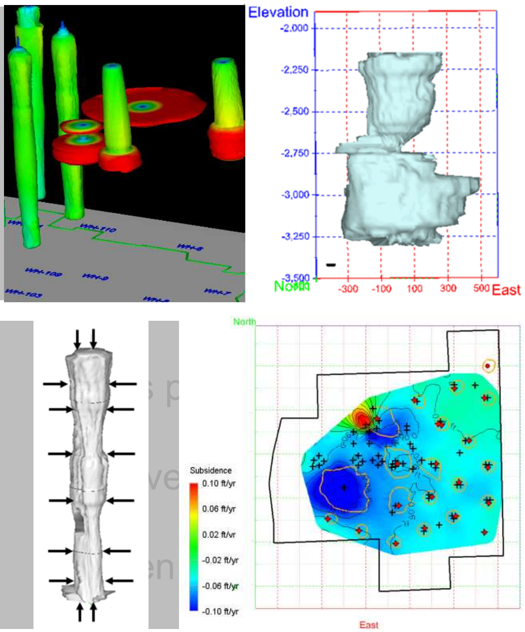
SAND2015-3985C

Operation, Maintenance, and Monitoring of Large-Diameter Caverns in Oil Storage Facilities in Domal Salt



8th Conference on the Mechanical Behavior of Salt
Rapid City, South Dakota, USA
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by

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Sandia National Laboratories

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NNSA National Nuclear Security Administration

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Outline

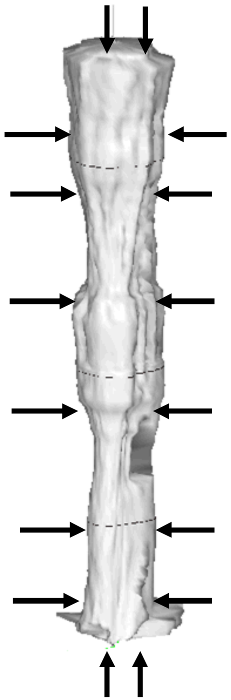
- Comparison of typically cylindrical vs. large-diameter caverns
- Introduce large diameter caverns of US Strategic Petroleum Reserve (SPR) West Hackberry site
- Discuss issues regarding Caverns 6 and 9, including:
  - WH-6 operations, oil removal, and follow-up diagnostics;
  - WH-9 workover scheduling, and differential pressure between WH-6 & 9 during that workover.
- Introduce large diameter caverns of SPR Bryan Mound site
- Discuss issues regarding Bryan Mound caverns, including:
  - Unknown status of abandoned cavern BM-3, monitoring equipment recently installed;
  - Ongoing concerns of stability of BM-2;
  - Effects of leaching of huge cavern BM-5 on salt falls, hanging string survival.

Cylindrical storage caverns

Typical cylindrical caverns: H/D >> 1 (~7 to 10), 7-12 MMB

Primary benefits

- Creep primarily in radial direction, floor rise
- Optimal shape for minimal tensile stresses, strains created in wellbore casings
- Minimize salt fractures from roof



Secondary effects

- Minimize subsidence effects transmitted to surface
- Minimize formation of dilatancy, cracks around perimeter
- Easier shape for fluid exchange
- Easy geometry to map with sonar

Large-diameter storage caverns

H/D < 1, 7-36 MMB, 350-m roof

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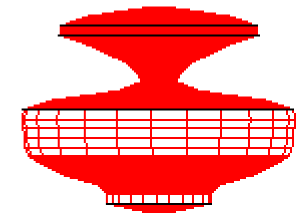

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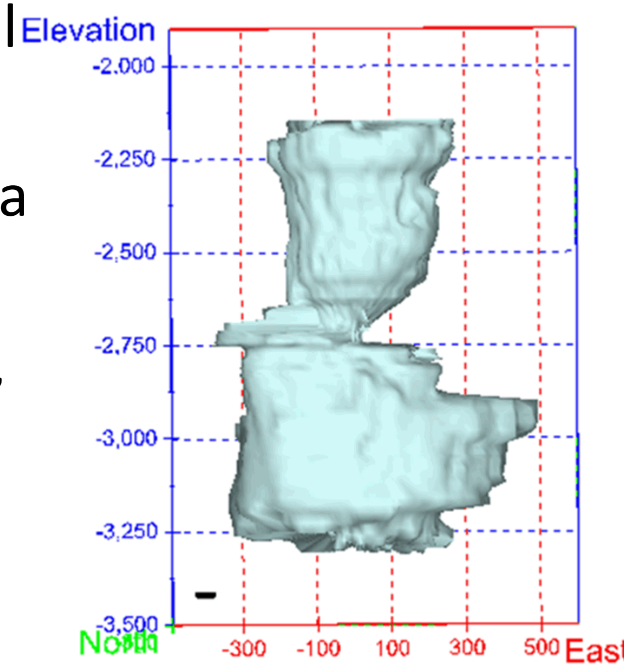
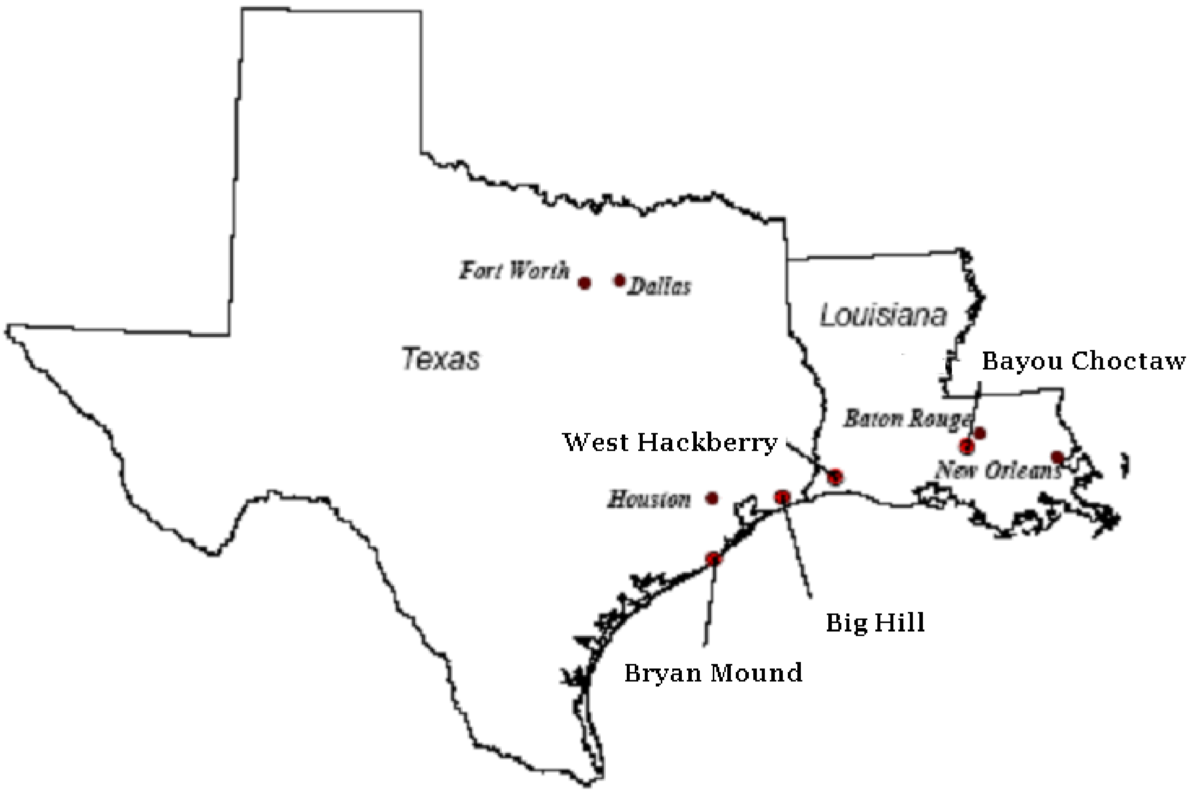
Resulting problems

- For large diameter, creep primarily in roof and floor, creating substantial tensile stresses, strains created in wellbore casings
- Large diameter roof more prone to potential failure, possibly to surface
- Larger subsidence, transmitted to larger area on surface
- Greater potential for formation of dilatancy, cracks around perimeter, particularly for close proximity caverns
- Difficult shape for fluid exchange
- Difficult geometries to map with sonar

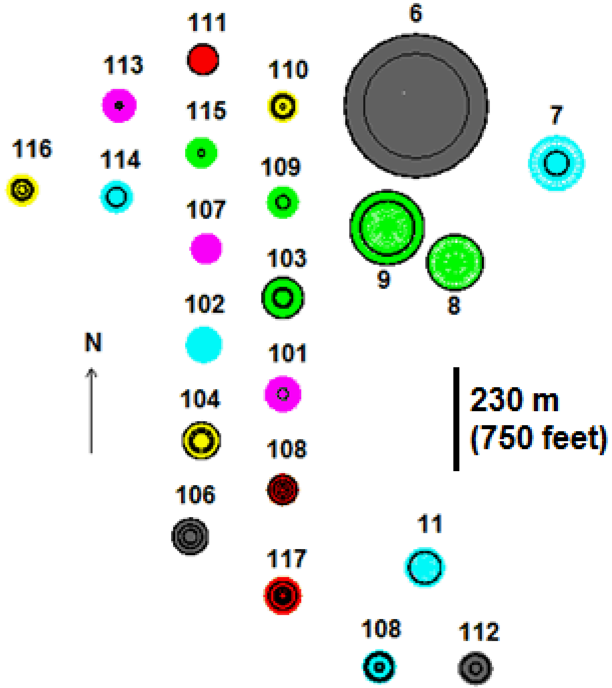


West Hackberry SPR Site



- West Hackberry site includes:
- ~228 MMB of oil storage in 22 caverns.
- 5 unusually-shaped, reasonably axisymmetric storage caverns (**6**, 7, 8, **9**, 11) built in 1940s-1950s.
- 17 cylindrical-shaped storage caverns (#101-117) built in early 1980s.
- Approximately 480m sandstone overburden, 120 m anhydrite/ carbonate caprock over salt dome.
- WH salt is reasonably homogeneous, isotropic, relatively high creep

West Hackberry Cavern Layout



- Cavern 6 shape (~350 m diameter, 6 MMB) causes significant ceiling subsidence, creating excessive potential for casing failures, loss of access to oil
- Cavern 9 (~180 m diameter, 9 MMB) has mid-height ledge prone to high shear, in close proximity of Cavern 6 rim (closed in early 1990s)
- High creep rates put excessive tension on casings
- Proximity of Caverns 6/9/8 (~70 m between edge of Cavern 6, top lobe of Cavern 9) increases sympathetic pressure response, presents other operational issues regarding casing, cavern damage

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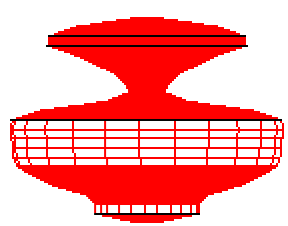

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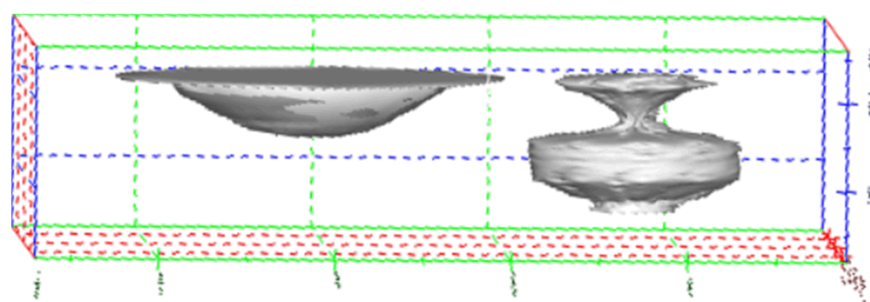
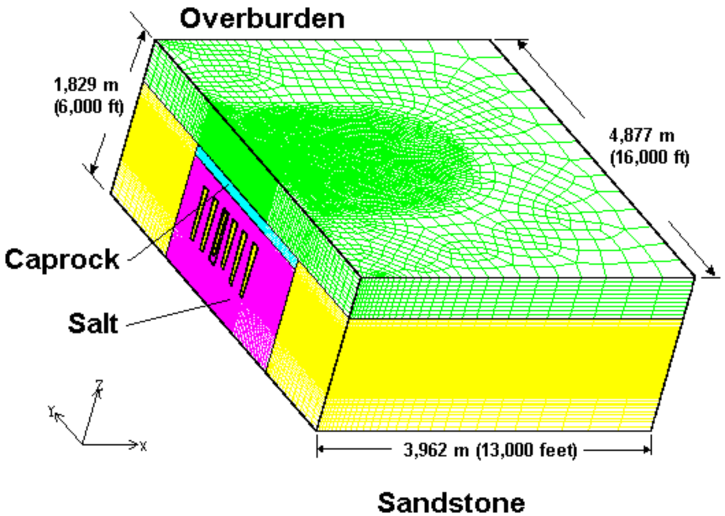
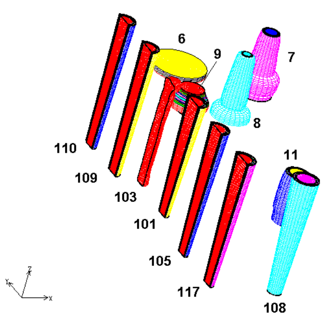


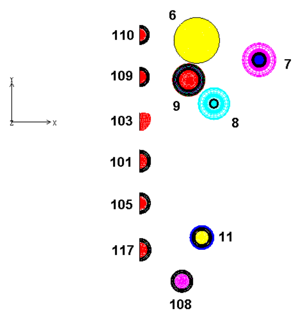
West Hackberry half dome model

- Original model (2009) was a half-dome model – eastern half of site, roughly half of cavern volume.
- Model implements Sierra geomechanical code Adagio, M-D creep model.
- Several simulations of cavern operations performed, 2009-2014.
- Simulations specifically analyze operations of WH-6 & 9 related to workovers, oil withdrawal from 6, continued operations.

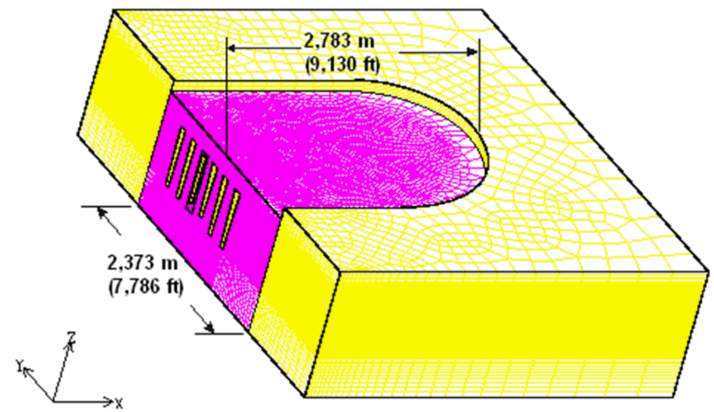




West Hackberry caverns, including five leachings (except for cavern 103)



West Hackberry caverns, including five leachings (except for cavern 103)

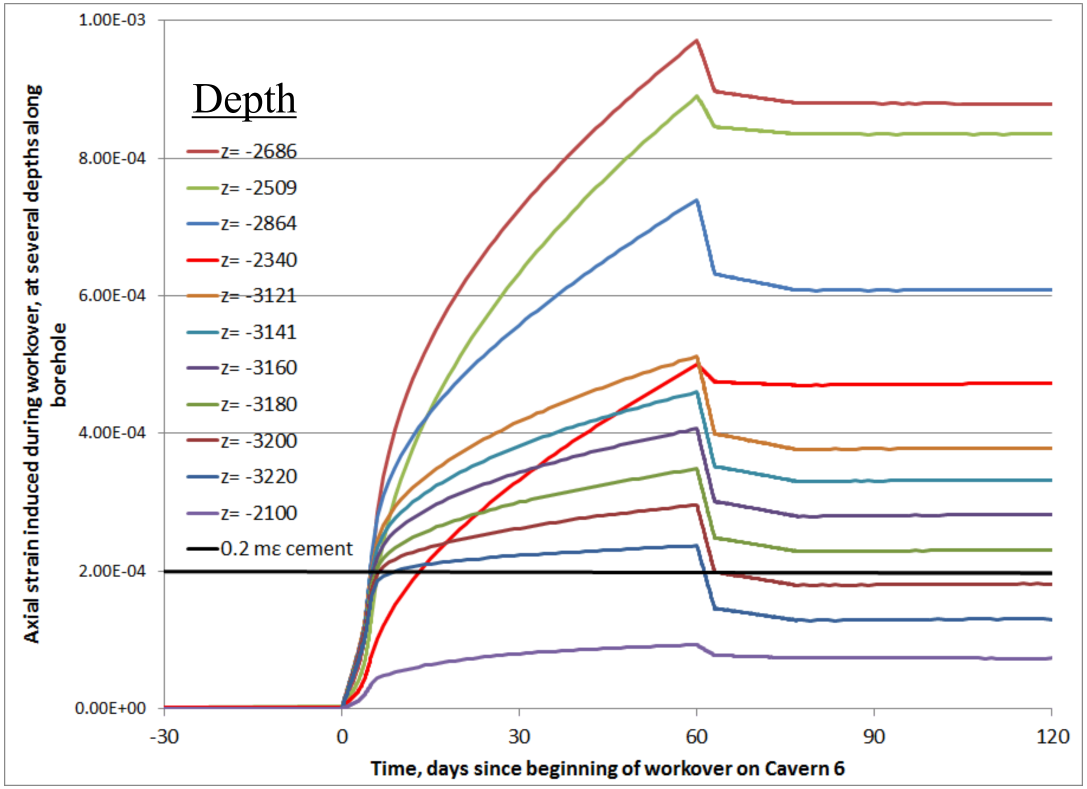


West Hackberry

- General Issues:
  - Cavern 6 shape causes excessive potential for casing failures (including failures in 2010, 2012, only 1 of 4 boreholes still operational), loss of access to ~6 MMB oil due to roof sag
  - Proximity of Caverns 6/9/8 presents other operational issues to prevent casing, cavern damage
- Resulting effects on site operations
  - Based on SNL recommendations, Cavern 6 oil has been removed (probably permanently) for better ability to assess roof, perimeter, volume of trapped oil
  - Sonar measurements of Cavern 6 has been performed
  - Operations for Caverns 6, 8, 9 must be carefully scheduled
  - GPS/tiltmeter installation above WH-6

Predicted strain on WH6 casing during workover

- Axial strains in the salt around the well bore are significant every time a workover on Cavern 6 is performed, exerting as much as 1 additional millistrain during a 60-day procedure (cement threshold strain 0.2 mε, steel casing 1.6 mε).
- Highest strains predicted to occur at 2500-2700 feet depth.
- Strains continue to grow as the cavern is held at low pressure.



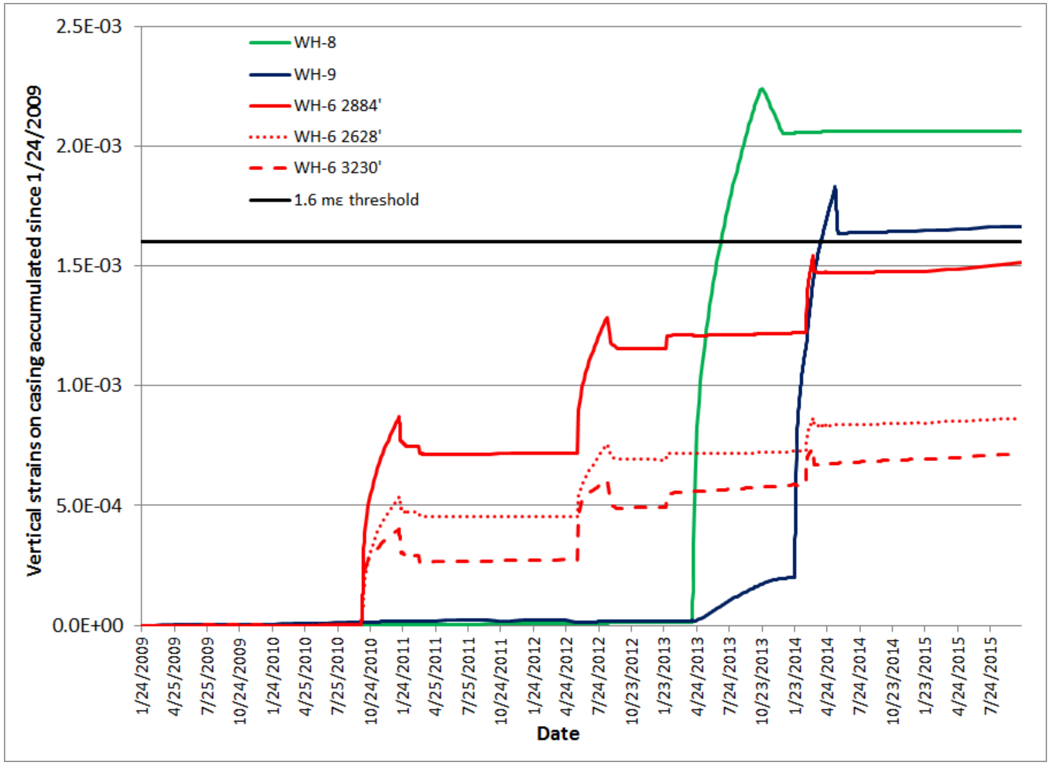
Simultaneous WH6, 8, 9 operations

Planned 2014 WH-6 oil removal/ WH-8/9 workover schedule simulated for effect on casings:

- WH-8 workover induces over 2 mε near the bottom of its casing
- Simultaneous depressurization of WH-6, 8 causes significant strain in WH-9 casing
- WH-9 workover induces nearly 1.6 mε in its casing

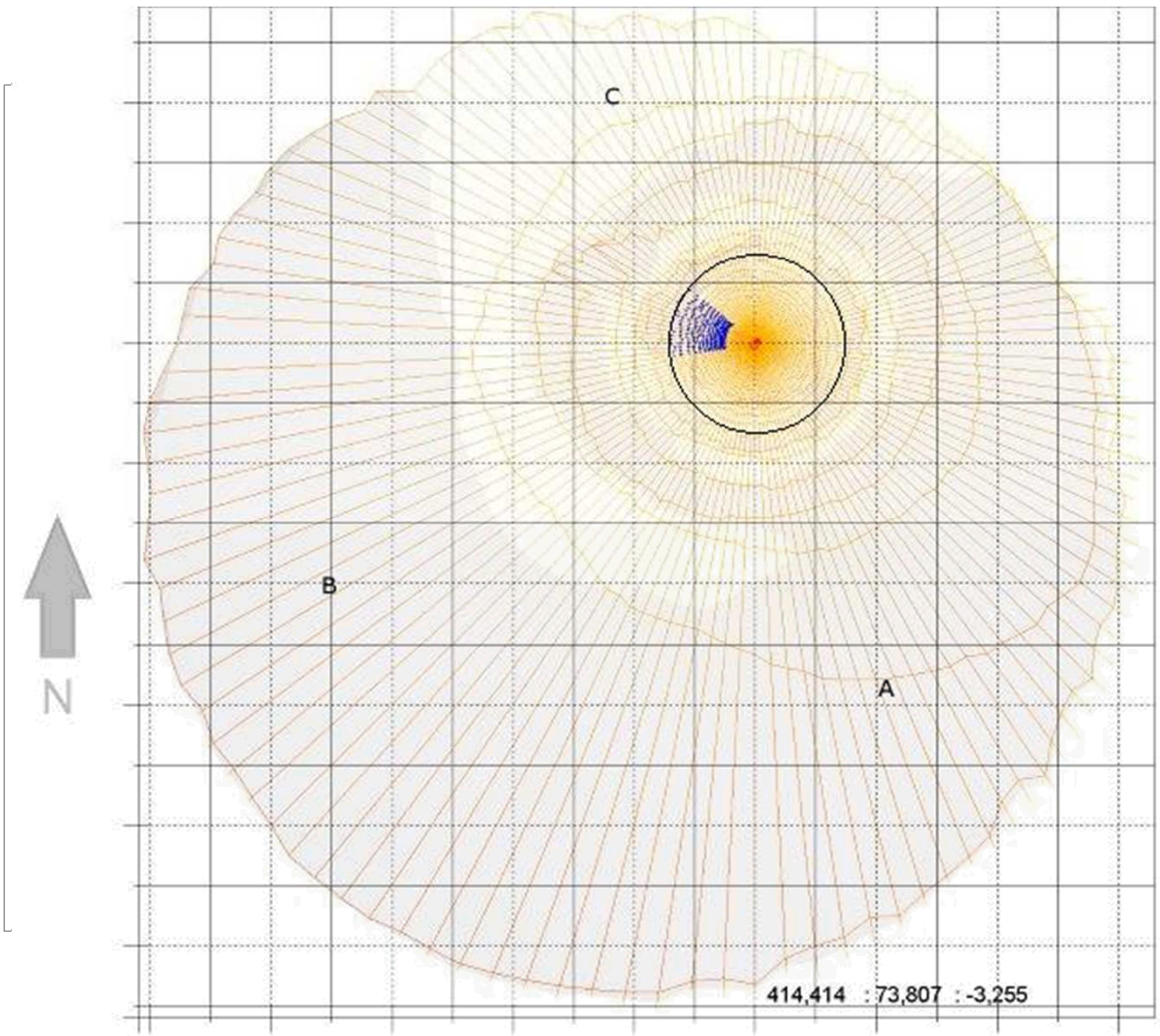
Recommendations:

- No simultaneous WH-6 & 8 workovers
- Slow dp/dt rates (minimum 5 days) pre- and post-workover
- For cavern integrity standpoint, no need to specify a maximum wellhead/cavern roof pressure differential between WH-6, 9 if ΔP operations are performed slowly



Roof Sag in WH-6

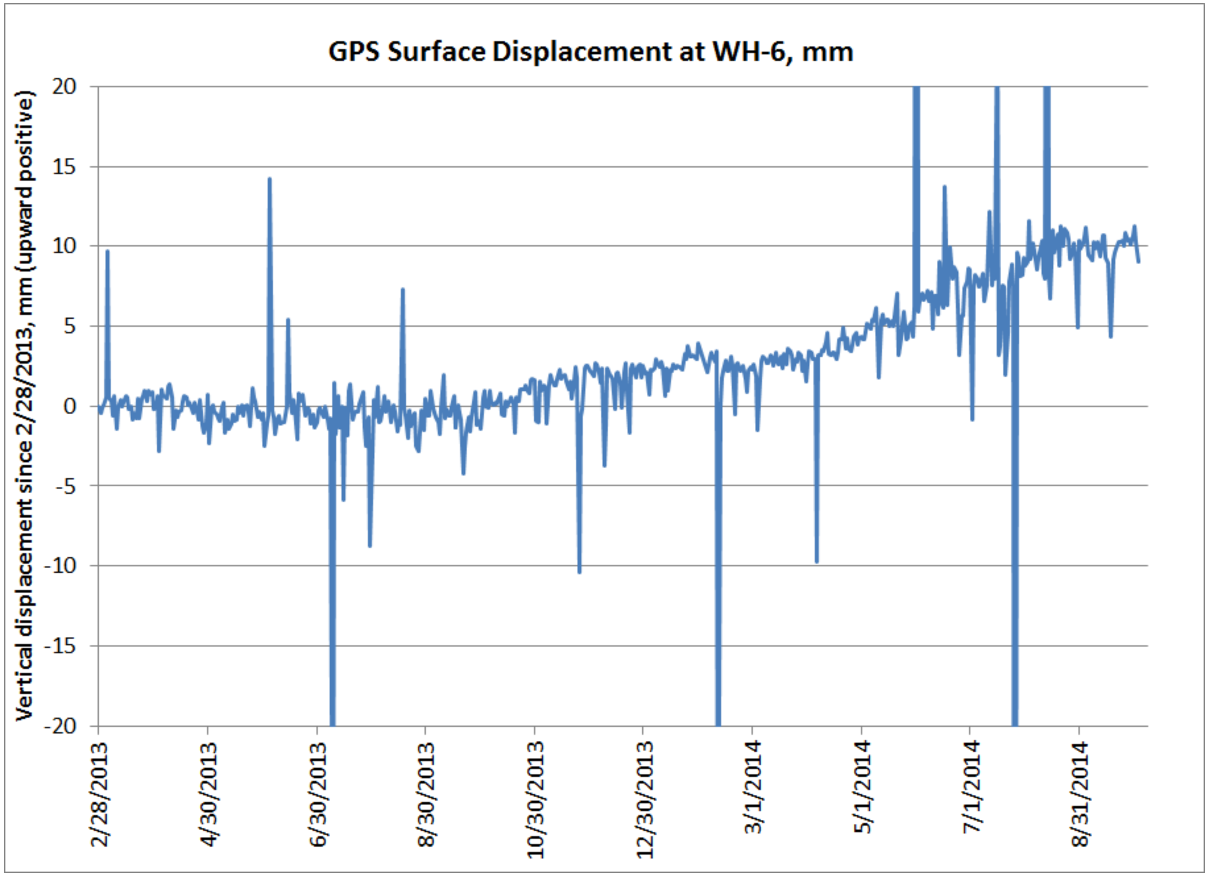
- Simulations predict 100-170 thousand barrels (MB) of oil above bottom of Well 6B, roof sag of 11 feet (3.3 m)
- Sonar performed Oct. 2014 shows roof sag of 12 feet (3.6 m), likely mapped oil/brine interface, did not reduce uncertainty of remaining oil volume
- Only 314 barrels of oil positively identified; remaining oil estimated at 100 MB



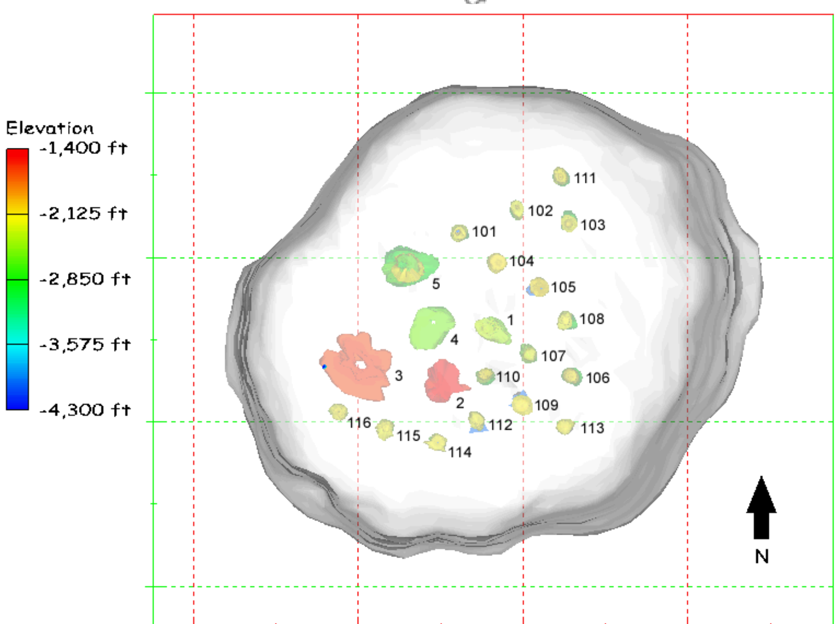
GPS Surface Displacement at WH-6

GPS/tiltmeter system was installed in 2013 at WH-6 wellhead.

- Continuously monitor ground elevation, surface tilt
- Warning if ground displacement exceeds 76 mm or if tilt exceeds 0.1°; alarm at 190 mm or if tilt exceeds 0.3°
- Annual monument surveys show subsidence of 15-20 mm/y
- Upward movement trend begins around October 2013, about 10 mm; cause of this apparent surface rise is currently unknown.



Bryan Mound SPR Site

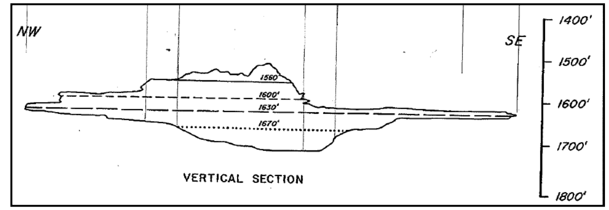


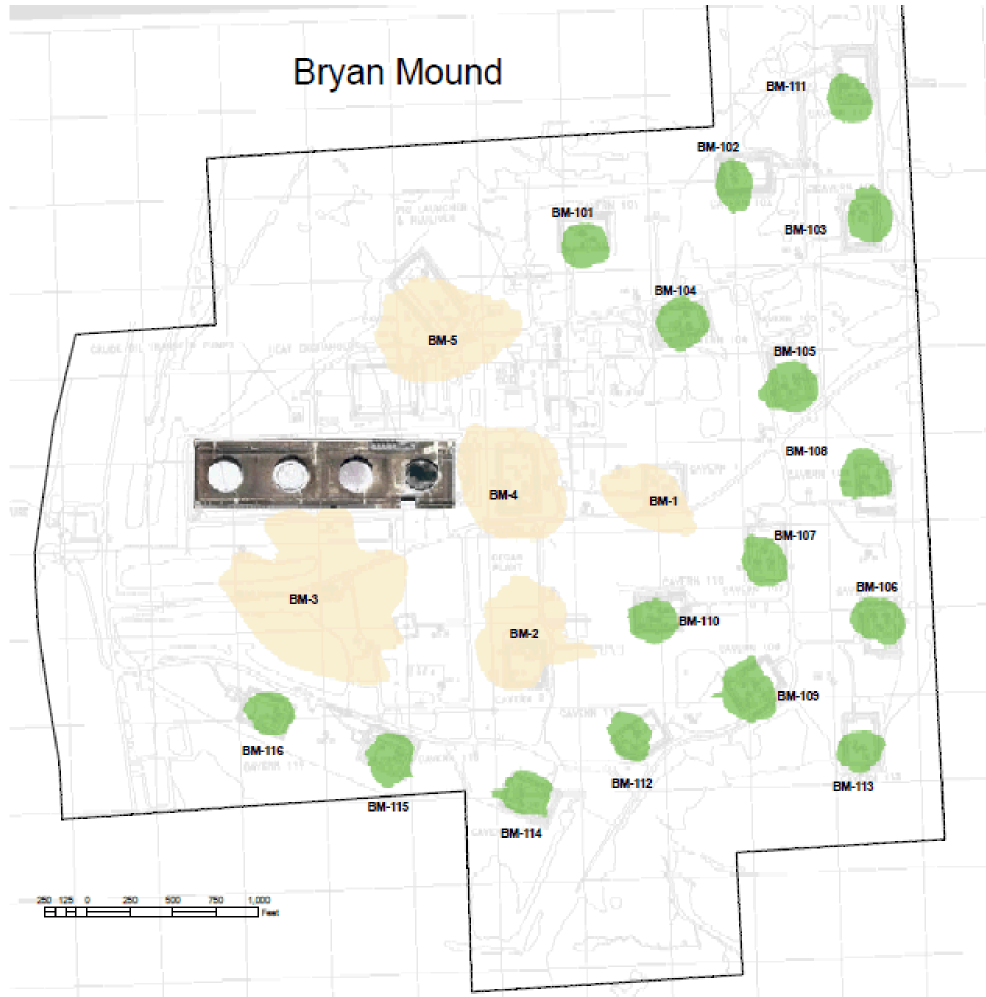
Bryan Mound site includes:

- ~240 MMB of oil storage in 20 caverns.
- 4 unusually-shaped storage caverns (1, **2**, 4, **5**) built in 1940s-1950s.
- 16 cylindrical-shaped storage caverns (101-116) built in early 1980s.
- Approximately 232m sandstone overburden, 85 m anhydrite/ carbonate caprock over salt dome.
- Highly nonhomogeneous salt, caprock damaged by sulfur mining.
- Large diameter **abandoned Cavern #3** near top of salt dome.

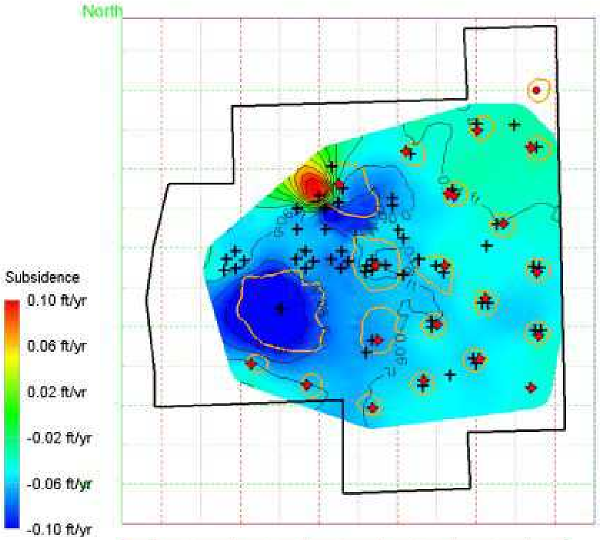
Bryan Mound Cavern 3 Information

- 410-m diameter cavern constructed for brine production, storage in 1940s; **plugged/abandoned in 1980, with no downhole monitoring instrumentation**.
- Drilling records indicate leaching fluids reached salt/caprock interface; several reports of lost fluid during operation as brine cavern until 1980.
- Cavern's depth is ~450 m, only about 90 m beneath the overlying caprock, conditions that raise concerns about cavern collapse extending to the surface [Karimi-Jafari et al. (2008), New Mexico EM&NR Dept. (2011), etc.].
- Cavern 3 is located in close proximity to several significant features of the Bryan Mound site, including four large oil and brine storage tanks, two storage caverns, and primary access road for the site.

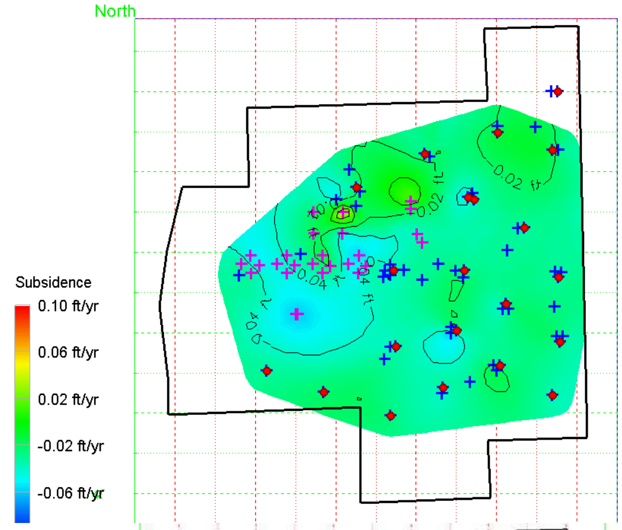




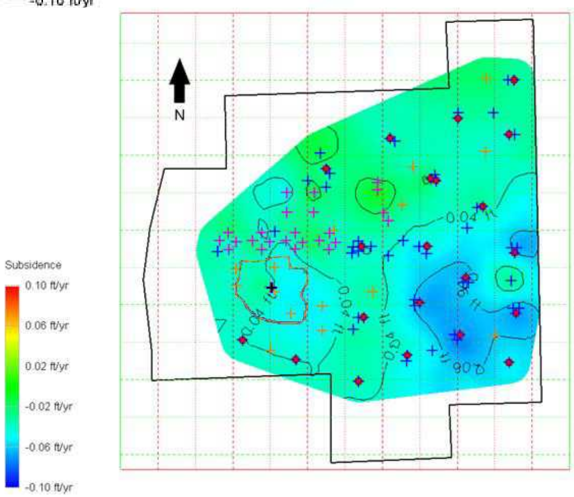
Surveyed Subsidence Data



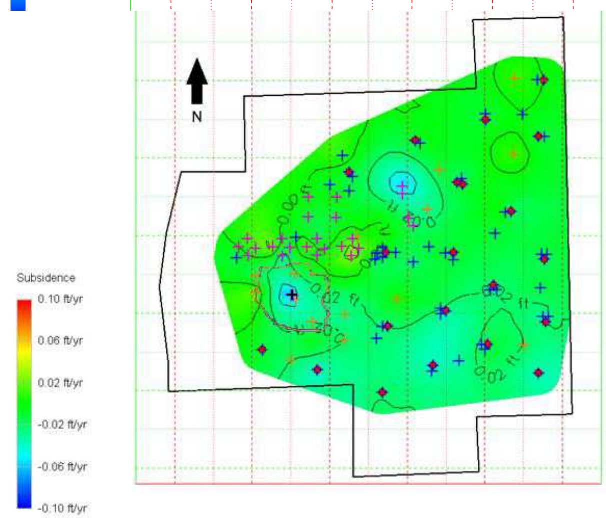
Jan. 2007-
Apr. 2009



Apr. 2009-
Oct. 2010



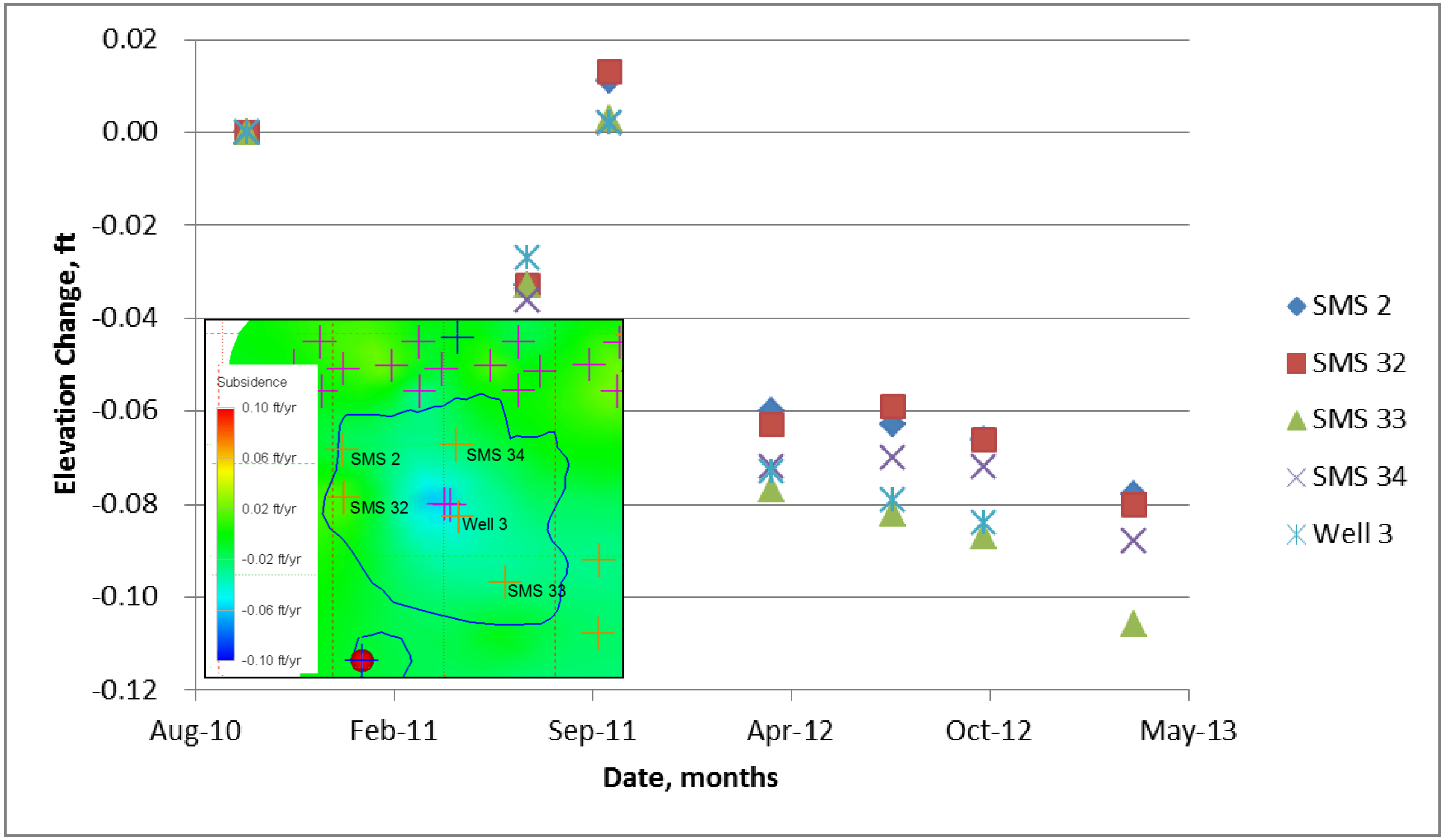
Oct. 2010-
Mar. 2012



Mar. 2012-
Mar. 2013

- Subsidence data from 88 monuments across BM site; higher subsidence over BM-3 observed since 1999.
- Subsidence rates in the region over Cavern 3 are always among the highest of the site, varying between 0.02 and 0.14 ft/yr (6 to 42 mm/yr).

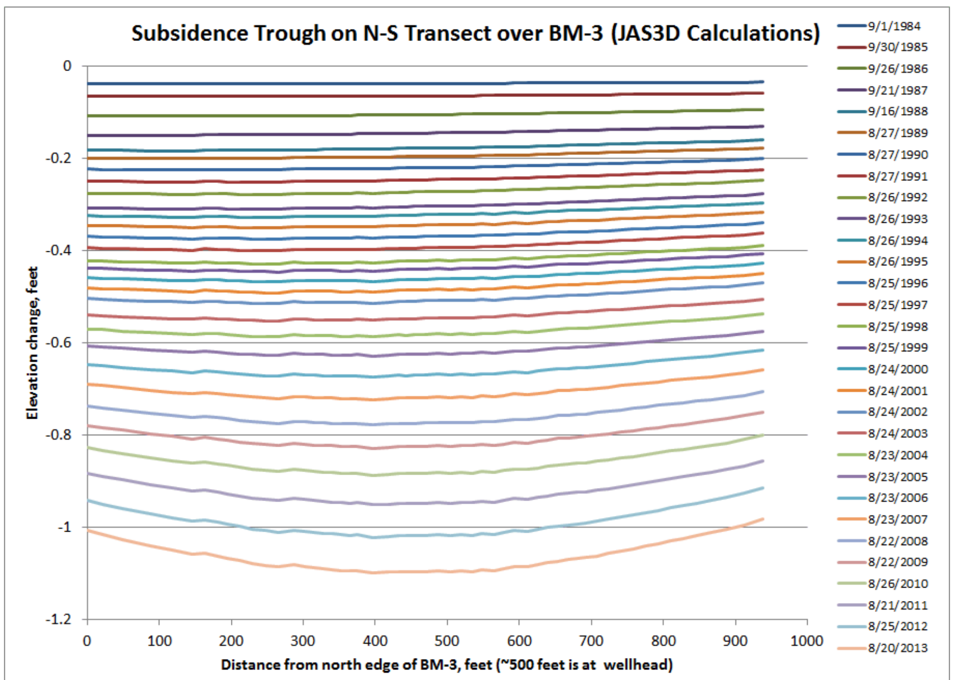
Surveyed Elevation Change Over Cavern 3

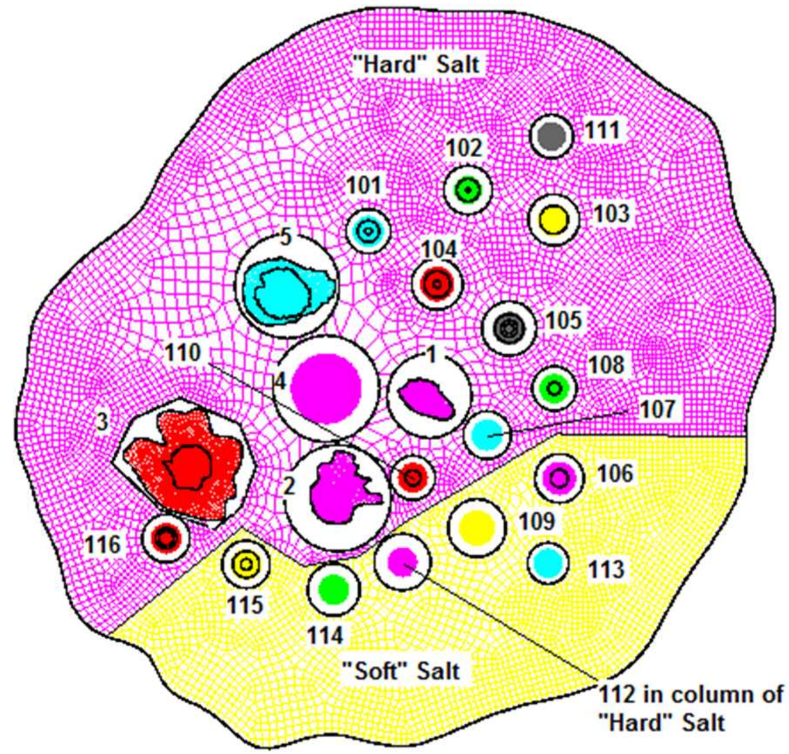


- In 2010 five new monuments were established over the expanse of Cavern 3, including the Cavern 3 well head. Since May 2010 quarterly surveys have been conducted over Cavern 3.
- Change in subsidence rate after March 2012, to 0.02 ft/yr (6 mm/yr), considered normal.
- SMS 33, on southern edge of cavern, has higher subsidence than rest of cavern footprint.

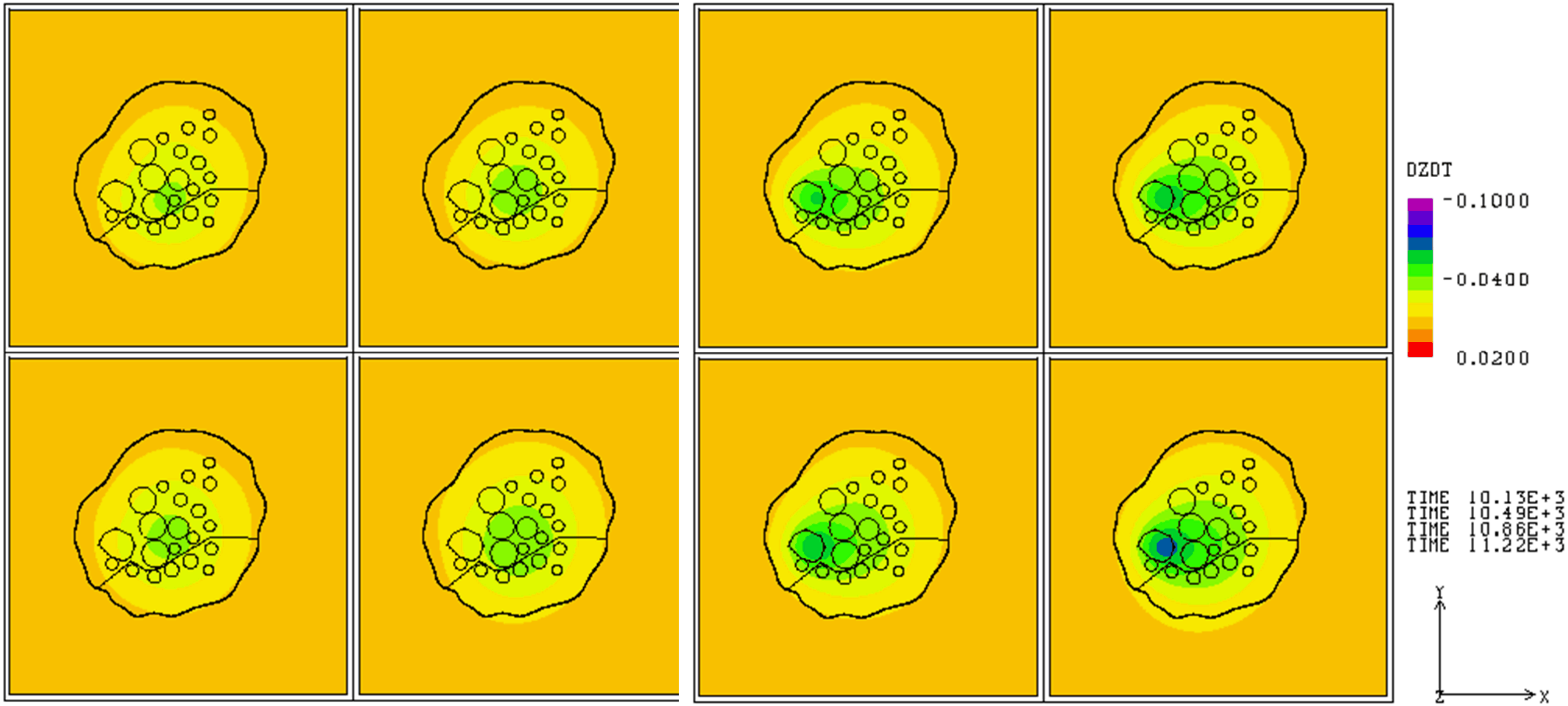
Bryan Mound Geomechanical Model

- Geomechanical calculations performed using finite element of full dome, caverns meshed to sonar-based geometries (ARMA 2012).
- Power law creep model (secondary creep component of M-D model) applied to salt.
- Predicted subsidence over Cavern 3 after 30 years of 1.1 feet (335 mm), with 0.03° tilt.





Predicted Surface Subsidence Rates, Undamaged vs. Damaged Cavern 3



Undamaged Damaged

Model times at August of 2010, 2011, 2012, 2013

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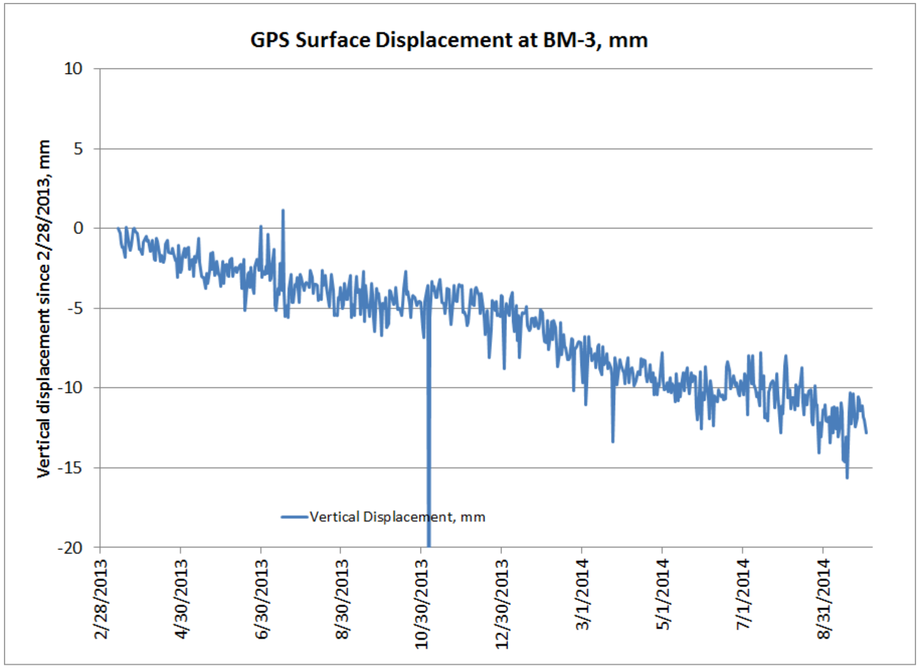
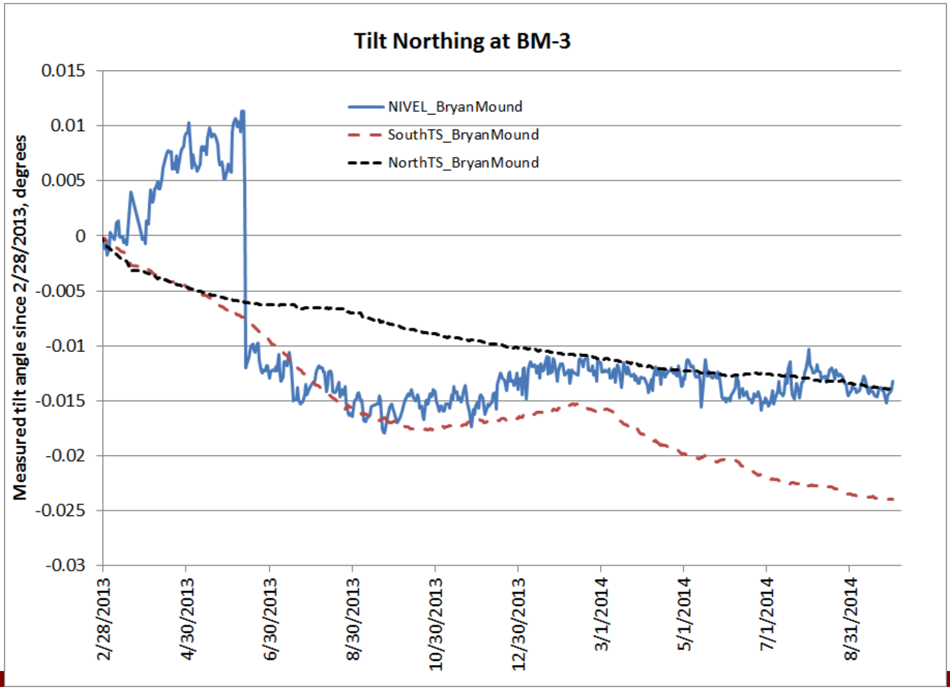
2013: Installation of GPS, Tiltmeters



- GPS installed at Cavern 3 wellhead.
- System issues warning if daily/weekly ground displacement exceeds 0.25 inch (6.35 mm), or if tilt exceeds 0.1°. Alarm will sound if ground displacement exceeds 0.625 inch (15.9 mm) or if tilt exceeds 0.3°.
- Over five months the GPS is averaging -0.04 feet/yr (12 mm/yr), twice the rate of the quarterly monument subsidence data.

- 3 tiltmeters installed at wellhead, north and south boundaries of cavern.
- Measured tilt well below warning settings; both tiltmeters are tilting towards the south with the southernmost meter tilting at a greater angle.
- Annual, quarterly data show that highest subsidence is also over the southern half of the cavern.



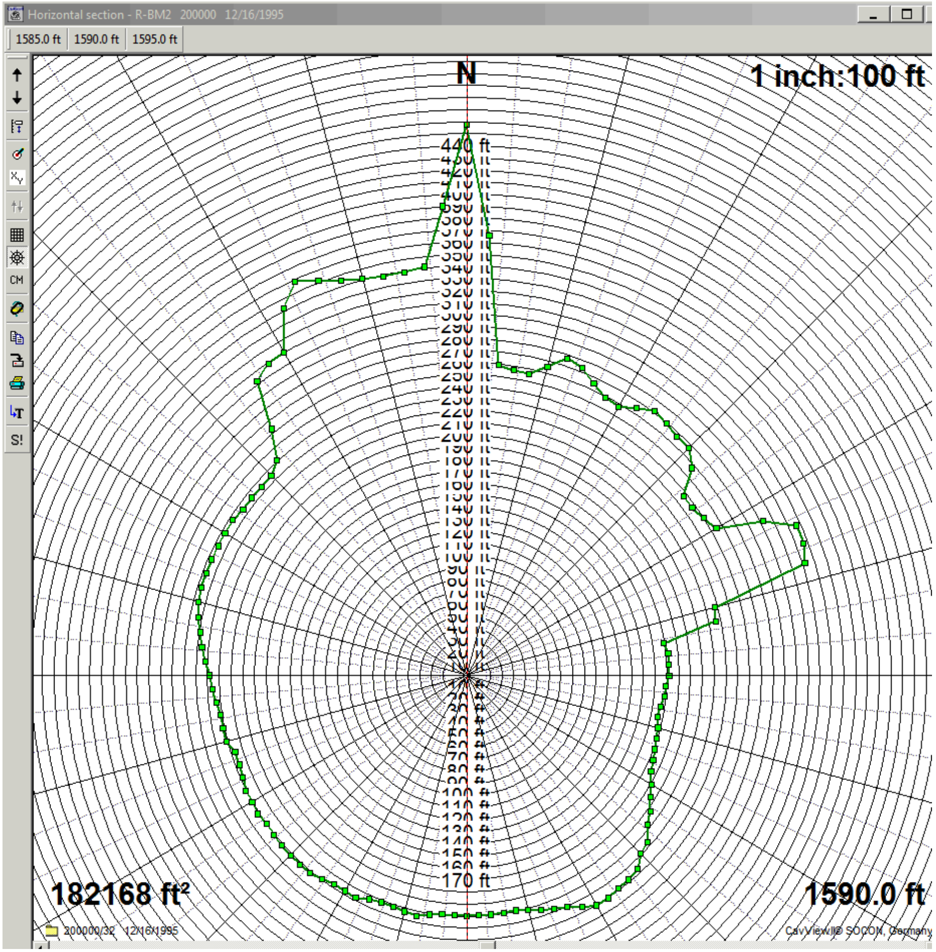
Evaluation Plan for BM Cavern 3

To monitor the ongoing status of BM Cavern 3 and determine cause for the apparent enhanced subsidence, 3 priorities have been identified:

- Real-time monitoring of surface subsidence to **detect the possible imminent collapse of cavern** and thus trigger emergency procedures
  - GPS/tiltmeter data are processed hourly, and values that exceed the established thresholds trigger specific notification and inspection procedures and/or alarms.
- Acquisition of **historical subsidence data to determine the cause and specific location** of the source of the enhanced subsidence
  - Investigating the acquisition of historical interferometric synthetic aperture radar (InSAR) data; may be able to determine location of leak.
- Installation of **other equipment to monitor subsurface events** such as cavern or casing failure
  - Installation of geophones or other surface seismic instrumentation to detect subsurface events. This application has not yet been addressed.

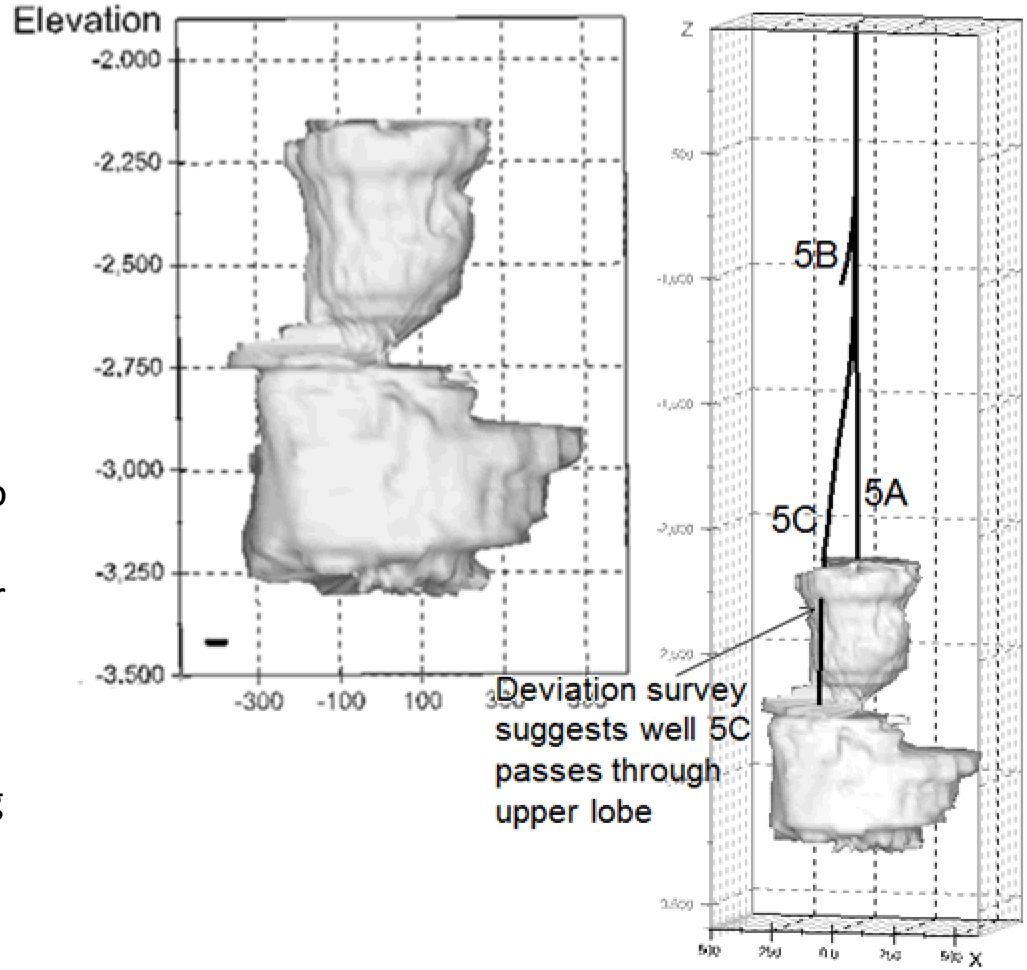
Bryan Mound Cavern 2 Information

- Diameter of about 200 m, a height of about 67 m, and holds 7.2 MMB of oil.
- Two-well cavern, neither has had any modifications to their original completion in 1979.
- Location high in the salt dome (450 m depth, only about 90 m beneath overlying caprock) raises concerns of long-term cavern stability.
- Much like WH-6, analyses and inspection indicate roof has experienced significant sag, and there may be oil trapped above the OBI inaccessible for brine re-placement recovery.
- Evidence both wells have extensive damage, venting gas for many years.
- Decision has been made to remove oil, inspect cavern, evaluate for future disposition; plan for cavern to b maintained with pressurized brine, montiored.

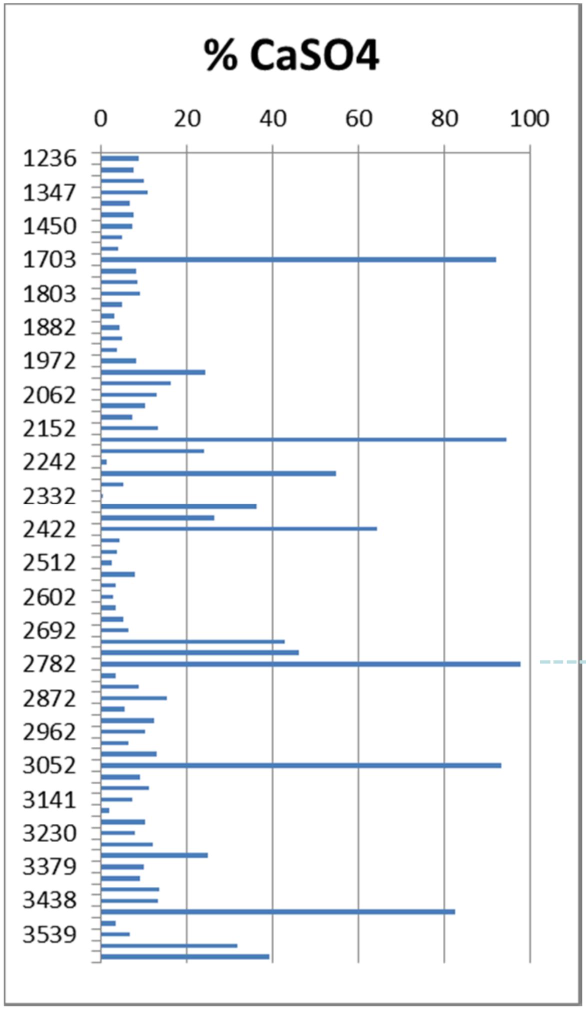


Bryan Mound Cavern 5 Information

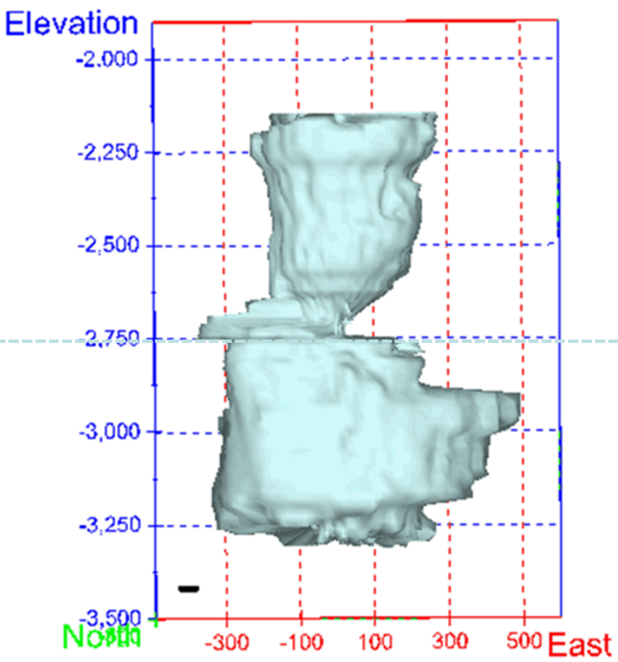
- Cavern 5 is a giant cavern characterized by upper and lower lobes separated by a small neck.
- Erratic geometry is highly related to the level of anhydrite encountered at each depth.
- Cavern was drilled in 1957 for brine production, converted to oil storage by DOE around 1980; currently holds about 36.8 MMB.
- Four wells were drilled into BM-5 prior to DOE ownership, though only two are active: Well 5A penetrates into the upper lobe, and has hanging string that extends well into the lower ; Well 5C intersects upper lobe, then proceeds through salt into the lower lobe, has 273-mm hanging string broken off in the upper lobe with oil in the brine string.



Heterogeneity of Salt: Anhydrite vs. Depth



Example: Anhydrite % from well BM5 core samples taken in 1957



Cavern geometry creates difficulties in using fresh water to draw down the cavern for oil removal.

Note neck region coincides with one anhydrite spike at ~2780 ft

Conclusions

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- WH-6 & 9: Oil has been removed from WH-6, will be brine pressurized and monitored long-term; workover procedures developed for WH 8 & 9 to prevent casing, cavern damage.
- Bryan Mound 3: Abandoned cavern continuously monitored to detect potential failure; additional data under consideration to evaluate need for cavern reentry, remediation.
- Bryan Mound 2: Oil removal process initiated, wells to be inspected, evaluated for repair potential, future disposition to be determined.
- Bryan Mound 5: Ongoing concerns about ability to perform fresh-water drawdown, removal of oil without emulsion issues.
- For all caverns: Improvement of analytical techniques, acquisition of additional data ongoing for more informed evaluation of cavern behavior, future usage.

THANK YOU FOR YOUR ATTENTION!