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Conversion of the Bryan Mound Geological Site Characterization Reports to a Three-Dimensional Model

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Abstract

The Bryan Mound salt dome, located near Freeport, Texas, is home to one of four underground crude 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 Bryan Mound site into three-dimensional geologic models. The new models include the geometry of the salt dome, the surrounding sedimentary units, mapped faults, and the 20 oil-storage caverns at the site. This work provides an internally consistent geologic model of the Bryan Mound site that can be used in support of future work.

TABLE OF CONTENTS

Table of Figures	5
Table of Tables	5
Introduction	7
Background	7
Existing Data	9
Site Characterization Reports	9
Well Information	10
Structure Contour Maps	11
Geologic Cross Sections	12
Geologic Units Identified at Bryan Mound	13
Cavern Geometry at Bryan Mound	14
Conversion Methodology	15
Coordinate Systems	16
Generation of Salt Dome Model	19
Generation of Sediment Models	20
Generation of Fault Models	20
Generation of the Cavern Models	22
Results	23
Salt Dome Model	23
Sediment Model	25
Caprock Model	27
Fault Models	28
Cavern Models	29
Discussion	31
Salt Dome Model	31
Sediment Models	32
Fault Models	34
Cavern Models	34
Conclusions	34
References	36

TABLE OF FIGURES

Figure 1. Index map showing the location of the Bryan Mound SPR facility and other SPR sites.....	6
Figure 2. Well data constraining the depth to the tops of sedimentary units surrounding and above the Bryan Mound salt dome.	9
Figure 3. Well data constraining the depth to caprock at the Bryan Mound salt dome.	10
Figure 4. Digitized control points from the structure contour maps at the Bryan Mound salt dome.....	11
Figure 5. Digitized control points from the geologic cross sections at the Bryan Mound salt dome.....	12
Figure 6. Top view of the Bryan Mound salt dome and selected cavern models.....	14
Figure 7. Coordinate reference map for the Bryan Mound site.....	16
Figure 8. Method used to develop fault models surrounding the Bryan Mound salt dome.	21
Figure 9. Semi-transparent aerial photo of the Bryan Mound site colored by surface elevation and showing the lateral extent of the underlying salt dome model.	23
Figure 10. Bryan Mound salt dome model viewed from the southwest.....	23
Figure 11. Three-dimensional view from the southeast of the Bryan Mound salt dome sediment model based on borehole data.....	25
Figure 12. Three-dimensional view from the southeast of the Bryan Mound salt dome sediment model based on sediment contour maps.	25
Figure 13. Three-dimensional view from the southeast of the Bryan Mound salt dome sediment model based on four geologic cross-sections.	26
Figure 14. 3-D model of caprock made by kriging well data.....	27
Figure 15. Aerial view of fault models surrounding the Bryan Mound salt dome.	28
Figure 16. Visualization of 19 Bryan Mound caverns within the salt dome.....	29
Figure 17. Bryan Mound salt dome model showing locations where the edge of salt was identified in boreholes.....	30
Figure 18. Map of the maximum difference in the elevation of the top of the Miocene surrounding the Bryan Mound salt dome.....	32
Figure 19. Map of the maximum difference in the elevation of the top of the Anahuac surrounding the Bryan Mound salt dome.....	32

TABLE OF TABLES

Table 1. Geologic Units Included in Model Conversion.....	12
Table 2. Digitized Coordinates Used to Define Affine Polynomial Transformation Formula for Bryan Mound, SPR Site.	17
Table 3. Affine Polynomial Transformation Coefficients.....	18
Table 4. Dates and Other Information for Sonar Surveys Used in Modeling Bryan Mound Caverns.	28

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INTRODUCTION

The Bryan Mound salt dome, located approximately 60 miles south of Houston, Texas, near the city of Freeport, is one of four underground oil-storage facilities run by the U.S. Department of Energy (DOE) Strategic Petroleum Reserve (SPR) Program and is the largest of the sites in terms of oil-storage capacity (currently 226 million barrels). 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 existing two-dimensional (2-D) geologic interpretations to three-dimensional (3-D) geologic models of the Bryan Mound SPR site. This work provides a more realistic and consistent geologic model of the Bryan Mound site that can be used in support of future work.



Figure 1. Index map showing the location of the Bryan Mound SPR facility and other SPR sites.

BACKGROUND

The Bryan Mound SPR site was acquired by DOE, by condemnation, in April 1977 from the Freeport Mineral Company and other owners. At that time there were five caverns at the site. An analysis of these existing Phase I caverns from 1977 to 1979 resulted in four of them being certified for crude oil storage. As early as October 1977 oil injection commenced at the site. The first geological site characterization report was completed in this period (Hogan, 1980). The report contains general information about the regional geography and geology of the site, geometry of the salt dome and caprock, and a detailed geometric analysis of the five acquired Phase I caverns. The report contains no data on the geologic units that surround the salt dome. Phase II expansion at the site lasted from 1980 to 1984 and resulted in the leaching of 16 additional caverns with semi cylindrical shapes. Sandia published a new geological characterization report in 1994 (Neal and others, 1994), which included an updated analysis of the salt dome and

caprock geometry as well as an interpretation of geology surrounding the dome. This update report provides most of the information for this model-conversion report, except where noted.

Geologic information at the Bryan Mound site is primarily derived from drilling activity centered over the top of the salt dome in pursuit of brine and sulfur resources that are located within the dome and caprock. A few deeper wells have been drilled in search of oil along the flank of the dome, but no profitable reservoirs have been found and thus the area surrounding the dome has seen far less drilling activity than at the other SPR sites. As a result of this history, the caprock at Bryan Mound is quite well characterized, whereas the surrounding geology is not nearly as well constrained. Any geologic models of the units surrounding the dome are uncertain.

The geologic 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 mathematical 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 configuration 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 Bryan Mound without performing a full recharacterization of the site, SNL has converted the existing 2-D models that are included in the original site characterization reports (Hogan, 1980; Neal and others, 1994) to true 3-D site models. These site models include the geometry of the salt dome and caprock, the solution caverns used for oil storage, lithologic (biostratigraphic) 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 Bryan Mound salt dome.

The 3-D modeling environment used for this work is the 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 Bryan Mound site was completed in the late 1970s and documented in a Sandia National Laboratories SAND Report (Hogan, 1980). This report was compiled after DOE acquired the land and the five Phase I caverns, but before Phase II leaching activities were completed. The objectives of that report were limited to the following:

1. Acquire, compile, evaluate, and interpret existing geologic data at the Bryan Mound site,
2. Characterize the surface and near-surface geology and hydrology,
3. Characterize the caprock,
4. Characterize the internal geometry and quality of the salt dome, and
5. Assess the possible effects of natural events such as hurricanes and earthquakes on the site geology.

Objectives 1-4 were met by compiling historical drilling records, plotting borehole locations on 2-D maps, and contouring depths to the tops of salt and caprock. A limited list of borehole locations and depths to the top of caprock and salt were included as data tables in the reports. However, no data was presented in this report on the depth to geologic units other than caprock and salt. An analysis of existing cavern shapes identified a possible shear zone trending from SE to NW through the middle of the dome.

A site characterization update report was completed after the 16 Phase II oil-storage caverns were leached (Neal and others, 1994). This report included information from boreholes drilled after the original report was completed, including 38 wells drilled in preparation for solution mining of the Phase II caverns. The objectives of this report were as follows:

1. Refine salt dome and caprock characterization in light of new data and advances in the field of salt tectonics, and
- 4.2. Add geologic interpretations of identified units that surround the salt dome.

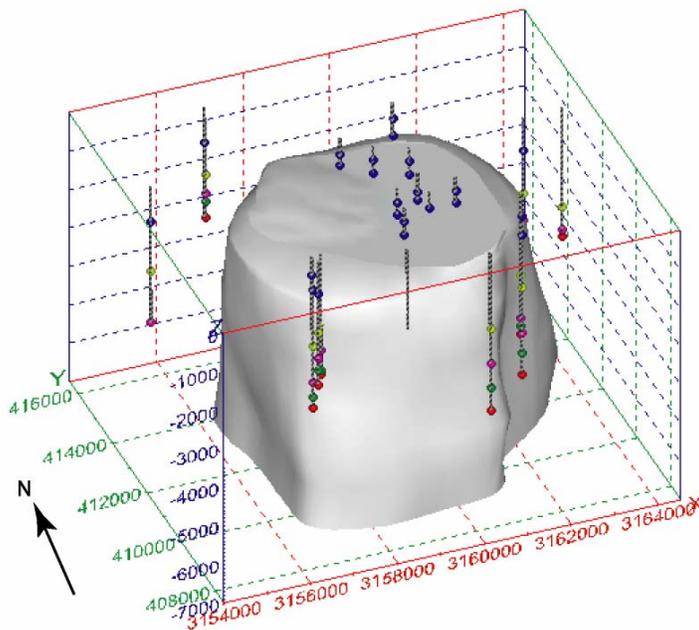
This characterization update report included structure contour maps of salt, caprock, and two geologic units that extend beyond the dome. Four geologic cross-sections were also included in this report. In addition, a comprehensive appendix was included that lists depths to selected geologic units in available boreholes. Unfortunately, the only source of borehole locations is from a small-scale map showing wellhead locations. In order to tabulate well-location data, these points must be digitized. Numerous wells listed in the appendix are not shown on the map and some mapped wells are incorrectly labeled, thereby resulting in some ambiguous data, which cannot be used in the present conversion.

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. Consecutive surveys in the same caverns allow evaluation of changes in cavern geometry with time.

Well Information

A limited number of well locations and depths to caprock and salt are listed in tables included in the original site characterization report (Hogan, 1980). However, there are no well data presented for other geologic units in this report.

An appendix included with the update site characterization report (Neal and others, 1994) includes well numbers and depths to the tops of 32 distinct geologic, lithologic, biostratigraphic, or other horizons identified in borehole logs around the Bryan Mound SPR site. However, only 10 of these 32 horizons are clearly defined in the report¹, which limits the utility of the complete dataset. In addition, the only source of wellhead locations presented in the update report is a map showing these locations graphically. This map has been digitized to obtain well head locations. However, a number of inconsistencies exist in this map, including a few wells shown with two locations and several wells that do not appear on the map. Figure 2 shows the locations where geologic units (excluding the top of caprock) have been identified. Figure 3 shows all of the locations where the top of caprock has been identified.



¹ There are 32 horizons included in Part 2 of Appendix C of Neal and others (1994). The ten identified horizons include 8 horizons named in Table 1 of Appendix A of Neal and others (1994) and two additional horizons (tops of caprock and salt) identified in the same report.

Figure 2. Well data constraining the depth to the tops of sedimentary units surrounding and above the Bryan Mound salt dome.

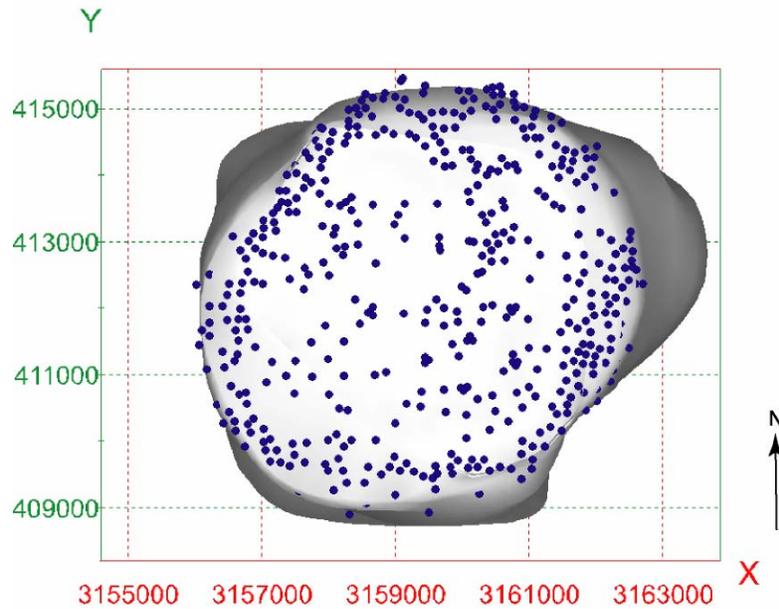


Figure 3. Well data constraining the depth to caprock at the Bryan Mound salt dome.

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 Bryan Mound site characterization report (Hogan, 1980), but only for the top of salt and caprock.

The update report included updated structure contour maps for the tops of salt and caprock, and, in addition, two new structure contour maps for the top of the Miocene and the top of the Anahuac-age shale. The data from these two new structure contour maps is illustrated in figure 4.

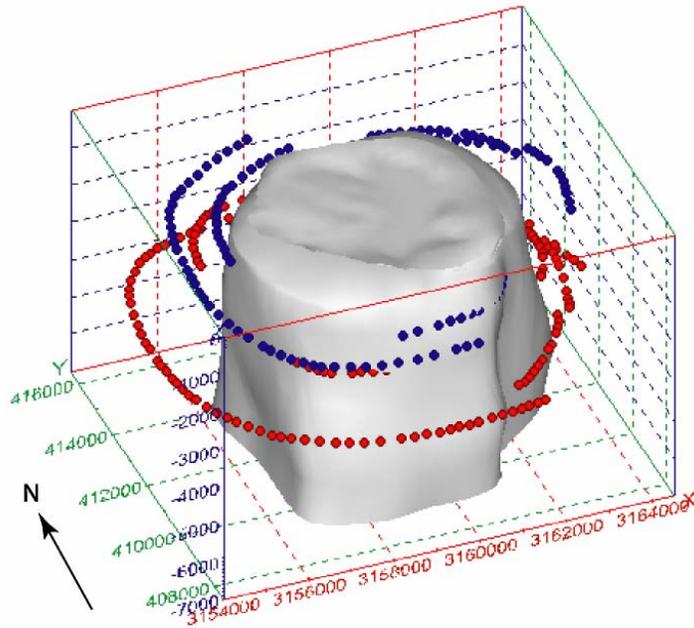


Figure 4. Digitized control points from the structure contour maps at the Bryan Mound salt dome. Blue is Miocene, Red is Anahuac.

Geologic Cross Sections

Four geologic cross sections were included in the original site characterization report, however, only two of these sections included any information about units laterally away from the edge of the salt dome. In addition, a cross check between the cross sections and data included in the appendix of the update report indicate that there are significant inconsistencies between the cross sections and the data. For instance, wells shown on the original cross sections as intersecting various units at certain depths are listed in the appendix to the update report as either not intersecting that unit or doing so at a significantly different depth. Because the updated report contains the most internally consistent information, the cross sections from the original report are not used in this model conversion.

Four different geologic cross sections were included in the updated site characterization report. These cross sections were constructed by projecting well data to straight cross-section lines that intersected at the dome axis, and plotting the depths of selected geologic units with distance along the lines of cross section. These cross sections all extend beyond the edge of the dome and are generally consistent with the well data included in the appendix to the report. These cross sections are included as part of this model conversion (Figure 5).

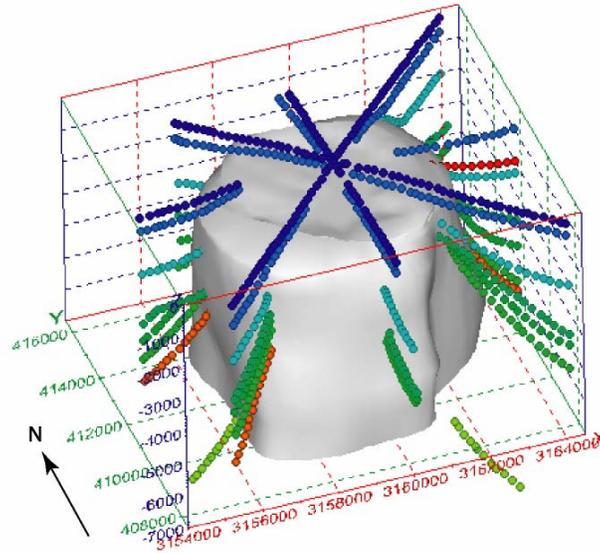


Figure 5. Digitized control points from the geologic cross sections at the Bryan Mound salt dome.

Geologic Units Identified at Bryan Mound

Table 1 lists ten geologic units that are included in this model conversion. These ten units were chosen from the list of 32 because they were the only units identified by name in the update report (the majority of the units listed in Appendix C were only identified by a two letter symbol, but never described in the report). This lack of traceability raises significant questions as to the utility of this other data. The column listing “number of picks” gives the number of wells where each unit was documented in Appendix C of the update report. The columns “Structure Contour” and “Cross Section” indicate whether the unit was represented in either of these two forms.

Table 1. Geologic Units Included in Model Conversion

Symbol	Age	Unit Name	Number of Picks	Structure Contour	Cross-Section
MO	Pleistocene	Montgomery sand of the Lissie Unit	11	no	yes
LS	Pleistocene	Bentley mud of the Lissie Unit	14	no	yes
CR	N/A	Caprock	466	yes	yes
PL	Pliocene	-	0	no	yes
MI	Miocene	-	10	yes	yes
TS	N/A	Top of Salt	67	yes	yes
AB	Miocene	Lagarto shale	11	no	yes
RL	Miocene	Oakville deltaic sand	7	no	yes
DR	Oligocene	Anahuac shale	8	yes	yes
F	Oligocene	Frio shale and turbidite sand	1	no	yes

Cavern Geometry at Bryan Mound

The geometric configurations of the underground storage caverns leached into the salt mass at Bryan Mound are unique in that five of the twenty-one existing caverns were leached prior to DOE acquiring the property and have non-standard shapes. Four of these five Phase 1 caverns are presently used to store oil (caverns BM-1, BM-2, BM-4, and BM-5). Cavern BM-5 is by far the largest oil-storage cavern in the SPR complex (37.87 MMB) and BM-4 is the second largest (20.68 MMB). These caverns are much larger than the “design” standard cavern volume of 10 MMB.

There have been significant technical problems with several of the caverns at Bryan Mound. As described in the update report, from 1978 to 1994 there have been 37 incidents in which long portions of the hanging strings have been lost or damaged. In addition, in 1982 a well casing failure in BM 4 resulted in the leaking of approximately 44,000 barrels of oil into the caprock. This casing failure was attributed to the presence of hot, acidic pore fluids within the caprock, which are the result of Frasch-process sulfur solution-mining activities that occurred during the 1930's.

Cavern geometry is 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 Bryan Mound SPR site, however various generations of primitive graphical representations of cavern geometries are included in both the original and update reports. With new 3-D modeling software, it is now possible to convert the sonar survey data to a true 3-D cavern model. These new models are included in this conversion and shown in Figure 6. As shown in the figure, sonar data is not available for cavern 4.

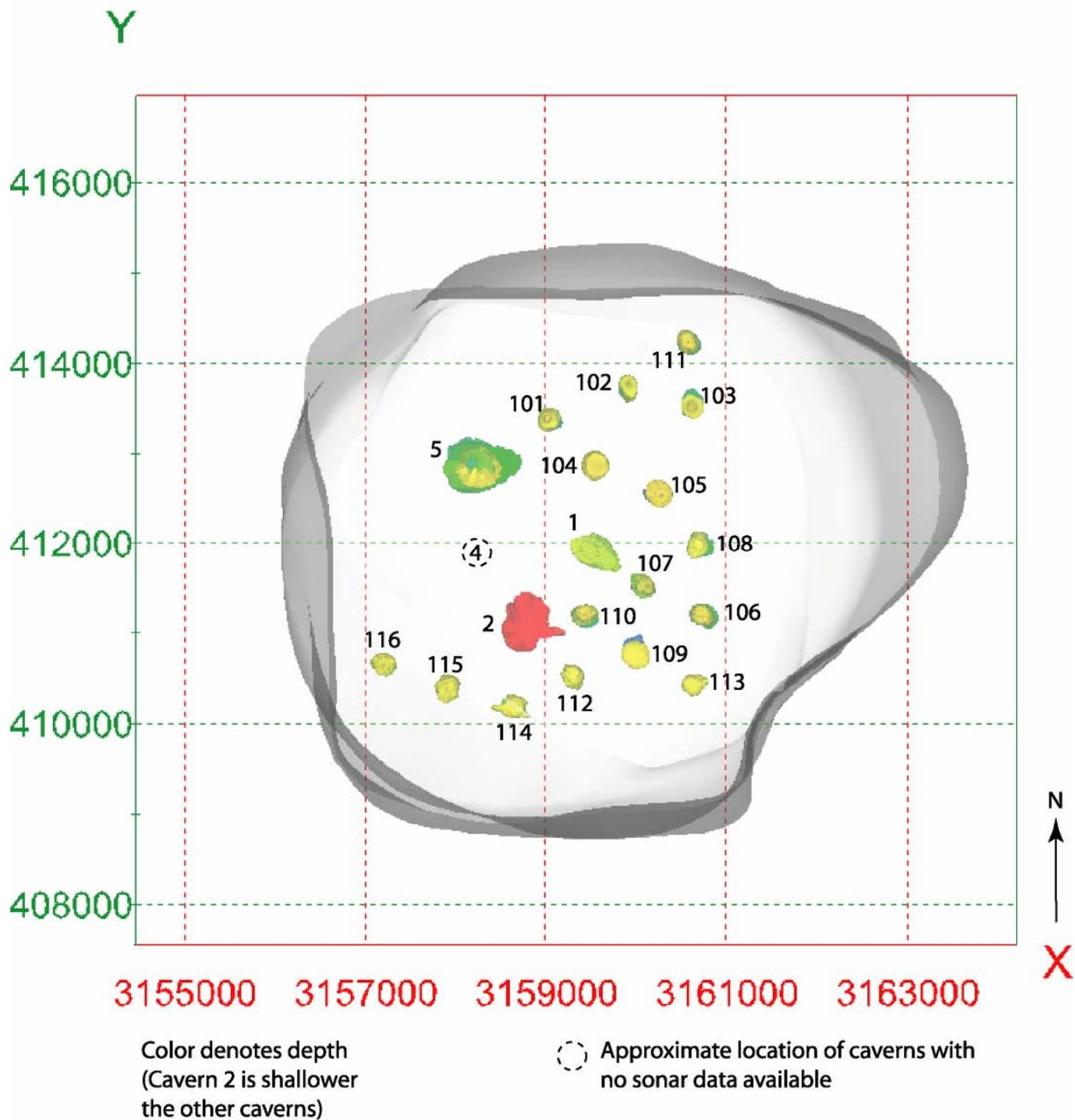


Figure 6. Top view of the Bryan Mound salt dome and selected cavern models. Note that Cavern BM-4 is not represented with a sonar model.

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 Bryan Mound SPR site. The complete 3-D model consists of a collection of components, of which each required a distinct conversion methodology. These methodologies are described below.

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.

Geologic characterization data for the Bryan Mound Strategic Petroleum Reserve Site were originally recorded using a number of different coordinate systems. Oil and gas well locations are referenced to the Texas land survey as distance along survey boundaries, sulphur wells are referenced to a site-specific grid system developed by the Freeport Sulphur Company, and DOE wells are referenced to another site-specific grid system called the Baker Coordinate System. Site characterization reports generated by Sandia National Laboratories and its contractors have listed all well coordinates in the Baker Coordinate System (Hogan, 1980; Neal and others, 1994). Hogan (1980) alludes to a mathematical transformation that has been used by surveyors to covert between Baker and Texas state plane (Lambert) coordinates, the citation to this conversion consists of a personal communication from 1980, which means that this detailed information is essentially no longer available (Hogan, 1980). Lambert coordinates most likely refer to Texas state plane coordinates (south-central zone). The Texas state plane coordinate system is a Lambert conformal conic projection, almost invariably using the North American Datum of 1927 (NAD-27). However, there is no indication of the datum used. The absolute magnitudes of the coordinates shown by marginal ticks on maps 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 Lambert coordinates shown on the reference maps belong to the Texas state plane coordinate system, south-central zone, NAD-27.

The only material available in the site characterization reports that links the Baker and Lambert coordinate systems are two maps that show Baker, Lambert, and several other grids on a common base (Hogan, 1980). These maps can be used to calculate transformation formulas that can be used to convert between Baker and Lambert systems. This process is described below.

For this work it is assumed that the Baker and Lambert coordinate systems are related by an affine polynomial transformation, which is a subset of the more general bilinear transformation. Bilinear transformations account for rotation, shift, and differential scaling in X and Y. The affine polynomial transformation of a plane results in squares and circles being transformed to parallelograms and ellipses of the same orientation.

The general form of the affine transformation is:

$$\begin{aligned} X &= a + bx + cy \\ Y &= d + ex + fy \end{aligned} \quad (1)$$

where X , Y and x , y are pre and post transformed coordinates and a - f are the transformation coefficients. The transformation coefficients can be calculated by a least-squares method using a dataset of points with coordinates from both systems. Such a dataset was obtained by digitizing 25 points on the maps included in Hogan (1980) (Figure 7). The map was first calibrated to the Lambert grid. Then the 25 points referenced to Baker coordinates on the map were digitized. Both the original Baker coordinates from the map and the calibrated Lambert coordinates from digitizing are listed in Table 2.

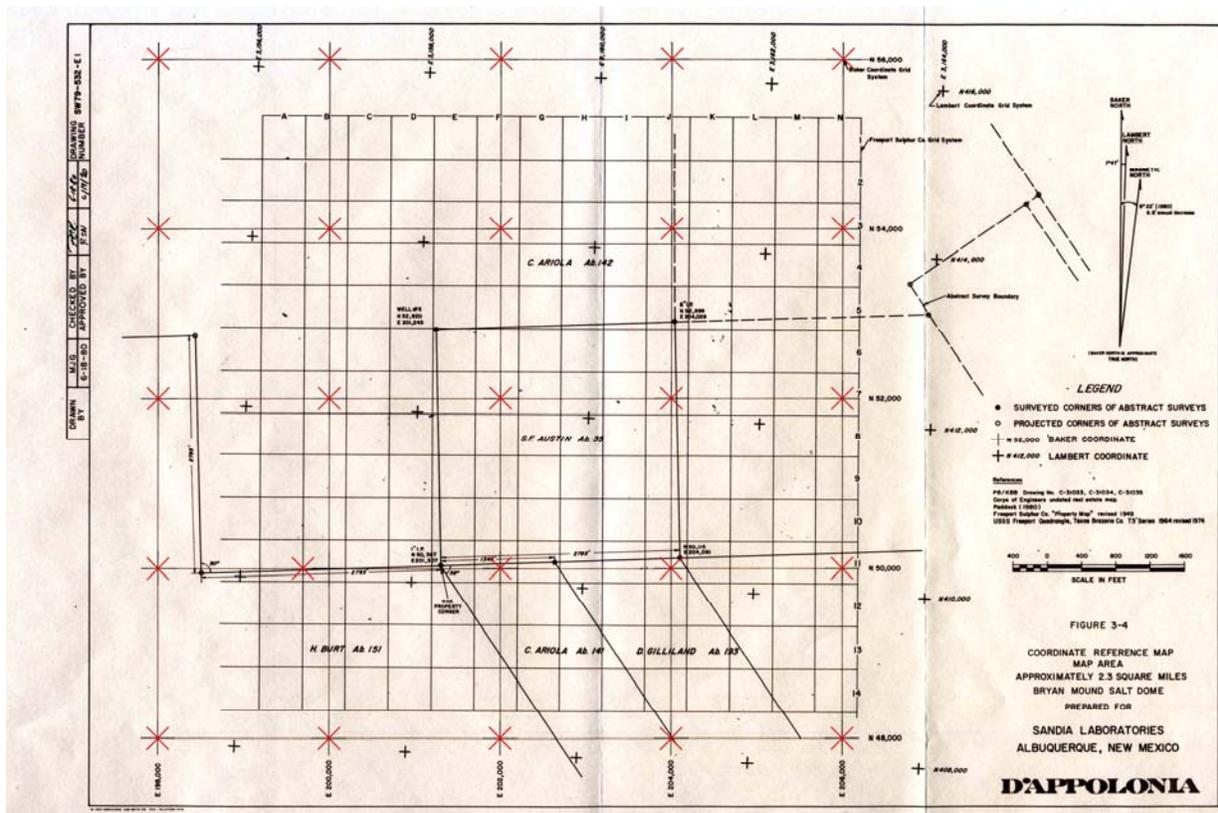


Figure 7. Coordinate reference map for the Bryan Mound site from Hogan (1980). Red Xs show the location of the 25 points chosen to define the coordinate transformation between Baker and Lambert coordinates.

The method used to calculate the optimal set of transformation coefficients is as follows:

1. Three of the 25 points were used to solve the six linear equations to estimate initial values for the six unknown transformation coefficients.
2. The solver add-in in Microsoft Excel was then used to optimize the values for the six unknown transformation coefficients by minimizing the sum of squared differences between the calculated and digitized coordinates. This procedure

was repeated for the inverse transformation. The resulting transformation coefficients are listed in Table 3.

Table 2. Digitized Coordinates Used to Define Affine Polynomial Transformation Formula for Bryan Mound, SPR Site.

	Baker X [feet]	Baker Y [feet]	Lambert X [feet]	Lambert Y [feet]
1	206000	48000	3163097.21	408328.78
2	204000	48000	3161099.63	408257.77
3	202000	48000	3159101.81	408193.61
4	200000	48000	3157104.12	408126.02
5	200000	50000	3156727.54	410112.96
6	202000	50000	3159033.10	410190.96
7	204000	50000	3161027.38	410258.44
8	206000	50000	3163024.95	410329.45
9	206000	52000	3162956.24	412326.81
10	204000	52000	3160958.54	412259.22
11	202000	52000	3158964.14	412195.17
12	200000	52000	3156963.15	412124.04
13	206000	54000	3162890.82	414327.71
14	204000	54000	3160893.13	414260.12
15	202000	54000	3158895.43	414192.53
16	200000	54000	3156897.86	414121.52
17	206000	56000	3162825.53	416325.18
18	204000	56000	3160824.29	416260.91
19	202000	56000	3158826.72	416189.89
20	200000	56000	3156825.60	416122.19
21	198000	56000	3154821.06	416054.37
22	198000	54000	3154896.74	414053.82
23	198000	52000	3154965.58	412053.03
24	198000	50000	3155034.41	410052.25
25	198000	48000	3155103.00	408058.31

Table 3. Affine Polynomial Transformation Coefficients

a	-2.969260E+06	
b	9.990165E-01	Lambert to Baker
c	3.740117E-02	$BX = a + b * LX + c * LY$
d	-2.519800E+05	$BY = d + e * LX + f * LY$
e	-3.413124E-02	
f	9.990487E-01	
a'	2.958128E+06	
b'	1.002245E+00	Baker to Lambert
c'	-3.136307E-02	$LX = a' + b' * BX + c' * BY$
d'	3.531110E+05	$LY = d' + e' * BX + f' * BY$
e'	3.502743E-02	
f'	1.000085E+00	

The mean errors introduced by these transformations are approximately 24 ft in the X-direction and 3 ft in the Y-direction.

Generation of Salt Dome Model

There are two existing 3-D models of the extent of the salt dome at Bryan Mound, one from the original site characterization report, and one from a more recent characterization from the update report. The method used to convert these models of the 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 contained in the two reports, 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.

The most obvious difference between the two models of the salt dome is that the updated model extends to 7,000 ft, 2,000 ft deeper than the original model. There are also other more subtle differences between the models, which are discussed in the report by Rautman and Stein (2003). For the purposes of this report, the updated salt dome model will be used in this model conversion.

Generation of Sediment Models

All the units listed in Table 1 are converted to a 3-D model in this report. This section will discuss the conversion methodology used for all of the sedimentary units (Table 1 excluding the top of salt and caprock units). Geologic data that constrains the geometry and structure of sedimentary units at the Bryan Mound SPR site exists in three forms: geologic picks from borehole data (figures 2 and 3), structure contour maps (figure 4), and cross sections (figure 5). The borehole locations of the geologic picks were digitized in Baker coordinates and then converted to State Plane coordinates according to the transformation described earlier. Structure contour maps and cross sections from the update report were digitized directly and converted to State Plane coordinates following the same methodology. The results of these conversions are presented separately in the results section. Note that only the cross-section dataset includes all the units listed in Table 1.

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.

We used the kriging functionality of MVS to convert the geologic data (depths to the top of geologic units) from the various sources to 3-D surface and volume meshes. The *Krig3D_Geology* module of the MVS modeling software performs the 3-D kriging for all units sequentially but in one continuous computational pass for each type of data (e.g. geologic picks, digitized structure contours, and digitized cross-sections).

Generation of Fault Models

Only four faults intersecting the sedimentary units were identified in the update site characterization report on structure contour maps. To include these faults in the 3-D modeling we followed a series of steps:

1. Fault traces from each sediment 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 based on the structure contour map 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 two available sediment structure contour maps using the application Didger 3 from Golden Software (www.goldensoftware.com). Each structure contour map was scanned to produce a bitmap image. Bitmap images were imported into Didger and were calibrated spatially, 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 represented by ten equally spaced (x,y) points. These two-dimensional points were then projected onto the modeled three-dimensional geologic surface based on the structure contours (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 both of the geologic surfaces intersected by the fault (Miocene and Anahuac). Finally the complete fault surface was generated by connecting the (x,y,z) points from the two stratigraphic surfaces intersected by the fault into a triangulated irregular network using the MVS module: *scat_to_tin*.

Figure 8 illustrates the methodology used to construct one of the fault models. The process described above and illustrated in this figure was repeated for each of the four faults identified on the structure contour maps. Note that the faults were not named on the structure contour maps and therefore it was assumed that (1) the same faults were mapped on each structure contour map and (2) that the fault traces correspond between the two geologic units such that the faults are as steeply dipping as possible. The first assumption is reasonable because the layout of fault traces on both structure contour maps is similar. The second assumption is reasonable given the tectonic environment, which typically results in steeply dipping radial faults around the rising salt dome.

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 Bryan Mound site. The effort is not a remodeling of the site

geology. Overall, the distortions induced by this simplistic modeling approach are minimal.

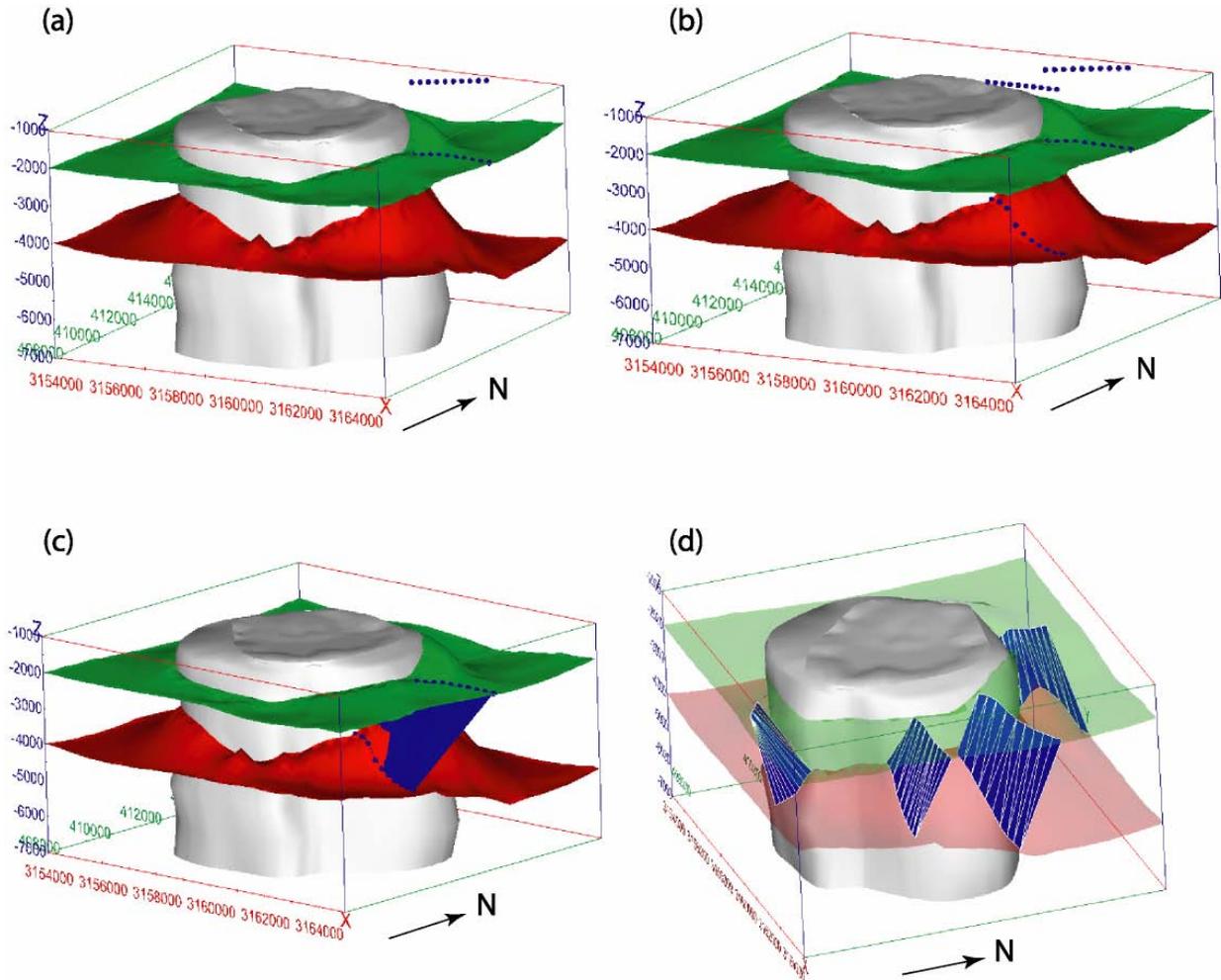


Figure 8. Method used to develop fault models surrounding the Bryan Mound salt dome. (a) Digitized fault trace is projected from surface on to the modeled surface of the geologic unit (Miocene). (b) Step is repeated for the Anahuac. (c) A triangulated irregular network joins the projected points between the two sedimentary units. (d) Four fault models shown with grid lines.

Generation of the Cavern Models

Cavern sonar surveys were converted to 3-D models 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 is essentially a line and that the reflecting surface is oriented 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. This limitation is especially relevant for the irregularly shaped Phase 1 caverns.

RESULTS

3-D geologic models of the Bryan Mound SPR site have 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-Dimensional /Interactive Model] 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 Bryan Mound salt dome model is presented in an aerial view in figure 9 and in perspective from the southwest in figure 10. Figure 9 shows a partially transparent areal photo color coded to land surface elevation with the dome visible below. The dome is generally cylindrical in shape and is slightly inclined toward the west. The top of the dome is relatively flat and lies at a depth between 1,000 and 1,100 feet below the surface. The sides of the dome are quite vertical with minor overhangs on all sides except for the east flank. The dome model as represented in the original site characterization report (Hogan 1980) is modeled only to a depth of 5,000 feet below the surface; the actual dome unquestionably extends to far greater depths. The updated dome model included in this report extends to 7,000 ft.

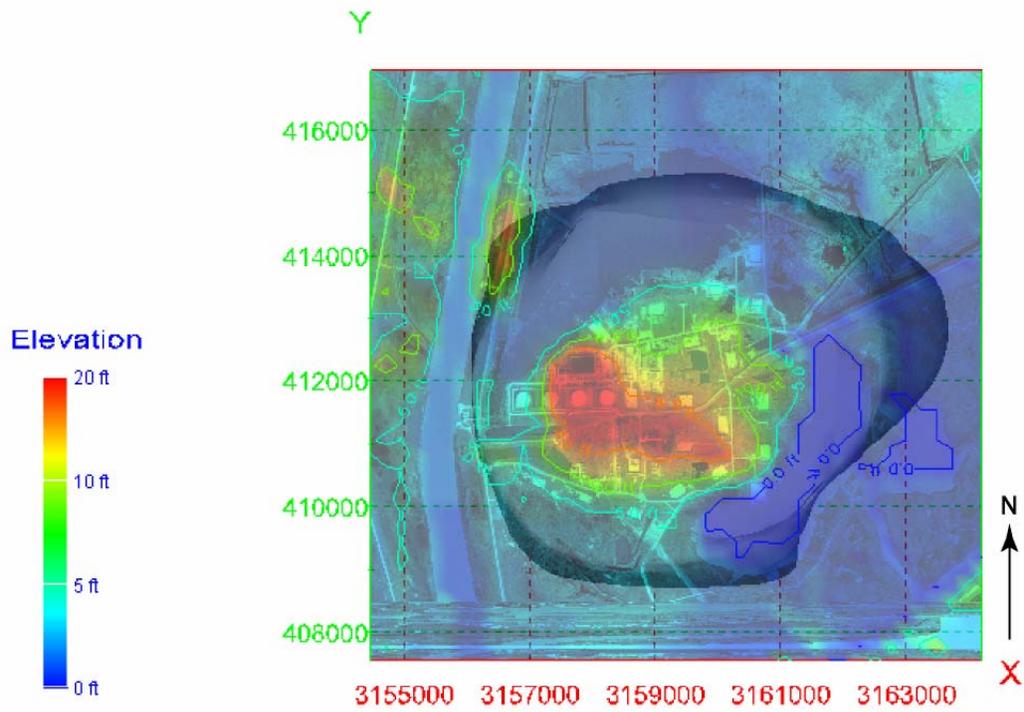


Figure 9. Semi-transparent aerial photo of the Bryan Mound site colored by surface elevation and showing the lateral extent of the underlying salt dome model.

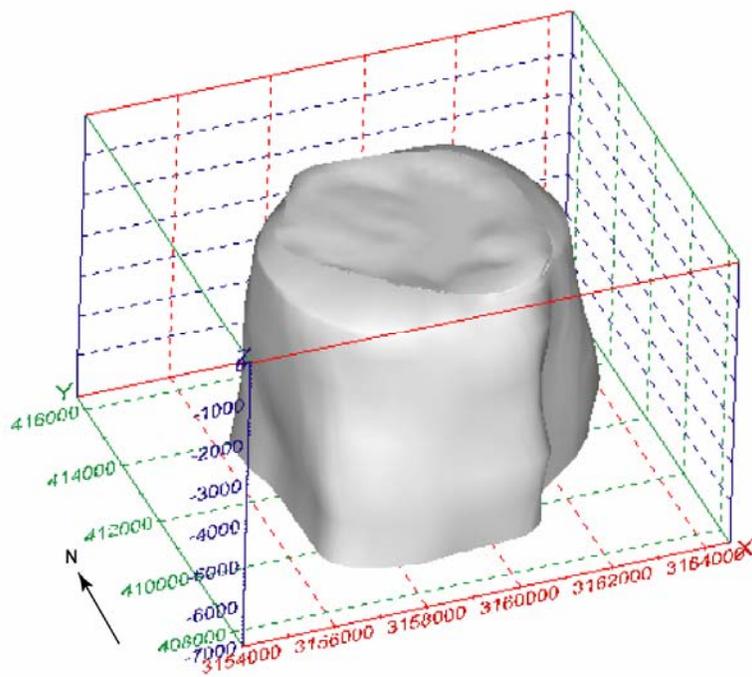


Figure 10. Bryan Mound salt dome model viewed from the southwest.

Sediment Model

The three geologic models of the sedimentary layers surrounding the dome are shown in figures 11 to 13. The color of each unit is different for illustration purposes and does not represent any physical property. The first model based on the borehole data includes the tops of six geologic units (figure 11). While this model is the only one of the three that agrees with the limited data set, it is probably the least representative of the group because it is based on so few data points. For example, close examination of this model (see 4-DIM version) shows that in the northern half of the domain the units of the Lagarto shale (AB) and the Oakville deltaic sand (RL) appear to merge together. This artifact occurs as a result of kriging a small number of data points with large areas where geologic units are not identified. In this instance neither of the wells furthest to the east and west include the Oakville deltaic sand. Furthermore the easternmost well does include the Anahuac shale, which lies below the Oakville. The fact that the Oakville unit is missing in that well likely means that there is an unconformity in that vicinity. However, the method of kriging in combination with the small number of available data cannot be used alone to identify such a feature. The second model includes only two geologic units (Miocene (MI) and Anahuac (DR)) and is based on interpretations documented in structure contour maps (figure 12). The mismatch between contour data and the resulting model in certain regions is due to the presence of discontinuities caused by fault offsets, which tend to be smoothed out in the process of kriging. The third model is based on four geologic cross-sections and includes seven geologic units (figure 13). Interestingly, this model does include an angular unconformity between the Lagarto shale and the Miocene units located on the east, northeast, west and northwest flanks of the dome. Presumably this interpretation was based upon boreholes where the Oakville deltaic sands appeared to be missing from the section. Even though this model appears to be somewhat more consistent with data and geologic principles, it is still quite rudimentary because of the small number of boreholes and the fact that the depths of units far from the cross-sections were used directly to define the depth at the cross-section locations.

Based on the different methods used to create the models, it is not surprising that each of these models is quite different. Because the first model was developed by kriging a limited set of actual borehole data, it is the only model of the three that actually honors that data. However, this model shows only limited tilting of geologic units near the edge of the dome, which would be expected as a result of the upward movement of the dome. The second and third models of the sediments represent a geologist's interpretation of the limited dataset and include features such as tilting and an angular unconformity, which are inferred to exist near the flank of the dome.

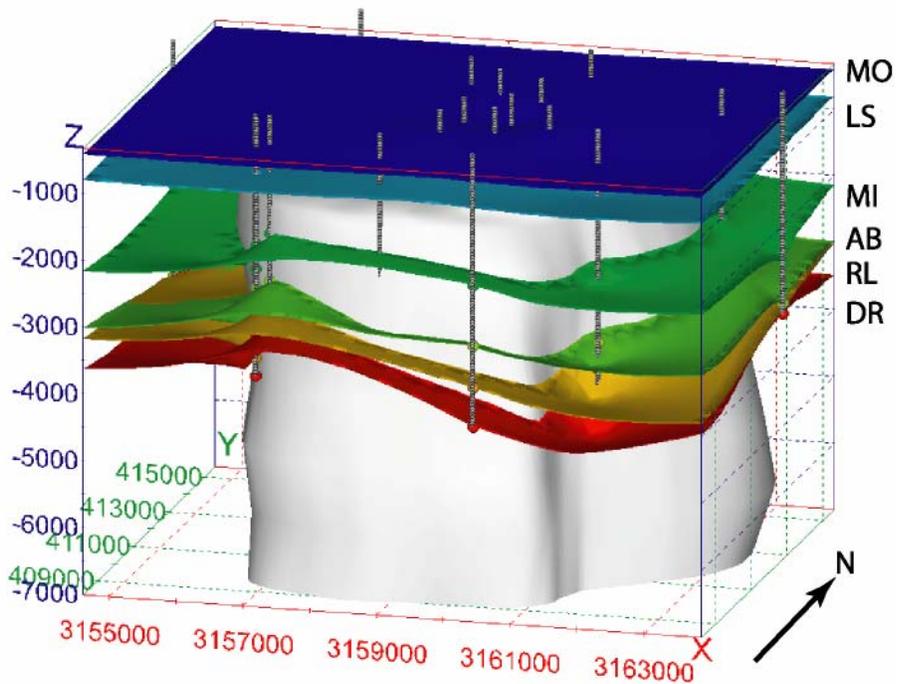


Figure 11. Three-dimensional view from the southeast of the Bryan Mound salt dome sediment model based on borehole data, which is displayed. No vertical exaggeration.

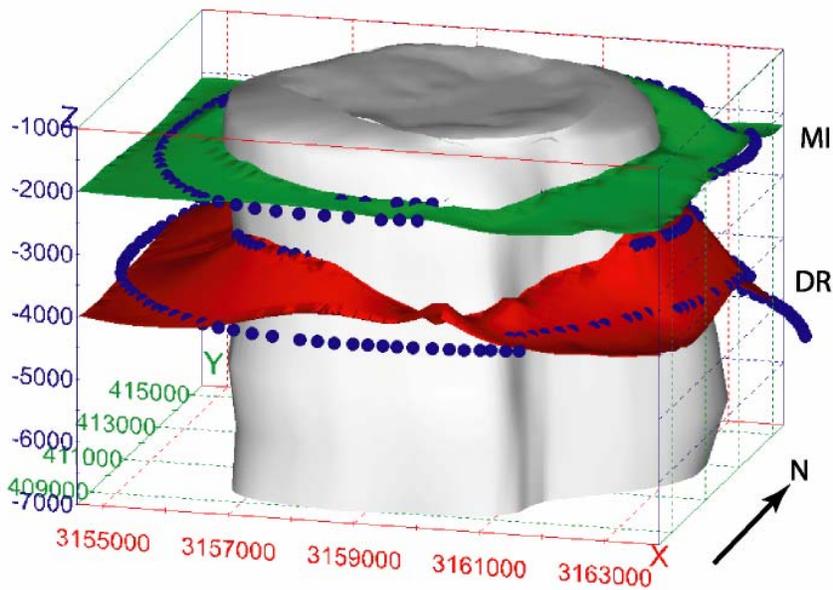


Figure 12. Three-dimensional view from the southeast of the Bryan Mound salt dome sediment model based on sediment contour maps. Digitized data points shown as blue spheres. No vertical exaggeration.

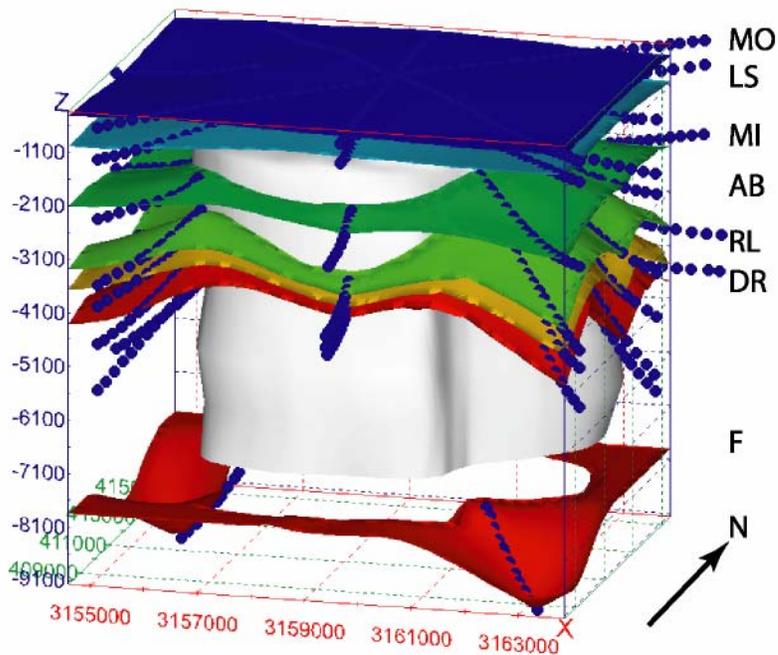


Figure 13. Three-dimensional view from the southeast of the Bryan Mound salt dome sediment model based on four geologic cross-sections. Digitized data points shown as blue spheres. No vertical exaggeration.

Caprock Model

Caprock is an accumulated dissolution product that forms and is altered as the salt mass rises and encounters shallow groundwater. Over time the dissolution products (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.

There are 466 wells that intersected caprock at the Bryan Mound SPR site and that were recorded in the updated site characterization report. This high density of caprock wells means that a relatively accurate representation of the caprock can be made by kriging these data. The bottom of caprock is estimated using data from 67 wells that intersected the top of salt. Figure 14 shows the resulting caprock model. The majority of the caprock is 300-400 ft thick.

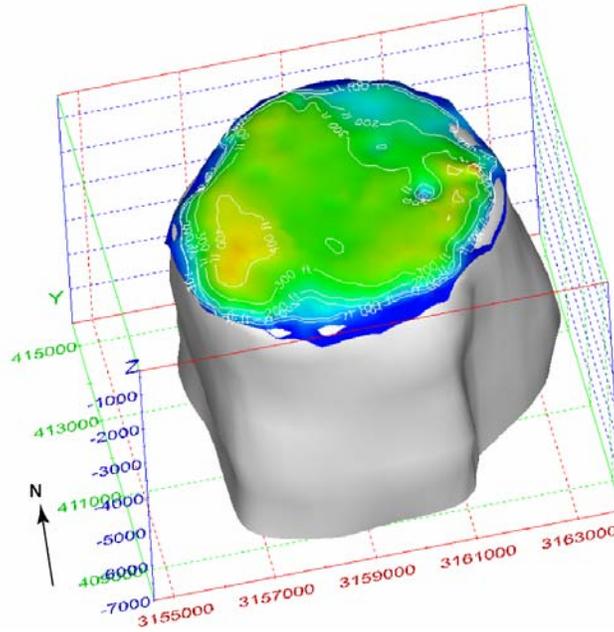


Figure 14. 3-D model of caprock made by kriging well data that define the top of caprock and the top of salt (considered to be bottom of caprock). Contours are of caprock thickness in feet.

Fault Models

The geometric models of faults surrounding the Bryan Mound salt dome are displayed in figure 15, with the view from the top. The faults tend to have relatively steep dips and extend radially away from the edge of the salt dome. The fault models presented here only extend between the Miocene and the Anahuac, but presumably faults would extend beyond these units, depending upon the timing of fault movement at the site. In addition, no offset in the sedimentary layers is shown, since the faults are simply 3-D surfaces connecting the fault traces. The reasons for and implications of this simplified modeling process are discussed under the section, *Generation of Fault Models*.

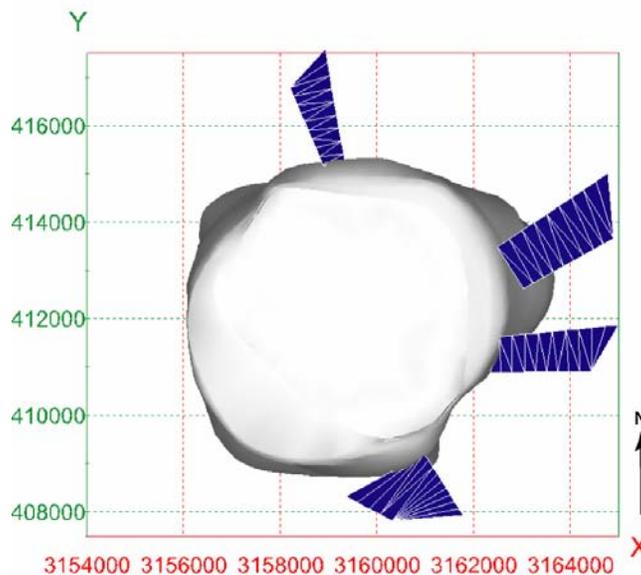


Figure 15. Aerial view of fault models surrounding the Bryan Mound salt dome.

Cavern Models

The most recent available sonar data for 19 of the 20 Bryan Mound caverns are listed in table 4. Figure 16 presents an aerial view of these 3-D cavern models colored by elevation.

Table 4. Dates and Other Information for Sonar Surveys Used in Modeling Bryan Mound Caverns

Cavern ID	Survey Well	Date of Survey	Original File Name
BM-1	A	Jun 17, 1996	COMP-BM1.asc
BM-2	2	Dec 16, 1995	r-bm2.asc
BM-4	-	-	Not available
BM-5	A	Sep 24, 1987	1-bm5a.asc
BM-101	A	Aug 27, 1996	BM-101A.asc
BM-102	C	May 20, 2003	Bm-102c.asc
BM-103	B	Mar 27, 1997	BM-103B.asc
BM-104	C	Dec 18, 1997	r-bm104c.asc
BM -105	B	Feb 8, 1998	R-BM105B.asc
BM -106	B	Jan 19, 2000	Bm-106b.asc
BM -107	B	Jun 19, 1997	R-BM107B.asc
BM -108	A	Jun 8, 2000	Bm-108a.asc
BM -109	B	Sep 18, 1997	BM-R109B.asc
BM -110	B	Jan 24, 2001	bm-110b.asc
BM -111	A	Sep 9, 1997	BM111A.asc
BM -112	A	Feb 15, 2000	Bm-112a-2000.asc
BM -113	A	Oct 26, 1995	2-BM113A.asc
BM -114	A	Feb 25, 1996	R-BM114A.asc
BM -115	A	Mar 15, 2004	bm-115a.asc
BM -116	A	Mar 23, 2004	bm-116a.asc

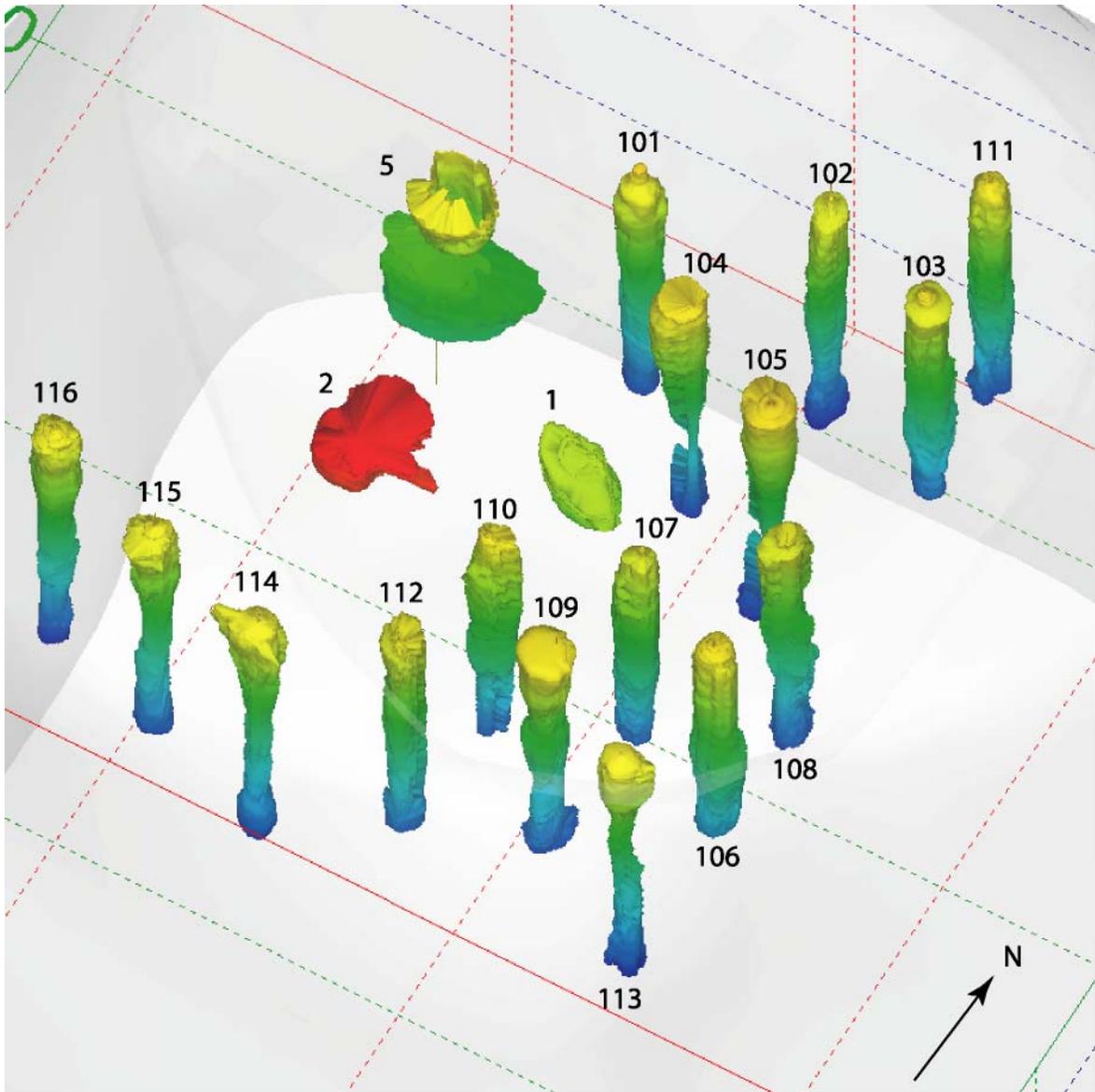


Figure 16. Visualization of 19 Bryan Mound caverns within the salt dome. Color represents elevation.

Phase I caverns 1, 2, and 5 have non-cylindrical shapes due to way they were solution mined. The remaining Phase II caverns all have similar semi-cylindrical shapes and are located at approximately the same depth interval. The nominal design shape of approximately cylindrical, slightly downward-tapering cavities is quite apparent for many of the caverns, as is appropriate for the 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.

Although these types of geologic features would be important in a full-scale recharacterization of the Bryan Mound salt dome, full discussion of their implications is beyond the scope of this model-conversion report.

DISCUSSION

Salt Dome Model

The salt dome model was constructed by digitizing the structure contour map for salt included in the update site characterization report. A detailed description of the methodology used to create this model is described in another report (Rautman and Stein, 2002), which also presents an earlier version of the Bryan Mound salt dome model. 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. 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 17 shows two views of the dome model along with 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 much of the dome model, especially along the flanks are very poorly constrained. 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.

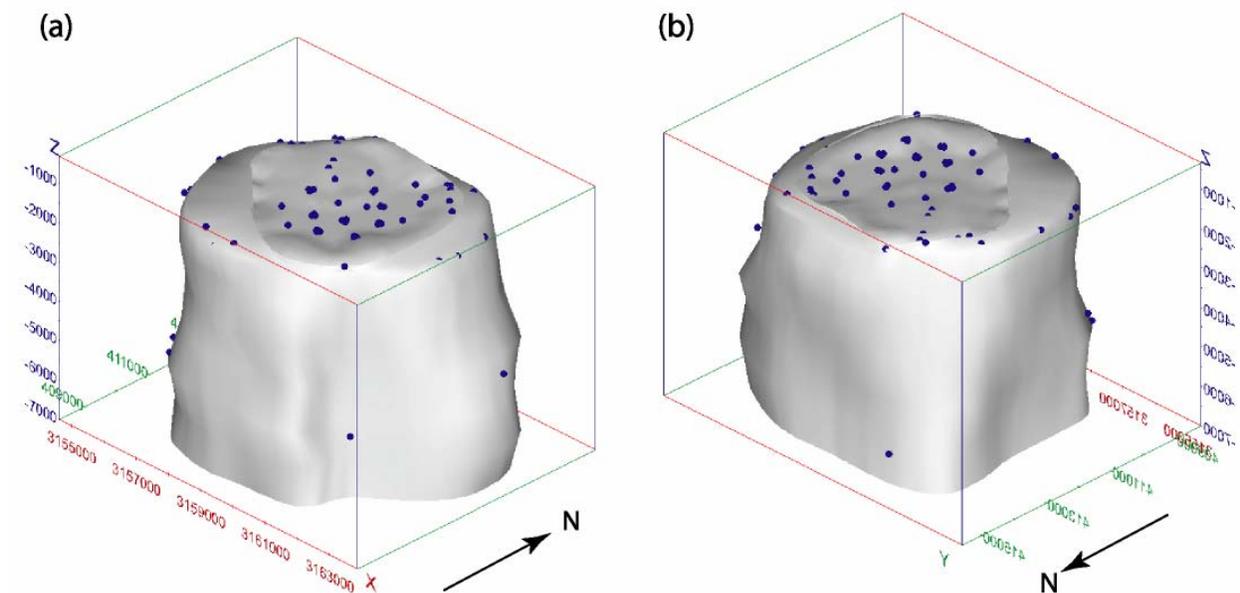


Figure 17. Bryan Mound salt dome model showing locations where the edge of salt was identified in boreholes. (a) View from the southeast. (B) View from the northwest.

Sediment Models

Three distinct sediment models, each based on a different dataset were developed for this report. Each model included a subset of the geologic units that have been identified at the site. Different models of the same sedimentary unit are significantly different, which indicates that, in general, the overall geology surrounding the Bryan Mound site is not very well constrained. The model based on well data is only constrained by eight boreholes away from the salt dome's edge. The models based on structure contours and geologic cross sections represent two interpretations of the same data and therefore the magnitude and spatial distribution of differences between all these models is one representation of the uncertainty in the surrounding geology around the site. Figures 18 and 19 show a map of the maximum difference in elevation of the tops of the Miocene and Anahuac units among the three models. Note that the maximum elevation difference varies considerably by location. For example, the maximum difference in elevation of the top of the Miocene occurs near the northern flank of the dome. This position corresponds to the location of one of the faults identified on the structure contour maps. This fault is associated with a relatively large vertical displacement (~500 ft), which is represented explicitly in the model based on the structure maps, but not in the other models. Because of this discrepancy, there is a significant difference in elevation of this unit between the three models at this location. There are three distinct regions where the differences between models of the Anahuac are quite large. These locations correspond to regions across which the geologic cross sections pass. The geologic cross-sections are derived from well data that frequently is projected onto a cross section line over significant distances. For example, the cross section oriented east-west, which passes directly through two of the areas of large differences between models, uses data on its east end that is projected from wells over 1500 ft from the cross section. Therefore, the uncertainty in this estimate of the depth to the Anahuac at that location is quite large and it is not surprising that significant differences between the models occur in these regions. In addition, in two of the regions where large differences are identified, the cross-section model includes a representation of an angular unconformity at a depth between the Miocene and Anahuac units. This geologic feature is not represented in either of the other models and therefore this may explain why certain areas exhibit very large differences between the models.

Another limitation of the current sediment models is that they are 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.

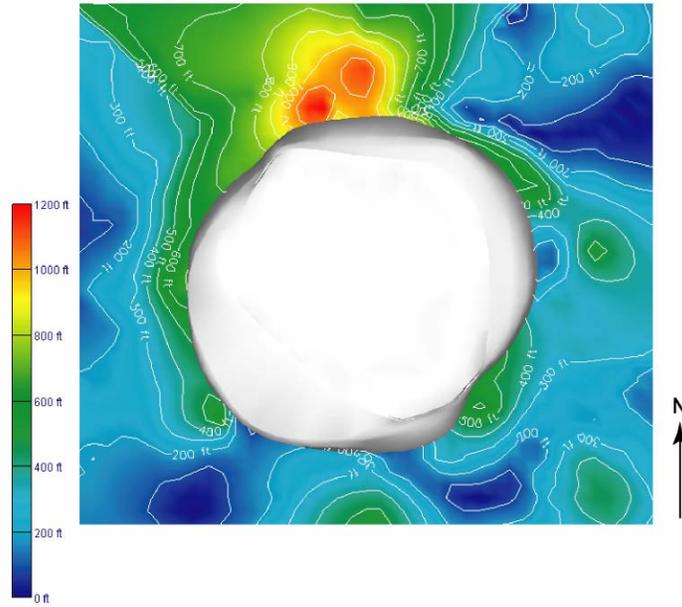


Figure 18. Map of the maximum difference in the elevation of the top of the Miocene surrounding the Bryan Mound salt dome among the three different sediment models based on well data, structure contours, and geologic cross-sections.

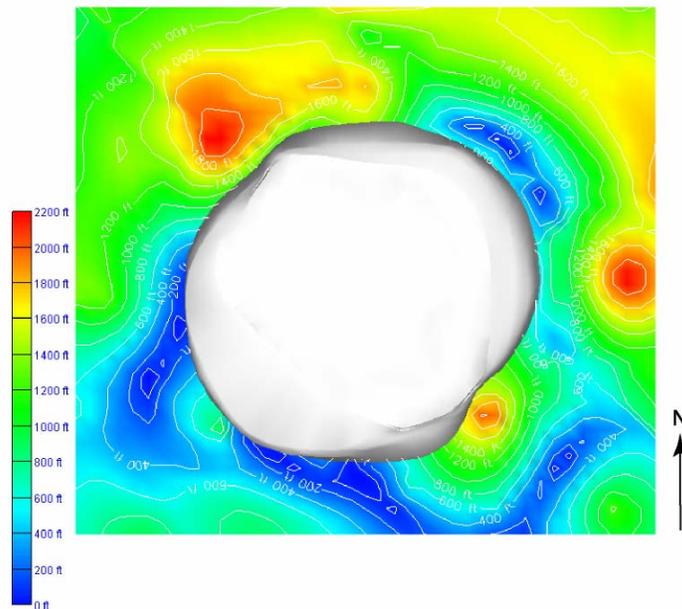


Figure 19. Map of the maximum difference in the elevation of the top of the Anahuac surrounding the Bryan Mound salt dome among the three different sediment models based on well data, structure contours, and geologic cross-sections.

Fault Models

The fault models presented in this report are quite idealized. The models are based on inferred fault traces digitized from two structure contour maps. 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 Bryan Mound site. However, because the details on how these traces were selected are not well documented in the update 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 geometries. At present, such data are not readily available.

Because of the limited data available to define discrete offsets along faults, we chose not to represent these features explicitly. Instead, 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. 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 well constrained, with each nodal point on a cavern mesh constrained by sonar measurements. Nevertheless, there are limitations to the models as discussed earlier. In some caverns where wall irregularities are significant, the sonar measurements become more inaccurate. These irregularities can be deep sub-cavities wherein sonar measurements may underestimate the degree of irregularity since the sonar beams cannot “see” around corners. In these cases some of the sub-cavities may extend further than can be imaged.

CONCLUSIONS

We have presented several complementary 3-D geologic models of the Bryan Mound SPR site. The models are constrained by borehole data and geologic interpretations presented in the updated site characterization report, of Neal and others (1994). The features of the model include the geometry of the salt dome, caprock, surrounding sediments, faults, and oil-storage caverns.

The 3-D models created in this report are a significant improvement on the original 2-D representations because they are geometrically, geologically, and internally consistent. There are significant differences between the models, but these occur because each are based on different interpretations of data. Kriging the borehole data is one method of interpreting the geology. Drawing structure contours and geologic cross-sections is another. Each method has its advantages. The uncertainty in the geology around the Bryan Mound site is due to the limited number of deep boreholes that have been drilled

in this area. In future studies seismic data would be especially valuable for improving our knowledge of the site's geology.

The models presented here provide a baseline for future work at the Bryan Mound 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 improved understanding of the geology surrounding the Bryan Mound and other SPR sites. Because data density is sparse, such three-dimensional geologic models can provide valuable information for defining and quantifying the geologic uncertainty at all SPR sites. With this 3-D visual data, managers can perform real cost-benefit analyses that allow efficient, informed decisions to be made, saving money, time and resources.

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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 (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 at 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 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 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 Bryan Mound 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 BM_Fig_3-6.4d	Figures 3-6
2. File BM_FIG_7+16.4d	Figures 7 and 16
3. File BM_FIG_8.4d	Figure 8
4. File BM_FIG_9-10.4d	Figure 9 and 10
5. File BM_FIG_11.4d	Figure 11
6. File BM_FIG_12.4d	Figure 12
7. File BM_FIG_13.4d	Figure 13
8. File BM_FIG_14.4d	Figure 14
9. File BM_FIG_15.4d	Figure 15
10. File BM_FIG_17.4d	Figure 17

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