FINAL REPORT

Walden 3-D, Inc.

Creatively
Combining Concepts

Interpretation of Seismic Data in the area of the Boling Salt Dome
A Comprehensive Written Report

Interpretation Problem

Interpret seismic data across and adjacent to a proposed salt cavern based industrial waste disposal site on the north central portion of the Boling Salt Dome in Wharton County, TX. The specific objective was to evaluate if there is a salt overhang that could decrease the horizontal extent of salt between the edge of the cavern and the salt-sediment interface.

Key Data Sets

- Topography maps.
- Well data.
- Seismic survey location maps.
- Three sets of seismic data are available in the area of interest (Figure 1):
  - A high-resolution (0.25 ms sample rate or approximately 9 inches per sample at the Top of Caprock) 3-D seismic survey across the site of interest: SEM.
  - A 2-D seismic line orthogonal to the Boling Salt Dome: S-2.
  - A high-resolution (2.0 ms sample rate or approximately 6 feet per sample at Top of Caprock) 3-D seismic survey off the north flank of the Boling Salt Dome: Sheik.
- Maps of the Top of Caprock and the Top of Salt, based on well control data.

Data Preparation and Data Loading

The seismic data for each of the three surveys was loaded on a Landmark Graphics interpretation workstation. Three projects were set up: SEM; Sheik; and Composite. The initial well-based "Top of Caprock" map (SEM Figure 6-6) was gridded and the grid entered as a horizon into the Composite project. This Top of Caprock horizon was generated by interpolating between points taken on a 2,500 foot grid in X and Y directions, triangulating a surface between these points, writing these surfaces into an horizon in 100 foot square bins in the "Composite" project, smoothing the results, and thus creating a "violet" colored horizon. This violet well-based Top of Caprock horizon was exported and then imported into the "SEM" project.

The four proposed caverns in the project were superimposed into the seismic record to provide a reference point during review of the information. The size of the projected Salt Caverns was converted to seismic travel time and horizons were made to show the anticipated location within the SEM 3-D seismic volume. The proposed west cavern

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(WDW-320) was colored red, the south cavern (WDW-321) blue, the north cavern (WDW-322) orange, and the east cavern (WDW-323) green.

In addition, location maps, the description of the proposed caverns, the paper seismic section for line S-2, and other relevant information was scanned and entered into the HyperJournal named ESF. The ESF HyperJournal is the on-line repository for interpretation results and key data examples. This HyperJournal can be delivered to anyone with a Sun or Silicon Graphics workstation for a detailed review of the interpretation process and the work flow.

Interpretation Results from the SEM 3-D Seismic Survey

A detailed interpretation was done on the SEM 3-D seismic survey. The most obvious reflector was determined to be the Top of Caprock reflector. This interpretation was confirmed in two ways: (1) by bringing the gridded well-based Top of Caprock map derived from drilling results into the SEM project and displaying the results as a violet horizon; and (2) by checking several drilling locations with well logs, and using average velocities to plot the top-of-caprock and top-of-salt directly on the appropriate seismic sections. The violet horizon tracks the strong reflector fairly closely through-out the SEM 3-D seismic survey. There are a few places where, because of variations in the Top of Caprock surface, the violet horizon is up to 50 ms away from the strong reflector (150 foot vertically at the Top of Caprock), but overall the Top of Caprock horizon is within about 20 ms of the strong reflector (60 foot vertically at the Top of Caprock). Based on the fact that this contour map was interpolated from widely spaced well logs and from a sparsely sampled grid, the average 20 ms variation in the plotted horizon indicates a consistent interpretation. Recall that the violet well-based Top of Caprock map was developed by interpolating points on a 2,500 foot grid and then triangulating the surfaces on a 100-foot bin size and smoothing the results.

The strong reflector has a strong peak-trough-peak, and the Top of Caprock was picked on the trough as a "red" horizon (yellow 'active horizon' on cross-sections). There was no consistent seismic reflector that could be picked as the Top of Salt. Based on drilling information a 30 ms (~200 foot) "phantom" of the Top of Caprock horizon was created to define the Top of Salt as a "blue" horizon. The well control and seismic interpretation of the Top of Caprock are shown on Line 36 (Figure 2), which runs through both the proposed blue and green (south and east) caverns. The caprock portion of the section has been highlighted with a semi-transparent gray overlay. The Top of Caprock horizon is generally at about 300 ms (~900 feet), but varies somewhat across the site. Figure 3 shows the proposed west (WDW-320, red) cavern just northwest of the SEM 3-D survey on Trace 12. Figure 4 shows the proposed location of the south (WDW-321, blue) cavern on Trace 18. Figure 5 shows the proposed north (WDW-322, orange) cavern, just northwest of the SEM 3-D survey on Trace 37. Figure 6 shows the proposed location of the east (WDW-323, green) cavern on Trace 43. The proposed blue and green caverns are also shown on seismic cube displays in Figures 7 and 8 respectively.

The map of the Top of Caprock horizon dips 75 ms (~225 feet) from the south end of the survey to the north, with a general east-west strike (Figure 9). The relative spatial location of the four proposed salt caverns is shown in perspective view on Figure 10. There are a series of in-line (southwest to northeast) 100 to 500 foot offsets in the contours. These are interpreted as the result of very small displacements. Smoothing through these offsets, shows a maximum vertical offset of 10 ms (~30 feet). The displacements are interpreted as due to caprock alteration and volume change. The apparent strike-slip component may be related to historical salt growth movement. These small compaction displacements can be interpreted on the seismic sections. Figures 11 and 12 show the displacement interpretations on Trace 18. The maximum displacement on any of these displacements is less than 15 ms (~45 feet). There was nothing located on the seismic data to imply that any of these displacements in the sediments above the Boling Salt Dome have had any active movement during the time period in which the last 100+ms (~300+ feet) of sediment have been deposited in the area. This means that these features are at least older than Pleistocene Age. Figures 13 and 14 show the displacement interpretations on Trace 43. On both of the SeisCube displays it is evident how the in-line seismic direction is right along the strike of the displacement.

The seismic reflectors beneath the Top of Caprock horizon are not coherent enough to show the push-down effect of low velocity zones that would indicate high porosity or vuggy intervals. Therefore, in order to more closely evaluate any seismic evidence of variations in the internal structure of the caprock, a series of seismic amplitude extraction maps were made. Figure 15 shows an amplitude extraction of the maximum absolute seismic amplitudes between the Top of Caprock and the Top of Salt horizons. The strong amplitude variations in this map are interpreted as being related to calcite distribution in the caprock. The low amplitude variations are interpreted as being related to the normal anhydrite caprock. Calcite has a higher seismic velocity and there is therefore a higher acoustic impedance. This implies more seismic energy is reflected from those areas with calcite stringers and is the basis of this interpretation of lithology distribution.

Plots showing these various caprock amplitudes in map view are provided as figures 70-73. This series of maps shows the maximum absolute seismic amplitude for different intervals within and just beneath the caprock of the Boling salt dome. The map showing the amplitudes for the first five milliseconds (<30 feet) under the Top of Caprock horizon looks much the same as Figure 15. Of course, these amplitudes are influenced by the wave form generated at the Top Caprock interface. But it is interesting how a map of the first 10 ms (<60 feet) under the Caprock interface smoothes out the sharp amplitude contrasts. An amplitude map from the interval from 10 to 20 ms (~30-60 feet) beneath the Top of Caprock shows the high amplitude contrasts missing. We interpret this to mean that this section is below the calcite zone.

Interpretation Results from S-2, a 2-D Seismic Line

The 2-D seismic section S-2 is orthogonal to the salt dome. A composite section was generated that shows the tie between this seismic line and the two 3-D seismic surveys. There is a good tie to the Top of Caprock interpretation from the SEM 3-D survey. The tie to the interpreted Top of Caprock from the Sheik 3-D survey fits spatially, but there is not a good seismic reflector for this interface. Figure 16 shows the interpretation of the Top of Caprock and the Top of Salt horizons on line S-2. The identification of the Top of Caprock interface is straight forward. The dip of the salt-sediment interface means that there would need to be very long offsets to get accurate direct reflection imagery of this surface.

A letter dated August 25, 1994 from Mr. Cameron Walker of Walker Geophysical Company stated "No anomalous geological structures appear on this data set, and no evidence of late-arriving seismic events suggestive of turning waves was present." However, Dave Hale of Chevron Corporation presented his Turning Wave Theory at The Society of Exploration Geophysicists' Convention in Houston and stressed that special seismic processing was needed to find these seismic events. As depth increases in the area of the Sheik 3-D survey, there are small increases in velocity. Seismic waves bend at these small increments of depth and velocity and refract along the acoustic interface boundaries. At the angle of incidence the head wave between the refractions and the reflections has been shown to form a reflection that can be used to map the side of a salt dome. The fact that there are no reflections on S-2 at these depths, and the straight forward identification of the salt-sediment interface do not justify additional special seismic processing to identify Turning Waves.

Interpretation Results from the Sheik 3-D Seismic Survey

There is not an obvious salt-sediment interface, nor Top of Caprock reflectors in the Sheik 3-D seismic survey. However, there are areas of non-reflection that imply there is salt or that salt moved through the area and disrupted the sediments. Figure 17 shows the interpretation of the Top of Caprock and the shadow Top of Salt based on projecting these reflectors from S-2 and areas of non-reflection. The horizontal reflectors in the Sheik area can be nicely correlated with the reflectors coming up against the salt on line S-2. Some of these reflectors also show a characteristic up turn that is common at the edge or very near the edge of a salt flank. Here it is interpreted as being near the edge of the salt stock or possibly a salt weld.

Interpretation Results Composited from the Available Seismic Data Sets

The structure of the Top of Caprock is simple in the area of the proposed salt caverns. The map of the Top of Caprock outside the immediate area of the 3-D program to also be relatively simple. Based on the integrated interpretations described in this report, of the SEM 3-D, S-2 2-D, and Sheik 3-D seismic surveys, there is no evidence of any salt overhang on the north side of the Boling Salt Dome.

A Report Supplement

Several horizons were interpreted across the SEM 3-D seismic survey above and including the Top of Caprock to evaluate the amount of throw on the various displacement planes. In addition to the travel-time horizons, isochron maps were generated to show the amount of relative deposition at various geologic times. The following maps are black and white contour maps (1" = 400'):

- Figure 56, Horizon 1 (Pink) Map, note there were no displacements identified at this layer (contours were at 8 ms, which at 6,250 '/s is equivalent to 25' contours)
- Figure 57, Horizon 2 (Violet) Map, also has no displacements identified
- Figure 58, Isochron Map (Horizon 1-2) shows gradual thickening to the north
- Figure 59, Horizon 4 (Green) Map, show s the maximum number of small displacements or fault heave polygons, identified in doing this interpretation. Again there is general thickening to the north, where there is a small 'growth fault' which appears to be associated with sediment removal accompanying caprock alteration
- Figure 60, Isochron Map (Horizon 2-4) shows gradual thickening to the north with a minor 'depocenter' associated with the largest displacement and its antithetic
- Figure 61, Horizon 6 (Orange) Map, shows the same thickening to the north with the small 'graben' coming together just to the south of the proposed salt caverns
- Figure 62, Isochron Map (Horizon 4-6) shows a generally constant thickness depositional layer
- Figure 63, Horizon 7 (Red) Map is a contour map of the Top-of-Caprock, showing fairly constant dip to the north
- Figure 64, Isochron Map (Horizon 6-7) shows another generally constant thickness depositional layer, with a little bit of thinning associated with what appears to be alteration driven removal of sediments controlling the 15 ms graben
- The Sky and Blue Fault Plane Maps (Figures 46 and 48) show the only two displacements that have throw up to or slightly exceeding 15 ms
- A plot is also included with a color bar that shows the direction and contour depths of the two fault planes

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The synthetic seismograms generated by Loren & Associates (See Attachment A), indicate that the seismic data should be displayed with reverse polarity. The four images show extracted seismic wavelets for normal and reverse polarity seismic data at a location that emphasizes the strongest reflections (interpreted to be where there is caprock alteration to calcite with possibly some sulfur) and at a location where there is an average reflection amplitude (interpreted to be anhydrite/gypsum). Based on these data the seismic images generated to meet the requested displays have all been displayed with reverse polarity. Note that this does not affect the travel time of the mapped seismic horizons or the isochron maps derived from these mapped horizons.

The lateral extent of the processing based mute gaps in the first 100 ms of the SEM 3-D seismic survey. On the following time-slice seismic sections are depicted:

- Figure 68, 0 ms with a red marker to highlight no data areas
- Figure 69, 20 ms with a red marker to highlight no data areas

A series of black & white seismic sections were generated at 1'=400' horizontal scale and 9' per second vertical scale. This is the same as the base map scale in the horizontal direction and is approximately a 1:1 horizontal:vertical scale. The travel times to the top and base of the proposed caverns were calculated based on the attached RMS Velocity from a sonic log at the Boling Dome by Walker Geophysical Company (dated September 1993). The following calculations show that the proposed caverns are 445 ms at the top and 579 ms at the base:

(300 ms)	x	(6140 '/s) / 2	=	921'
(1,079')	/	(14,925 '/s) * 2	=	145 ms
(2,079')	/	(14,925 '/s) * 2	=	279 ms

or Top of cavern = 300 ms + 145 ms = 445 ms
and the Base of the proposed caverns = 300 ms + 279 ms =579 ms

The following map and seismic sections plots are included:

- A location map of the 8 sections, also showing the location of the two most significant displacement 'fault planes', Figure 25
- Trace 12 through proposed WDW-320 (Red) Cavern with and without interpretations, Figures 34, 35
- Trace 18 through proposed WDW-321 (Blue) Cavern with and without interpretations, Figures 36, 37
- Trace 36 touching proposed WDW-322 (Orange) and WDW-323 (Green) Caverns with and without interpretations, Figures 38, 39
- Trace 65 with and without interpretations, Figures 42, 43
- Line 15 touching proposed Red and Orange Caverns with and without interpretations, Figures 26, 27
- Line 36 through proposed Blue and Green Caverns with and without interpretations, Figures 28, 29
- Line 59 with and without interpretations, Figures 30, 31
- Line 82 with and without interpretations, Figures 32, 33

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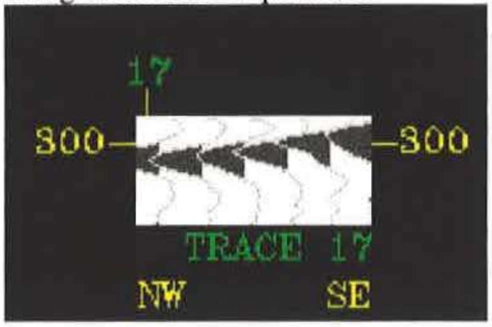
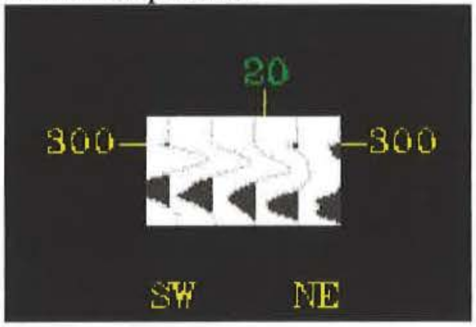
Extracted Seismic Wavelets to be compared with Synthetic Seismograms:

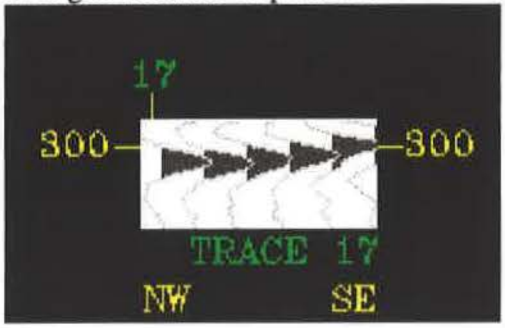
Line 40 Trace 17 showing normal polarity extracted seismic wavelets in an area of strongest acoustic impedance.



Line 19 Trace 20 showing normal polarity extracted seismic wavelets in an area of average acoustic impedance.



Line 40 Trace 17 showing reverse polarity extracted seismic wavelets in an area of strongest acoustic impedance.



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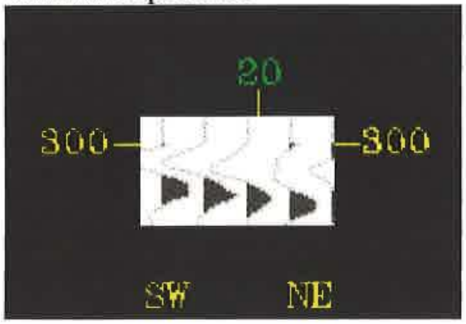
Line 19 Trace 20 showing reverse polarity extracted seismic wavelets in an area of average acoustic impedance.



Conclusions:

The structure of the Top of Caprock of the Boling Salt Dome is simple in the area of the proposed salt caverns. Based on the integrated seismic interpretations described in this report, of the SEM 3-D, WGC S-2, and Sheik 3-D seismic surveys, there is no evidence of a salt overhang on the north side of the Boling Salt Dome. Although there has been some post salt displacement in the study area, probably due to caprock alteration; there is no evidence of any active movement during the time period when the last 100+ ms (~300+ feet) of sediment have been deposited in the area.