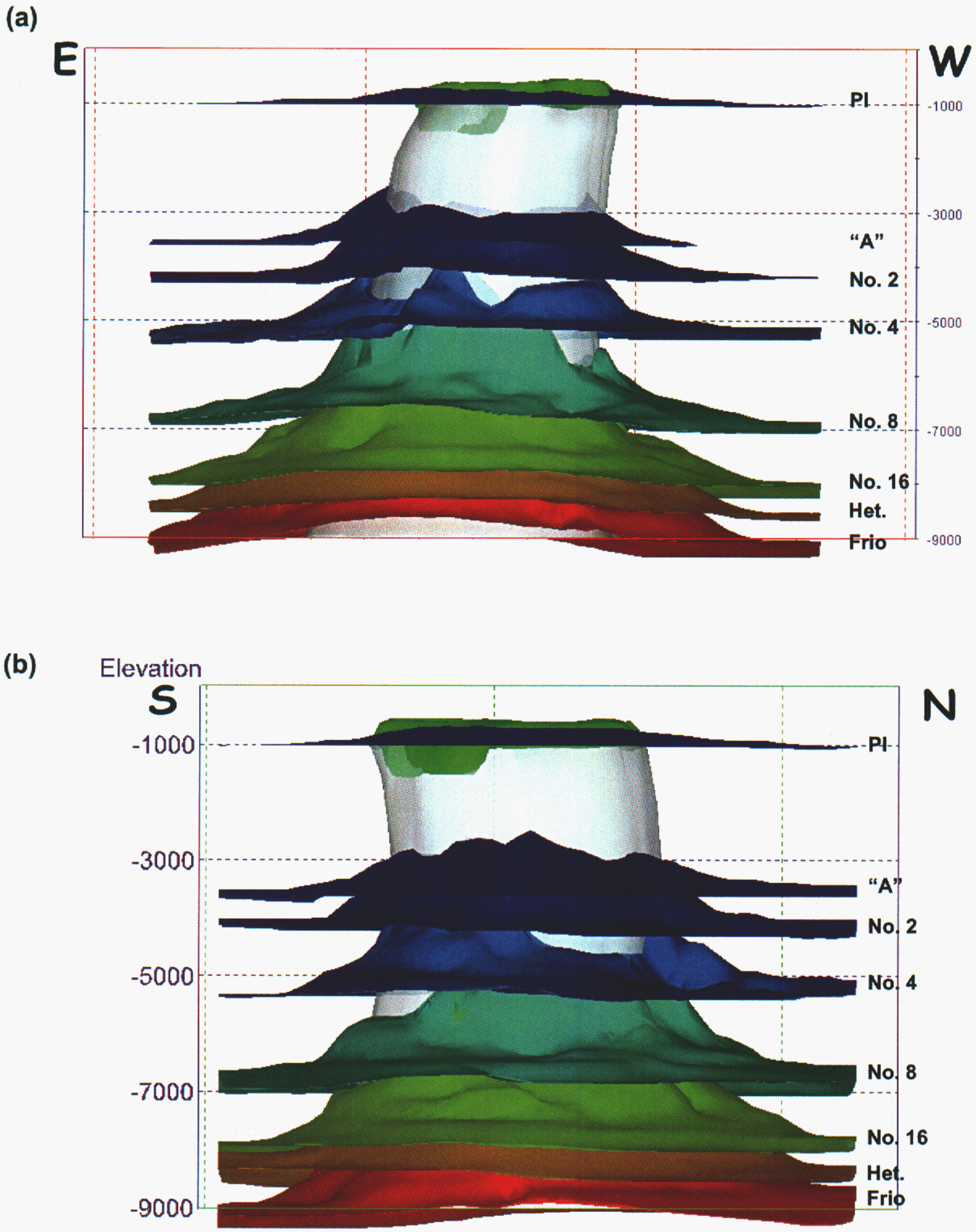

Figure 10. Two horizontal views of the Bayou Choctaw sediment and salt model from (a) the north (azimuth 0°) and (b) the east (azimuth 90°). Abbreviations as in fig. 9; no vertical exaggeration.

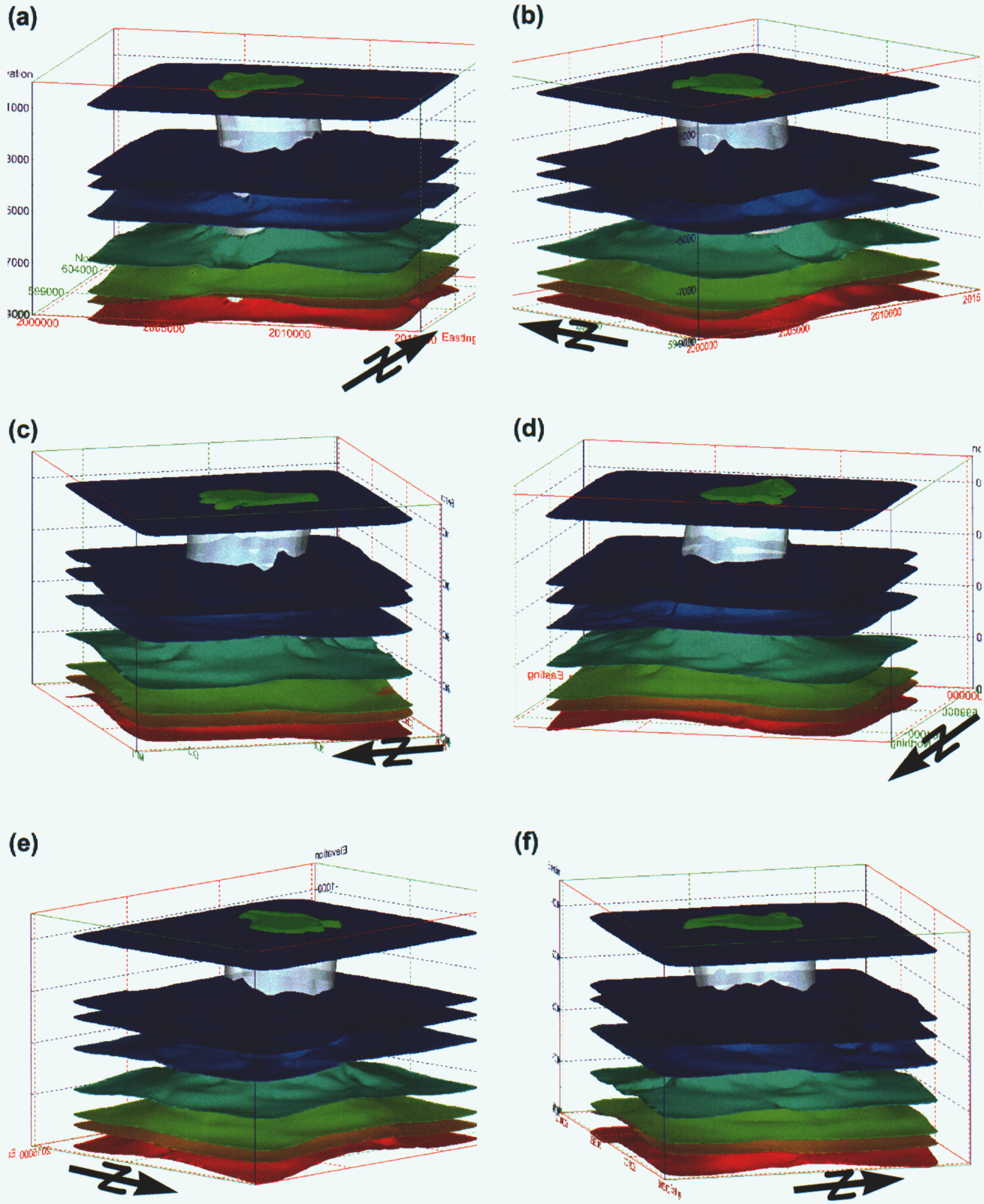

Figure 11. Geometry of the tops of the modeled sedimentary horizons (including the caprock). View is from azimuths of (a) 165°, (b) 225°, (c) 285°, (d) 45°, (e) 105°, (f) 165°. Elevation 20° above the horizontal. Horizon abbreviations not shown for clarity; see figs. 9 and 10. No vertical exaggeration.

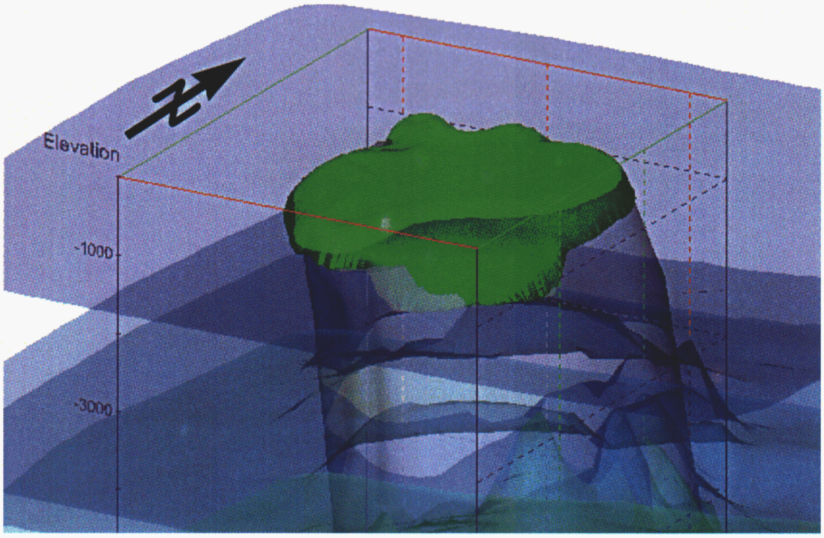

Figure 12. The caprock on top of the Bayou Choctaw salt dome protruding through the highest stratigraphic unit modeled, the top of the Pliocene shale (partly transparent). View from azimuth 150°, elevation 20°. No vertical exaggeration. Note wrapping of caprock (green) down the southeastern flank of the dome margin.

CAPROCK MODEL

Visualizations of the caprock overlying the Bayou Choctaw salt dome are presented in figures 12 through 14. Figure 12 shows the relationship of the caprock with respect to the highest stratigraphic surface modeled, the top of Pliocene shale (table 1). Note that the caprock (shown in green) largely protrudes through this sedimentary horizon, but that part of the caprock wraps over the salt margin (shown in grey) and extends some distance down the southeastern flank of the dome.

Figure 13 presents the modeled thickness of the caprock, as determined by the difference in elevation of the top-of-caprock and the top-of-salt surfaces. The view is from directly overhead, and the thickness of the caprock can be observed to be in excess of 400 ft locally. Figure 14 presents two oblique views of the same caprock-thickness model, highlighting the unequal build-up of caprock mass and the differing degrees of wrapping of the caprock down the flanks of the salt dome at different radial positions.

Interestingly, the greatest thickness of caprock is near the margins of the dome, rather than in the center of the lateral extent of the salt mass. The origin of this configuration is not certain, except that the inflection point from salt dome crest to salt dome flank is an obvious location where insoluble residues from dissolution of the salt crest could build up, less affected by large-volume groundwater flows across the actual high point of the salt. Current ground water conditions in the vicinity of Bayou Choctaw indicate that flow in the shallow Pleistocene aquifer is directly tied to the stage of the Mississippi River, which is located a few miles to the east of the site. Flow directions are thus from east to west during high stages and from west to east when the river is low (Hogan and others, p 4.4, 4.6).

The observed distribution of caprock can be interpreted as compatible with these changing flow directions. High stages of the Mississippi would logically be accompanied by large (?) inflows of fresh river water and flow to the west, dissolving salt and other minerals from the eastern side and potentially precipitating thicker caprock on the western margin as salinities increase. Conversely, low-stage river flow could be associated with slower (?) eastward migration of highly saline to near-saturated ground waters. Despite this potential, but speculative interpretation, however, paleo-ground-water flow directions during the time of principal dome rise and caprock formation are not

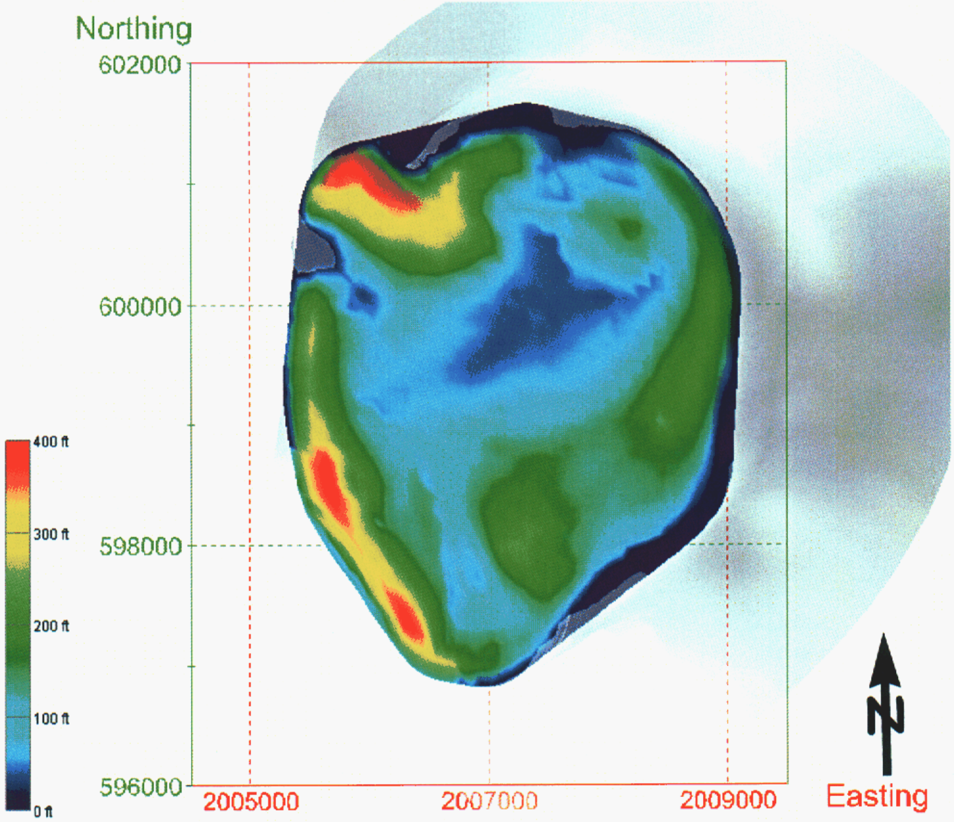

Figure 13. Thickness of the caprock on top of the Bayou Choctaw salt dome. Thickness indicated by color-scale bar. Grey represents the lateral extent of the salt mass to –9000 ft elevation.

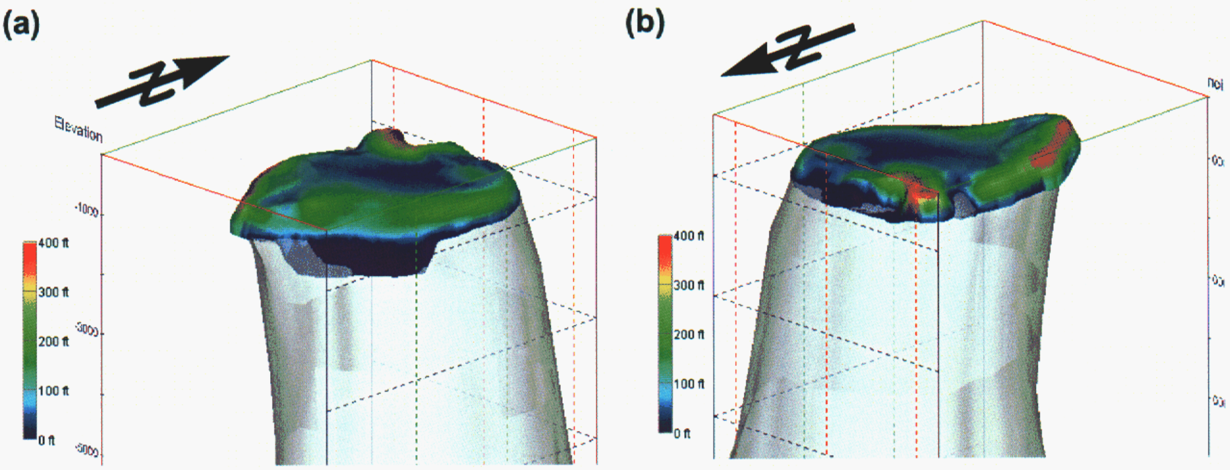

Figure 14. Oblique views of the thickness of the caprock on top of the Bayou Choctaw salt dome. Views from azimuths of (a) 135° and (b) 315°. Elevation 20° above the horizontal. No vertical exaggeration.

known, and they may have been quite different from current conditions.

Fault Models

A large number of faults cutting the sediments surrounding the Bayou Choctaw salt dome were mapped as part of the original site characterization effort. Ten of these faults were given identifying numbers (table 3), and presumably these represent the more major, through-going faults. A much larger number of unnumbered faults were also mapped on the various structure contour maps of the eight sedimentary marker horizons. No attempt was made to convert these smaller, unnamed faults to numerical models, as there is no easy method of correlating these inferred breaks from one marker horizon to the next.

A set of visualizations of the separate faults that have been inferred at the Bayou Choctaw site (table 3) is presented in figure 15. A set of visualizations of each fault is presented separately in figures 16 through 20. A three-part method of presentation has been adopted for the latter figures. First, we present a top view of each individual fault, looking down from directly overhead. Two additional oblique views of each fault are presented, in an attempt to represent how the fault intersects the mass of the salt dome and the geometry of the dipping fault relative to the salt margin. There are examples of both radial faults extending more or less away from the center of the salt mass and tangential faults that are somewhat subparallel to the salt-dome margin..

In general, the faults are steeply dipping surfaces (F-7 is an exception) that cut through — but do not numerically offset (see discussion on page 21) — the surfaces corresponding to the various stratigraphic horizons. Figure 21 presents an example of the influence of faulting on the No. 2 Sand stratigraphic horizon. A scanned version of the original map corresponding to figure 21(a) is presented for comparison as figure 22.

Figure 21 clearly indicates that faulting is the cause of the detailed shape of the modeled sedimentary surface. Furthermore, even though the modeled surface is not literally offset by the faults, the displacement of many of the faults is quite distinct, and the "blurring" of the modeled offset is caused — in part — by the discretization of the modeled surface as a mesh. Interestingly, it is not at all obvious, at least for this surface representing the No. 2 Sand, that the named (numbered) faults are necessarily the faults with the most offset. For example, the most prominent offset in the modeled surface is to the northeast of the dome. Yet reference to the original map of figure 22 confirms that this fault is not one of the named fault traces. Lacking specific identification, it is impossible to trace the faults from one surface to the next without essentially remodeling all of the geology and developing an independent fault-naming convention.

Table 3. Numbered faults mapped at the Bayou Choctaw site

[Horizon abbreviations: PL – Pliocene; A – A sand; 2 – No.2 sand; 4 – No.4 sand; 8 – No.8 sand; 16 – No.16 sand; Het – *Heterostegina* Limestone. NM–not mapped (only within an otherwise continuous sequence)]

Fault ID	Color in figures	Stratigraphic Horizons Intersected							
		PL	A	2	4	8	16	Het	Frio
F-1	dk blue	X	X	X					
F-2	blue	X	X	2	4	8	16	X	X
F-3	cyan	X	X	NM	X	X	X	X	X
F-4	dk green		X	X	X	X	X	X	X
F-5	green		X	X	X				
F-6	yellow green		X	X	X				
F-7	yellow		X	X	X	X			
F-8	orange brown		X	NM	X				
F-9	orange		X	NM	X				
F-10	red			X	X				

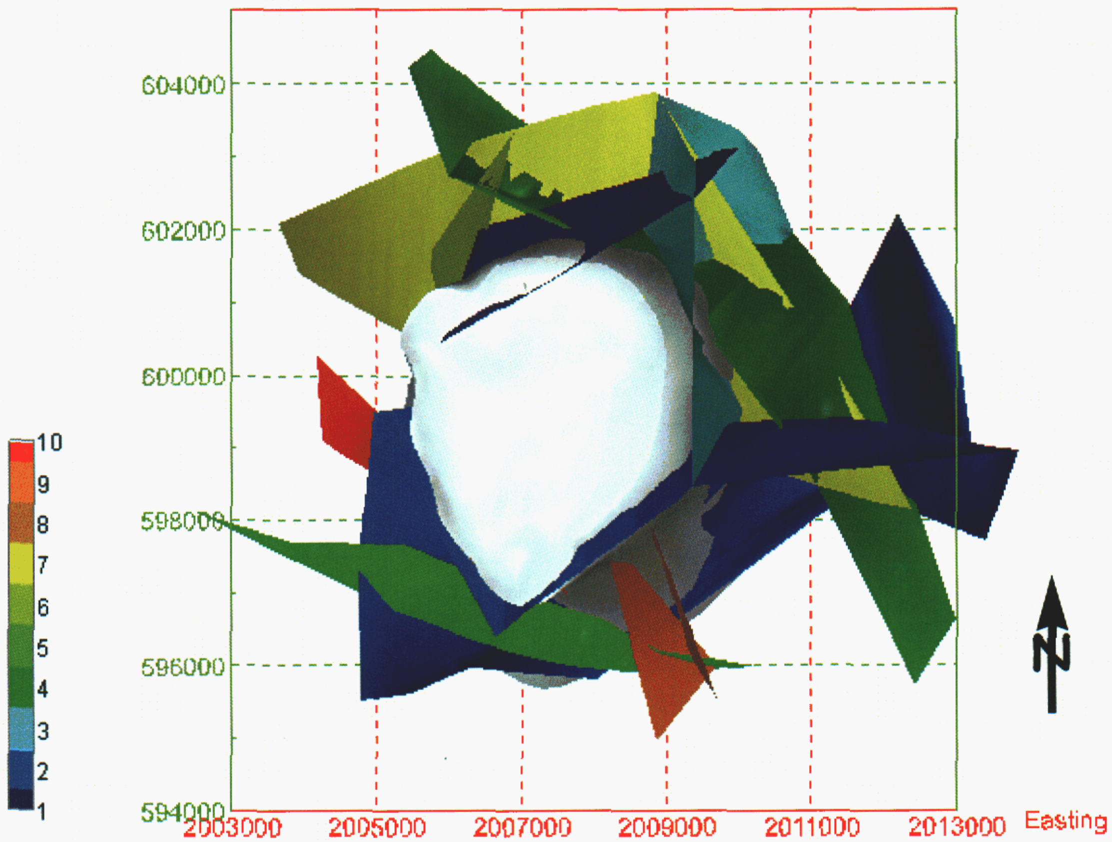

Figure 15. Fault model of the Bayou Choctaw salt dome. Individual numbered faults identified by color bar modeled after Hogan and others (table 3). Top view.

The geometry of most of the mapped faults is fairly straightforward and the modeled surfaces are relatively planar. However, some faults, for example the F-2 fault represented in figure 16, parts (d) through (f), exhibit geometries as mapped in the site characterization report, that are physically impossible. Although we performed no independent evaluation of faulting at the Bayou Choctaw site, our presumption is that correlations that appeared to make sense in two dimensions simply do not stand up in 3-D, and that the original fault interpretations simply mistook one fault for another.

Note that the number of different faults displayed is only a subset of the total number of faults indicated in the original site characterization report. As shown in figure 22, which is a scanned reproduction of the structure contour map on the number 2 sand from that original report, there are a large number of faults that have been mapped in the sediments surrounding the salt dome. Furthermore, as suggested by the distribution of wells used in that characterization study (*not all of which necessarily reach to the depth of the number 2 sand*), the control for many of these faults is somewhat sketchy at best, particularly in the more peripheral regions away from the dome. Additionally, not all of the faults indicate exhibit large offsets, even in regions where the well control is modestly closely spaced. Not all of the mapped faults are numbered in a manner that would allow correlation of the fault intersections across the full number of stratigraphic marker horizons. According, the ten faults converted to numerical form and

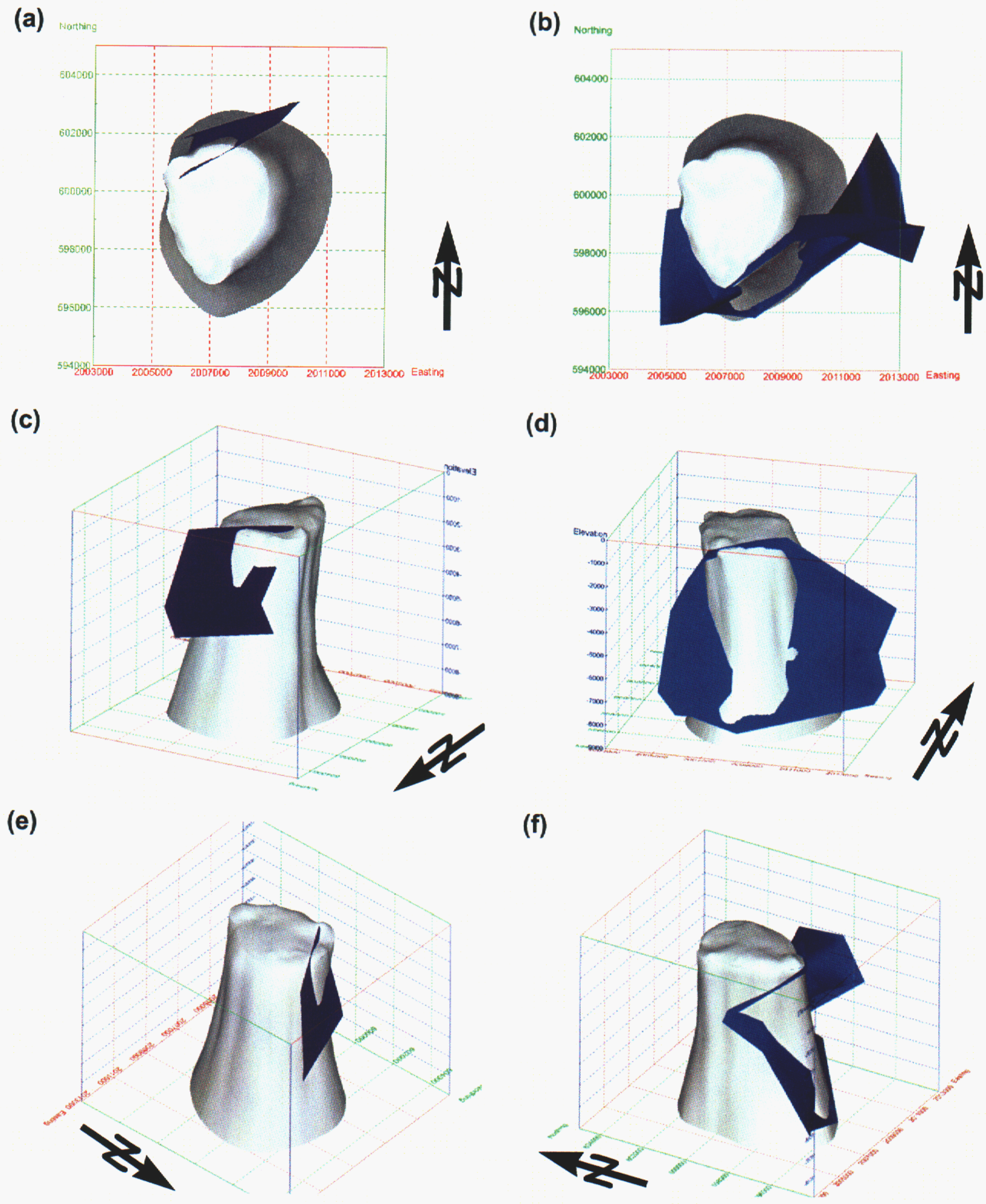

Figure 16. Visualizations of Faults F-1 and F-2. (a) F-1, top view; (b) F-1, view from azimuth 330°, elevation 20°; (c) F-1, view from azimuth 50°, elevation 40°. (d) F-2, top view; (e) F-2, view from azimuth 165°, elevation 20°; (f) F-2, view from azimuth 240°, elevation 20°.

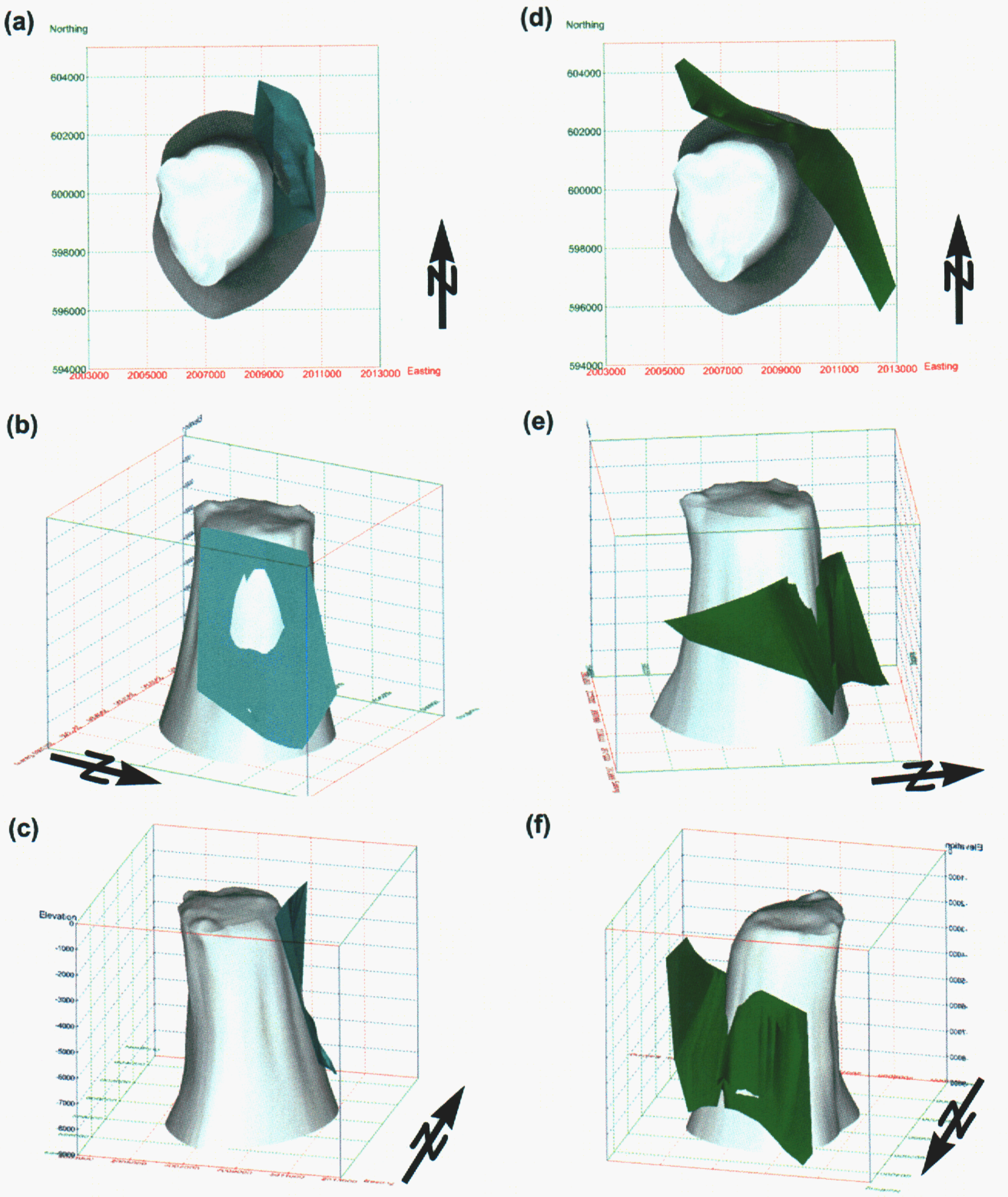

Figure 17. Visualizations of Faults F-3 and F-4. (a) F-3, top view; (b) F-3, view from azimuth 60°, elevation 20°; (c) F-3, view from azimuth 165°, elevation 20°. (d) F-4, top view; (e) F-4, view from azimuth 95°, elevation 30°; (f) F-4, view from azimuth 345°, elevation 20°.

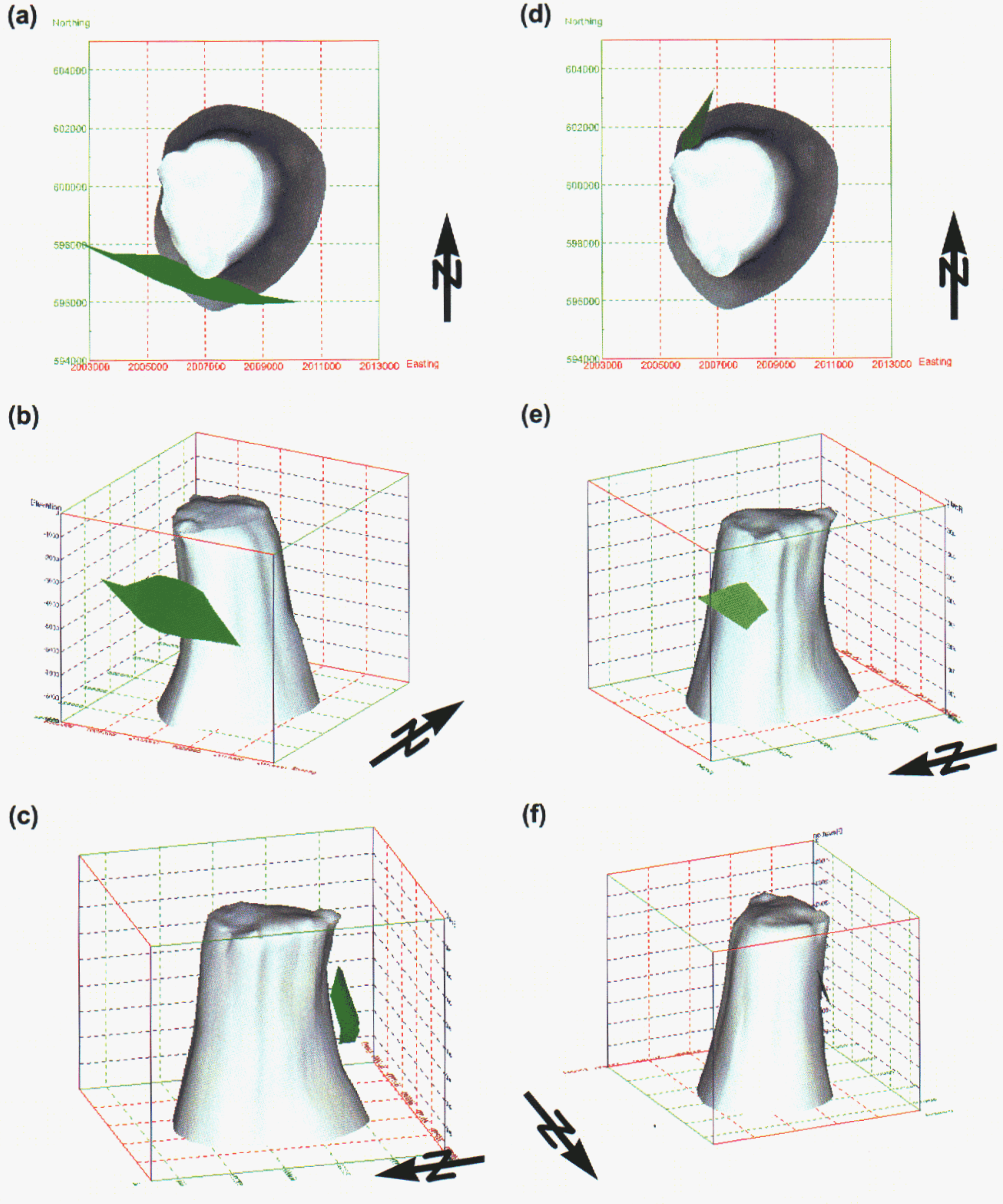

Figure 18. Visualizations of Faults F-5 and F-6. (a) F-5, top view; (b) F-5, view from azimuth 150°, elevation 20°; (c) F-5, view from azimuth 285°, elevation 20°. (d) F-6, top view; (e) F-6, view from azimuth 300°, elevation 20°; (f) F-6, view from azimuth 25°, elevation 20°.

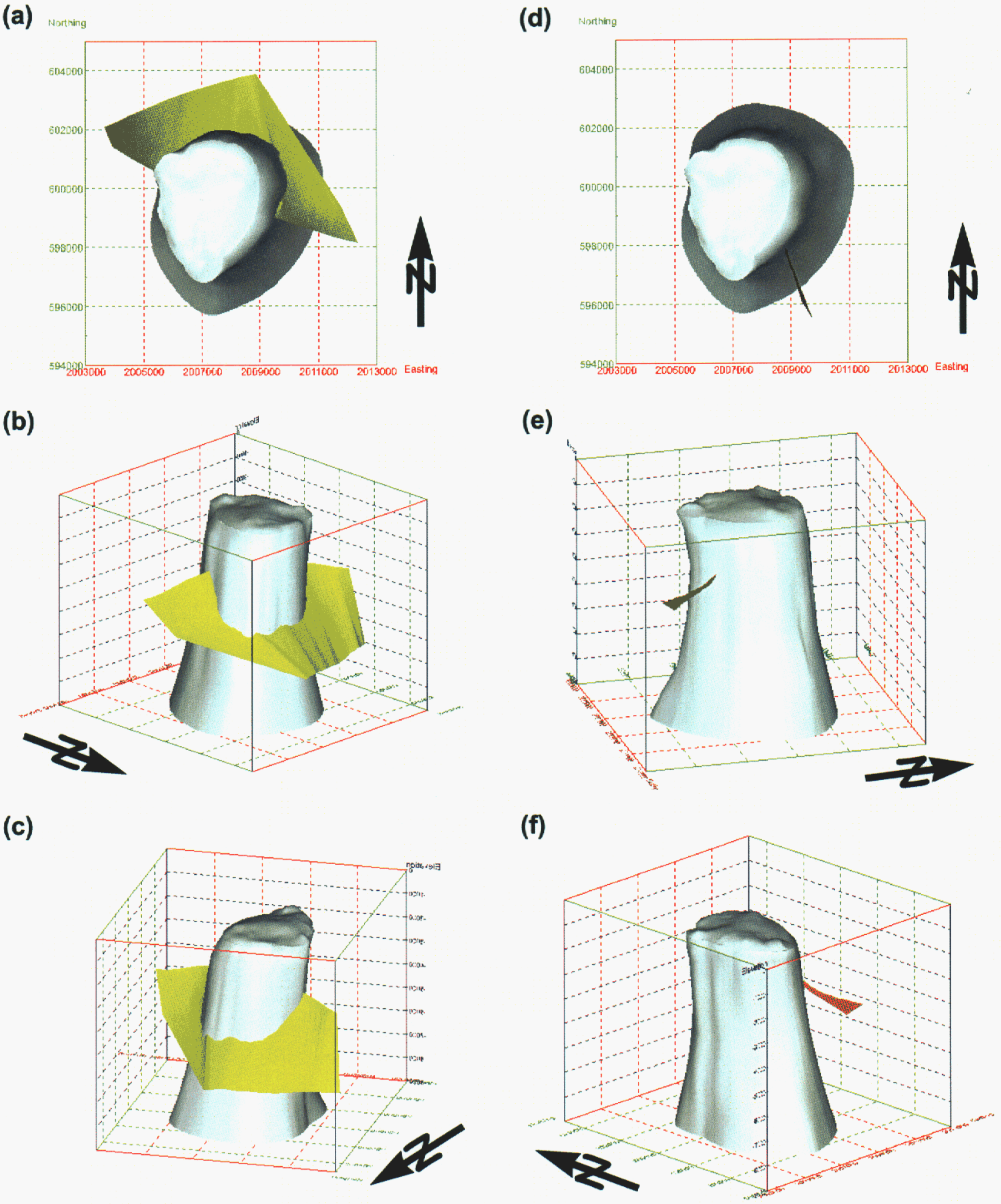

Figure 19. Visualizations of Faults F-7 and F-8. (a) F-7, top view; (b) F-7, view from azimuth 45°, elevation 20°; (c) F-7, view from azimuth 345°, elevation 20°. (d) F-8, top view; (e) F-8, view from azimuth 105°, elevation 20°; (f) F-8, view from azimuth 225°, elevation 20°.

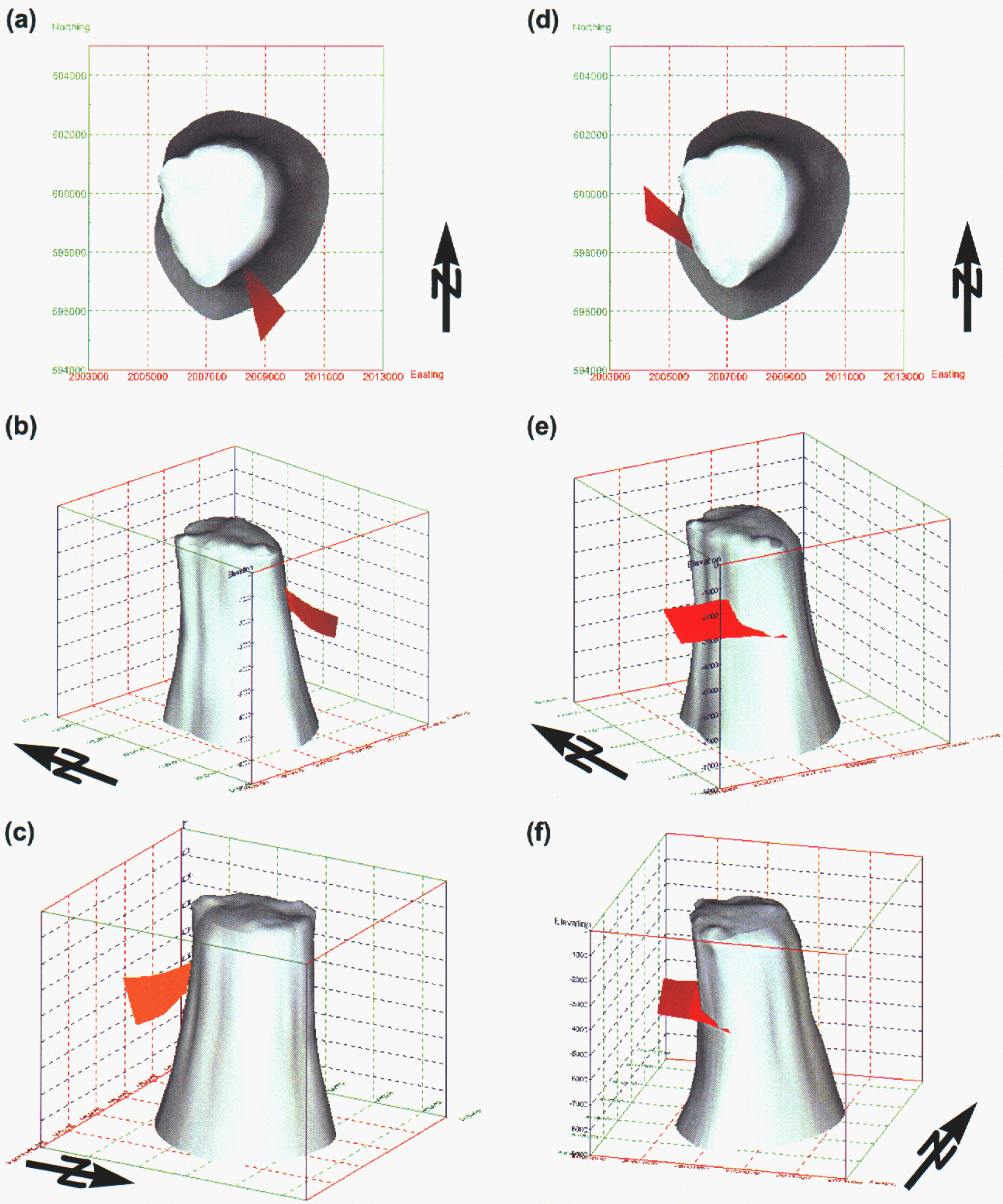

Figure 20. Visualizations of Faults F-9 and F-10. (a) F-9, top view; (b) F-9, view from azimuth 225°, elevation 20°; (c) F-9, view from azimuth 60°, elevation 20°. (d) F-10, top view; (e) F-10, view from azimuth 210°, elevation 20°; (f) F-10, view from azimuth 165°, elevation 20°.

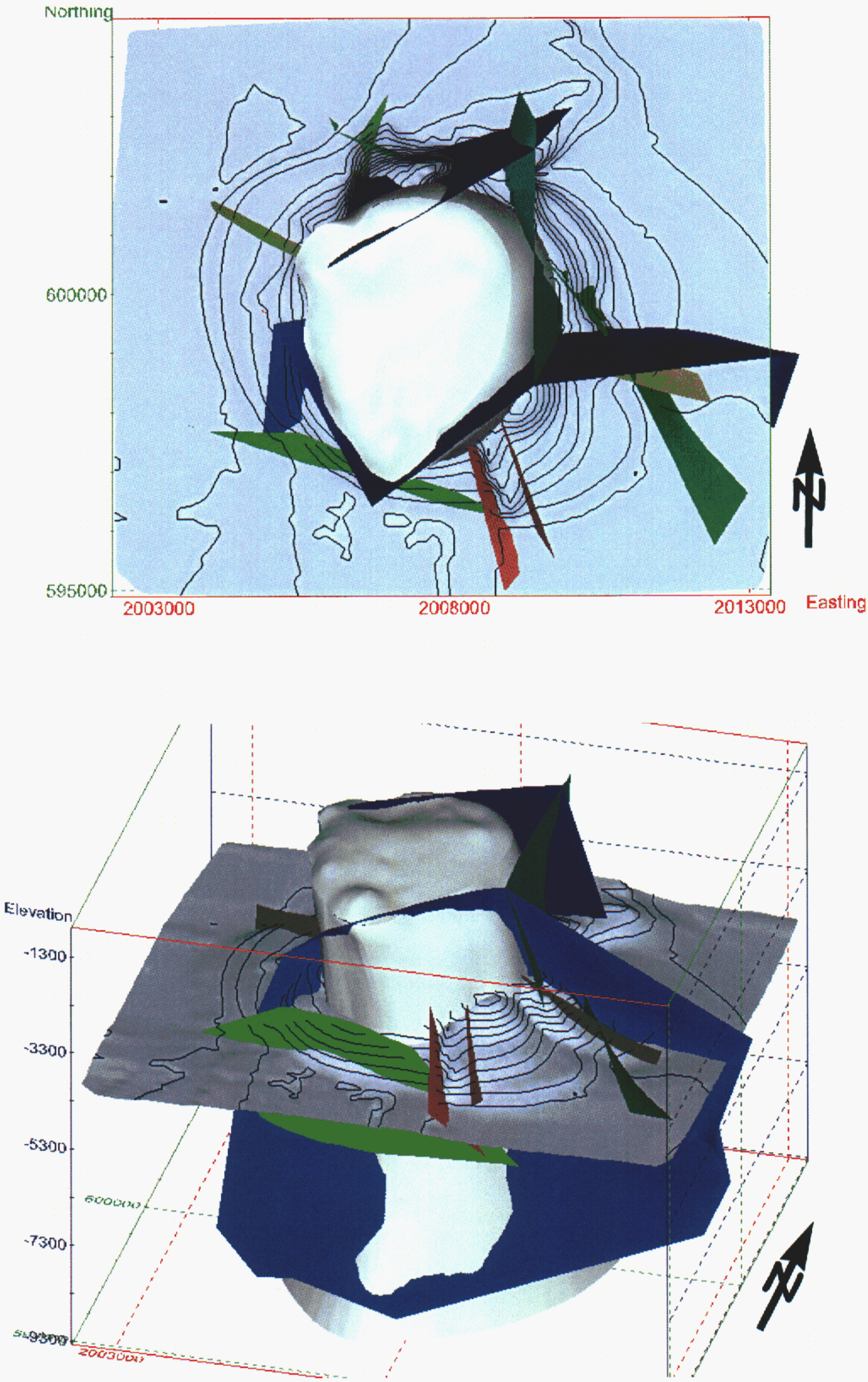

Figure 21. Structure contour map of the modeled No. 2 Sand stratigraphic horizon (grey) showing influence of named faults. (a) View from vertically above; (b) view from azimuth 165°, elevation 30°. Contours approximately 100-ft increments, comparable to those in the original. Compare to figure 22, below.

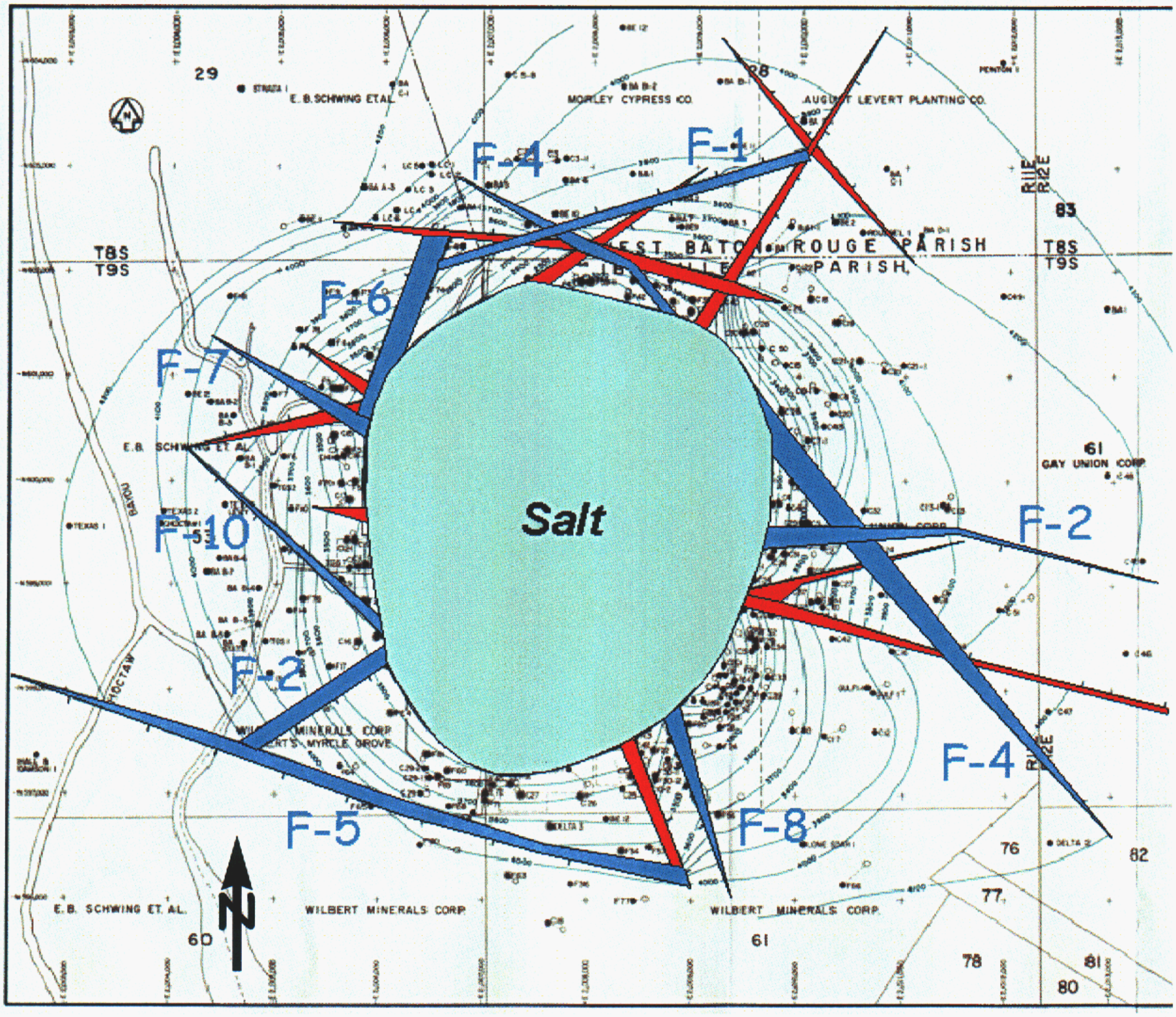

Figure 22. Reproduction of the structure contour map for the Number 2 sand at the Bayou Choctaw site showing the complexity of faulting inferred in the original site characterization report (Hogan and others, 1980a, their fig. 6.14). Named faults (from table 3) shown in blue; unnamed faults shown in orange.

presented in figures 15 through 20 are only a very few of the total number of faults originally identified. The number of unnamed faults appears to increase for the deeper stratigraphic horizons.

Cavern Models

The oil-storage and other caverns that have been leached into the Bayou Choctaw salt dome are only peripherally part of a geological site characterization, except to the extent that either features encountered by the cavern wells or that the external form or operating history of the cavern shed light on the internal structure of the salt mass. However, no model of an SPR site would be complete without some representation and discussion of the cavern field. This is particularly true for the Bayou Choctaw site, as the examination of the preexisting caverns that was presented as part of the two vintages of site characterization reports were strictly two dimensional where only cross sections of the various caverns were portrayed.

A set of visualizations of the *partial* cavern field for the Bayou Choctaw site is presented in figure 23. Recall, however, that the DOE shares ownership of the Bayou Choctaw dome with other cavern operators. Therefore, although we include cavern models for all of the caverns for which we have sonar-survey records (table 2), there are addi-

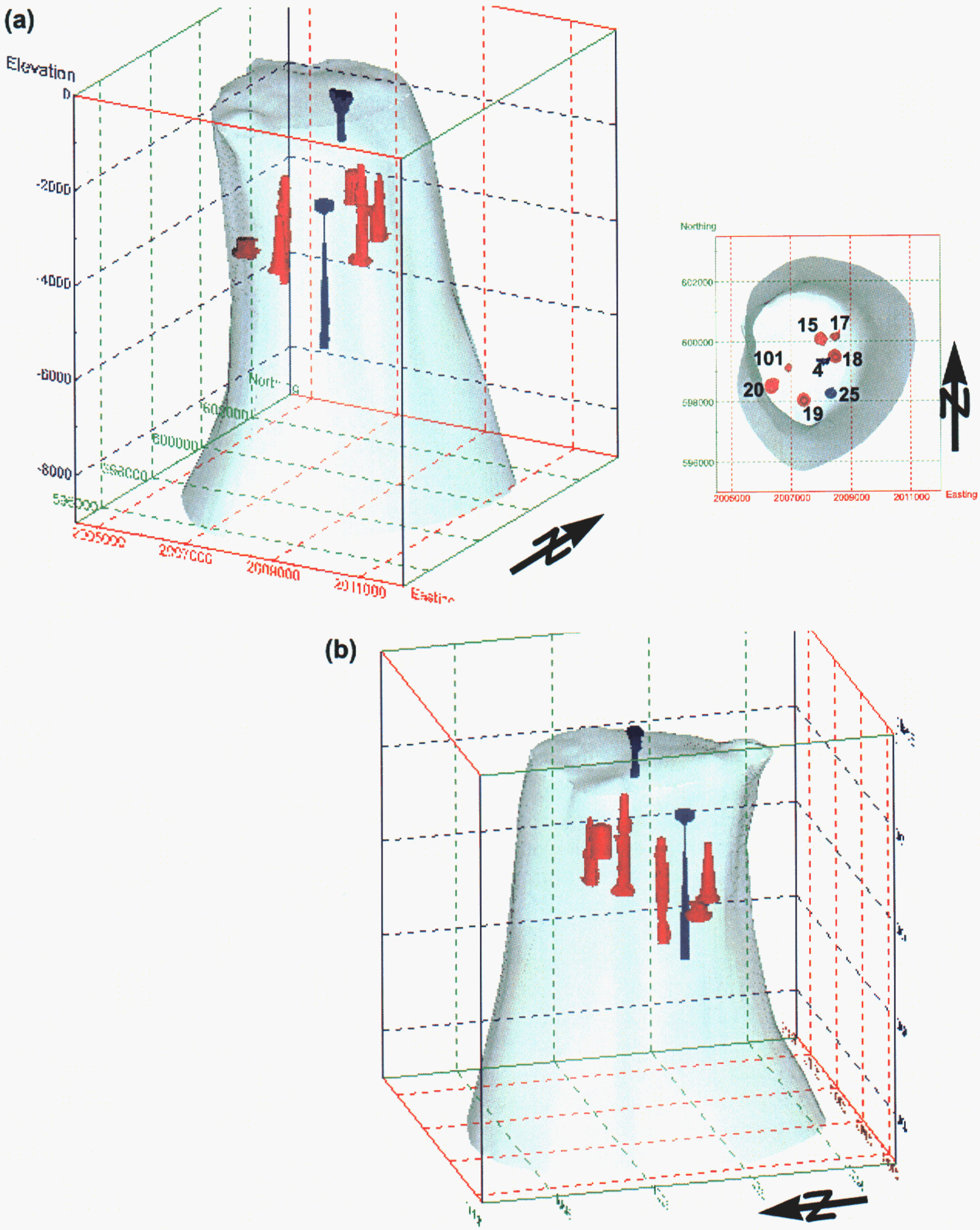

Figure 23. Visualizations of the Bayou Choctaw cavern field within the margins of the salt dome itself (semitransparent grey). (a) View from azimuth 150°, elevation 20°; (b) from azimuth 285°. Inset map is top view. Caverns operated by the SPR Program are shown in red; caverns owned by other operators are in blue. No vertical exaggeration. Note proximity of some caverns to the edge of the salt dome.

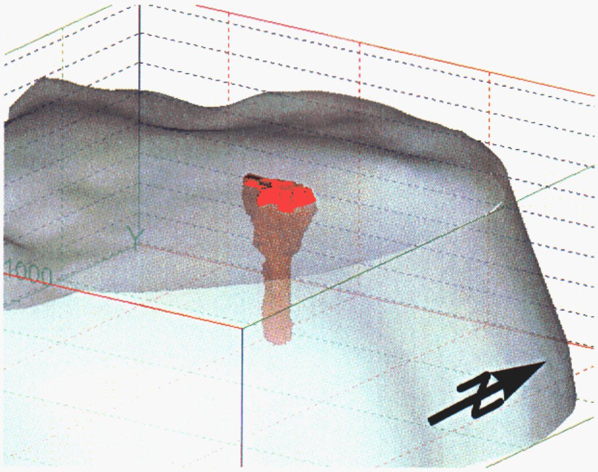

Figure 24. Enlarged view of Cavern 4 (red) protruding through the top-of-salt surface (grey).

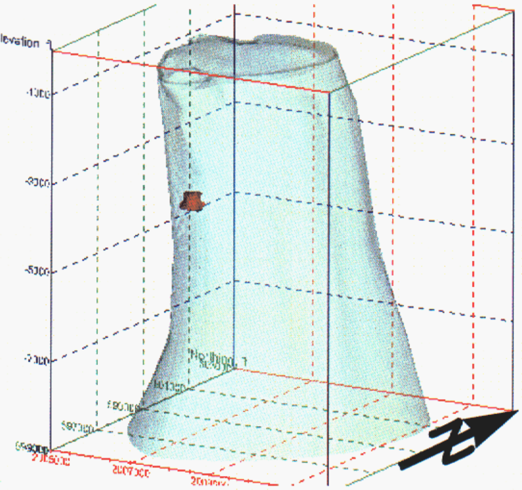

Figure 25. Enlarged view of Cavern 20 (red) adjacent to the edge of salt.

tional caverns present at the site that are not shown in the visualizations. Some of these "missing" caverns are collapsed (e.g., cavern 7; fig. 2), abandoned, or otherwise inactive. Figure 2 (page 13) shows schematic outlines of all the caverns known at the time of the original site characterization studies. It is unknown at this time if any downhole survey data exist for these other leached cavities.

Note that Cavern 4, the small non-SPR cavern located high within the northeastern part of the salt dome, was ultimately leached through the top of salt into the caprock. The best representation of this anomalous and undesirable geometry is in figure 24, which is an enlargement of a portion of figure 23.

Bayou Choctaw Cavern 20 is another cavern at the site that deserves comment. This Phase I cavern is located quite close to the edge of salt on the southwestern flank of the salt dome (fig. 23). A perspective view emphasizing Cavern 20 is presented in figure 25. Although nominal offset of the southwest extent of the cavern to the edge of salt is some 175–200 ft (Rautman, 2003), there is sufficient uncertainty in the precise position of the salt margin that the minimum stand-off distance might be as little as 25 ft. The uncertainty relates to inference of the salt margin from limited well control only. No seismic data were available as part of the original site characterization modeling. Additionally, Hogan and others report a zone of poor-quality salt surrounding this part of the salt mass

Discussion

Discussion of Salt Dome Model

The model of the Bayou Choctaw salt dome itself as illustrated in figures 6–8 appears fairly straightforward and complete, although no evaluation of the underlying data set has been performed as part of this model conversion exercise. The model as shown is based on the original site characterization report structure contour map. The geometry shown in the visualizations matches all published descriptions in general: relatively cylindrical form, substantial salt overhang on the west and southwest sides, and a relatively flat though slightly convex crestal surface.

The main point of contrast of this model with that given in the updated site characterization report concerns the crest of the dome. The original model, used in this conversion, shows an unfaulted top-of-salt surface, although one with a few hundred feet of relief and some complexity in detail on the north-northwest and south-southeast portions. The updated site characterization report presents a structure contour map of the dome crest (fig. 26) that exhibits several faults: two that trend east-northeast and one that trends north-northeast. Interestingly, there is some coincidence between the complex "topography" shown on the model in figure 8 in the southeastern part of the dome and the

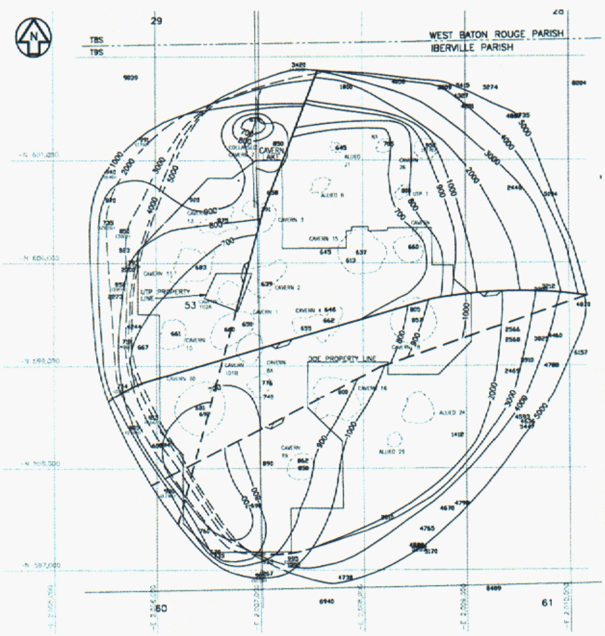

Figure 26. Scanned image of the top-of-salt structure contour map from the updated site characterization report showing complexity induced by inferred faulting.

faulting interpreted in that same part of the dome in the updated-report version.

This revised interpretive model for the top of the Bayou Choctaw salt dome was not converted to a digital model for two reasons. First, as indicated in figure 26, the updated report modeled the dome only to a depth of 5000 ft subsea (vs. 9000 ft in the original version). Second, capturing the inferred faulting shown in figure 26 is quite difficult and beyond the capabilities of the **`ctr2evs`** program (Rautman and Stein, 2003) at its current state of development. This limitation will be addressed in future development of the modeling code.

Discussion of Sediment Model

The model of the enclosing sediments at Bayou Choctaw was presented in figures 9 through 11 in a variety of different views. We infer that the geometry of the various sedimentary horizons selected for mapping in the original site characterization report are a fairly reasonable representation of the expected geometry of sediments in the immediate vicinity of an intrusive salt dome. The horizons are generally upturned adjacent to salt, although there is no particular evidence for a rim syncline, such as is found adjacent to some Gulf Coast salt diapirs. There is some suggestion of increased upturning in the deeper layers, as might be anticipated if the salt dome were rising during on-going deposition, although this potential geometry has not been evaluated in detail. Potential thinning of individual sedimentary packages caused by concurrent rise of the dome during deposition has not been evaluated. There is some suggestion that such thinning is present in the cross sections associated with the original site characterization report.

The greatest weakness with the sediment model, as converted as part of this modeling exercise, is that the various surfaces were reconstructed using only the original structure contour maps. This manner of construction was forced by the difficulty of correlating the numerous stratigraphic picks of unit tops with well-location data that had to be obtained from a separate source. As described previously, this modeling approach essentially uses one interpretive model to construct another. Given that professional judgment was used to construct the original structure contours, it is highly likely that some features implicit in the original data may have been omitted or simplified for the site characterization maps.

A second weakness of the sediment model is the restricted number of stratigraphic horizons that were selected originally for structure-contour mapping. As indicated by table 1, there are a large number of presumably mapable horizons that were not included in the site characterization model, and so could not be included in the current conversion process. Additionally, the horizons selected for mapping are essentially all the tops of sands. Accordingly, there is little concept of the many "shale" units contained within the site characterization model or its numerical conversion. Thus, it is not possible with this model to evaluate the lithology immediately outside the salt margin adjacent to any particular cavern. As some caverns at Bayou Choctaw have been leached quite close to the edge of salt, it might be useful to know if the adjacent lithology were shale or high-permeability sand.

Although the eight selected surfaces capture the essence of the sediments surrounding the salt mass fairly well, this selection of horizons is likely inadequate to deduce the evolutionary history of dome emplacement. Differential movements of salt spines during diapiric rise is thought to be important in cavern stability at some salt domes, and this aspect of the Bayou Choctaw site should be addressed in more detail if a new, full recharacterization is undertaken in the future. Three-dimensional visualization may be particularly useful in helping to identify discordances in the thickness or structural attitude of different sedimentary horizons, something that may indicate salt uplift in one location and not in another during a specific time interval. The use of computer-based technology *to some extent* separates initial construction of model from the later "dissection" and evaluation of that model. In this manner, the ease of recasting different aspects of a numerical model may encourage more intensive evaluation of the implications of small features of the modeled geology.

Another issue or limitation that involves the original site characterization model is that the well control used in the original modeling is restricted to that quite close to the dome itself. Most of the wells shown on the original site characterization report structure contour maps are within approximately one-half mile of the domal margin. Whereas this selection of data was sufficient for initial characterization purposes, development of an emplacement history focused on differential salt movements over time probably would require examination of isopach patterns in sediments to some substantially larger distance away from the region of structural influence of the salt body. The apparent absence of a prototypical rim syncline resulting from withdrawal of salt at depth into the diapir may be caused by the limited lateral extent of the well data used in the original model construction.

The use in the updated site characterization report of biostratigraphic markers instead of horizons comparable to those mapped in the original characterization study makes it impossible to compare the two sediment models directly.

Discussion of Caprock Model

The principal model of the caprock presented in this report as figures 13 and 14 was derived from the elevation difference between the structure model on the top-of-caprock surface and the analogous model drawn on the top of salt. Somewhat as a check on the accuracy of this model, and because the technique had been used previously in modeling for a different SPR site, two other models of the caprock were generated using the isopach thickness map of the caprock presented in the original site characterization report. The resulting model was attached alternately to the top of the caprock or to the top-of-salt structural models in order to position the caprock volume properly in 3-D space. Because the thickness of the caprock is defined as the difference between the top and bottom of caprock lithologies, and because the base of the caprock is equivalent geometrically to the top of salt where the caprock exists, the two modeling approaches should yield identical results.

Figure 27 presents the comparison of the three alternative modeling approaches. Figure 27(a) is a restatement of figure 13, but at the same size and using the same color scale and isopach lines for clarity as for the other two models [figs. 27(b) and (c)]. As indicated by the composite figure, the models of figures 27(b) and 27(c) are virtually identical in appearance. Indeed, these two models should be very similar, as the thickness of the caprock unit is what is being displayed by the colors and the isolines. The basis for both of these models is the digitized caprock isopachs. In marked contrast, the caprock model of figure 27(a) appears similar in general but quite different in detail.

The most pronounced difference involves the southern and southwestern portions of the caprock. In this region, there appears to be a marked buildup of caprock material along the southwestern flank of the salt dome. In contrast to the isopach-based versions that shows a caprock thickness slightly in excess of 200 ft in this location, the difference between the top-of-caprock and top-of-salt surfaces suggests a potential caprock thickness in excess of 450 ft — more than double the isopach-based version. The caprock is also divided into two thicker portions by a north-south-trending thin region in figure 27(a) in the southern half of the dome. A thinning of the caprock in this region is indicated by the isopach-based models in parts (b) and (c) of the illustration, but the division is nowhere near so pronounced. A thicker region on the east side of the dome is also indicated in the model developed as the difference between the two structural horizon, and the thinning of the caprock in the central portion of the dome is also more pronounced.

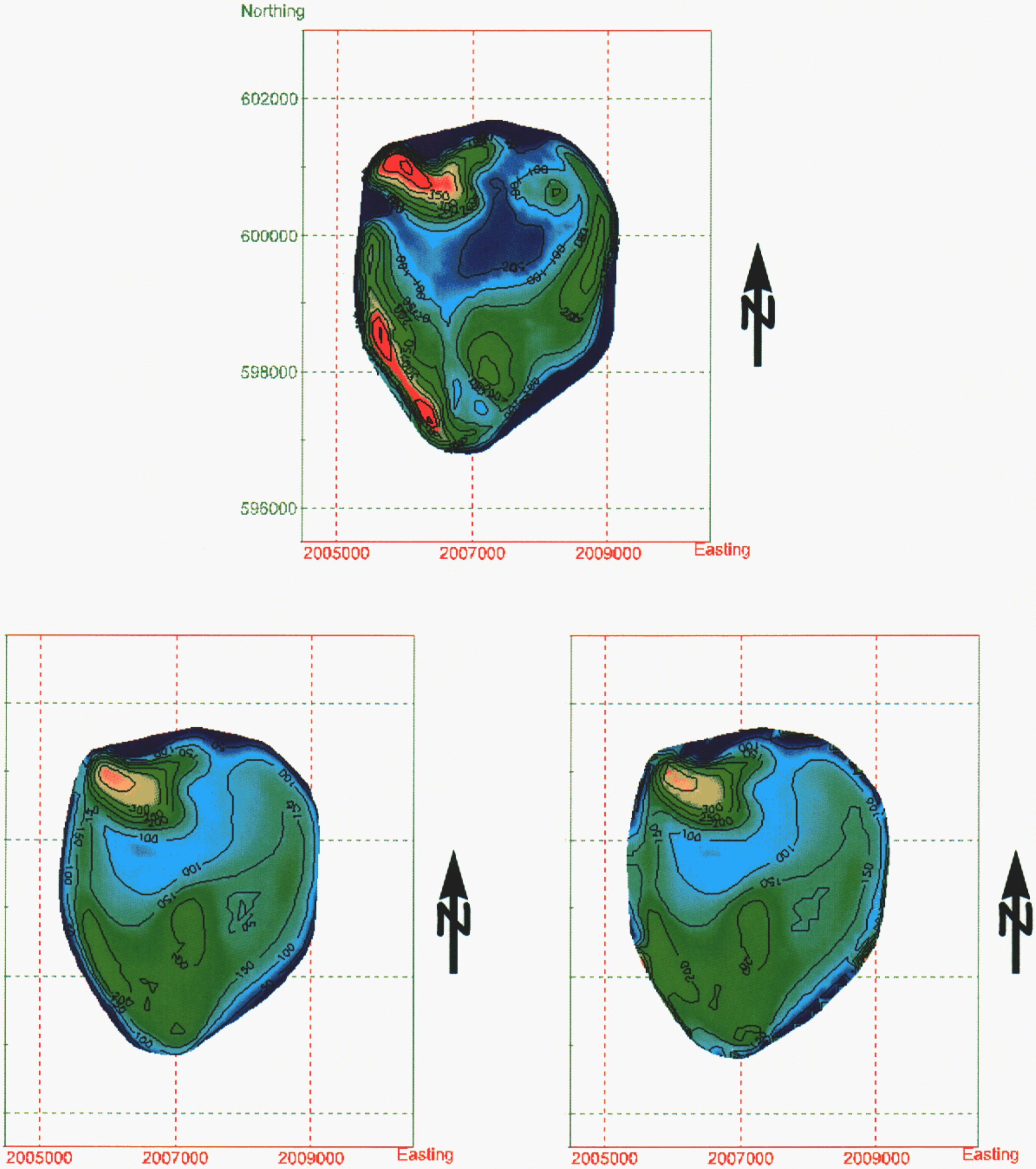

Figure 27. Comparison of three different models of the caprock overlying the Bayou Choctaw salt dome. (a) Generated as the difference between the top-of-caprock and top-of-salt structural models. (b) Generated from the isopach map of caprock thickness and hung below the top-of-caprock structural model. (c) Generated from the isopach map of caprock thickness and stacked on top of the top-of-salt structural model. Contour lines at identical intervals and color scale with the same range.

Discussion of Fault Models

Faulting at the Bayou Choctaw salt dome, as modeled in figures 15 through 20, appears quite complex. This is true even without representation of the many faults that are smaller (?) than the ten numbered faults identified in the original site characterization report. Inclusion of the various subsidiary faults — were it possible to trace these non-coded breaks from one stratigraphic horizon to another — would present a far more complicated model.

Of the numbered and mapped faults, all but fault number F-2 exhibit geometries that are at least reasonable. However, as figure 16 and particularly part (f) of that figure indicate, the geometry of this fault in the western portion of the modeled volume appears geometrically implausible. To exhibit the geometry portrayed, the fault would have to have formed early and to have been folded by later diapir movement (?) to have produced such a marked kink in the fault plane. Although it is highly probable that some faults formed earlier than others, and that some degree of distortion of the original fault geometry has occurred later in the history of the Bayou Choctaw dome, this pronounced bend seems unlikely to be geologically feasible, as there is no indication of equivalent folding of the enclosing sediments [for example, see figure 9(b) for an edge-on view from the west]. The most likely explanation for the geometry of fault F-2 may simply be that the correlation of the fault across the dome is in error, and that there are actually two separate faults that have been combined improperly.

Reference to table 3 suggests that there are additional difficulties with some of the faults that are not immediately apparent geometrically in figures 15 through 20. Specifically, the intersections of faults F-3, F-8, and F-9 with the top of the No.2 sand has not been mapped in the original site characterization report, *even though these faults intersect the over- and underlying horizons* (the table lists these intersections as "not mapped"). Although the omission of these faults (or of their labels) from the relevant structure contour maps in the original site characterization may simply have been a drafting oversight, it is clear that no true fault can "skip" intersecting a horizon where it cuts the horizons both above and below. Mechanically, this issue of omission of a mandatory intersection is a good example of a truly three-dimensional geological modeling software package "insisting" on geometrical consistency among various components. Note, however, that the visualizations of faults 3, 8, and 9 appear geologically reasonable if the omission of the intervening horizon intersection is neglected.

The fault numbered F-7 (fig. 19) stands out as dipping at a much lower angle than the remainder of the named faults. The cause of such a geometry, which is clearly indicated on the structure contour maps and relevant cross sections in the original site characterization report, is not known. As no age ordering of the named faults has been worked out, it is possible that F-7 represents a very early fault that has been cut diapirically during intrusion of the salt mass. However, the indicated planar geometry of the fault makes this explanation appear unlikely.

Discussion of Cavern Models

The cavern models presented in figure 23 are straightforward and easy to construct assuming that downhole sonar data are available. The problem with the cavern model for the Bayou Choctaw site is that data for a modest number of caverns are unavailable (compare fig. 23 with fig. 2). Furthermore, what survey data are available for the non-DOE-owned caverns may be substantially dated and not representative of current subsurface conditions. To the extent that emphasis is on SPR activities only, this quantity of information is sufficient. However, it may not be adequate for all purposes. Information, principally in cross-section format, presented in the two site characterization reports indicates that the caverns other than the ones shown in this model conversion are located at elevations within the salt dome higher than the SPR caverns. Accordingly, those other caverns may be ignored for many purposes. However, a detailed evaluation of surface subsidence at the Bayou Choctaw site might require additional information regarding these high-level caverns, as the continued creep closure of *all* caverns contributes to deformation of the entire salt mass and to subsidence.

If representation of these non-SPR caverns is desired for the sake of completeness — or because it is determined at some future time that they are relevant to some SPR operational problem — it may be possible to generate a simplified 3-D representation using the information contained in the site characterization reports. This information consists of cross sections through the caverns, usually in two profiles at right angles to one another. These profiles could be digitized and the coordinates/radii interpolated from one profile to the next as a function of the angular distance to the desired interpolated radial direction. The result would be an approximation of the true cavern shape as of the date of the relevant survey, but the approximation would be more accurate than simply assuming an average and constant diameter over the known depth of the cavern.

Conclusions

The geologic model implicit in the site characterization report for the Bayou Choctaw SPR site has been converted to a numerical, 3-D representation for visualization and analysis. Conversion of the model as-is was largely successful with minimum external information required for the conversion process. An examination of the model in three dimensions indicates that the model contained in the original site characterization report is geologically reasonable, although there are some definite problems with geometric consistency and feasibility. This is particularly true with respect to the geometries of the mapped faults. No evaluation of the underlying characterization data themselves has been conducted, however.

The representation of the salt dome itself seems quite reasonable, and it appears to capture essentially all of the principal known attributes of this dome. The model of the enclosing sedimentary mass surrounding the salt diapir appears geologically reasonable, given the existing site characterization report and its illustrations of the several geologic horizons that were mapped in that work. The number of sedimentary horizons is limited and these surfaces do not adequately capture lithologic distinctions within the stratigraphic section at Bayou Choctaw. The isopach-based model of the caprock presented in the site characterization report appears to be somewhat inconsistent with the two bounding structure contour maps drawn on the top of caprock and on the top of salt. The cause for this inconsistency is not immediately apparent. A model of the SPR oil-storage caverns and selected non-SPR solution caverns is included, even though this information is from post-site-characterization sources (table 2).

The conversion of the fault model for the Bayou Choctaw site is was accomplished in a relatively straightforward fashion. However, the geometry of some of the faults as represented in the original mapping appears to be geologically unreasonable. That this is the case is not unexpected for a paper model that was constructed solely from well information and without benefit of seismic data. This observation alone would seem to justify the added costs of using three-dimensional visualizations as part of constructing a geological model for a site, in that these newer techniques allow a definitive check on the internal consistency and an evaluation of the geological realism of structures otherwise inferred from only a minimal amount of information.

Three-dimensional models and user-manipulable visualizations of a site such as the Bayou Choctaw SPR facility can be a powerful tool for examining geologic relationships and the data underlying these interpretations. Visual representations of geologic features are intuitive to an extent that conventional geologic representations such as structure contour maps or isopach maps are not. The portrayal of all information regarding a site in a common coordinate system and through the use of rigorous mathematical algorithms enforces a degree of geometric consistency not always achievable in manual modeling practice. Additionally, some spatial relationships are more easily identified by "moving" images than through even a large number of static representations.

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Appendix A: Installation and Use of 4DIM Files

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Introduction

This appendix describes a powerful and relatively novel means for examining a three-dimensional geologic model. The geological modeling software environment collectively known as MVS (*M*ining *V*isualization *S*ystem) developed by C Tech Development Corporation (on the internet at **`www.ctech.com`**) includes a derivative model "type" known as 4DIM files (for *4-D*imensional *I*nteractive *M*odel). 4DIM models are fully three-dimensional representations of selected model components developed through the use of C Tech's modeling software.

The unique aspect of 4DIM models is that they are user manipulable. In contrast to a static still image or screen capture, the user may rotate, pan, and zoom in or out on any part of the model that is desired. The ability to rotate and change the viewing perspective of a three-dimensional model may be critical to understanding and conceptualizing the detailed spatial relationships, in that objects closer to the viewer behave in subtle but importantly different ways than objects located farther away. Such interaction with a model is simply not possible in any static view.

C Tech Development Corporation makes an "unlicensed" 4DIM viewer freely available over the internet. A "licensed" version is also available for purchase. *Unlicensed* in this context means that the player will *not* play all 4DIM files. A specially encoded 4DIM file is required. Only 4DIM models that have been created using the higher-end versions of C Tech software are capable of writing such model files. 4DIM models generated by the lower-cost and more simplistic versions of C Tech's software do not generate these encoded files, and thus a licensed version of the 4DIM player is required to view these files.

Sandia National Laboratories owns MVS, the top-end modeling software produced by C Tech Development Corporation. Accordingly, all 4DIM files generated by Sandia for the SPR using MVS are encoded with the necessary key for use with the unlicensed version of the player.

4DIM Player Software

Installation Instructions

The 4DIM player software currently (2003) runs on personal computers under the Microsoft Windows™ operating system. The unlicensed version of the player may be downloaded over the internet from http:\\www.ctech.com. As the website changes episodically, some internal navigation of the site may be required to locate the downloadable version. A functioning version of the unlicensed 4DIM player is included on the CD-R at the back of this report. *Administrator privileges are required to install the 4DIM player.* However, these privileges are not required for routine running of the software.

To install the 4DIM player, locate the file **`4DIM_setup.exe`**, within the **`install`** subdirectory (folder) of the CD-R. Note that the .exe extension will not necessarily be visible if the Windows file manager option to "**`Hide file extensions for known file types`**" option is checked. Double-click or otherwise open this file. The preferred installation location on a standard PC is in a c:\4DIM directory (at the root level of the boot or system disk). This is the default location, and it may be changed as desired so long as the pop-up caveat regarding installation to a directory whose name contains a space is observed. All defaults may simply be accepted during the installation process.

Operating Instructions

Once properly installed, the file extension **`.4d`** is associated by Windows with 4DIM model files and with the 4DIM player. Therefore, a 4DIM model may be viewed simply by navigating to the storage location of any .4d file and double-clicking on the relevant icon. The 4DIM player may also be started via the Windows Start | Programs menu command structure or by use of a desktop shortcut. In either of these latter instances, it will be necessary to open a particular 4DIM model file using the player's File | Open menu command. The remaining menu buttons operate in a manner consistent with standard Windows programming.

Once a .4d file is opened in the viewer, the visible model may be manipulated as follows:

1. To rotate the model, left-click and drag somewhere on the visible model.
2. To pan (shift) the model on the screen, right-click and drag somewhere on the model.
3. To zoom in, left-click while holding down the Shift key and move the mouse pointer upward on the screen. To zoom out, left-click while holding down the Shift key and move the mouse pointer downward on the screen. Zooming in either direction is toward the center of the screen, so it may be necessary to pan the model (see above) to maintain the desired postion centered on the screen.
4. To specify the view *from* a particular direction, click the Az-El (azimuth & elevation) menu button at the top of the 4DIM player screen. This operation will bring up a separate window that will allow specification of the azimuth from which to view the model, the elevation above (+) or below (–) the horizon from which to view the model, and the scale factor which controls the magnification of the image. Either the radio buttons, the slider bar or the indicated type-in boxes may be used to specify the view.
5. If the view becomes hopelessly confused or the model disappears completely from view, there are two ways to recenter the default view: (a) Use the "RNC" (for "Reset-Normalize-Center") menu button at the top of the 4DIM player screen or (b) click on the multicolored button on the Az-El window.

More than one interactive "model" may be contained in a 4DIM file. If this is the case, the slider bar at the bottom of the main player window will indicate "Current frame [*xx* of *nn*]," where *nn* is the total number of individual model representations within the file. To step through the sequence of a multi-frame 4DIM file, simply click on the arrows at either end of the slider bar or left-click and drag on the slider itself.

Depending upon how a 4DIM file containing multiple model representations was constructed, the successive frames *may* constitute an animated sequence. To view such sequence, use one or more of the eight arrow buttons at the bottom left of the main player window. It will most likely help to increase the "Delay (seconds)" setting on the bottom right of the main window from its default value of 0.00. This sets the time between successive images, and the value may be adjusted as desired to achieve an aesthetically pleasing progression of frames.

An *important setting for 4DIM files generated by Sandia National Laboratories* is the screen background color. The default value is black. However, many sequences contained on the CD-R with this report are predicated on a white background. Certain text and other objects may not be visible unless this setting is changed. To do so, issue the menu command "Settings | View | Background | Set to white."

Description of 4DIM Model Files for the Bayou Choctaw SPR Site

A quasi-narrative description of the various 4DIM files generated for the Bayou Choctaw SPR site geologic model is presented in the sections that follow. The files are somewhat correlated with the various sections of the main body of this report. Approximations of many of the report figures may be generated from these 4DIM files. Experimentation is encouraged, both with the view aspects and with the various settings of the viewer itself.

File BC_4DIM_1.4d

This 4DIM file provides an overview of both the site and the underlying salt dome. The file is intended to be viewed with a white background, but some of the later frames may be quite striking with a black background.

1. Orthorectified image of the Bayou Choctaw site (surface image only).
2. Surface elevations of the Bayou Choctaw site, color coded (surface image only).
3. The above two entities merged together (surface image only).
4. Frame 3 with the salt dome at depth; salt is colored by depth.
5. Identical to frame 4, but the salt dome is opaque white.
6. Opaque white salt dome by itself.
7. Opaque white salt dome with structure contours at selected intervals.
8. Same as above, except with semi-transparent surface elevations and photo.

File BC_4DIM_2.4d

This 4DIM file portrays more of the sedimentary geology of the site, together with the salt dome, shown as an opaque white mass.

1. Salt dome with the several mapped sedimentary horizons.
2. Same as above, but with addition of caprock horizon.
3. Sediments, caprock, plus surface topography and photo.

File BC_4DIM_3.4d

This file is a continuation of file `BC_4DIM_2.4d`, placed in a separate 4DIM file because of the overly large size of files when complex geology is involved.

1. Full (solid) model of the sedimentary units. Not terribly instructive because the entire modeled volume is opaque, but this frame shows the topography and air photo at the surface, and rotating the model to look up from underneath shows the "empty" salt dome.
2. The same model, except that several solid units have been "turned off" so that one may look into the modeled volume Two layers are shown as solid volumes for emphasis that the model is, in fact, a 3-D "solid."

File BC_4DIM_4.4d

This entire file, consisting of nine frames, is a sequence of cross sectional views of the Bayou Choctaw model. The major contacts for all units are shown, including the caprock. The various cross sections are at 20° angular increments roughly centered on the salt mass. Note the upturning of the sedimentary horizons adjacent to the salt diapir. Some of the "faulted" offsets in the mapped horizons show up nicely in this set of views.

File BC_4DIM_5.4d

This file is virtually the same as the previous file, `BC_4DIM4.4d`, except that the cross sections stand on their own. The mapped horizons have been omitted to allow visualization of only the vertical profiles.

File BC_4DIM_6.4d

This 4DIM file focuses on the leached caverns within the salt dome.

1. The caverns within a partially transparent visualization of the salt diapir.
2. Same as above, only the various stratigraphic horizons have been added. This view emphasizes the positioning of the various caverns with respect to the stratigraphic sequence.
3. Identical to frame 2, only the stratigraphic contacts are partially transparent to allow better viewing toward the "inside" of the model.
4. Identical to frame 3, but with the opaque green caprock omitted. Note that BC Cavern 4, the highest-elevation cavern was (presumably inadvertently) leached through the top-of-salt surface into the caprock. Cavern 4 is a non-SPR cavern, and it is now abandoned.

File BC_4DIM_7.4d

This set of visualizations emphasizes the faulting at Bayou Choctaw.

1. This frame shows all 10 mapped faults with respect to the salt dome. Note the complex arrangement and "interpenetration" of the various surfaces; also recall that only a subset of the faults shown on the structure contour maps have been modeled. In the real world, of course, faults do not penetrate one another. Rather, some faults offset other faults. The sequence of fault movements at Bayou Choctaw is not known at present. If the model is rotated to view it upward from underneath, it is apparent that the faults are visible "within" the salt mass. This is a highly unlikely geologic situation, and the existence of the fault planes within the dome itself is a modeling artifact: we did not "cut" the faults with the salt-dome margin in the same manner that was used to generate the sedimentary horizons (which also do not exist within the salt).
2. The ten mapped faults are shown intersecting the various stratigraphic horizons. It is interesting to notice that some of the more major "offsets" of various of the different marker horizons are *not* associated with the ten mapped faults. Reference to the original site

characterization maps shows that these abrupt kinks in the horizons are associated with faulting, but the characterization report did not correlate these particular faults from one horizon to another.

3. This frame is identical to the preceding one, except that the stratigraphic horizons have been made partially transparent, thus allowing the viewer to see into the central portions of the model.

File BC_4DIM_8.4d

This 4DIM file focuses on the caprock, and in particular on the two different methods for modeling that unit. Refer to the discussion beginning on page 42 for a more complete description of the modeling approaches.

1. The first frame in this file `BC_4DIM8.4d` is of the caprock sitting on top of the salt dome.
2. This frame is the caprock model colored by the thickness of the caprock as derived by subtraction of the elevation of the top-of-salt surface from the elevation of the top of caprock. Note the positions of the thickest portions of the caprock (red).
3. Identical to frame 2, but with isopach contours shown.
4. Isopach map similar to the above (with contours), only the thickness model has been generated by digitizing the original isopach map of caprock thickness and "hanging" this thickness model from the top of the caprock.
5. Identical to frame 4, except that the thickness model has been stacked on top of the top-of-salt surface. The thickness isopachs of this frame and the preceding one are virtually identical (as they should be, having been generated from the same underlying map), but their elevation in space is slightly different.

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