Preprint

Integrating Multiple Seismic Surveys to Interactively Interpret a Salt Dome Flank

by

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ABSTRACT

Three seismic surveys were integrated to interactively interpret the northern flank of a salt dome, onshore South Texas. The specific objective was to evaluate if there is a salt overhang that could decrease the horizontal extent of salt between the salt-sediment interface and four planned salt caverns proposed as an industrial waste disposal site. The seismic surveys consisted of: (1) SEM, a high-resolution (0.25 ms sample rate) 3-D seismic survey on the crest of the dome; (2) Sheik, a high-resolution (2.0 ms sample rate) 3-D seismic survey off the north flank of the salt dome; and (3) S-2, a 2-D seismic line orthogonal to the salt dome and passing near both the SEM and Sheik surveys.

The seismic data for each of these surveys was loaded on a Landmark Graphics interpretation workstation at the offices of Interactive Interpretation & Training. Three projects were set up: SEM; Sheik; and Composite. A well based interpretation of the Top-of-Caprock was gridded and entered into a horizon in the Composite Project. The smoothed travel-time exported version of this horizon was imported to the SEM survey to provide a check for picking the Top-of-Caprock. There is a direct correlation to a strong reflector consistent across the SEM survey. This reflector was interpreted as the Top-of-Caprock. This reflector ties nicely to the salt-sediment-interface interpreted on S-2. The S-2 salt-sediment-interface projects to the top of a no-data-area in the Sheik 3-D seismic survey, which was interpreted as top-of-salt. The proposed salt caverns were converted to seismic travel-time and loaded into the SEM survey as both "faults" and "horizons" to show their spatial relationship to the Top-of-Caprock.

The interpretation process and results were captured in the ESF HyperJournal, a hyperlinked multimedia "living report." Key stages from this report are available on the INTERNET at http://www.walden3d.com/w3d/geotechnology/W3D95C/index.html using a browser like NetScape or Mosaic. The interpretation results were also transferred to The University of Houston's Virtual Environment Technology Laboratory and the spatial relationships evaluated in their visually immersive CAVE (for those familiar with StarTrek terminology, a computer generated 'holodeck'). This virtual environment has proven to be a very useful means of communicating complex spatial relationships.

One of the more interesting results to be presented is the relationship of seismic amplitudes to calcite distribution in the caprock. Using the interactive system we evaluated the seismic amplitudes from 10 ms intervals (less than 30 feet). We interpret the strong difference between these amplitude maps to mean that the calcite zone is totally within the top 30 feet of the caprock. The map across the entire dome shows this to be a relatively simple dome. The structure of the Top-of-Caprock is simple in the area of the proposed salt caverns. Based on this integrated interpretation, there does not appear to be any salt overhang on the north side of the dome. This means there is virtually no possibility of water reaching the proposed salt caverns and their proposed storage of industrial wastes within the next few thousand years.

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Interpretation Problem

The interpretation problem was to interpret seismic data across and adjacent to a proposed salt cavern based industrial waste disposal site on the north central portion of a salt dome onshore South Texas. 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 proposed caverns and the salt-sediment interface.

Three seismic surveys were integrated to interactively interpret the northern flank of this salt dome. The seismic surveys consisted of: (1) SEM, a high-resolution (0.25 ms sample rate) 3-D seismic survey on the crest of the dome; (2) Sheik, a high-resolution (2.0 ms sample rate) 3-D seismic survey off the north flank of the salt dome; and (3) S-2, a 2-D seismic line orthogonal to the salt dome and passing near both the SEM and Sheik surveys.

(Slides 1L & 1R)

Key development stages from this study are available on the INTERNET at:
http://www.hypermedia.com/w3d/geotechnology/W3D95C/index.html
using a browser like NetScape or Mosaic. The first slide on the left is the index to an interpretation report prepared on the 8th of January of 1996.

Key Data Sets

The relative location of the data used in this interpretation project are shown in the slide on the right. This data includes:

- Topography maps.
- Well data.
- Seismic survey location maps.
- Three sets of seismic data are available in the area of interest :
  - 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 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 salt dome: Sheik.
- Maps from drilling to the Top of Caprock and to the Top of Salt.

Data Preparation and Data Loading

The seismic data for each of the three surveys was loaded on a Landmark Graphics interpretation workstation at the offices of Interactive Interpretation & Training in downtown Houston. Three projects were set up: SEM; Sheik; and Composite. The Top of Caprock map was gridded and the grid entered as a horizon into the Composite project. The well-based Top of Caprock horizon was generated by interpolating between points taken on a 2,500 foot grid in X and Y, triangulating a surface between these points, writing these surfaces into an horizon in 100 foot square bins in the Composite project, smoothing the results, converting from depth to time using a constant velocity, and creating the purple horizon. This purple well-based Top of Caprock horizon was exported from the Composite project and then imported into the SEM and Sheik projects to provide a check for picking the Top-of-Caprock horizon. There is a direct correlation to a strong reflector consistent across the SEM survey. This reflector was interpreted as the Top-of-Caprock.

The size of the projected Salt Caverns was converted to seismic travel time and both assigned "faults" and regular "horizons" were made to show the relative spatial locations of the proposed caverns within the SEM 3-D seismic volume. The west cavern was colored red, the south cavern blue, the north cavern orange, and the east cavern green. These "faults" and "horizons" were exported and then imported into the Composite project.

In addition, location maps, the description of the proposed caverns, the paper seismic section for line S-2, and other relevant information were 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 work flow, the interpretation process, and the interpretation results. Key images from the ESF HyperJournal were captured and converted to gif files and used to build World-Wide-Web versions of reports and presentations.

(Slides 2L & 2R)

Interpretation Results from the SEM 3-D Seismic Survey

A detailed interpretation was done on the SEM 3-D seismic survey. Because this presentation is prepared for review by geophysical interpreters and solution mining engineers this paper will focus on the interpretation results from the SEM 3-D seismic survey. This was the best quality data set, and there are many interesting and subtle characteristics to this data set.

The most obvious reflector was determined to be the Top of Caprock reflector. This interpretation was confirmed by bringing the gridded well-based Top of Caprock map derived from drilling results into the SEM project from the Composite project and displaying the results as the purple horizon. The purple 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 purple horizon is up to 50 ms from the strong reflector (150 foot vertically at the Top of Caprock), but overall the well-based Top of Caprock horizon is within about 20 ms of the strong reflector (60 foot vertically at the Top of Caprock). There has only been one sonic log available to this stage of the interpretation and these misties are easily explained by small lateral velocity changes.

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 50 ms phantom of the Top of Caprock horizon was created to define the Top of Salt as the blue horizon. The well-based and seismic interpretation of the Top of Caprock are shown on Line 36 (the left slide), which runs through both the proposed blue and green (south and east) caverns. Notice that the caprock has been highlighted with a semi-transparent gray overlay. The Top of Caprock horizon is generally at about 300 ms. The right slide shows the proposed west or red cavern just northwest of the SEM 3-D survey on Trace 12.

(Slides 3L & 3R)

The left slide shows the proposed location of the south or blue cavern on Trace 18. The right slide shows the proposed north or orange cavern, just northwest of the SEM 3-D survey on Trace 37.

(Slides 4L & 4R)

The left slide shows the proposed location of the east or green cavern on Trace 43. The proposed green cavern is also shown on a seismic cube display in the right slide.

(Slides 5L & 5R)

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 (the left slide). The relative spatial location of the four proposed salt caverns is shown in perspective view on the right slide. There are a series of in-line (southwest to northeast) 100 to 500 foot offsets in the contours. These are interpreted as being due to very small displacements. Smoothing through these offsets, shows a maximum vertical offset of 15 ms (~45 feet). The displacements are probably due caprock alteration and/or volume change and the apparent strike-slip component could be related to salt growth movement. These small compaction displacements can be interpreted on the SEM seismic sections.

(Slides 6L & 6R)

These slides show the displacement interpretations on Trace 18, relative to the proposed Blue cavern, in section and SeisCube views. Again note that maximum displacement on any of these displacements is very small and we will show the relationship of these small displacements to caprock alteration. There was nothing identified on the seismic to imply that any of these settling cracks in the sediments above the salt dome have had any active movement during the geologic time that 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.

(Slides 7L & 7R)

These slides show the displacement interpretations on Trace 43, relative to the proposed Green cavern, in section and SeisCube views. On both of the SeisCube displays (right slide and previous right slide) it is evident how the in-line seismic direction is right along the strike of these small displacement.

(Slides 8L & 8R)

A phase SeisCube was made to bring out the detail that is available in the SEM seismic survey. These slides show the phase SeisCube with the top time-slice at 100 ms on the left and at 200 ms on the right. The color bar is one that Chuck Edwards uses to highlight subtle high frequency reflectors with phase. Although the data is noisy at 100 ms (on the left slide) there is no obvious displacements like there are at 200 ms on the right.

(Slides 9L & 9R)

Moving down through the SEM phase SeisCube, these slides show travel-time cuts at 300 ms and 350 ms. The 300 ms time-slice cut on the left the Top-of-Caprock red horizon. The 350 ms time-slice on the right cuts the phantomed Top-of-Salt blue horizon. The extra detail in the phase shows that there may be a miss-correlation of the Top-of-Caprock horizon across part of the SEM project area.

(Slides 10L & 10R)

Continuing down through the SEM phase SeisCube, there is a marked difference in the appearance of the data in the salt. Although there appears to be some coherency on the cross-sections on the side of the SeisCube display, there is no coherency in the time-slice data. The slide on the left is at 450 ms. The slide on the right is at 570 ms and cuts the very top of the proposed Blue and Green Salt Caverns

(Slides 11L & 11R)

These displays move the SeisCube time-slice back up to 300 ms, but move the Trace side of the SeisCube to cut two different proposed Salt Caverns. The slide on the left is at Trace 18 through the proposed Blue Cavern. The slide on the right is at Trace 43 through the proposed Green Cavern

(Slides 12L & 12R)

The interactive interpretation world allows the data to be evaluated in a variety of different ways. The left slide is a variable-density section along Trace 18 through proposed Blue Cavern. The slide on the right is along the same Trace 18, but is a wiggle section.

(Slides 13L & 13R)

These slides show another display option, where the same Trace 18 through the proposed Blue Cavern, which was displayed in the previous slides, displayed in wiggle-variable-area format. The slide on the left is the top half of this section and the slide on the right is the bottom half of this section.

(Slides 14L & 14R)

One of the more interesting results to be presented is the relationship of seismic amplitudes to calcite distribution in the caprock. Using the interactive system we evaluated the seismic amplitudes relative to the Top-of-Caprock horizon and the phantomed Top-of-Salt horizon. The slide on the left is a StratAmp extraction of the maximum absolute seismic amplitudes between the Top of Caprock and the Top of Salt horizons. The strong amplitude differences are interpreted as relating directly to calcite distribution in the caprock. We actually did several different StratAmp amplitude extractions, as is shown in the ESF HyperJournal poster on the right slide. This poster is also available for participant review after the presentation. The next series of slides are close-up views of this poster.

(Slides 15L & 15R)

The slide on the left is a description of the process we followed. It says:

> "This series of maps show the maximum absolute seismic amplitude for different intervals within and just beneath the caprock of the salt dome. At the top left (right slide) is the amplitude for the entire caprock. Note the strong variations which are interpreted as being related to calcite distribution in the caprock. The next map to the right looks much the same. It is the amplitudes for the first 5 ms (approximately 30 feet) under the top of the caprock. These amplitudes are influenced by the waveform generated at the top caprock interface, but we interpret them as relating to calcite distribution."

(Slides 16L & 16R)

> "Beneath this map is a map from 5-10 ms underneath the caprock interface. The right map on the left slide is StratAmp amplitudes from the Top-of-Caprock to 10 ms beneath the Top-of-Caprock."

"The right slide is the Poster's lower left StratAmp amplitude map showing amplitudes in the interval from 10-20 ms. Note that the high amplitude is lacking and we interpret this means that this section is below the calcite zone. This map is very similar to the right map on the right slide, which shows the amplitudes in the first 10 ms of the salt."

We interpret the strong difference between these amplitude maps to mean that the calcite zone is totally within the top 30 feet of the caprock. This will be important information when creating the salt caverns, in order to minimize lost circulation. The seismic reflectors beneath the Top of Caprock horizon is not coherent enough to show the push-down effect of low velocity zones that would indicate high porosity or cavernous intervals. It is interesting how a map of the first 10 ms under the Caprock interface smears 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.

(Slides 17L & 17R)

There is a direct relationship between the caprock alteration and the small displacements described above. The next series of maps highlight these spatial relationships using SurfCube displays. The slide on the left shows the Violet displacement. The slide on the right shows the Blue displacement. Notice how it lines up along the zone of calcite alteration. The slide on the right shows the Blue displacement, which like all of the small displacements follows the same trend.

(Slides 18L & 18R)

The left slide adds the Sky displacement, and the right slide the Green and Gold displacements. One of the fascinating points to the author was the scaling downward in size of geologic processes. These small displacements look exactly like the large faults common in Gulf Coast seismic sections.

(Slides 19L & 19R)

The left slides adds the Purple displacement and the right slide the Orange displacement.

(Slides 20L & 20R)

These slides add seismic sections to the SurfCube displays. On the left is strike Line 38 and on the right is dip Trace 43.

(Slides 21L & 21R)

To put these small displacements back in perspective, a strike Line 38 is displayed on the left with the displacements projected onto the section. On the right slide is dip line Trace 43 with displacements noted. Again note that the maximum displacement is 15 ms or less than 45 feet of throw, relative to proposed Salt Caverns interval from 2,000 to 3,000 depth.

(Slides 22L & 22R)

The left slide adds the Red displacement to the SurfCube display. The slide on the right shows all of the interpreted displacements and SEM Line 38 and Trace 43.

(Slides 23L & 23R)

SurfCube allows these data or any subset of these data to be rotated for better evaluation of spatial relationships. These two slides show two of these rotations with the projected map showing the Top-of-Caprock travel-time map.

(Slides 24L & 24R)

The slide on the left shows a third rotation of the Top-of-Caprock map. The slide on the right shows the StratAmp amplitude extraction replacing the travel-time horizon.

(Slides 25L & 25R)

The slide on the left rotates the last slide and then adds in Line 36, highlighting where the proposed salt caverns and Top-of-Caprock amplitude map also shown.

(Slides 26L & 26R)

The left slide zooms in on the previous display, and then the slide on the right zooms in more.

(Slides 27L & 27R)

These two slides continue to zoom in on the SurfCube displays. These views were included to introduce work being done to place these interpretation results in virtual reality environments for evaluation by individuals or groups. The interpretation results have been transferred to The University of Houston's Virtual Environment Technology Laboratory. We will be using their Virtual Reality systems to evaluate the spatial relationships of the project. This includes using their visually immersive CAVE (for those familiar with StarTrek terminology, a computer generated 'holodeck'). This virtual environment has proven to be a very useful means of communicating complex spatial relationships to a group of scientists and managers.

(Slides 28L & 28R)

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

The 2-D seismic section S-2 is orthogonal to the salt dome. The left slide shows the interpretation of the Top of Caprock and the Top of Salt horizons on line S-2. The identification of this interface is straight forward. The dip of the salt-sediment interface means there would need to be very long offsets to get accurate imagery of this surface. This reflector ties nicely to the salt-sediment-interface interpreted on SEM and Sheik. The S-2 salt-sediment-interface projects to the top of a no-data-area in the Sheik 3-D seismic survey, which was interpreted as top-of-salt.

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." When Dave Hale of Chevron presented the Turning Wave Theory at the SEG in Houston a few years ago, he stressed that special seismic processing was needed to find these seismic events. Line S-2 is a candidate for this type of processing. 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. These reflections typically come in at about 8-10 seconds depth according to Fred Hilterman. The fact there are no reflections on S-2 at these depths, and the straight forward identification of the salt-sediment interface do not justify special seismic processing to confirm the prescence of Turnlng 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 movėd through the area and disrupted the sediments. The slide on the right 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.

(Slides 29L & 29R)

The composite map on the left slide shows the relative location of the SEM, S-2, and Sheik surveys. The map across the entire dome shows this to be a relatively simple dome. The large dome contour map was derived from well data. The structure of the Top-of-Caprock is simple in the area of the proposed salt caverns.

The composite cross section shown in the poster on the left shows this same simple structure. Each of the seismic displays from the different projects were made at the same scale and then screen captures integrated in the ESF HyperJournal. This HyperJournal has proved to be a very valuable hyperlinked multimedia "living report." 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.

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 across the entire salt dome, shows this area is a relatively simple dome. 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 does not appear to be any salt overhang on the north side of the salt dome being studied. This means there is virtually no possibility of water reaching the proposed salt caverns and their proposed storage of industrial wastes within the next few thousand years.

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Creatively Combining Concepts

Slides:

1L. WWW Index to Comprehensive Report
1R. Location Map of the Area of Interest
2L. SEM Line 36 through proposed Blue and Green Caverns
2R. SEM Trace 12 through proposed Red Cavern
3L. SEM Trace 18 through proposed Blue Cavern
3R. SEM Trace 37 through proposed Orange Cavern
4L. SEM Trace 43 through proposed Green Cavern
4R. SEM SeisCube through proposed Green Cavern
5L. SEM map of Top of Caprock
5R. SEM perspective of Top of Caprock and four proposed salt caverns
6L. SEM displacement interpretation Trace 18 through Blue Cavern
6R. SEM displacement interpretation SeisCube Trace 18 through Blue Cavern
7L. SEM displacement interpretation Trace 43 through Green Cavern
7R. SEM displacement interpretation SeisCube Trace 43 through Green Cavern
8L. SEM phase cube travel-time 100 ms
8R. SEM phase cube travel-time 200 ms
9L. SEM phase cube travel-time 300 ms
9R. SEM phase cube travel-time 350 ms
10L. SEM phase cube travel-time 450 ms
10R. SEM phase cube travel-time 570 ms showing top of Blue and Green Caverns
11L. SEM phase cube travel-time 300 ms through Trace 18 and Blue Cavern
11R. SEM phase cube travel-time 300 ms through Trace 43 and Green Cavern
12L. SEM variable-density section Trace 18 through proposed Blue Cavern
12R. SEM wiggle section Trace 18 through proposed Blue Cavern
13L. SEM top half of wiggle-variable-area Trace 18 through proposed Blue Cavern
13R. SEM bottom half of wiggle-variable-area Trace 18 through proposed Blue Cavern
14L. SEM StratAmp extraction of the maximum absolute seismic amplitudes between the Top of Caprock and the Top of Salt horizons
14R. SEM Poster of StratAmp extraction study
15L. SEM Poster description
15R. SEM Poster top left map: StratAmp Top Caprock to Top Salt; right map: StratAmp first 5 ms (30') under caprock interface showing calcite distribution
16L. SEM Poster middle left map: StratAmp 5-10 ms beneath Top Caprock; right map: StratAmp 0-10 ms beneath Top Caprock
16R. SEM Poster bottom left map: StratAmp 10-20 ms beneath Top Caprock; right map: StratAmp 0-10 ms beneath Top Salt
17L. SEM Violet displacement
17R. SEM plus Blue displacement

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18L. SEM plus Sky displacement
18R. SEM plus Green and Gold displacements
19L. SEM plus Purple displacement
19R. SEM plus Orange displacement
20L. SEM all displacements on Line 38
20R. SEM all displacements on Trace 43
21L. SEM Line 38 with displacements
21R. SEM Trace 43 with displacements
22L. SEM plus Red displacement
22R. SEM all displacements on Line 38, Trace 43
23L. SEM SurfCube of Top Caprock rotation 1
23R. SEM SurfCube of Top Caprock rotation 2
24L. SEM SurfCube of Top Caprock rotation 3
24R. SEM SurfCube of Top of Caprock Amplitude Extraction rotation 1
25L. SEM SurfCube of Top of Caprock Amplitude Extraction rotation 3
25R. SEM SurfCube of Top of Caprock Amplitude and Line 36
26L. SEM SurfCube of Top of Caprock Amplitude and Line 36 zoom 1
26R. SEM SurfCube of Top of Caprock Amplitude and Line 36 zoom 2
27L. SEM SurfCube of Top of Caprock Amplitude and Line 36 zoom 3
27R. SEM SurfCube of Top of Caprock Amplitude and Line 36 zoom 4
28L. S-2 with Caprock interval noted
28R. Sheik 3D with Caprock interval noted
29L. Composite Map: well control, SEM, S-2, and Sheik
29R. Composite Sections: well control, SEM, S-2, and Sheik