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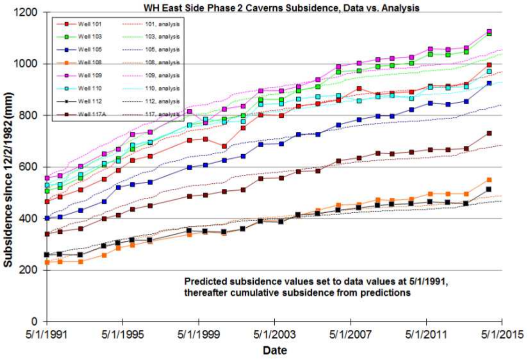

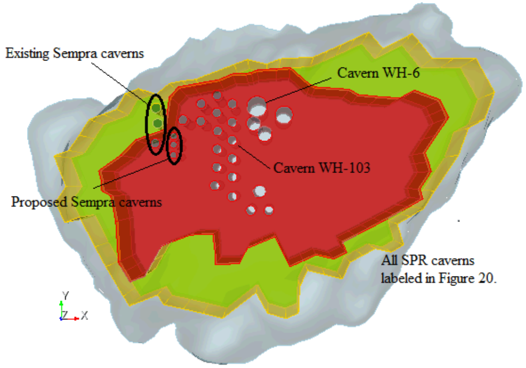

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Implementation of a Full-Dome, Sonar-Based Finite Element Geomechanical Model to Analyze Cavern and Well Stability at the West Hackberry SPR Site

50th U.S. Rock Mechanics Symposium

Houston, Texas, USA

June 29, 2016

by

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Highlights of the paper

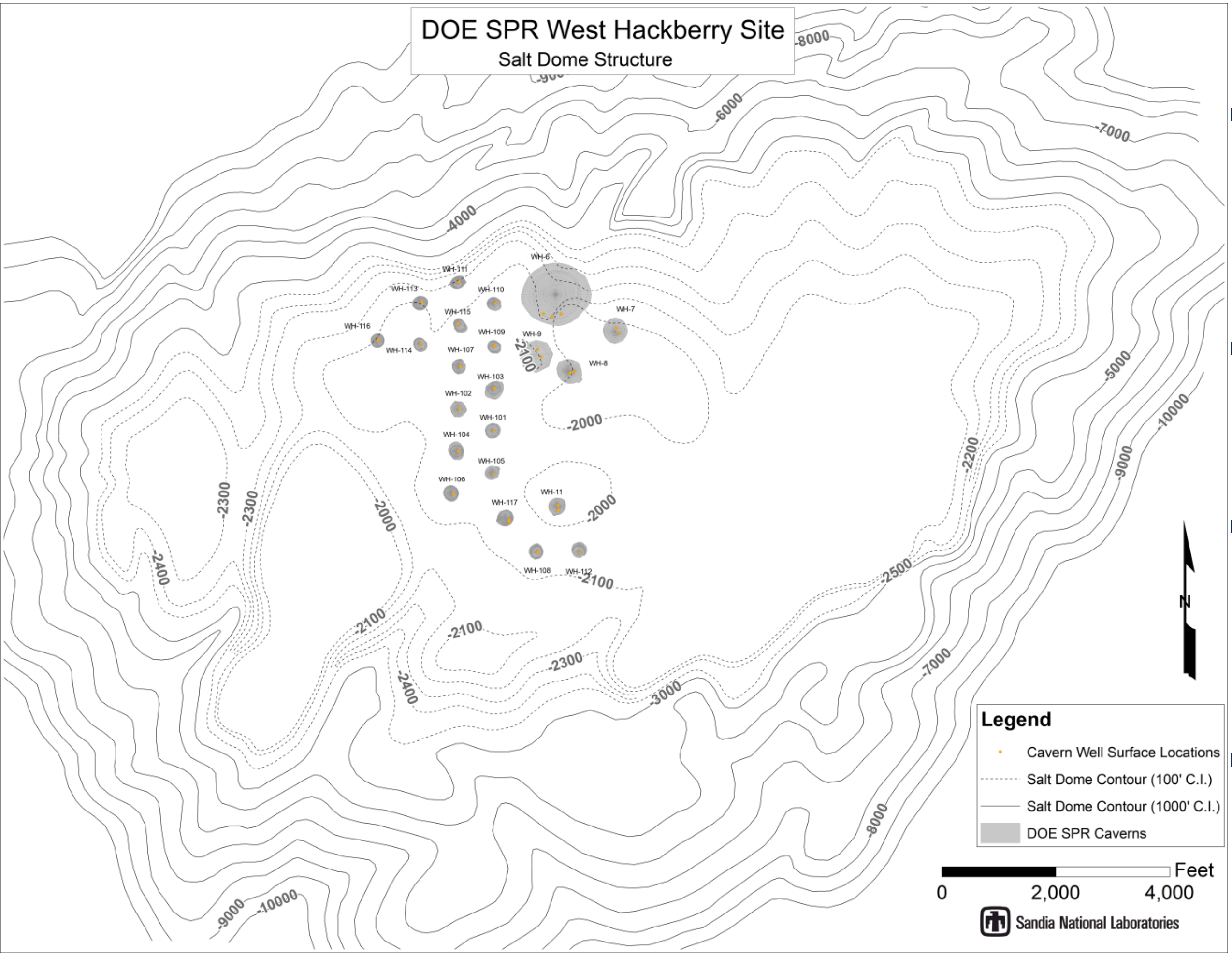
Updated West Hackberry geomechanical model

- Full dome included in model
- All caverns meshed to axisymmetric representations of sonar-measured geometries
- M-D creep model – properties developed by comparison of predictions to site data
- Actual wellhead pressure histories through April 2014 used

Application of model to site operations

- Well and cavern integrity evaluations
- Available drawdowns for each cavern
- Disposition of large-diameter oil storage cavern WH-6 (not described in this paper)

West Hackberry SPR Site



- ~228 MMB of oil storage in 21 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

Full Dome Model for WH

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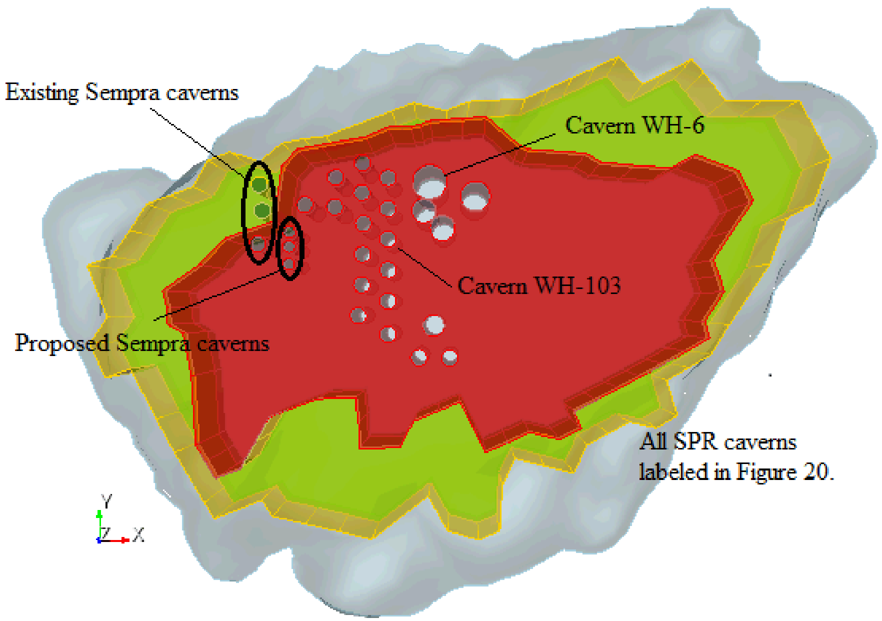
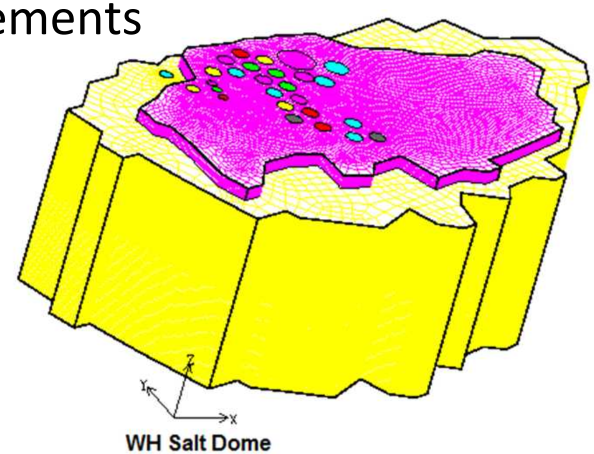
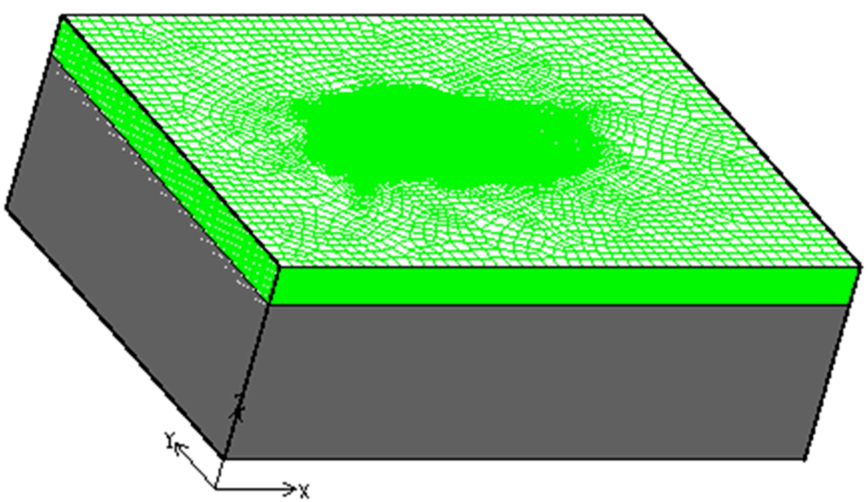
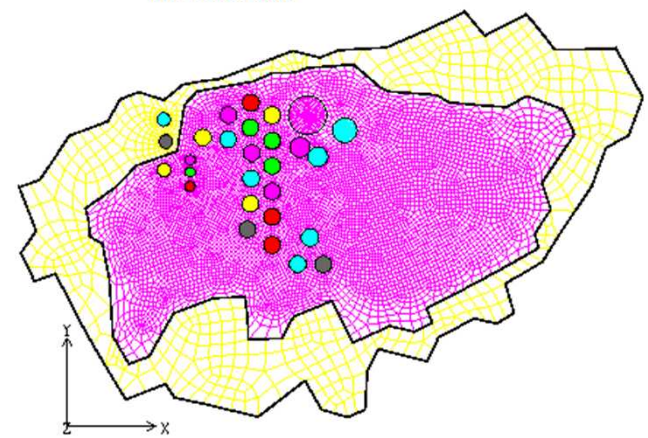


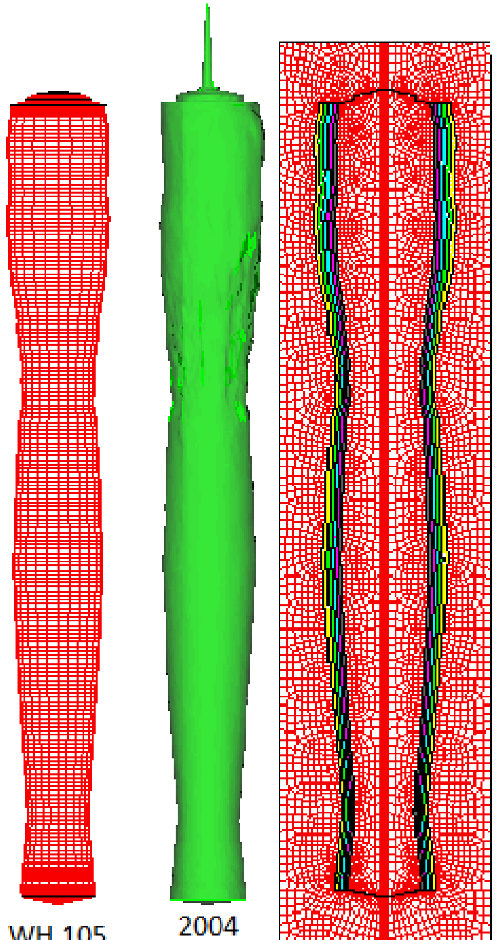
- Contains entire WH salt dome, all 22 WH storage caverns, 3 Sempra caverns west of WH site
- Full mesh contains 5.95 million elements







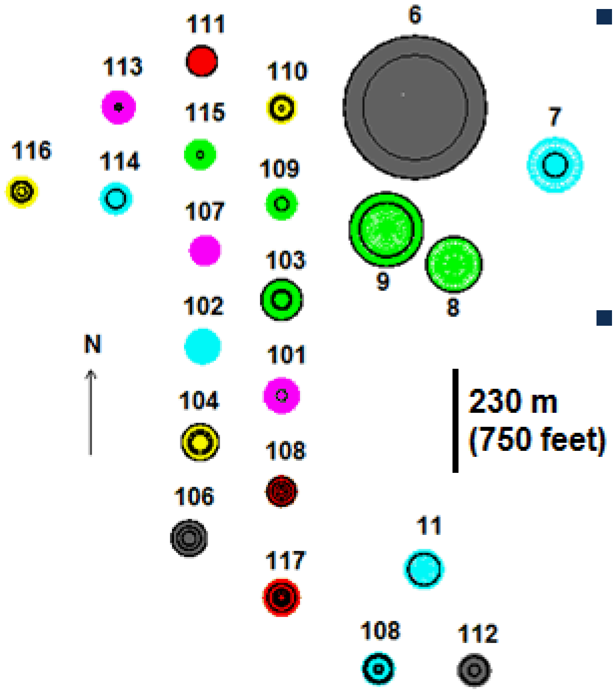
Full Dome Model for WH p. 2



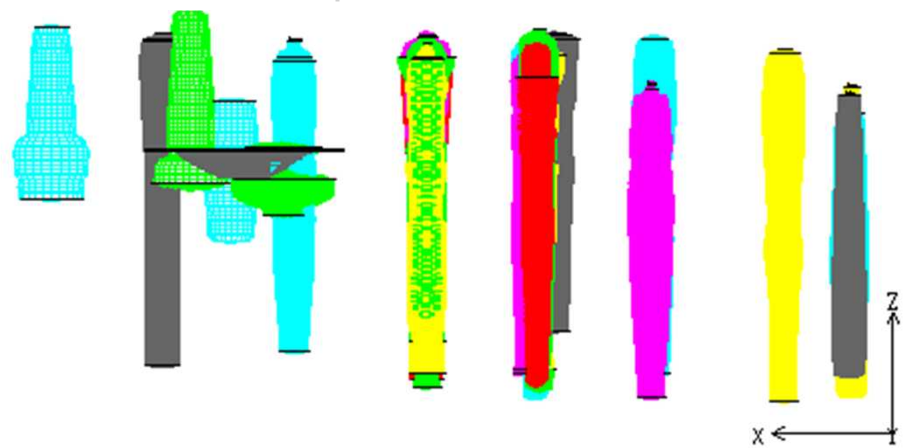
WH 105 mesh

2004 sonar

WH 105 with 5 drawdown layers ("onion skins")



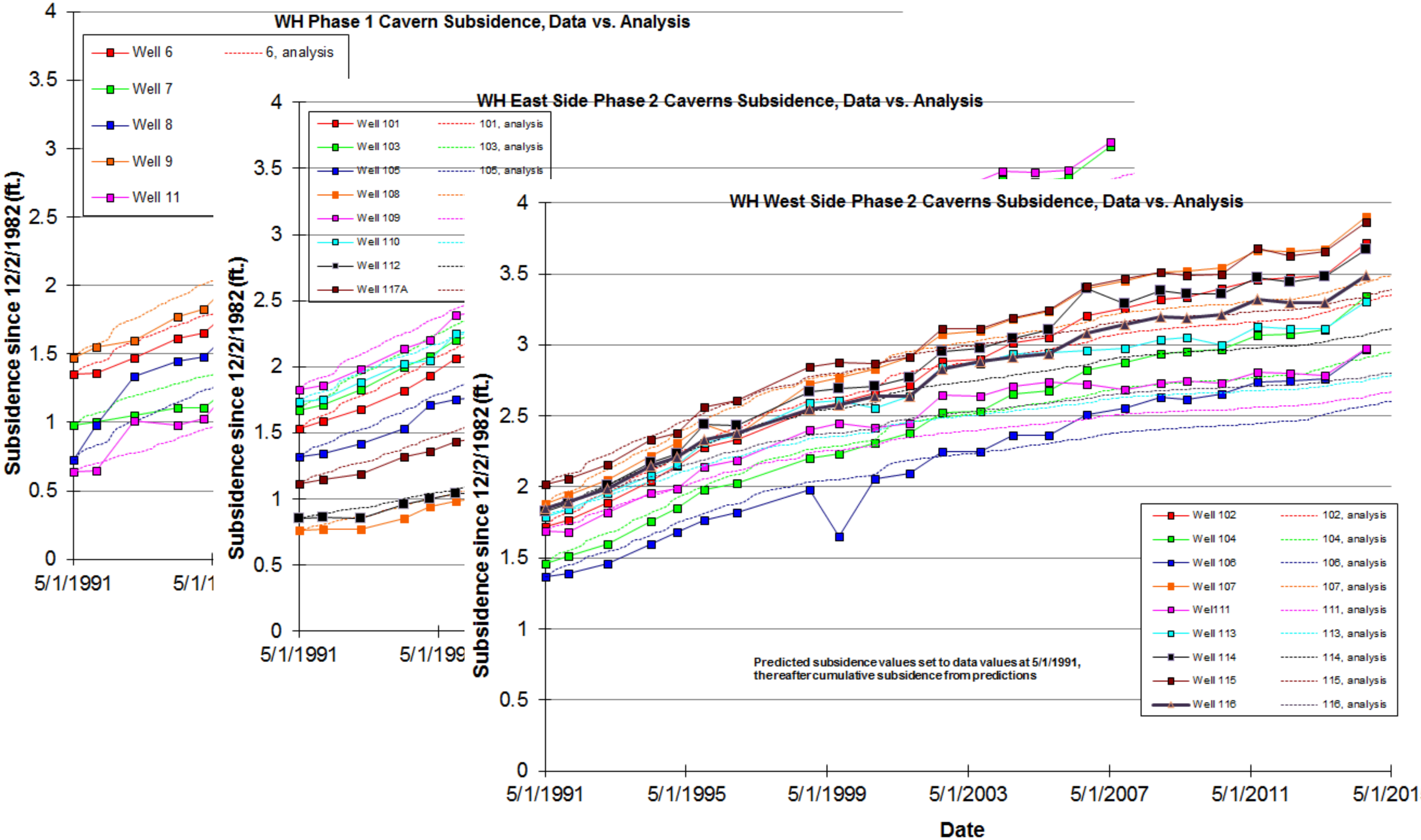
- All caverns meshed to sonar-based geometries – axisymmetric, based on area-averaged radius at each sonar depth
- 5 leach layers ("onion layers") included for nearly all WH caverns (4 layers for WH-8, 3 layers for WH-9, for ease of mesh construction)



Upgrades with Full Dome Model

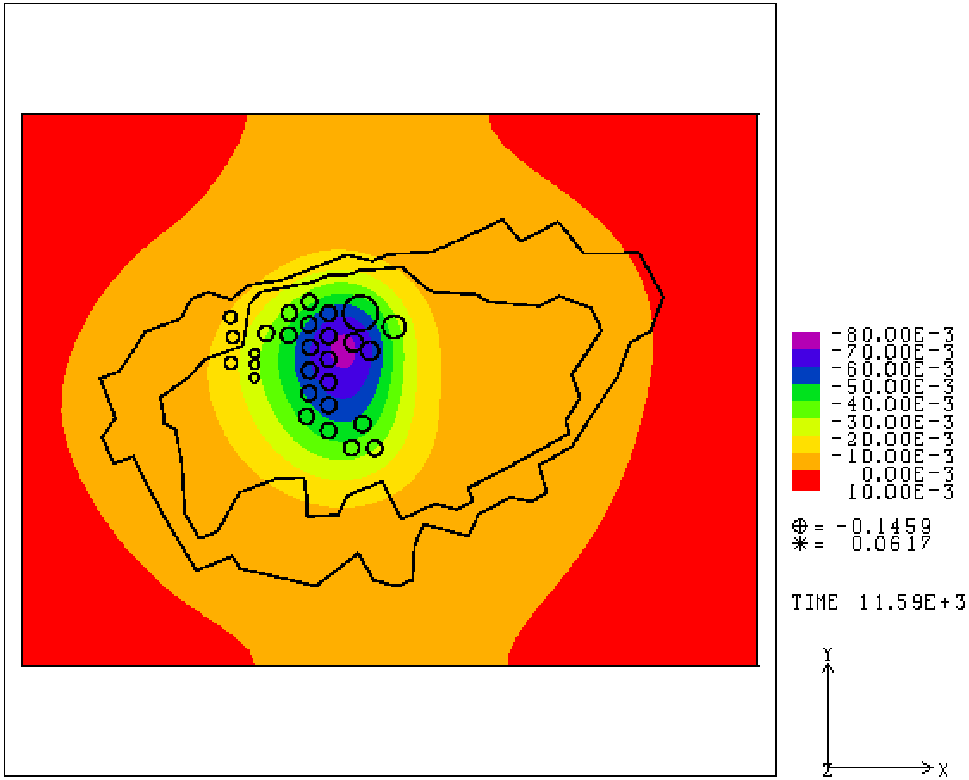
Earlier Models	New Model
Half-dome (symmetry along N-S axis)	Full dome included in model
Caverns shaped as frustums	Caverns shapes based on axisymmetric renderings of sonar-measured geometries
Power law creep model (single steady-state mechanism)	M-D creep model (Multiple steady-state creep mechanisms with transient mechanism; base properties from Munson, 1998)
Prescribed constant wellhead pressure with workovers at 5-year intervals	Historical wellhead pressures through April 2014, then future prescribed pressures
Single set of salt creep properties based on lab tests of up to 6 samples (Munson, 1998)	Cavern-specific creep properties (K_0 transient multiplier and A_2 steady-state coefficient) to try to match measured cavern volume closures
Historical cavern volume closure, surface subsidence compared to model predictions	Same data used for model calibration, with partial success; K_0 from Munson multiplied by 18.2, A_2 by 0.89-3.2

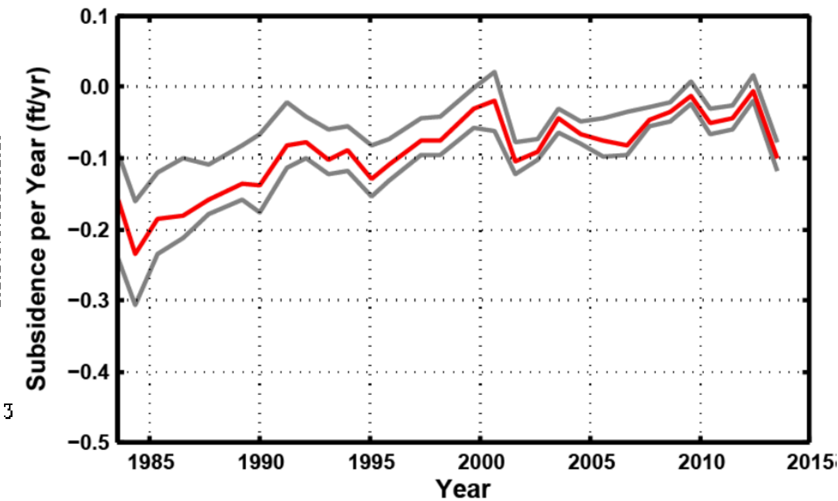
WH Model Results – Surface Subsidence



- WH model predicts surface subsidence over WH very well
- Slight underprediction of subsidence on west side – Sempra cavern influence?

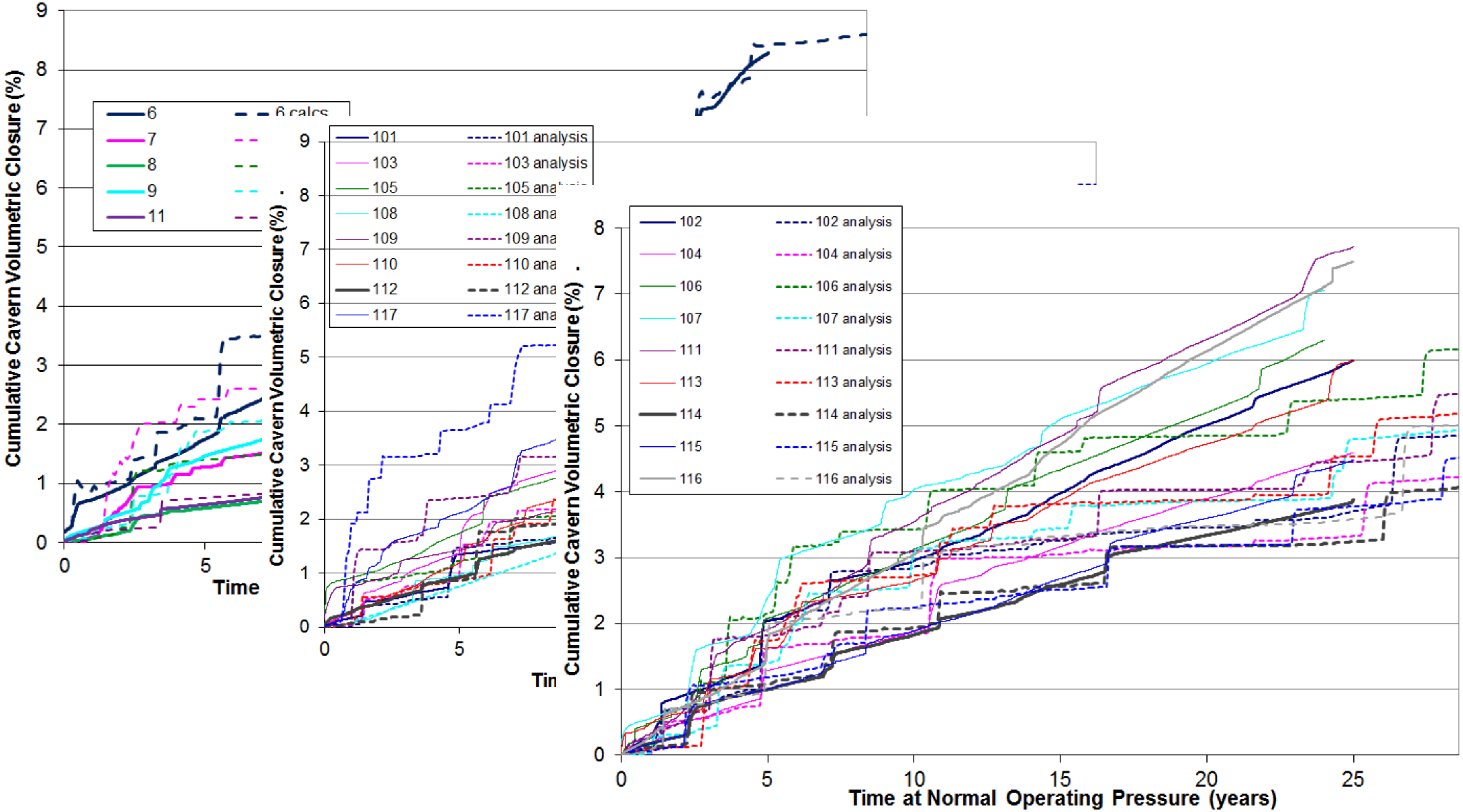
WH Model Results – Surface Subsidence





- Predicted subsidence rate, in feet/year, between August 2013 and August 2014

WH Model Results – Cavern Volume



- WH model predicts <u>overall</u> cavern closure fairly well; discrepancy on normal operating closure between wellhead pressure values, GM model

Average strain along length of casing in salt since 1985

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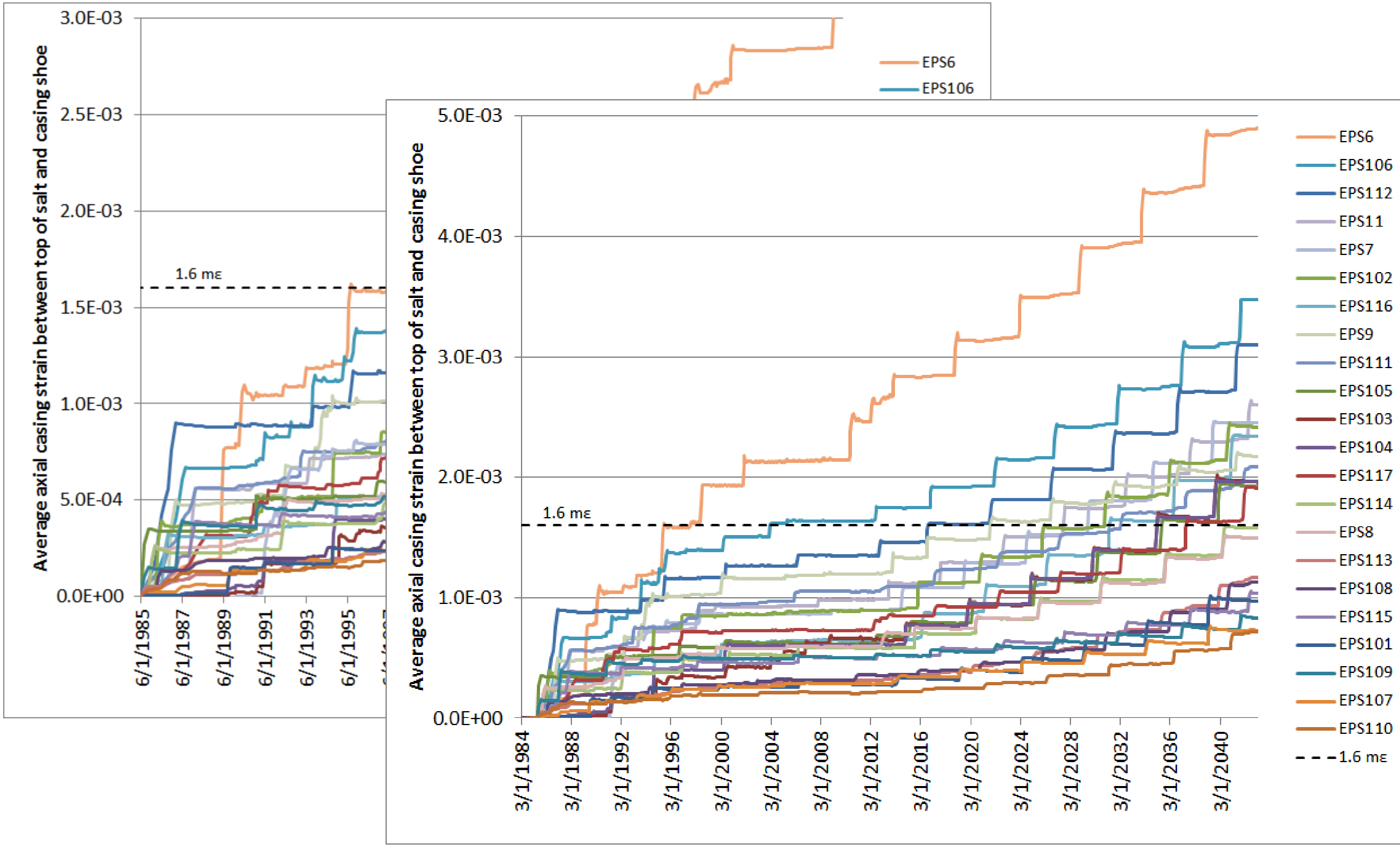
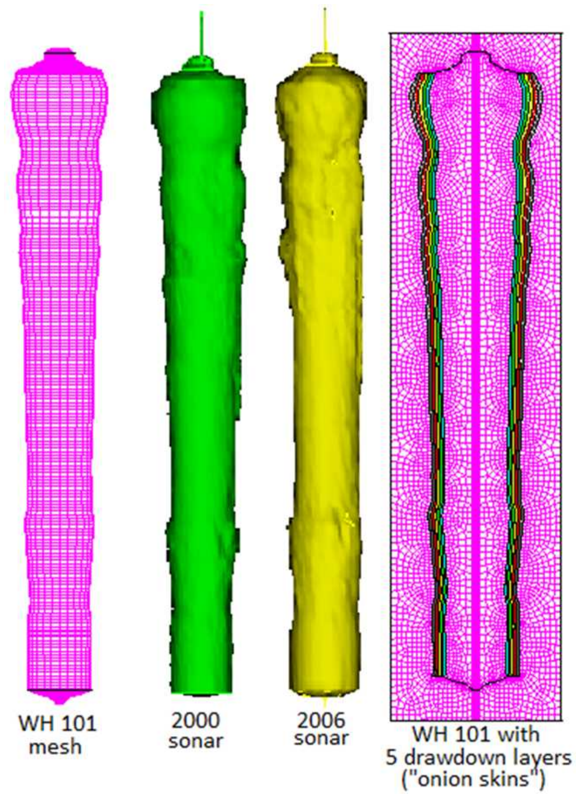
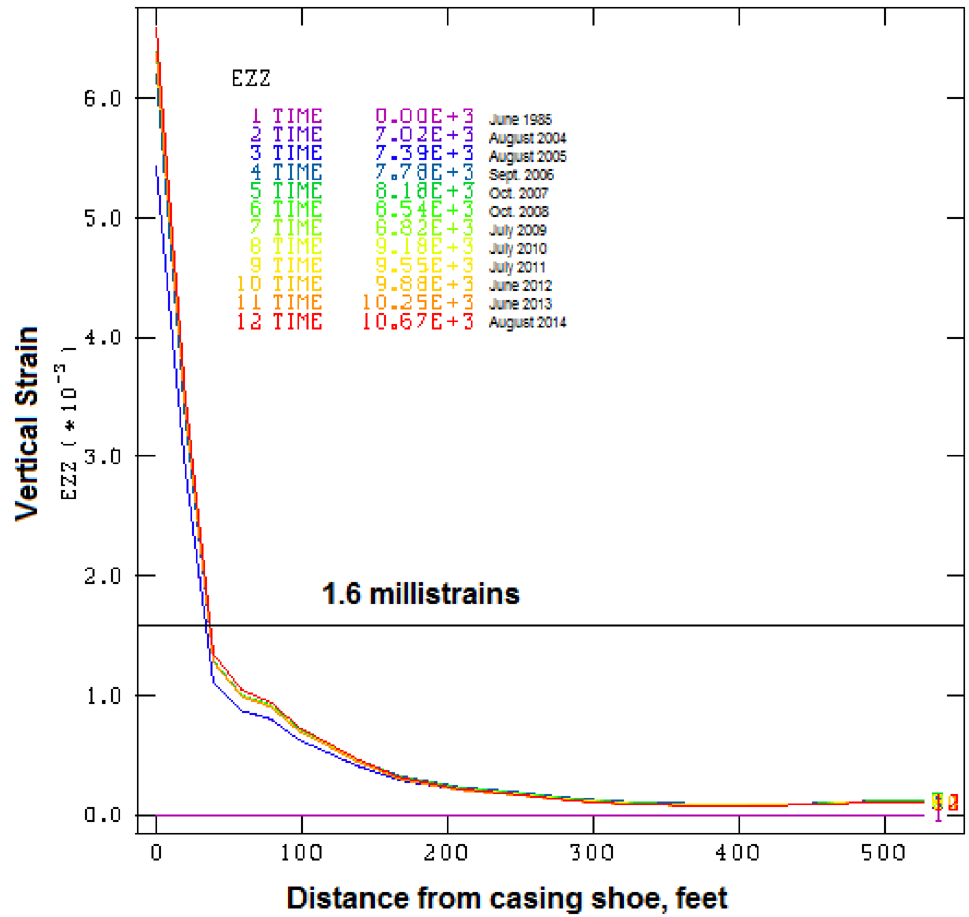


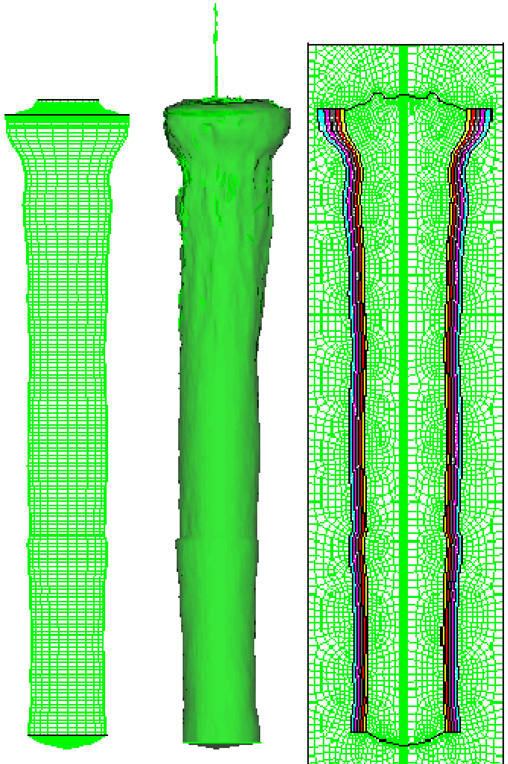
Casing strain along casing for WH-101



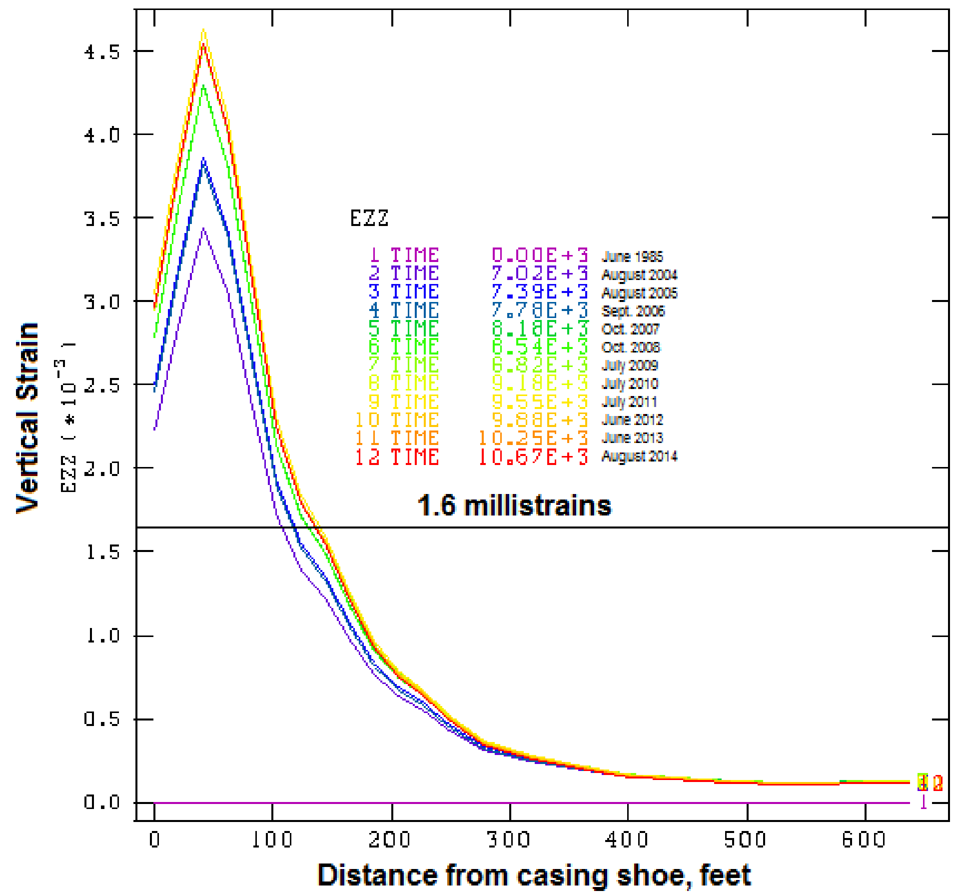


Relatively round cavern roof – maximum axial casing strains occurs near roof, casing shoe

Casing strain along casing for WH-103



WH103 mesh | 2004 sonar | WH 103 with 5 drawdown layers ("onion skins")



Somewhat wider, flatter cavern roof – axial casing strains increase from roof past shoe, maximum above shoe

Available Drawdowns Evaluation

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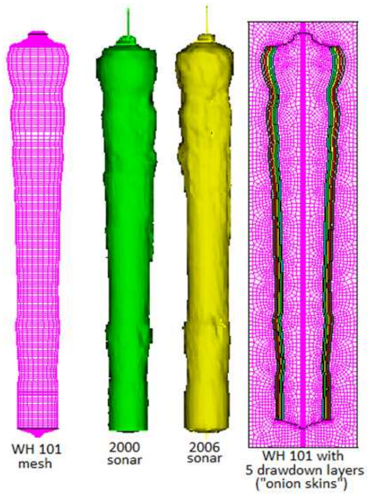
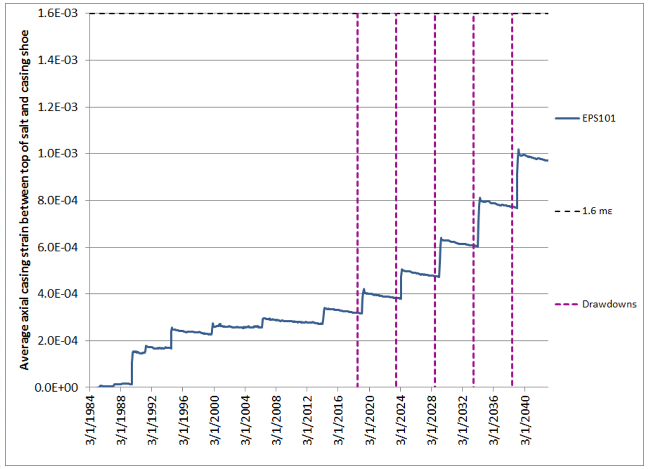
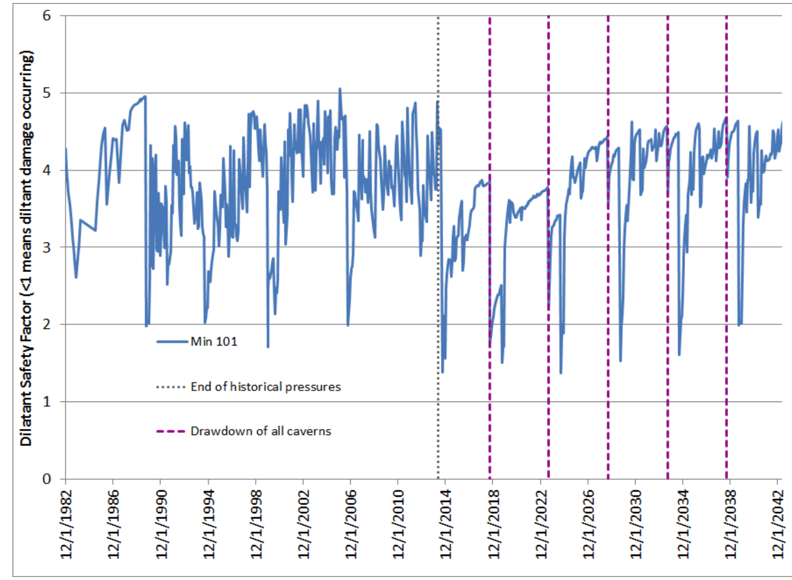
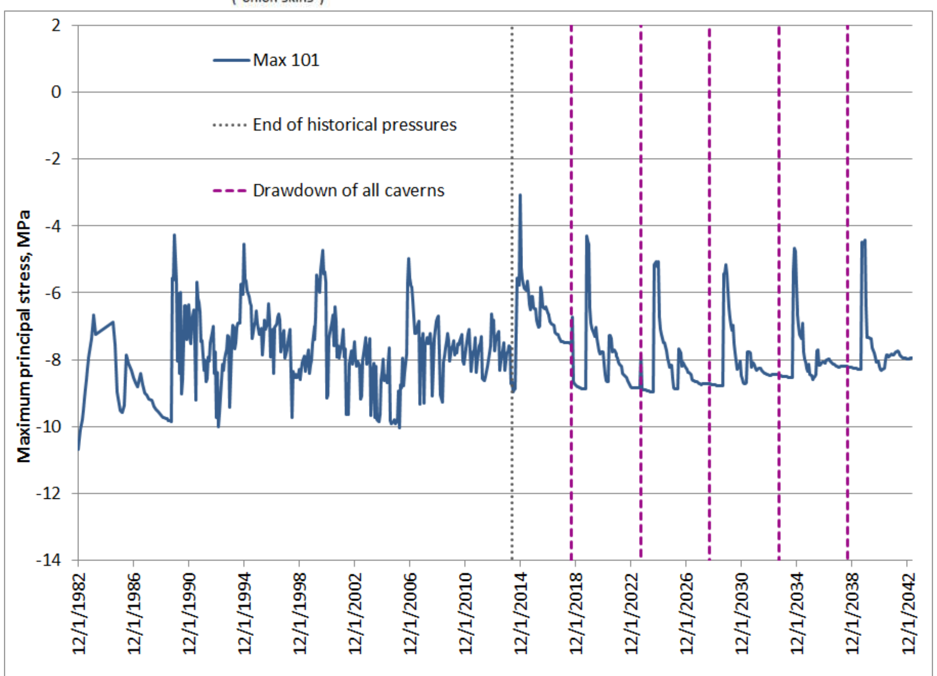








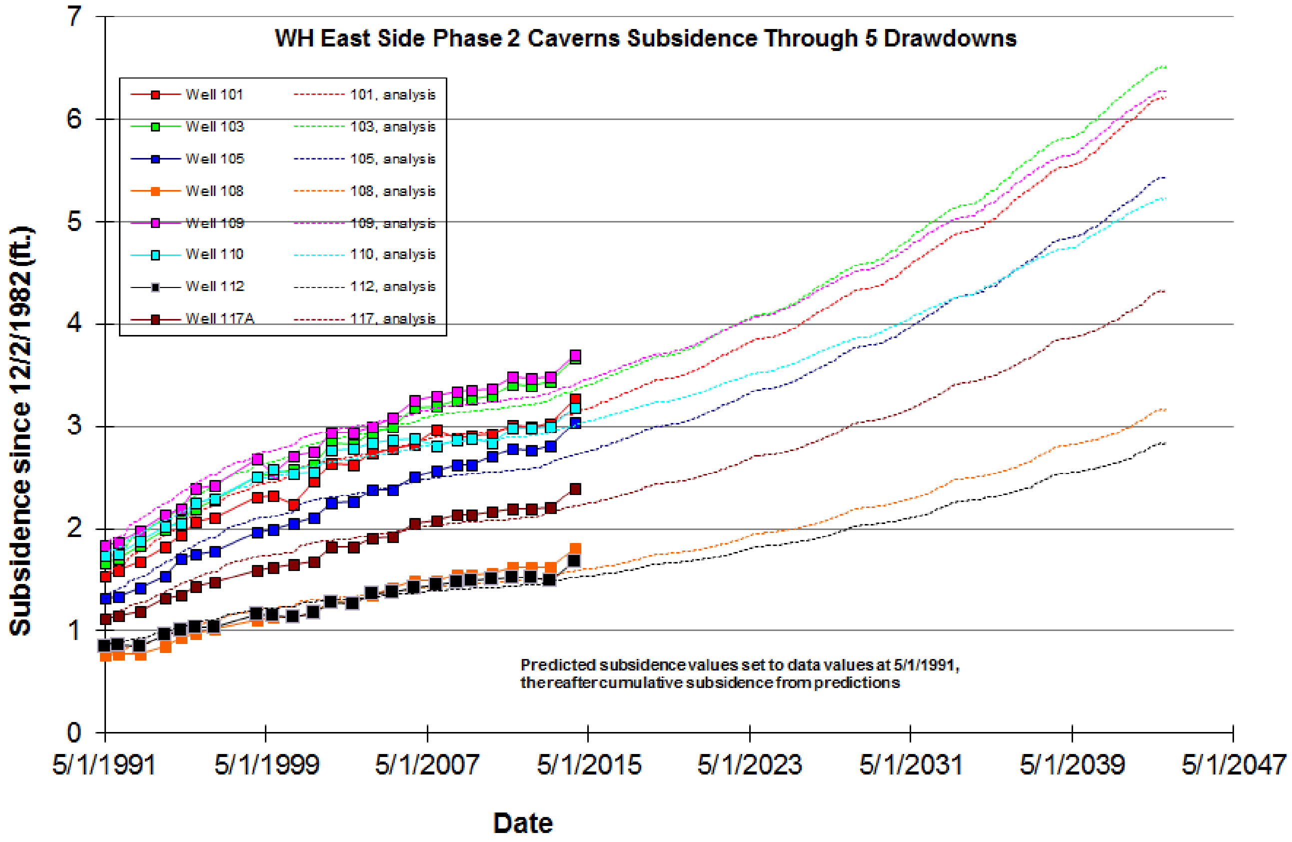
- Dilatant & normal (tensile) stresses, max casing strain
- All Phase 2, candlestick-shaped caverns (101-117) predicted to have at least 5 available drawdowns; caverns 8, 9 have 1-2 drawdowns due to unusual shapes, close proximity

Further applications of model

- Reevaluated estimates of available drawdowns for each WH cavern – reported to DOE in March 2016.
- Reevaluate how CAVEMAN calculates cavern volume closure based on wellhead pressure, OBI, fluid exchanges; use to fine-tune both CAVEMAN, GM model results
- Use results of analyses to understand pressurization effect on adjacent caverns during workovers, possibly develop predictive capability
- Apply predicted stresses/strains to wellbore model

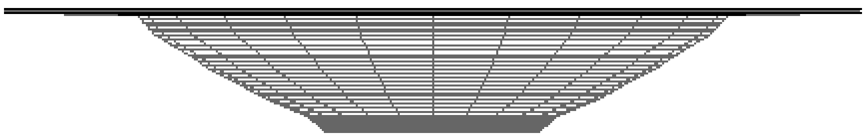
THANK YOU FOR YOUR ATTENTION!

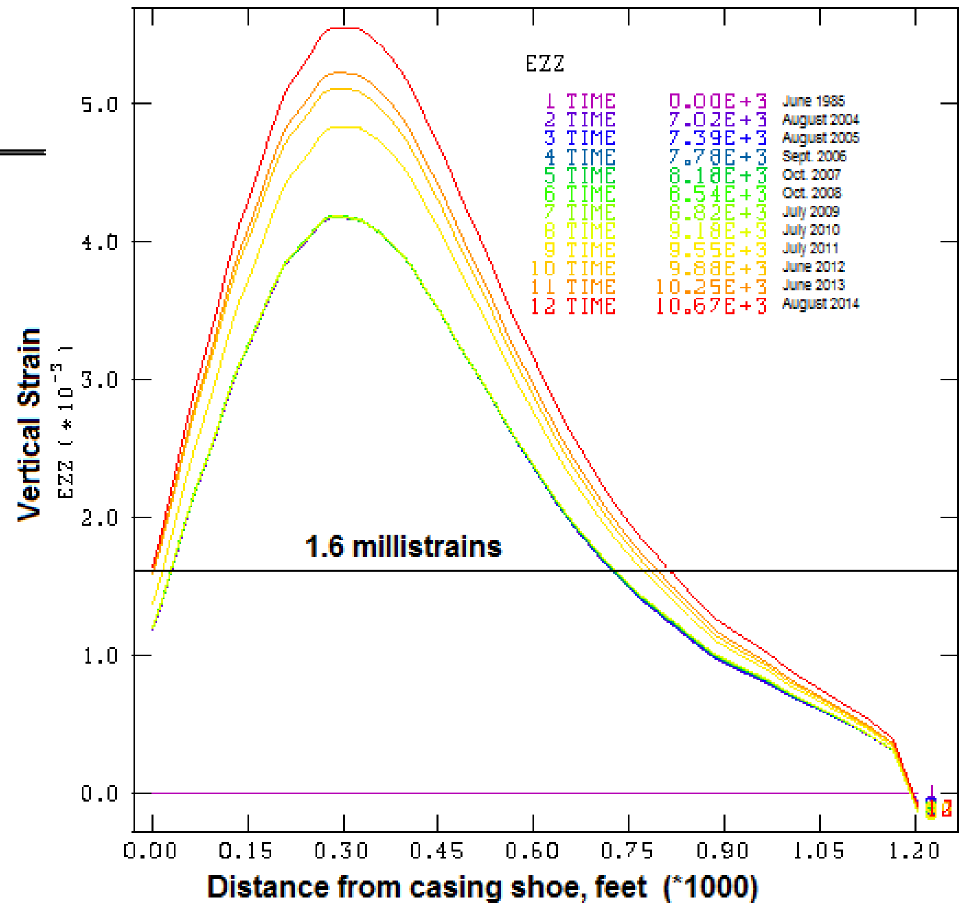
WH Model Results – Surface Subsidence



- Predicted subsidence in feet through 2044 (with five drawdowns for most caverns)

Casing strain along casing for WH-6

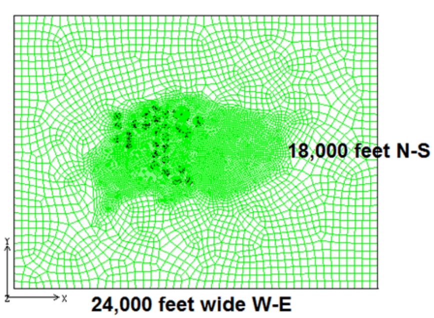


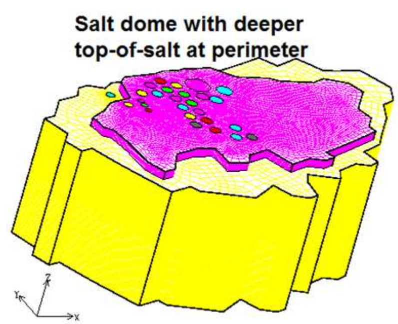


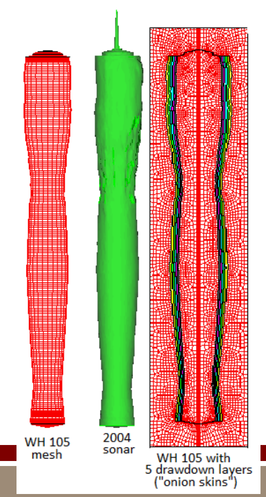
Much wider, flatter cavern roof – maximum axial casing strains occurs 25% distance between shoe, top of salt

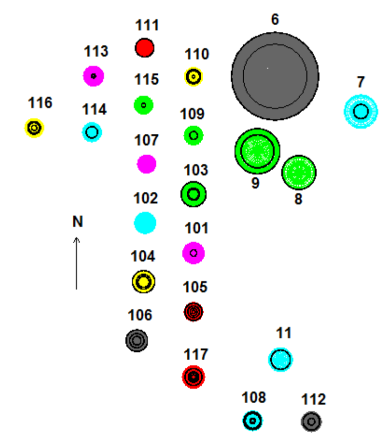
What is a geomechanical model?

- A geomechanical model calculates the stresses and strains at millions of points within a geological region. The modeler uses these calculations to predict cavern closure, surface subsidence, and stresses and strains on wellbore casings. It does this using the following:
  - A three-dimensional mesh representation of the rock types and features of an area, including the salt dome and caverns
  - Standard engineering mathematical equations for stresses and strains, including the mathematical models for different types of rock behavior
  - Salt creep property values determined from laboratory tests on salt core samples, and modified using site data to match predictions
  - Workover schedules
  - Geothermal gradient





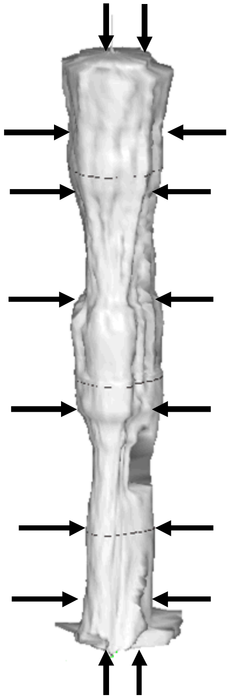




What is creep?

- Creep is a property of salt that causes it to deform and flow when exerted upon by unequal stresses (think “Silly Putty”)
- Salt, potash, cement are known to exhibit creep; most geological materials do not, or do so at much lower levels
- Salt is like water (and unlike most geological materials) in that the horizontal stresses at depth are equal to the vertical stress at depth due to overburden, called hydrostatic stress (most rocks have a lower horizontal stress due to elasticity)
- When a cavern is formed, the salt tries to move into the region of lower pressure to reach a hydrostatic stress state
- The oil/brine pressure cannot match the in situ (overburden) pressure in the salt; thus the salt creeps into the cavern.
- $\dot{\varepsilon} = A\left(\frac{\Delta\sigma}{G}\right)^{n} e^{\frac{-Q}{RT}}$; $\dot{\varepsilon}$ is strain rate, Δσ is difference between horizontal, vertical stresses

Effects of creep



Primary effects

- Loss of cavern volume
- Tensile stresses/strains created in wellbore casings due to stretching
- Cavern floor rises

Secondary effects

- Surface subsidence
- Salt falls (created by extreme stress states, geometric anomaly)
- Shear in wellbore casings (particularly around perimeter of cavern field)
- Change in pressure in nearby caverns during workover

Limits of Geomechanical models

- Simplified geometries in the mesh (although these are continually getting more realistic)
- Models reflect current understanding of site behavior, and can be improved with new info (i.e., BH salt/caprock slip)
- Model parameters are validated by comparison of model predictions to actual surface subsidence, cavern volume closure
- Pressure in caverns is explicitly input into calculations; i.e., calculations cannot be used to predict pressure change due to cavern closure, or pressure change in one cavern when adjacent cavern is in workover
- No flow modeling (oil/brine movement, gas intrusion, salt dissolution, etc.)
- Must explicitly (if desired) include features such as faults (which has been done for Big Hill) and casings

WH-6 work from 2014 also in report

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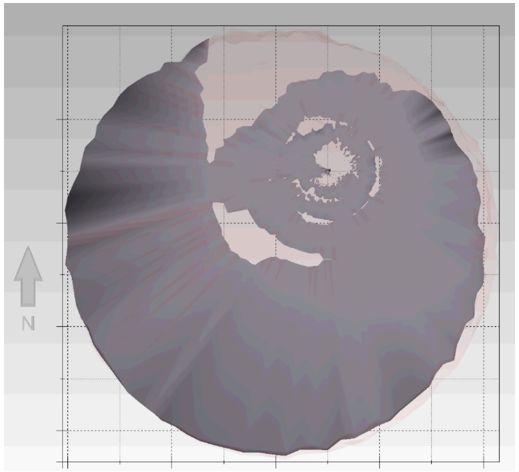
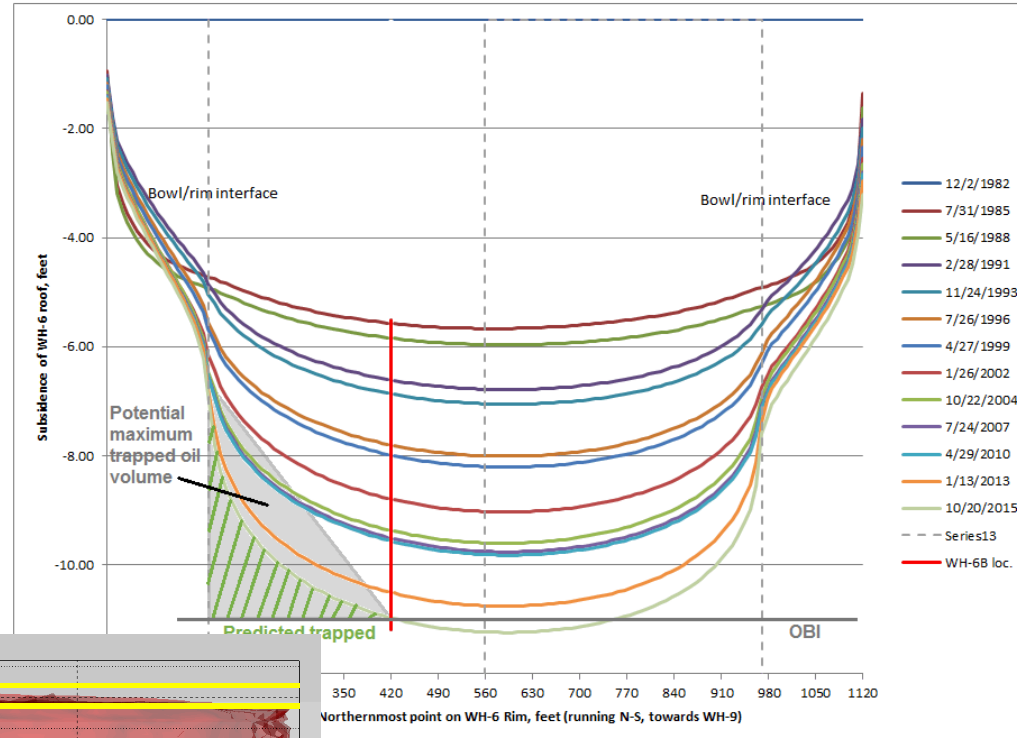
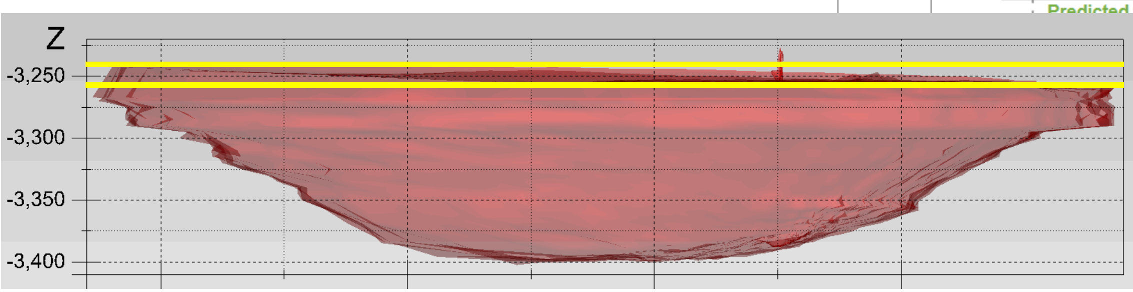


MVS slices indicate full connection to WH-6B borehole at a depth of 3256 feet





From -3240 to -3256 Total Computed Volume From MVS Slices is **522,795** BBL.

SonarWire Strapping Curve for Same Depth Gives a Total of **387,293** BBL.

Maximum horizontal strains on surface through 2015