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Conversion of the Big Hill Geological Site Characterization Report to a Three-Dimensional Model

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Abstract

The Big Hill salt dome, located in southeastern Texas, is home to one of four underground oil-storage facilities managed by the U. S. Department of Energy Strategic Petroleum Reserve (SPR) Program. Sandia National Laboratories, as the geotechnical advisor to the SPR, conducts site-characterization investigations and other longer-term geotechnical and engineering studies in support of the program. This report describes the conversion of two-dimensional geologic interpretations of the Big Hill site into three-dimensional geologic models. The new models include the geometry of the salt dome, the surrounding sedimentary units, mapped faults, and the 14 oil storage caverns at the site. This work provides a realistic and internally consistent geologic model of the Big Hill site that can be used in support of future work.

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INTRODUCTION

The Big Hill salt dome, located in southeastern Texas (Figure 1), is one of four underground oil-storage facilities run by the U. S. Department of Energy (DOE) Strategic Petroleum Reserve (SPR) Program. Sandia National Laboratories (SNL), as the geotechnical advisor to the DOE SPR Project Office, conducts site-characterization investigations and other longer-term geotechnical and engineering studies in support of the program. This report describes the conversion of two-dimensional (2-D) geologic interpretations to three-dimensional (3-D) geologic models of the Big Hill SPR site. This work provides a more realistic and consistent geologic model of the Big Hill site that can be used in support of future work.

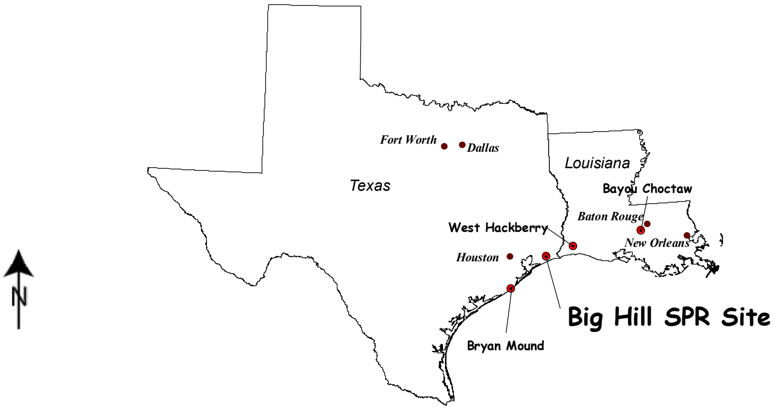

Figure 1. Index map showing the location of the Big Hill SPR facility and other SPR sites.

CONVERSION OF EXISTING REPORTS TO 3-D

Current knowledge of the subsurface geometry and extent of the Big Hill salt dome and its surrounding sedimentary environment is largely based on geologic interpretations of borehole records and logs, some of which were drilled and recorded in the early twentieth century. These data have been compiled and interpreted in published site characterization reports that include structural contour maps, geologic cross-sections, and data tables (Hart and others, 1981; Magorian and Neil, 1988). The interpretations contained in these reports use 2-D representations of the actual 3-D structures at the site. This was standard practice at the time that these reports were written. Today modern geological modeling software is available that allows fully 3-D representations of geologic features to be constructed and visualized. These modern tools have significant advantages over the older 2-D methods of geologic characterization. Many errors and geometric inconsistencies are obscured by 2-D representations of 3-D structures. Strict rules inherent in a true 3-D model will not allow for these inconsistencies. For example, a geologic feature, such as a fault, that is represented in several 2-D “slices” of a geologic model may look geologically reasonable in each slice but when these slices are combined in true 3-D space, the position of the fault no longer seems possible. In such cases the 3-D modeling allows the geologist to visualize the model and judge its validity by examining a virtual 3-D outcrop rather than a 2-D map of the area containing the outcrop. Moreover, features in 3-D models have easily measurable surface areas and volumes allowing the models to be used for quantitative engineering work.

In an effort to maximize the value of the existing geologic site-characterization data at Big Hill without performing a full recharacterization of the site, SNL has converted the numerous 2-D models that are included in the original site characterization report (Hart and others, 1981) to a true 3-D site model. This site model includes the geometry of the salt dome, solution caverns used for oil storage, lithologic tops of mapped sedimentary units that surround the dome, faults, and boreholes. This report presents the methodology and resulting 3-D models of the geology immediately surrounding the Big Hill salt dome.

The 3-D modeling environment used for this work is Mining Visualization System, (MVS) from C Tech Development Corporation (www.ctech.com). This application includes geostatistical algorithms that allow the user to convert a collection of raw data points into a coherent 3-D model. In addition, MVS allows the user advanced visualization and analysis techniques in order to extract useful information from the models.

EXISTING DATA

Site Characterization Reports

The original geologic characterization of the Big Hill site was completed in the late 1970s and documented in a Sandia National Laboratories SAND Report (Hart and others, 1981). This report was compiled before the oil-storage caverns were leached to help DOE decide where to place the 14 planned caverns within the dome. The objectives of that report were as follows:

1. Acquire, evaluate, and interpret existing geologic data surrounding the Big Hill salt dome,
2. Characterize the surface and near surface geology,
3. Characterize the geology of the caprock overlying the salt,
4. Define the geometry of the dome, including cap rock,
5. Determine the feasibility of locating and constructing 14 10-million barrel storage caverns in the south portion of the dome, and
6. Assess the effects of natural hazards on the Big Hill SPR site.

Objectives 1-4 were met by compiling historical drilling records, plotting borehole locations on 2-D maps, contouring depths to the tops of key geologic units, and drawing geologic cross-sections across the site. Borehole locations and depths to the top surface of geologic units were included as data tables in the reports.

A site characterization update report was completed after the 14 oil-storage caverns were leached (Magorian and Neal, 1988). This report included information from boreholes drilled after the original report was completed, including 28 wells drilled in preparation for solution mining of the SPR caverns. The objectives of this report were as follows:

1. Characterize the mineralogy of the salt dome,
2. Characterize the interior structure of the salt dome (i.e. salt spines or zones of differential movement),
3. Characterize the caprock geology, including caprock faulting, and
4. Evaluate future potential for leaching additional caverns.

This characterization update report included new geologic cross-sections and a table of anhydrite-layer correlations between and among the several cavern wells. However, no additional oil and gas wells appear to have been used to update the overall structure of the salt mass, and the structure contour map showing depths to salt is identical to that of the original report (Hart and others, 1981). The surrounding sedimentary layers were also not updated. Magorian and Neal (1988) did identify a major northeast-trending shear zone within the salt mass. This shear zone does not offset any structure contours as mapped in the report. Although Magorian and Neal describe the caprock at Big Hill as “complexly faulted,” their map of the top of caprock is essentially identical to that of Hart and others, and no fault is shown offsetting the mapped contours.

A subsequent, more topical report (Neal and others, 1993) described several “anomalous zones” within the Big Hill and Weeks Island salt domes. Such anomalous zones have properties that differ from pure halite and may be related to diapiric processes of salt dome development. The report aimed to map the distribution of these features within the salt domes because operational problems tend to occur where caverns or wells intersect these zones.

The topical report of Neal and others presented the results of a shallow seismic reflection survey at the Big Hill site. The survey identified numerous faults in the caprock above the Big Hill salt dome and the report contains a structure contour map exhibiting numerous northeast-trending, small-offset faults. However, because a good velocity model was unavailable, the survey failed to image adequately the geometry of the salt dome or the sedimentary units below the caprock.

Downhole sonar surveys have been conducted episodically within the caverns, both during and after the leaching process. These data consist of radial distance measurements to the cavern walls, and allow evaluation of changes in cavern geometry with time.

Well Information

Appendices included with the original site characterization report include well locations and depths to the tops of 15 distinct geologic units around the Big Hill SPR site (table 1). The data in these tables have certain inconsistencies and data gaps some of which can be corrected and others that result in unusable data. The table of well positions includes some wells listing only northing coordinates, some wells without API numbers, and various typographic errors in the coordinates (e.g., easting 200,000 ft apart from rest of wells in table). The table of depths to the tops of geologic formations includes some wells not listed in the well position table, meaning that the locations of these wells are unknown. In addition, sidetrack wells are included in the table but not the depth where the sidetrack begins, making it impossible to accurately use the information in the present model conversion. Despite these data problems in a few instances, the majority of the data are complete.

Structure Contour Maps

Structure contour maps define the geometry of a geologic interface, such as the top of a geologic unit. The locations of fault intersections with that interface may also be represented by breaks and horizontal offsets of one or more contours. Structure contour maps were included in the original Big Hill site characterization report (Hart and others, 1981) for only nine of the geologic surfaces (table 1), corresponding to the tops of major sandy intervals. Figure 2 shows a reproduction of the structure contour map for the C Sand, taken from Hart and others (1981). The wells shown on the structure contour map include *all* the wells at the surface and many of these drill holes do not penetrate to the depth of the C Sand and therefore could not be used in construction of the structure contours. Table 1 lists the number of well points that are documented for each unit. Interpreted locations of fault traces on each stratigraphic horizon are shown on the structure contour maps as hatched polygons.

Table 1. List of geologic units at the Big Hill SPR site (from Hart et al, 1981).

Unit	**SCR Name**	**SCR Symbol**	**Structural Contour Map?**	**Number of points**
Caprock		Top Cap	Yes	47
Anhydrite			Yes	
Salt		Top Salt and Base Salt	Yes	71
Lafayatte Gravel		L	No	39
Pliocene Sand		PL	No	40
Miocene Sand	A Sand	A	Yes	39
Lagarto Clay		BF	No	39
Oakville Sand	B Sand	B	Yes	42
Amphistegina B Shale		AB	No	53
Catahoula Sand	C Sand	C	Yes	59
Robulus L Shale		RL	No	63
Main Sand	D Sand	D	Yes	65
Siphonina davisi Shale		SD	No	61

Lower Sand	E Sand	E	Yes	62
Discorbis restricted Shale	Anahuac Shale	DR	Yes	45

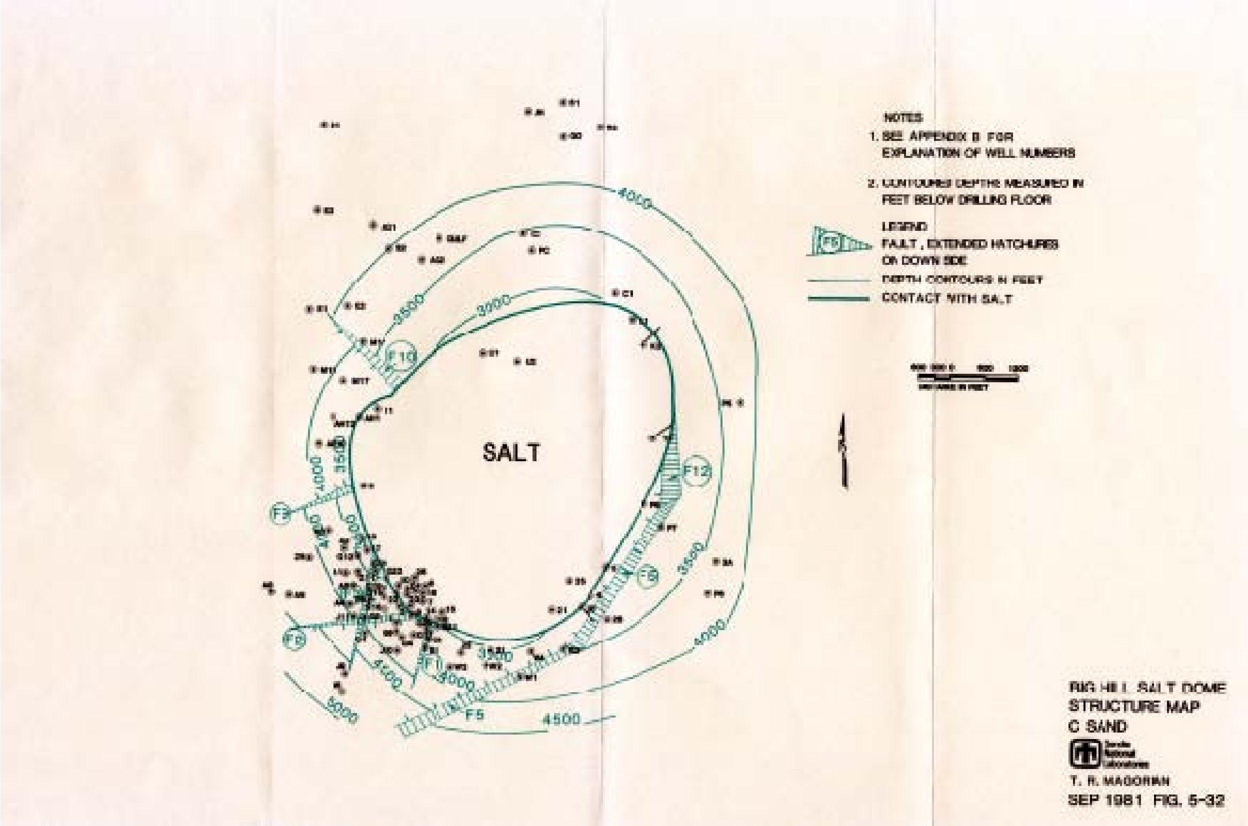

Figure 2. Structure contour map for the C Sand at the Big Hill SPR site (from Hart et al., 1981). The thick inner line shows the interface between the C Sand and the salt dome. Thinner green contours show the depth to the top of the C Sand. Hatched polygons represent fault traces that intersect the C Sand.

Geologic Cross Sections

Various geologic cross sections were also included in the site characterization reports. These cross sections were constructed by projecting well data to cross-section lines and plotting the depths of geologic units with distance along the lines of cross section.

Geologic Units Identified at Big Hill

Table 1 lists the geologic units in the vicinity and depth interval of the Big Hill SPR site that were included in the original site characterization report (Hart and others, 1981). As is typical of this interval in the Texas Gulf coast, the section is dominated by sands and shales. In certain instances, key units were identified in the site characterization report with site-specific names. These names are listed in table 1 in the column labeled “SCR Name” to denote that they come from the site characterization report and may not be used elsewhere. Abbreviated symbols used to represent the various geologic units in the site characterization report tables are also listed in table 1 and labeled as “SCR Symbol.”

The site characterization report of Hart and others (1981) included two representative geophysical logs from the Big Hill area, indicating the geophysical and lithologic character of the sedimentary section, together with the unit identifications of table 1. Examination of these “type” logs indicates that the actual geology, involving interbedding of sandy and shaly units, is significantly more complex than the 15 units identified in the table. Figure 3 presents a portion of one of these “type” logs for the Jayred Fitzhugh #9 well. This log shows the "B Sand," "AB Shale," and "C Sand" units. It is clear from the SP log that both the “B Sand” and the “AB Shale” are composed of a complex set of interlayered sands and shales. The designation of sand and shale in this region has less to do with the geology and more to do with whether a unit produces oil.

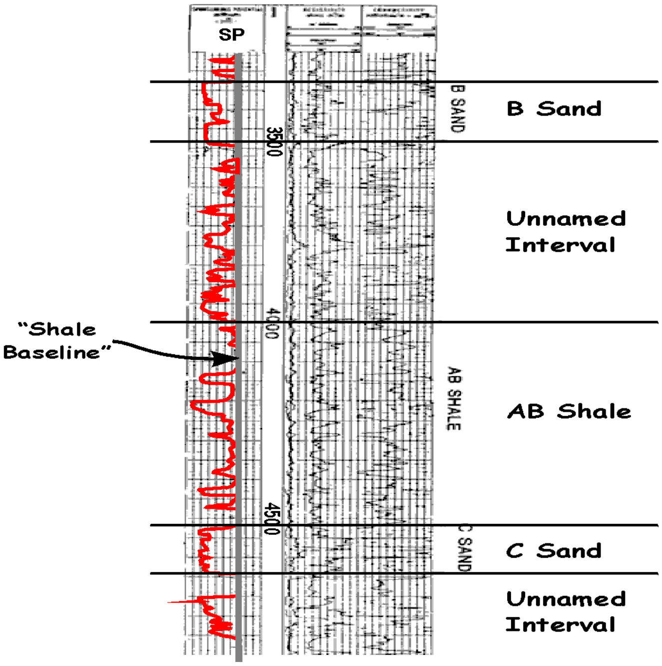

Figure 3. Geophysical well log (SP, resistivity, and conductivity traces) for a portion of the Jayred Fitzhugh No. 9 well at the Big Hill site, located in the extreme southwest corner of the area mapped for the site characterization report (Hart and others, 1981). SP log trace emphasizes the distinction between sands and shales within named intervals and also the existence of unnamed intervals within the overall stratigraphic section.

Cavern Sonar Surveys

The geometric configurations of the underground storage caverns leached into the salt mass are recorded at various stages during leaching and at episodic intervals during ongoing cavern operation 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, and which contains a transmitter and a primary receiver, and a secondary receiver that allows determination of the velocity of the medium immediately surrounding the tool (either 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.

The data for sonar surveys are not included in the site characterization reports for the Big Hill SPR site. This is particularly true for the original site characterization compilation (Hart and others, 1981), as the caverns were leached following this initial characterization. The updated site characterization report of Magorian and Neal (1988) presents only stylized cavern profiles of nominal diameter and height.

CONVERSION METHODOLOGY

In this section of the report we describe the methods used to convert the existing site characterization report model into a fully 3-D geologic model of the Big Hill SPR site. The complete 3-D model consists of a collection of components which each required a distinct conversion methodology. These methodologies are described below.

A Note on Coordinate Systems

Computerized geologic modeling mandates the use of a standardized coordinate system. In contrast, manual “spotting” of well locations and mapping on physical paper is much less demanding in this regard, as locations are typically placed relative to land-survey section lines or 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 from the Texas Gulf Coast have been recorded in state plane coordinates, which for this part of the state of Texas is the south-central zone of that system. The Texas state plane coordinate system is a Lambert conformal conic projection, almost invariably using the North American Datum of 1927 (NAD-27). A few more recent 7.5-minute topographic maps published by the U.S. Geological Survey in this region use a state-plane system based on NAD-83, the North American Datum of 1983. However, virtually all historical geographic information uses the NAD-27 system.

The site characterization reports for the Big Hill site do not state explicitly what coordinate system was used. However, the absolute magnitudes of the coordinates shown by marginal ticks on maps and figures correspond approximately to NAD-27. Because the magnitudes of roughly similar positions in other systems are markedly different (by design), we have assumed that the existing coordinates belong to the Texas state plane coordinate system, south-central zone, NAD-27.

Generation of Salt Dome Model

The method used to convert the model of the Big Hill salt dome margin is documented in a separate report (Rautman and Stein, 2003). The method involves digitizing in calibrated *x*- and *y*- state-plane-coordinate space the various structure contours drawn on the top of salt and contained in the report by Hart and others (1981), assigning each such discretized contour its relevant elevation (depth) as the *z*-coordinate value, and then connecting corresponding 3-D points on successively deeper contour "rings" to form a 3-D mesh. The geologic modeling software uses finite-element type meshes as the basis for visualization of all contained features. Thus, the model implied by the 2-D structure contour map is visualized directly by the software in full three dimensions.

Generation of Sediment Model

To convert raw spatial data into a 3-D model a method is needed that provides an estimate of the positions and depths of geologic interfaces in areas where no data exist. Kriging is a least-squares linear regression technique used to estimate values at locations where data does not exist (e.g., Deutsch and Journel, 1998). Typically, the values are estimated on a quasi-regular grid or mesh. A kriged value is computed as a weighted average of the values at points surrounding the point of interest. The weights are determined from both the distance to each surrounding data point and a model that describes how variable the values are in space (the semivariogram). The MVS geologic modeling application has built-in functionality that creates the semivariogram model and performs the kriging all in one step.

To convert the sediment models to 3-D we had two choices: (1) krige the raw data included in the site characterization report to produce a 3-D model, or (2) digitize the existing structure contour maps and krige those digitized points to produce a 3-D model. We chose the first approach to convert the sediment models surrounding the salt dome and the second approach to convert the caprock model.

We chose the first approach for the sediments because the second method presented several problems. First, only some of the sedimentary units had structure contour maps defining their geometry. Data tables in the back of the original site characterization report included data for all the identified units. Second, the contour intervals on the structure contour maps are 500 ft apart vertically. While this contour interval gives a general idea of the geology, it can obscure real features that are evident from the actual data. Third, a certain amount of information is lost in the process of the modeling itself. Digitizing and kriging one model (the structure contour maps) to produce a second model (the 3-D model) may increase errors and can introduce inconsistencies. For these reasons we converted the raw data published at the end of the site characterization report into the 3-D sediment model.

We used the kriging functionality of MVS to convert the geologic data (depths to the top of geologic units) from the reports to 3-D surface and volume meshes. Figure 4 shows the process of defining the top surface of the C Sand. The *Krig3D_Geology* module of the MVS modeling software performs the 3-D kriging for all units sequentially but in one continuous computational pass.

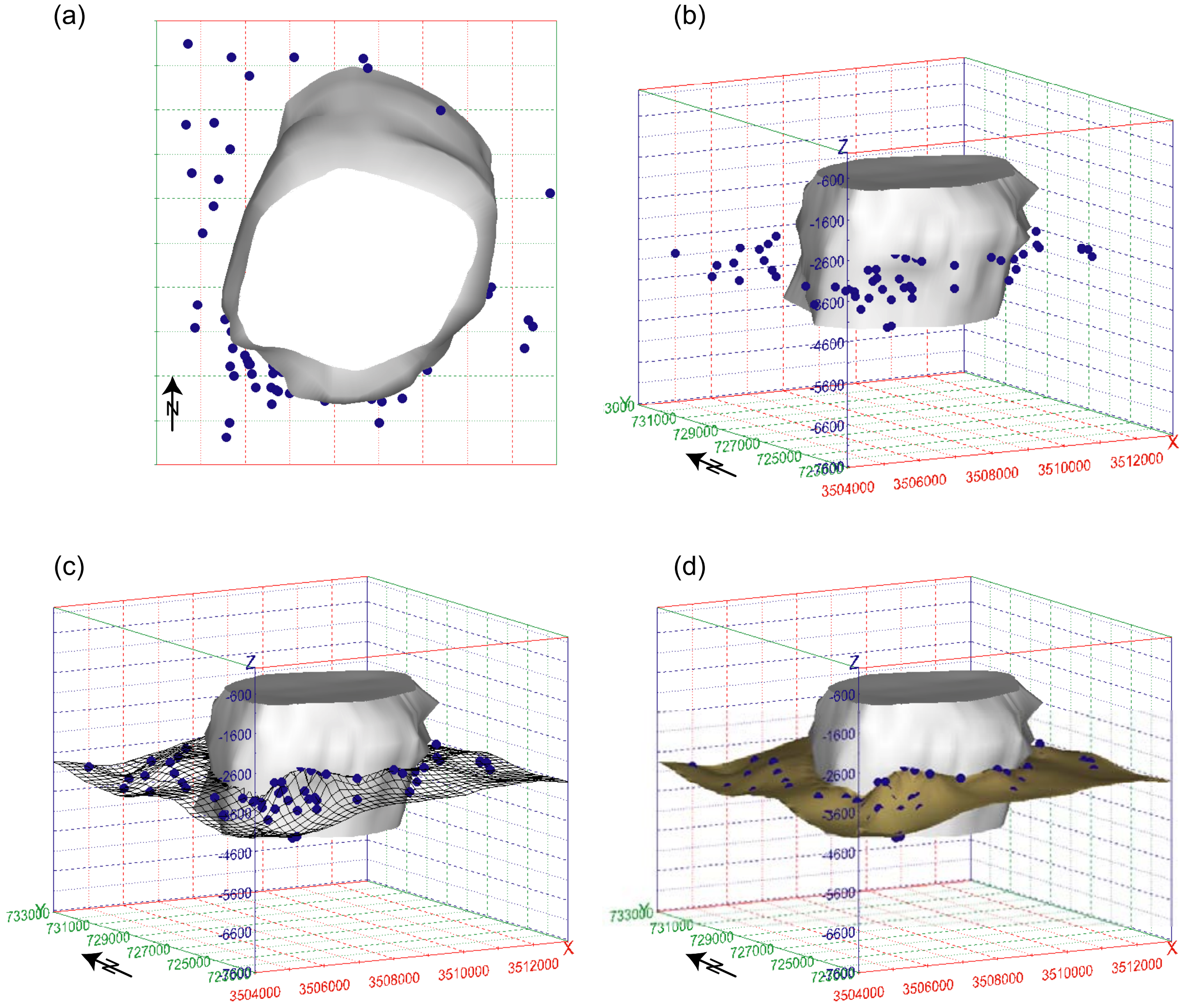

Figure 4. Three-dimensional views of the Big Hill salt dome model showing the steps used to model the top of the C Sand. (a). Top view showing locations of control points on the top of the C Sand. (b). Perspective view of the same control points from the SW. (c). A surface grid is constructed by kriging the points. (d). The final visualization model of the top of the C Sand is shown with the original points. No vertical exaggeration. [BH_FIG_4.4D]

Generation of Fault Models

Faults that intersect the sedimentary units were identified in the site characterization report and shown on the structure contour maps. To include these faults in the 3-D model we followed a series of steps:

1. Fault traces from each structure contour map in the site characterization report were digitized in calibrated state-plane-coordinate space.
2. Ten equally spaced (*x*, *y*) points along each trace were compiled.

3. The elevation (*z*-coordinate) of each point along the fault trace was interpolated from the kriged sediment model using the MVS module: *geologic_surfmap*.
4. All remaining (*x, y, z*) points for each fault were connected by a triangulated irregular network (TIN) mesh defined using the MVS module: *scat_to_tin*.

The fault traces were digitized from the structure contour maps (Hart and others, 1981) using the application Didger 3 from Golden Software (www.goldensoftware.com). Each structure contour map was scanned to produce a bitmap image (e.g., figure 2). Bitmap images were imported into Didger and were spatially calibrated, a procedure that links each pixel of the bitmap to a real world coordinate based on a set of reference locations which are assumed to be known in both the bitmap and world coordinate systems. The calibration process introduces some errors due to map projection and human errors in selecting the reference points used in the calibration. Didger reports a RMS calibration error for each calibrated bitmap. This error is the standard deviation between the reference positions and the map projection and represents the distance over which the position of a point on the bitmap is known within one standard deviation.

Following calibration, each fault trace was digitized and divided into ten equally spaced (*x*,*y*) points. These two-dimensional points were then projected onto the modeled three-dimensional geologic surface (using MVS module: *geologic_surfmap*), resulting in ten (*x*,*y*,*z*) points, where *z* is the elevation of the fault trace *on the geologic surface*. The process was repeated for each of the geologic surfaces intersected by the fault. Finally the complete fault surface was generated by connecting the (*x*,*y*,*z*) points from the several stratigraphic surfaces intersected by the fault into a triangulated irregular network using the MVS module: *scat to tin*.

Figure 5 shows the sequence of steps used to construct the *F10* fault model on the western flank of the dome. The process described above and illustrated in figure 5 was repeated for each fault identified on the structure contour maps.

It should be noted that the process described above does *not* produce actual offset of the modeled sedimentary surface. This is a distinct limitation of this particular modeling approach. However, this limitation was judged acceptable for several reasons. (1) The faults in question have relatively minimal displacement at the scale of the overall salt dome. (2) There are a very small number of well-control points available from which to infer the location of the fault and the displacement along it. (3) This model conversion effort is intended principally to produce visualizations to aid in the conceptual understanding of the Big Hill site. The effort is not a remodeling of the site geology. Overall, the distortions induced by this simplistic modeling approach are minimal.

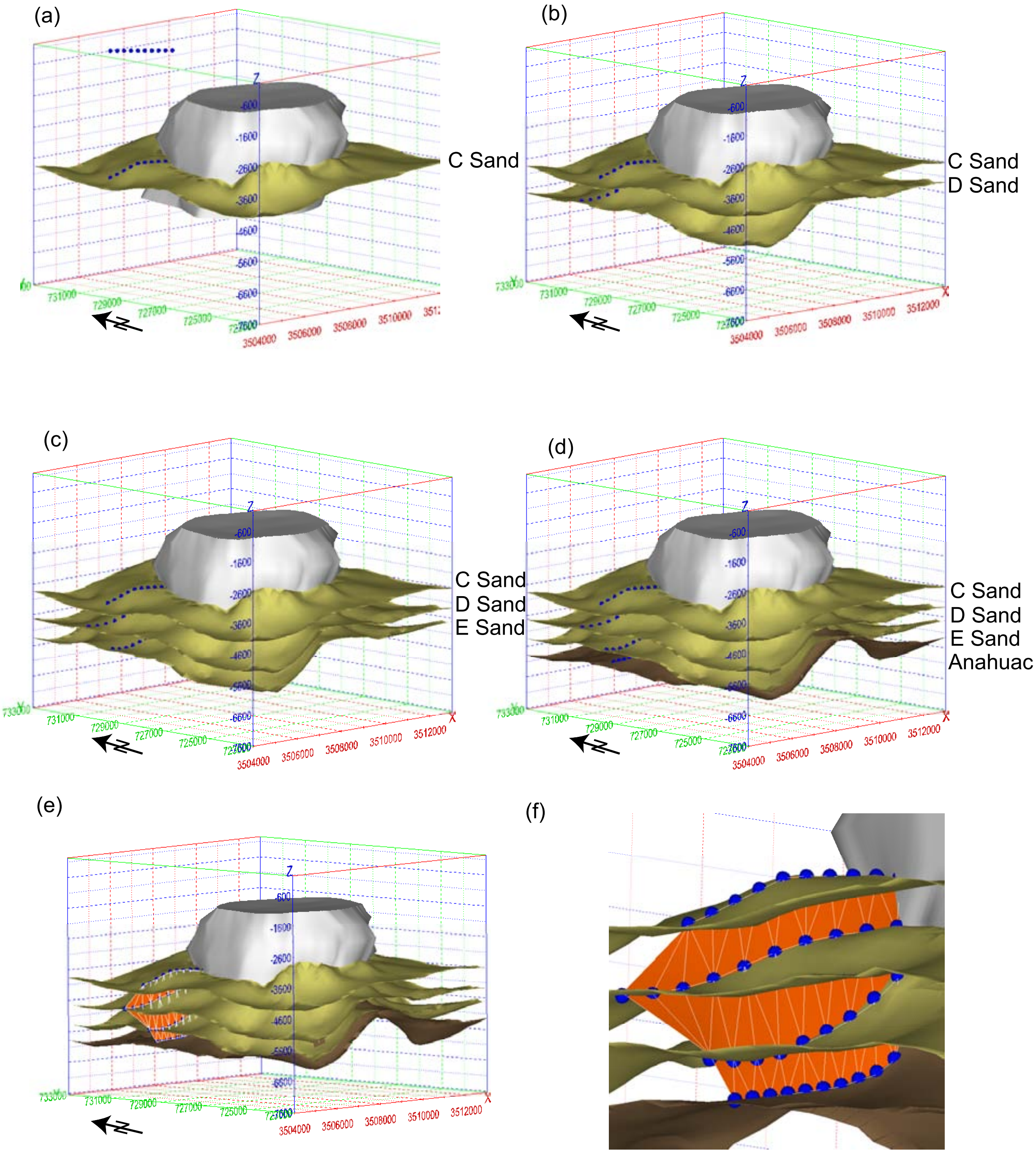

Figure 5. Steps used to construct a 3-D fault model of the *F10* fault. (a) Ten equally spaced (x,y) points along the fault trace (upper points) are transformed in elevation so they lie on the top of the modeled C Sand (lower points). (b) Points are added from the D Sand trace, (c) the E Sand, and (d) the Anahuac Shale. (e) The resulting *F10* fault surface model is shown. (f) The view is magnified. No vertical exaggeration. [BH_FIG_5.4D]

Generation of the Cavern Models

A sonar survey was converted to a 3-D model by computing the coordinates of the reflecting surfaces from the downhole measurements using simple trigonometry. The raw output from a typical downhole sonar survey consists of a set of radial distance measurements plus the depth and 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 relative to north.

Because the depth, rotation, and inclination sequence is known, it is a relatively simple matter to connect the coordinates where the focused sonar beam reflects 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 is 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 surveys was conducted as though the sonar beam was essentially a line and that the reflecting surface was oriented normal to the direction of travel of the sonar pulse. Although this was a necessary and probably geologically reasonable assumption for many caverns and at most depths, it need not apply rigorously in all circumstances.

RESULTS

The 3-D geologic model of the Big Hill SPR site has been constructed according to the methods described in preceding sections of this report. A 3-D geologic model is best illustrated using modern visualization tools that allow the viewer to “interact” with the model and examine it from different angles and at different levels of magnification. MVS has a free viewer (4-DIM [*4-D*imensional *I*nteractive *M*odel] viewer) that allows one to rotate and view the 3-D models from a variety of angles and at different magnifications. A set of .4D files are included on a CD that is part of this report. Appendix A describes how to install the viewer software and Appendix B lists the 4-DIM files and frames included on the CD.

A less ideal way to view these models is by examining still images. We include a set of these images in the sections that follow. Each still image has an associated 4-D file/frame that is noted in the figure captions.

Salt Dome Model

The geometry of the Big Hill salt dome model is presented from above in figure 6 and in perspective from the southwest in figure 7. The dome is generally cylindrical in shape and is inclined toward the south. The top of the dome is relatively flat and lies at a depth between 1300 and 1800 feet below the surface. A pronounced overhang is present on the southern flank of the dome and this overhang extends to the bottom of the model. The dome model as represented by Hart and others (1981) is modeled only to a depth of 5000 feet below the surface; the actual dome unquestionably extends to far greater depths.

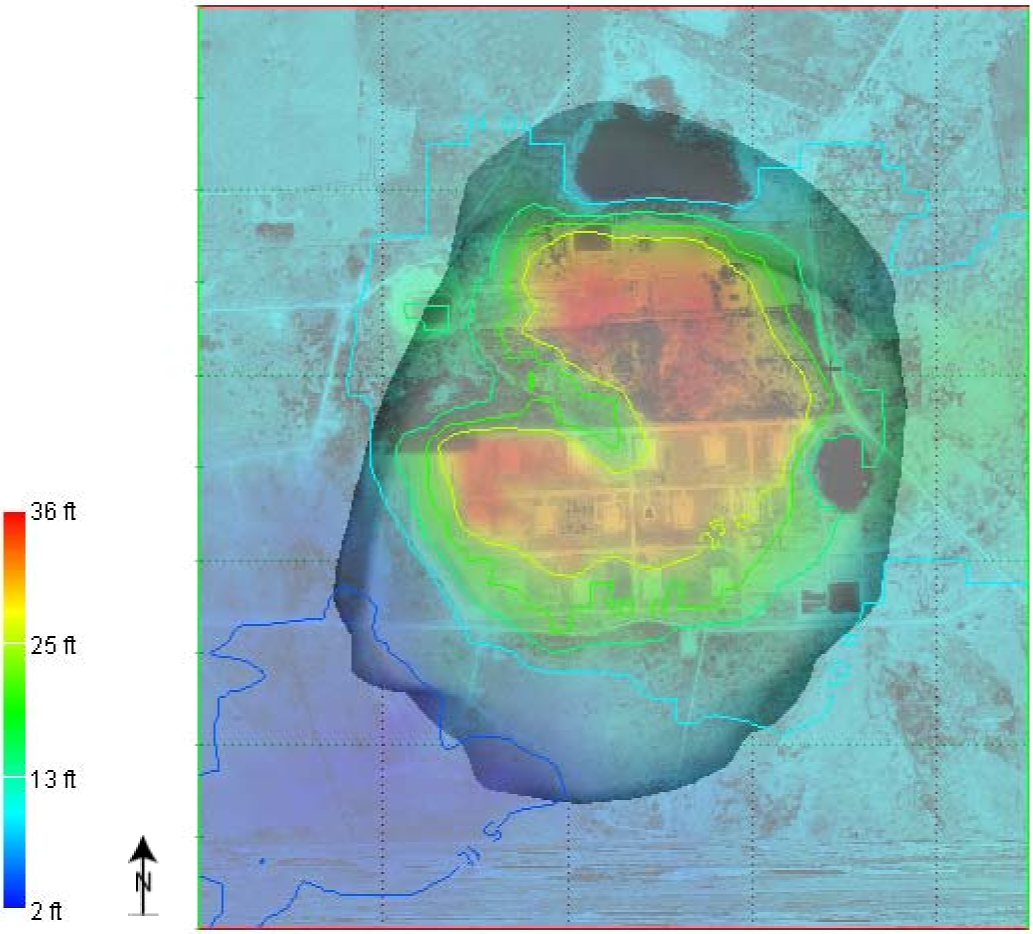

Figure 6. Semi-transparent aerial photo of the Big Hill site colored by surface elevation and showing the lateral extent of the underlying salt dome model. Color scale indicates land surface elevation. The 14 well pads that exist over the caverns are visible on the south half of the dome. [BH_FIG_6-7.4D]

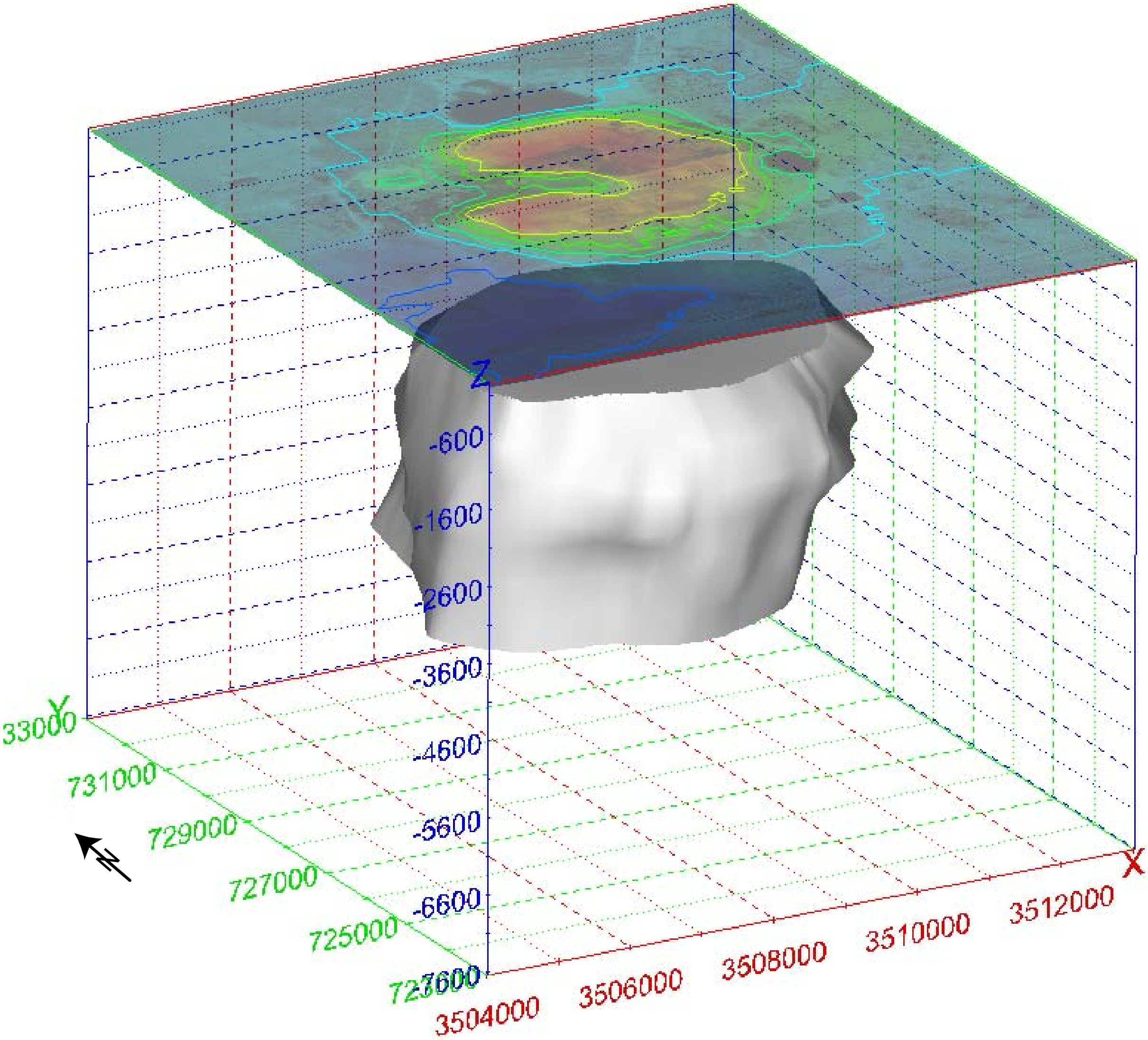

Figure 7. A view from the southwest of the Big Hill salt dome model shown with a semi-transparent aerial photo colored by surface elevation and showing the lateral extent of the underlying salt dome model to a depth of 5000 ft. Color scale is the same as in figure 6. [BH_FIG_6-7.4D]

Sediment Model

The geologic model of the sedimentary layers surrounding the dome is shown in figures 8 and 9. Figures 10 and 11 show cross-sections through the model. It is especially evident in the cross-sections that some of the sediment layers are tilted upward and may thin near the edge of the dome. This is particularly common on the south side of the dome.

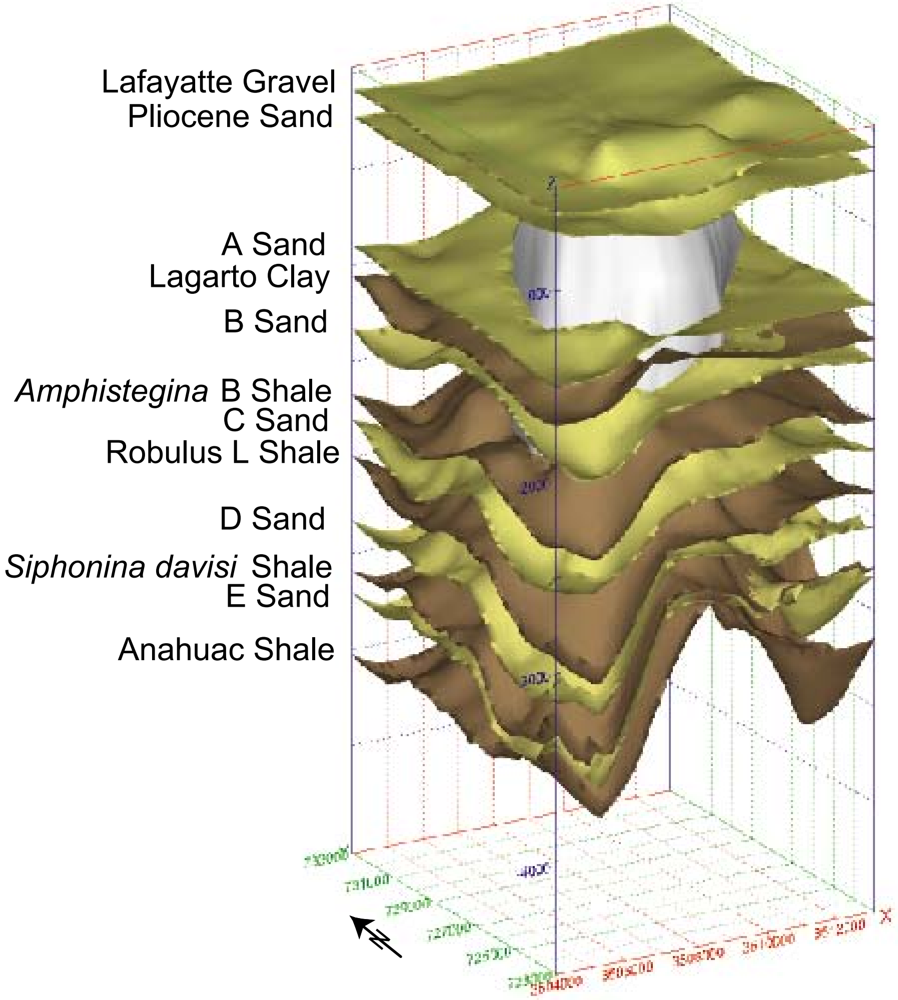

Figure 8. Three-dimensional view from the southwest of the Big Hill salt dome sediment model. Yellow (light-colored) surfaces represent tops of the major sand packages; brown (dark-colored) surfaces represent the tops of the major shaly intervals. 3X vertical exaggeration. [BH_FIG_8.4D]

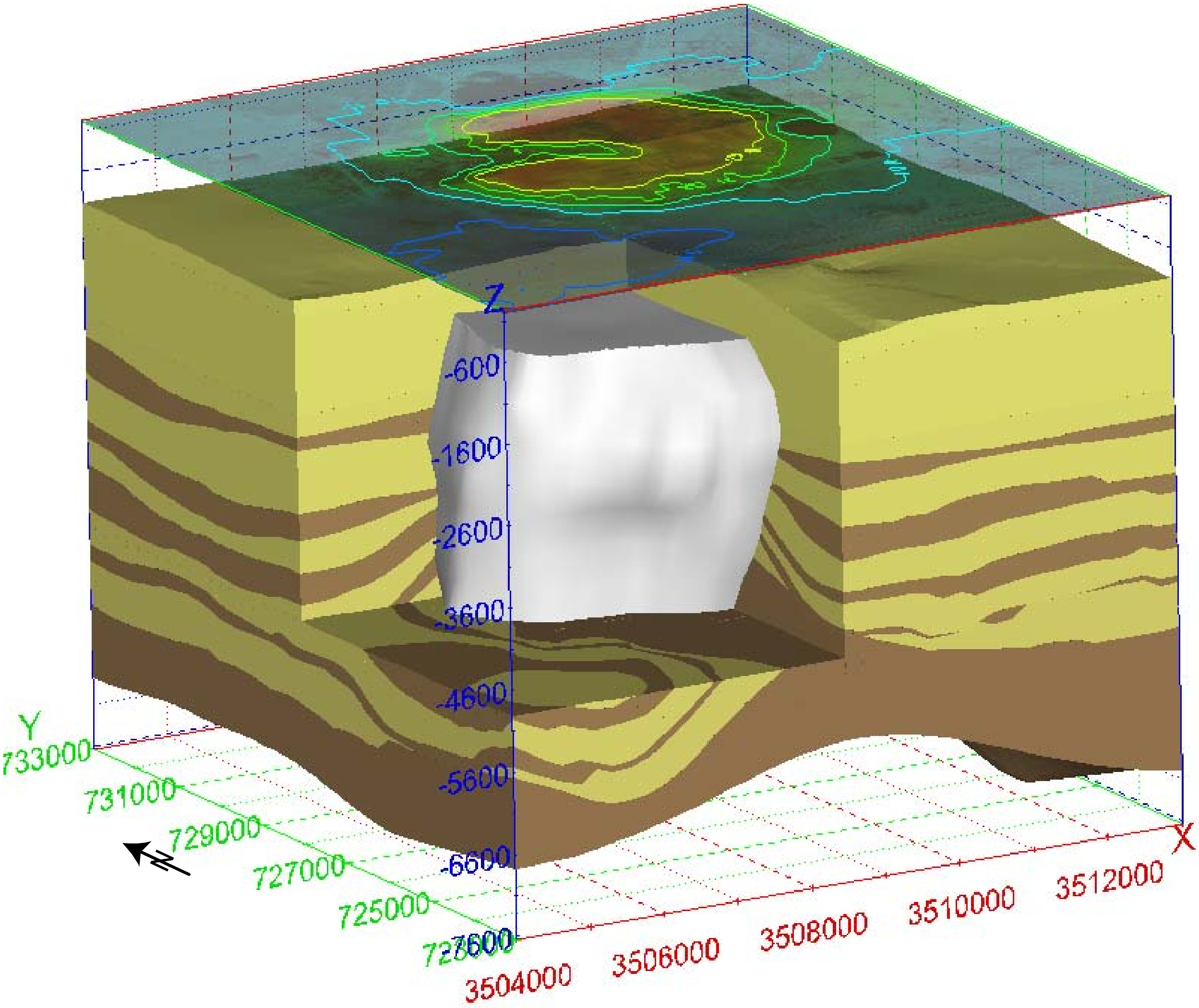

Figure 9. The Big Hill salt dome model and surrounding geologic units. Upper southwest quadrant is cut away. Yellow (light-colored) regions represent the major sand packages; brown (dark-colored) surfaces regions the major shaly intervals. No vertical exaggeration. [BH_FIG_9-11.4D]

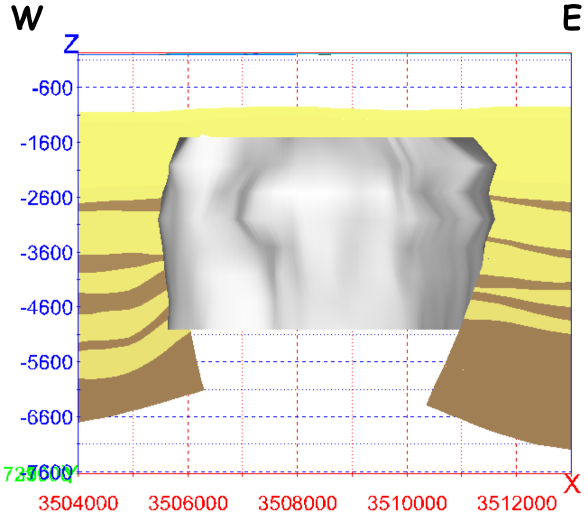

Figure 10. West-to-east cross-section through the sediment model. Light layers are "sands" with the top defined by the top surface of a sand unit and the bottom defined as the top surface of the underlying clay or shale unit. Dark layers are "shales" with the top defined by the top surface of a clay or shale unit and the bottom defined as the top surface of the underlying sand unit. No vertical exaggeration. [BH_FIG_9-11.4D]

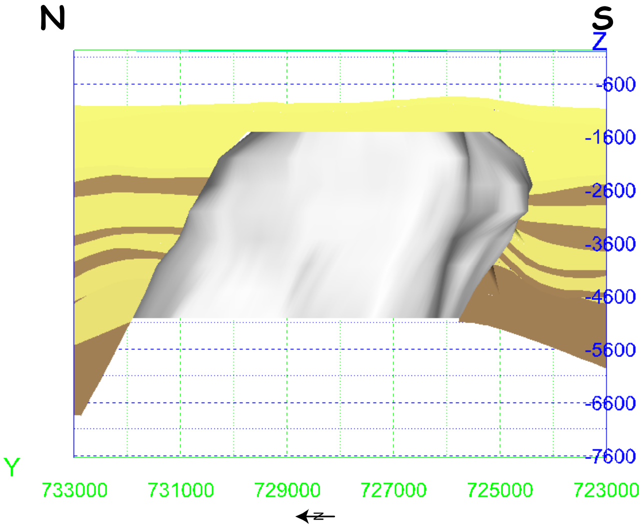

Figure 11. North-to-south cross-section through the sediment model. Light layers are "sands" with the top defined by the top surface of a sand unit and the bottom defined as the top surface of the underlying clay or shale unit. Dark layers are "shales" with the top defined by the top surface of a clay or shale unit and the bottom defined as the top surface of the underlying sand unit. [BH_FIG_9-11.4D]

Caprock Model

Caprock is an accumulated dissolution product that forms and is altered as the dome rises and encounters shallow groundwater. Over time the insolubles (mainly anhydrite) accumulate in a layer at or near the water table. If sufficient hydrocarbons and/or organic matter are present, methane from oxidation of organics and free sulfur from sulfate reducing bacteria can cause the anhydrite to undergo secondary alteration resulting in gypsum and calcite (limestone). At times the solutioning of the salt dome occurs faster than uplift rates and cavities can form as the salt mass is dissolved. These cavities can collapse producing faults in the overlying caprock.

A structure contour map showing the depth to the top of the caprock, and an isopach map showing the thickness of the caprock were included in the site characterization report (Hart and others, 1981). By combining the structure contour and isopach maps in MVS, we produced a 3-D representation of the caprock unit as interpreted in the site characterization report. Figures 12 and 13 show the resulting 3-D caprock model. The caprock drapes the dome and is thickest near the top of the dome gradually thinning toward the edges.

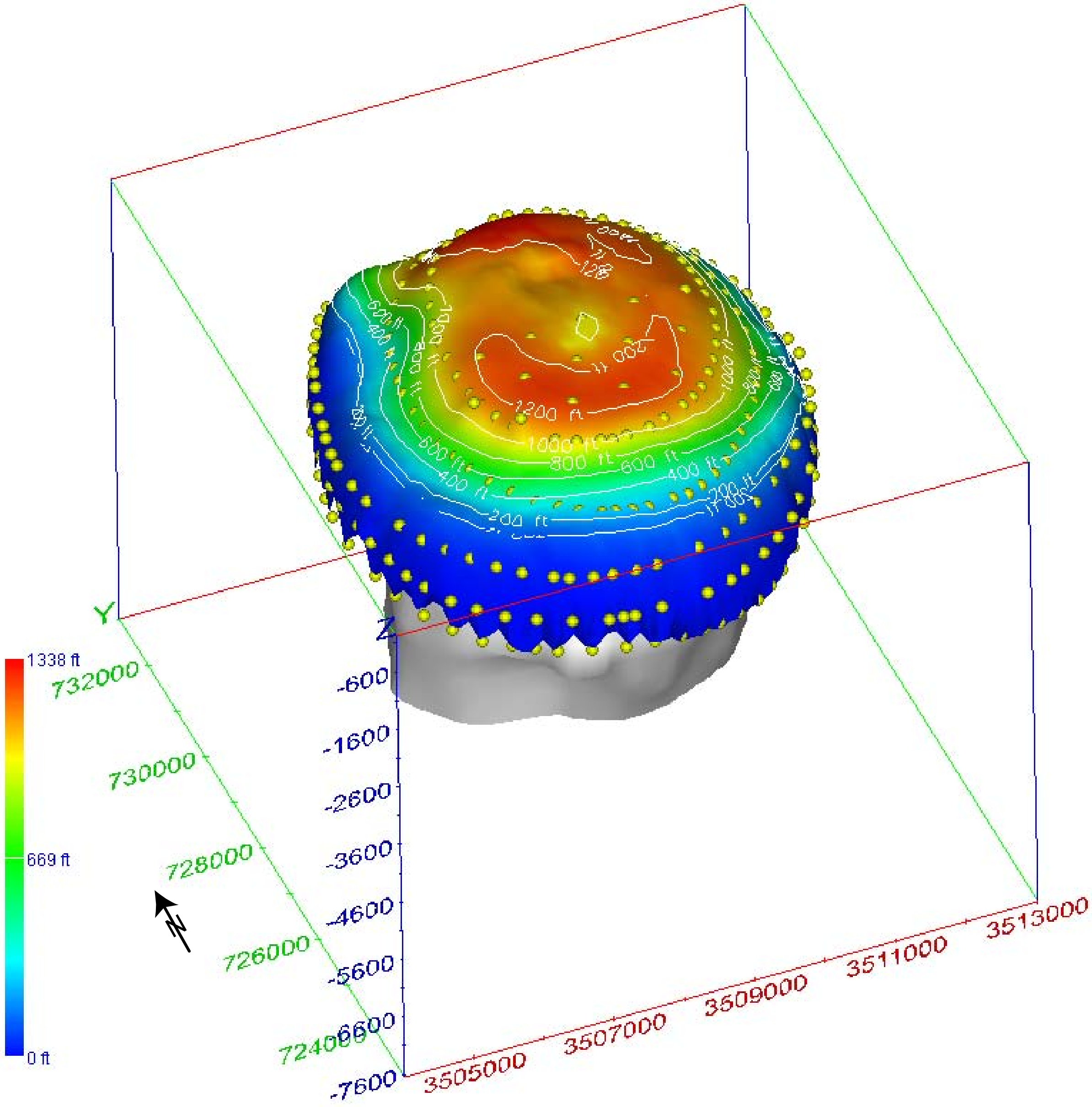

Figure 12. 3-D model of caprock made by combining the structure contour map and isopach map from the site characterization report (Hart and others, 1981). Data points (yellow spheres) used to constrain the model include digitized structure contour lines and intercepts between the cavern wells and the top of caprock. Thickness contours and color scale are shown. [BH_FIG_12-13.4D]

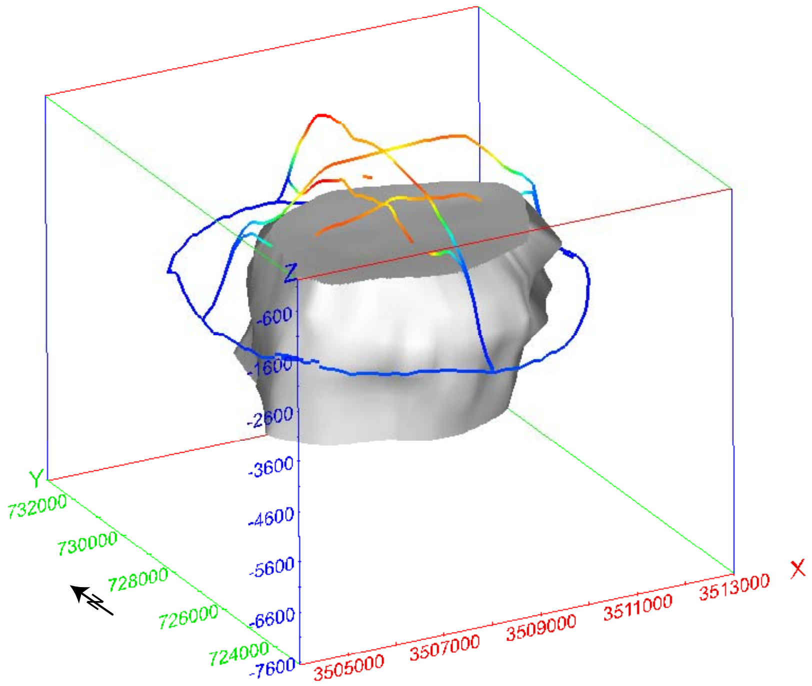

Figure 13. Big Hill salt dome model shown with north-south and east-west slices of the 3-D caprock model. No vertical exaggeration. [BH_FIG_12-13.4D]

Fault Models

The geometric models of faults surrounding the Big Hill salt dome are displayed in figure 14, with the view from the southwest. The faults tend to have relatively steep dips and extend radially away from the edge of the salt dome. The fault models presented here do not include any offset in the sedimentary layers, since they are simply 3-D surfaces connecting the fault traces. The reasons for and implications of this simplified modeling process is discussed under the section, *Generation of Fault Models.* Only the Anahuac shale is represented in figure 15, in order to allow visualization of a greater vertical extent of the modeled fault planes.

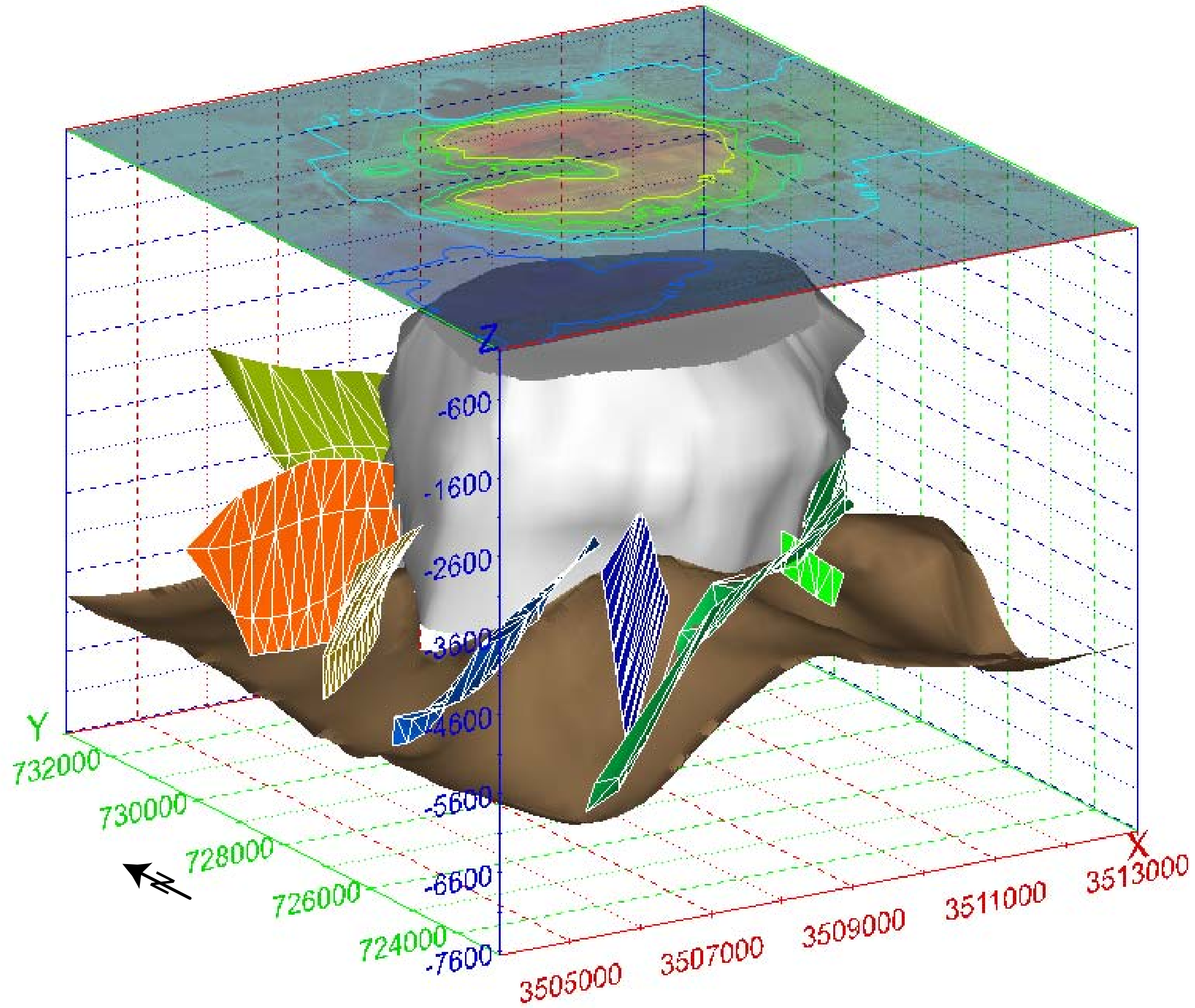

Figure 14. The Big Hill salt dome model with the Anahuac Shale (brown surface) and fault models viewed from the southwest. No vertical exaggeration. [BH_FIG_14.4D]

Cavern Models

The oil-storage caverns at the Big Hill site are not properly part of the site characterization description of the salt dome, particularly because the caverns themselves did not exist at the time of the original characterization by Hart and others (1981). Although the 14 caverns had been leached and partially filled with oil by the time of the updated characterization report (Magorian and Neal, 1988), that report did not contain any meaningful geometric description of the caverns. All representations of the caverns in the Magorian and Neal report are stylized drawings of nominal size and shape.

Figure 15 presents an overview of the 14-cavern field for the Big Hill SPR site. The sonar data used to construct these visualizations are tabulated in table 2. The 3-D model of the enclosing salt dome – minus the top of the salt surface for purposes of visualization – is shown also as the semi-transparent surface. The caverns are arranged in three approximately east-west rows. The caverns are numbered from east to west, starting from the northeastern corner of the array.

Table 2. Dates and Other Information for Sonar Surveys Used in Modeling Big Hill Caverns

Cavern ID	Survey Well	Date of Survey	Original File Name
BH-101	A	29 Jan 1991	BH-101A
BH-102	A	5 Feb 1991	BH-102A
BH-103	A	6 Dec 1990	BH-103A
BH-104	A	15 Jan 1991	BH-104A
BH-105	A	12 Jul 1990	BH-105A
BH-106	A	23 Jan 1991	2-BH106A
BH-107	A	15 Dec 1990	BH-107A
BH-108	A	20 Dec 1990	BH-108A
BH-109	A	3 Jan 1991	BH-109A
BH-110	B	9 Aug 1990	BH-110B
Bh-111	A	2 Aug 1991	BH-111A
BH-112	A	22 Jul 1991	BH-112A
BH-113	A	25 Jun 1991	BH-113A
BH-114	A	6 Sep 1991	BH-114A

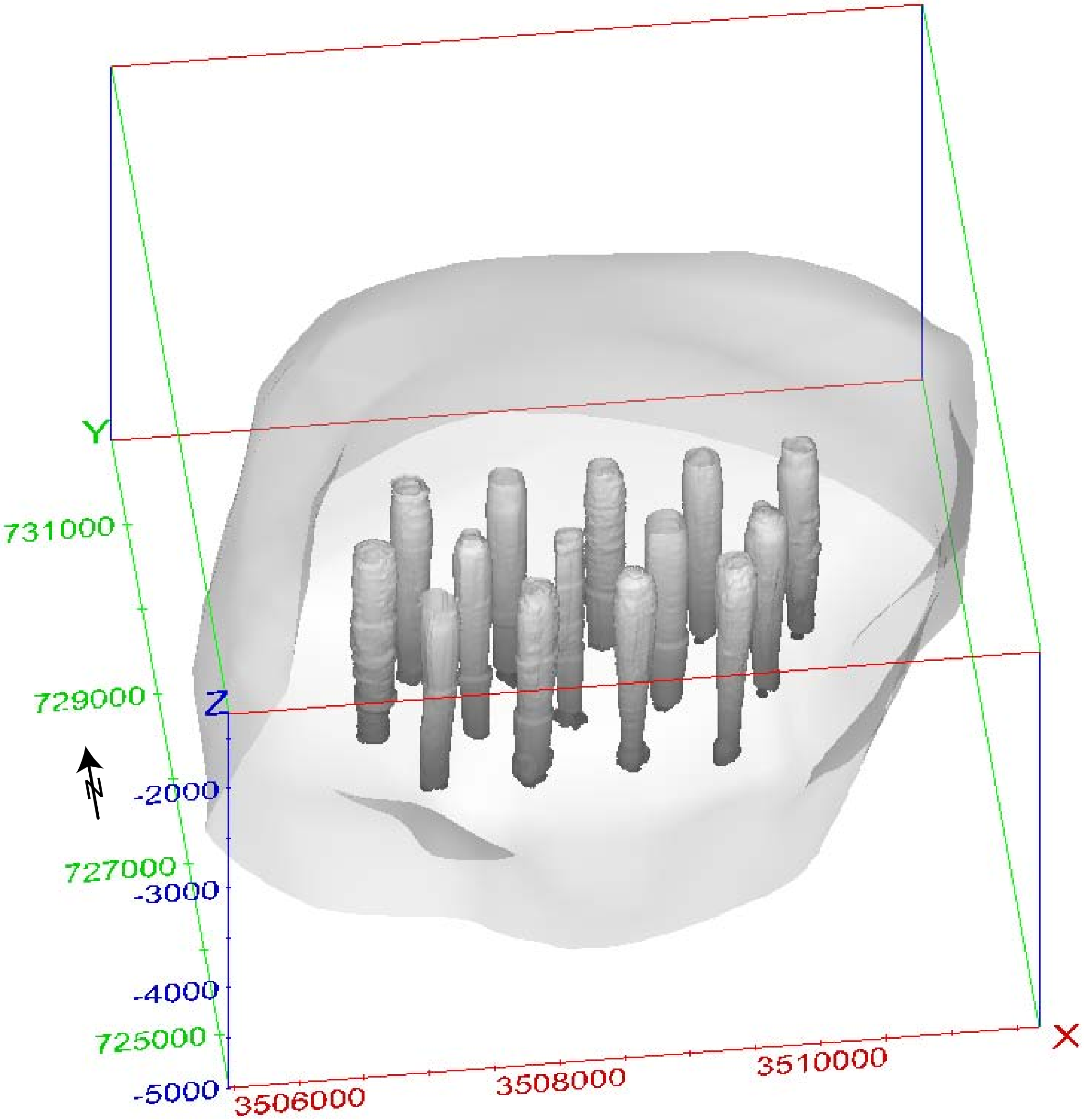

Figure 15. Visualization of the 14 Big Hill caverns within the salt dome. [BH_FIG_15.4D]

The nominal design shape of approximately cylindrical, slightly downward-tapering cavities is quite apparent for many of the caverns, as is appropriate for this stage immediately following construction. Some irregularly positioned local enlargements are visible; these are probably related to positioning of the various pipe strings during the different phases of solution mining. Several caverns exhibit prominent enlargement at the base of the cavity at the location of the leaching sump.

Additional enlargements and geometric asymmetries can be identified through examination of individual caverns, some of which may be related to the presence of shear zones, compositional inhomogeneities, or other internal features of the salt mass (e.g. figures 16 and 17). Although these types of geologic features would be important in a full-scale recharacterization of the Big Hill salt dome, full discussion of their implications is beyond the scope of this model-conversion report.

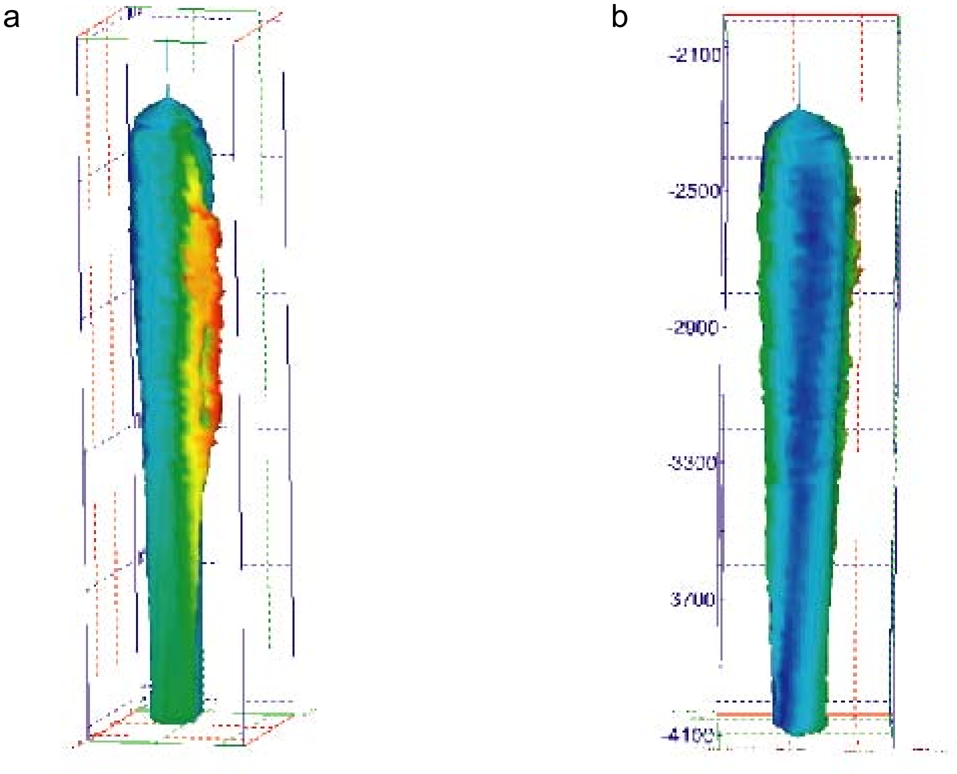

Figure 16. Visualization of Big Hill cavern 108 showing pronounced wall irregularities suggestive of preferential leaching and/or salt falls along a southwest-to-northeast trend. View is (a) from the south at a nearly flat angle and (b) from the northeast at a shallow angle. [BH_FIG_16-17.4D]

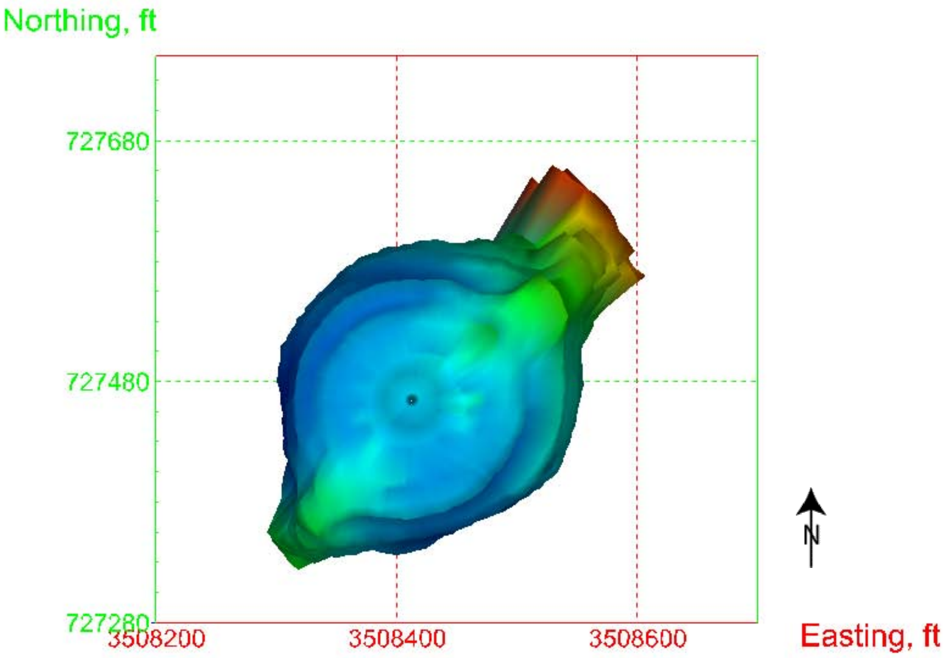

Figure 17. Visualization of Big Hill cavern 108 from above clearly shows pronounced wall irregularities suggestive of preferential leaching and/or salt falls along a southwest-to-northeast trend. Grid is presumed to be Texas State Plane coordinate system, south central zone, NAD-27, in feet. [BH_FIG_16-17.4D]

DISCUSSION

Salt Dome Model

The salt dome model was constructed by digitizing the structure contour map for salt included in the site characterization report. A detailed description of the methodology used to create this model is described in another report (Rautman and Stein, 2002). Because the model is based on sparse data and handdrawn contours it should be considered a “best guess” of the true 3-D geometry of the dome. There is considerable uncertainty as to the exact geometry and future work is underway to help define the extent of this uncertainty. One can appreciate the degree of uncertainty by looking at the dome model along with the data available to define the edge of salt. Figure 18 shows the 3-D locations where the contact between the salt dome and surrounding sediments was located from borehole logs. It is clear from the figure that certain parts of the dome model (southwest flank) are better constrained than others (northern half of the dome). The fact that the dome model does not honor all of the well data is probably a result of errors introduced by the process of constructing the structure contour map of salt, which was used to develop the dome model.

Work has already begun to quantify the magnitude and distribution of uncertainties inherent in the salt dome models at all the SPR sites.

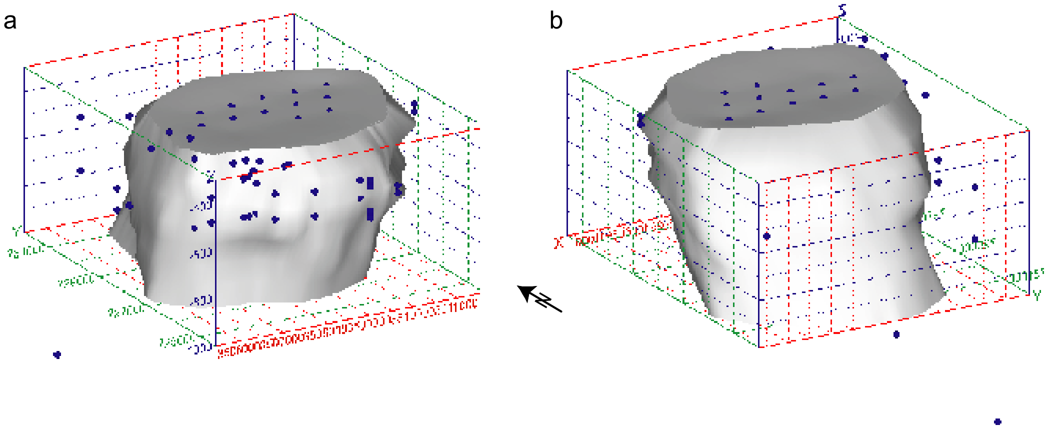

Figure 18. Views of the Big Hill salt dome model showing the locations of points where the edge of salt is known from borehole data. Dome is opaque in this figure and therefore obscures data points located "inside" the dome (a) View from the SW shows that numerous data points define the prominent overhang of the dome on this flank. (b) View from the NE shows that far fewer data exist in this area and the dome geometry on the north is therefore quite uncertain. [BH_FIG_18.4D]

Sediment Model

The sediment model presented here is based on a limited set of points identified in wells. New data may become available as additional wells are drilled or old well logs are reinterpreted. One source of potential errors in the current model is related to the certainty on the positions of the wells. Of particular concern are the several "side-track" wells reported in the site characterization report. Side-track wells are wells that begin at the surface in another well and then deviate from the original well at some depth. These wells have a different set of depths to sedimentary units than the main well but only the surface location of the two wells is recorded in the report. If the depth and orientation of the deviation were known for these side-track wells these data could be used to help constrain the sediment models.

Another limitation of the current sediment model is that it is limited to defining the *tops* of the various sedimentary units. There is no information in the site characterization report that defines the presumably varying layer thickness of these units. If the thickness of the sedimentary units needs to be defined in the future, the original well logs from those wells will have to be located and reinterpreted. Additional complications may arise from simplifications of complex sedimentary sequences into a few major "sand" or "shale" units.

A comparison between a structure contour map of the C Sand generated from the model described in this report and the structure contour map included in the site characterization report is shown in figure 19. These two structure contour maps differ from one another in several ways. First, there are many more wells shown on the site characterization map (lower) than actually penetrate the C Sand. This makes the site characterization maps appear to be better constrained than they actually are. Second, the krigged model does not consider faulting and any associated off-sets in the generation of the model. Finally, hand-drawn contours from the site characterization map are more circular and less irregular than the contours generated by the krigged model. This is due to the inclusion of “soft” information in the hand-contouring process. Soft information is interpretation not based on actual data from the site. For example, geologists have a conceptual model of salt domes as semi-cylindrical based on the way they form and from observations at other salt domes that are better characterized. Hand contouring includes such “soft” information so that the resulting structure honors the data and the conceptual model of the structure as interpreted by the geologist. In contrast, kriging uses the data and the semivariogram to construct the model. Both methods have their advantages. Kriging is purely objective and certain types of uncertainty in the model can be quantified. In cases where data density is very low, hand contouring may be better suited, however, there is no way to quantify uncertainty in the resulting model.

Figure 20 shows the structure contour map for the C sand based on the well data (red) and the digitized contour data (blue) from the site characterization report for comparison. The structure contour map is semi-transparent allowing one to see data that lie below the model. A detailed examination of this figure in 3-D verifies that the model tends to match the digitized contour data quite well where there is a dense clustering of well data (e.g. along the SW flank of the dome). In contrast, where there is little to no data the model tends to lie above the digitized structure contours with the exception of the short 3000 ft contour on the northern flank of the dome which lies significantly above the model. It is not surprising that there is a discrepancy between the present model and the structure contour map from the site characterization report where there is little to no data. These differences demonstrate the importance of acquiring sufficient data for interpreting the complex geology around a salt dome.

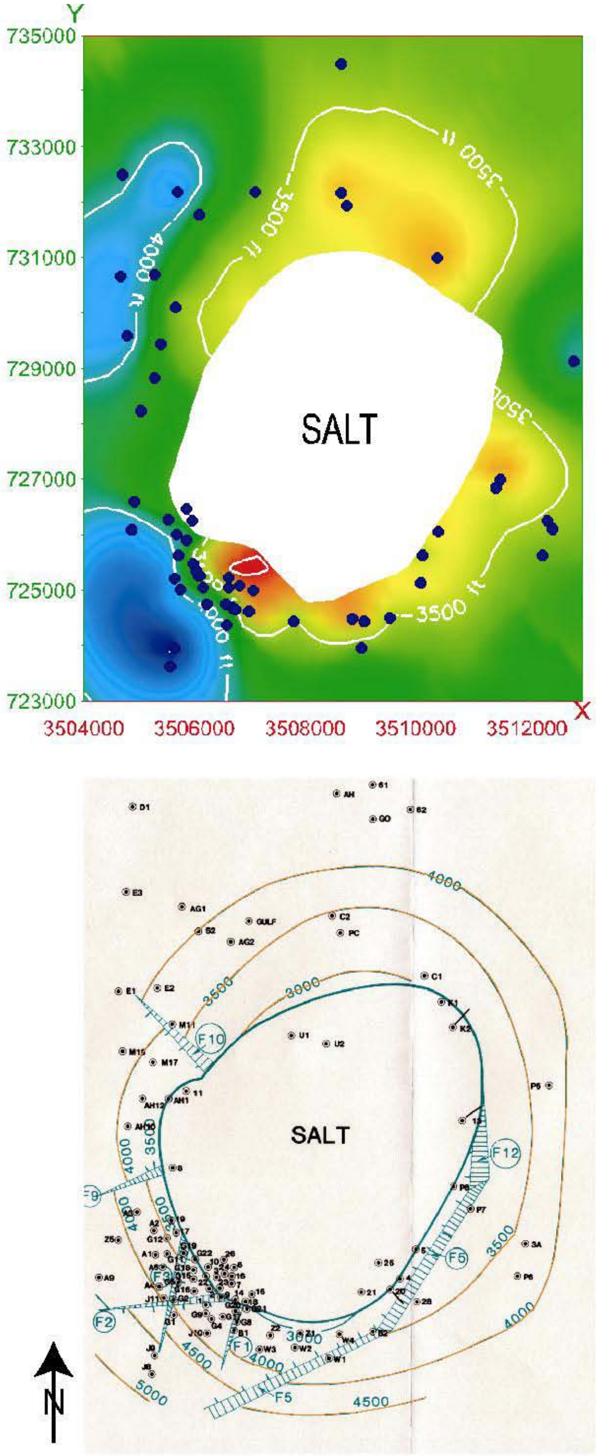

Figure 19. Top figure is a structure contour map for the C Sand generated from the 3-D model based on borehole data (blue circles). The salt dome profile is at a depth of 3500 ft. Bottom map is the structure contour map for the C Sand from the site characterization report (Hart and others, 1981) cropped to approximately the same domain as the figure above.

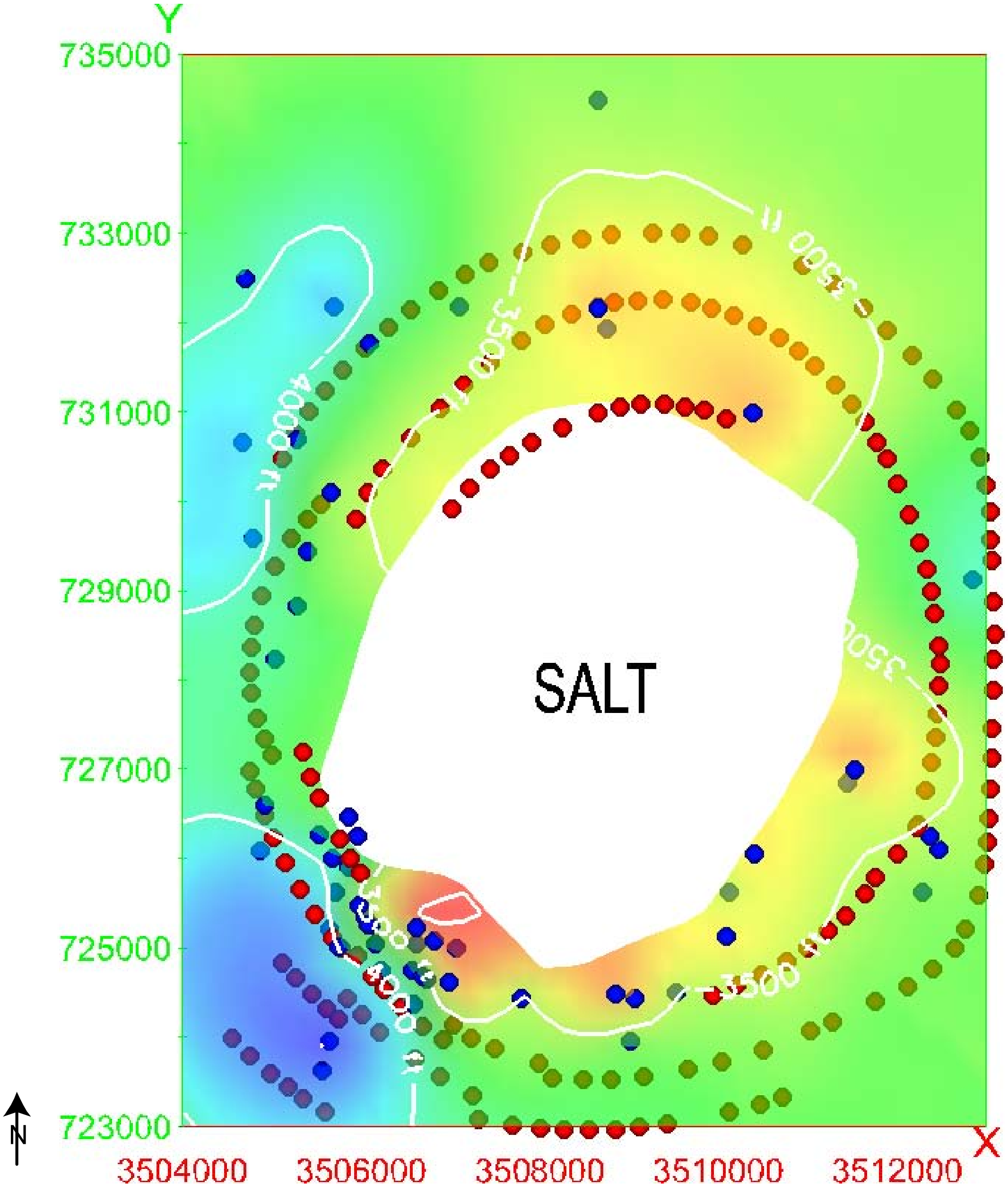

Figure 20. Semi-transparent structure contour map for the C Sand generated from the 3-D model based on borehole data (blue spheres). The map is cut by the salt dome at a depth of 3500 ft. Red spheres are digitized structure contours from the lower map in figure 20. Bright symbols either lie on or above the model surface. Symbols that lie below the model surface appear darker and faded.

Fault Models

The fault models presented in this report are quite idealized. The models are based on inferred fault traces digitized from the structure contour maps. The structure contour maps included in the site characterization report do not include a reference grid to use for the calibration. Instead, calibration was performed using a selected set of wells, which were shown on the maps. The typical RMS errors were typically about 65 ft, which adds to the uncertainty in the absolute positions of the faults. Moreover, the process of estimating the location of a subsurface fault plane is quite subjective when the data density is low, as is the case at the Big Hill site. However, because the details on how these traces were selected are not well documented in the site characterization report it is impossible to evaluate the reasonableness of the interpretations. A better strategy would be to try to obtain adequate seismic data that could help to image the fault geometry. At present, such data are not readily available.

An obvious limitation of the current models is the lack of any offset on the faults. In developing the methodology for converting the fault models we tried to preserve the offsets apparent in the structure contour maps. These offsets are represented by discontinuities in the structure contour lines as they cross a fault trace. For example, in figure 2 the C sand on the southwest side of the F10 fault is represented as being at a greater depth than on the northeast side of the fault. In an early attempt to convert the faults to 3-D we digitized all the points of intersection between each fault trace and structure contour line. These points should all lie on the fault plane. When we plotted these points in MVS many faults did not have enough points to adequately model a triangulated irregular network (TIN) surface or the modeled TIN surface did not appear reasonable (no apparent planar correlation). One problem with this approach may be that it depends on the accuracy of the structure contour lines, which have a contour interval of 500 ft. Such a large contour interval suggests that the error in the depth along each contour line may be considerable. This first attempt at converting the faults is a good example of how a 2-D representation of a 3-D geometry (fault offsets on a set of structure contour maps) can look reasonable on each map but when combined in 3-D space the model falls apart. The approach we present here produces geologically reasonable faults in the locations inferred in the site characterization report. We believe that if a more accurate fault model is required in the future then a detailed reinterpretation of the original well logs and other available data is necessary.

Cavern Models

The cavern models are the best-constrained models presented in this report. Each nodal point on a cavern mesh is constrained by sonar measurements. Nevertheless, there are limitations to the models as discussed earlier. In caverns such a BH-108, where wall irregularities are significant, the sonar measurements become more inaccurate. In these deep sub-cavities the sonar measurements may underestimate the degree of irregularity since the sonar beams cannot “see” around corners and some of the sub-cavities may extend further than can be imaged.

CONCLUSIONS

We have presented a 3-D geologic model of the Big Hill SPR site. The model is constrained by data and interpretations presented in the original site characterization report. The features of the model include the geometry of the salt dome, surrounding sediments, faults, and oil storage caverns.

The three dimensional model is a significant improvement on the original 2-D representation because it is geometrically and geologically consistent. The model provides a baseline for future work at the Big Hill site and can easily incorporate new data as it becomes available. Future needs of the project, such as a possible expansion of the reserve will require an advanced understanding of the geology surrounding the Big Hill and other SPR sites. Because data density is typically sparse, such three-dimensional geologic models can also provide valuable information for defining and quantifying the geologic uncertainty at the SPR sites. Armed with this information, managers can perform real cost-benefit analyses that allow efficient, informed decisions to be made, saving money, time and resources.

REFERENCES

Deutsch, C.V., and Journel, A.G. 1998. *GSLIB Geostatistical Software Library and User's Guide*. New York: Oxford University Press.

Hart, R.J., Ortiz, T.S., and Magorian, T.R. 1981. *Strategic Petroleum Reserve (SPR) Geologic Site Characterization Report Big Hill Salt Dome*. SAND81-1045. Albuquerque, NM: Sandia National Laboratories.

Magorian, T.R., and Neal, J.T. 1988. *Strategic Petroleum Reserve (SPR) Additional Geological Site Characterization Studies Big Hill Salt Dome, Texas*. SAND88-2267. Albuquerque, NM: Sandia National Laboratories.

Neal, J.T., Magorian, T.R., Thorns, R.L., Autin, W.J., McCulloh, R.P., Denzler, S., and Byrne, K.O. 1993. *Anomalous Zones in Gulf Coast Salt Domes With Special Reference to Big Hill, TX, and Weeks Island, LA*. SAND92-2283. Albuquerque, NM: Sandia National Laboratories.

Rautman, C.A., and Stein, J.S. 2003. *Three-Dimensional Representations of Salt-Dome Margins at Four Active Strategic Petroleum Reserve Sites*. SAND2003-3300. Albuquerque, NM: Sandia National Laboratories. 70 p.

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Appendix A: Installation and Use of 4DIM Files

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 (Mining Visualization System) developed by C Tech Development Corporation (www.ctech.com) includes a derivative model “type” known as 4DIM files (for 4- Dimensional Interactive Model). 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. This situation is clearly a marketing strategy aimed an encouraging purchase and use of the higher- end products.

Sandia National Laboratories owns MVS, the top-end modeling software produced by C Tech Development Corporation. Accordingly, all 4DIM files generated using MVS are encoded with the necessary key for use with the unlicensed version of the 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 caveat regarding installation to a directory whose name contains a space is observed. All defaults may simply be accepted during the installation process.

Software 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 an 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 location on the screen.
4. To specify the view from a particular direction, open 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 or 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" menu button at the top of the 4DIM player screen or 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."

List of 4DIM Model Files for the Big Hill SPR Site

A set of ten 4DIM files are included on the CD-R as part of this report. The files are all 3-D versions of the still figures in the report. Files are named with reference to the figure numbers. See figure captions and descriptions in the report for discussion of the features included in the models. Below is a list of the ten 4DIM files included:

	FILENAME	**FIGURES**
1.	*File B*H_FIG_4*.4d*	Figure 4
2.	*File B*H_FIG_5*.4d*	Figure 5
3.	*File B*H_FIG_6-7*.4d*	Figures 6-7
4.	*File B*H_FIG_8*.4d*	Figure 8
5.	*File B*H_FIG_9-11*.4d*	Figures 9-11
6.	*File B*H_FIG_12-13*.4d*	Figures 12-13
7.	*File B*H_FIG_14*.4d*	Figure 14
8.	*File B*H_FIG_15*.4d*	Figure 15
9.	*File BH_FIG_16-17.4d*	Figures 16-77
10.	*File BH_FIG_18.4d*	Figure 18

DISTRIBUTION:

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900 Commerce Road East
New Orleans, LA 70123

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Strategic Petroleum Reserve Program Office
1000 Independence Avenue, SW
Washington, D.C. 20585
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MS-0706	S. Wallace, 6113, for SPR library
MS 0735	R.E. Finley, 6115
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MS 0899	Technical Library, 9616 (2)