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GEOMECHANICAL TOOL FOR EVALUATING CASING DEFORMATION OF STORAGE CAVERNS IN SALT DOME

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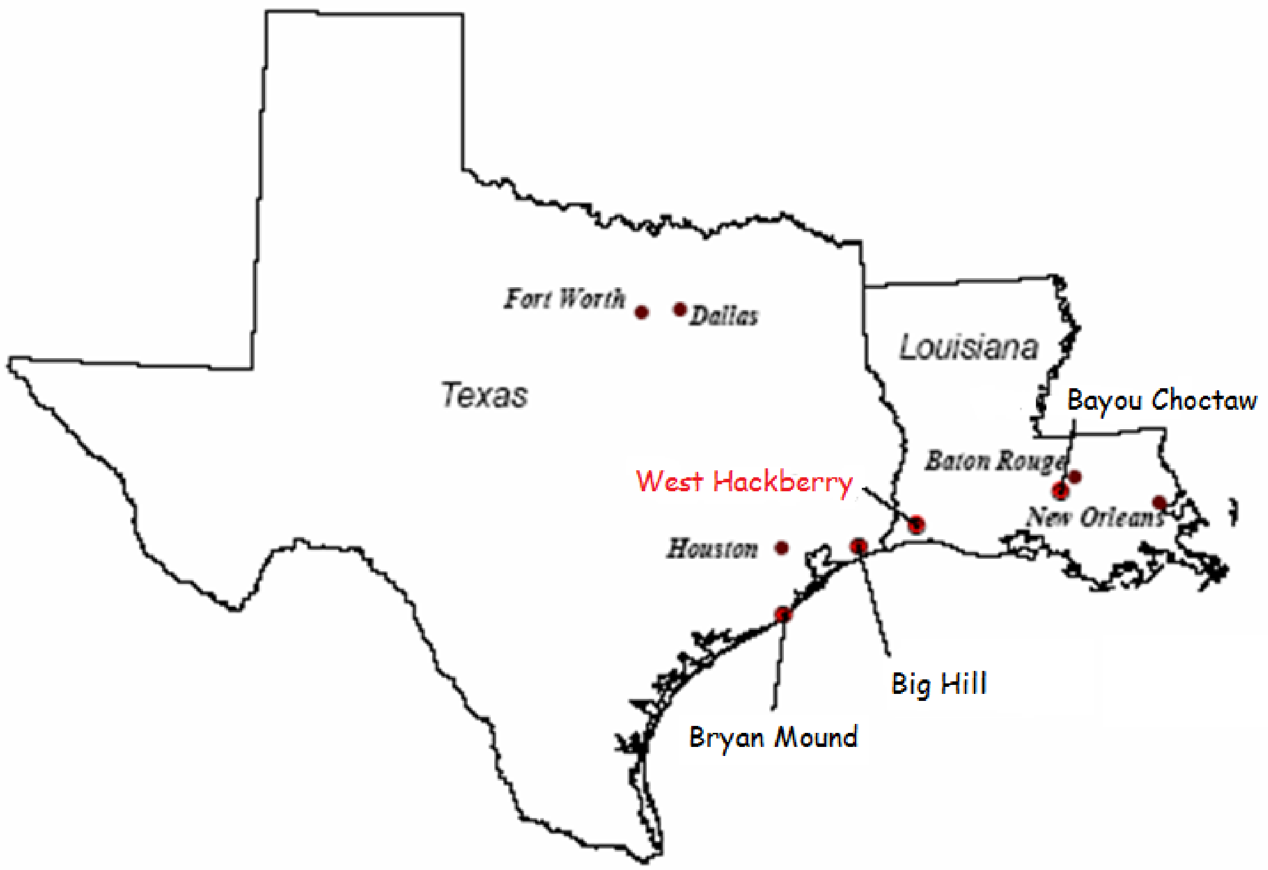
BACKGROUND - MOTIVATION

- Promote **physical understanding of the U.S. SPR (Strategic Petroleum Reserve) salt cavern behaviors** by implementing potential scenarios related to cavern operations and geologic conditions

  - U.S. SPR stores crude oil in 60 salt caverns located at four different sites in Texas and Louisiana.
  - Most of the caverns were solution mined by U.S. Department of Energy.

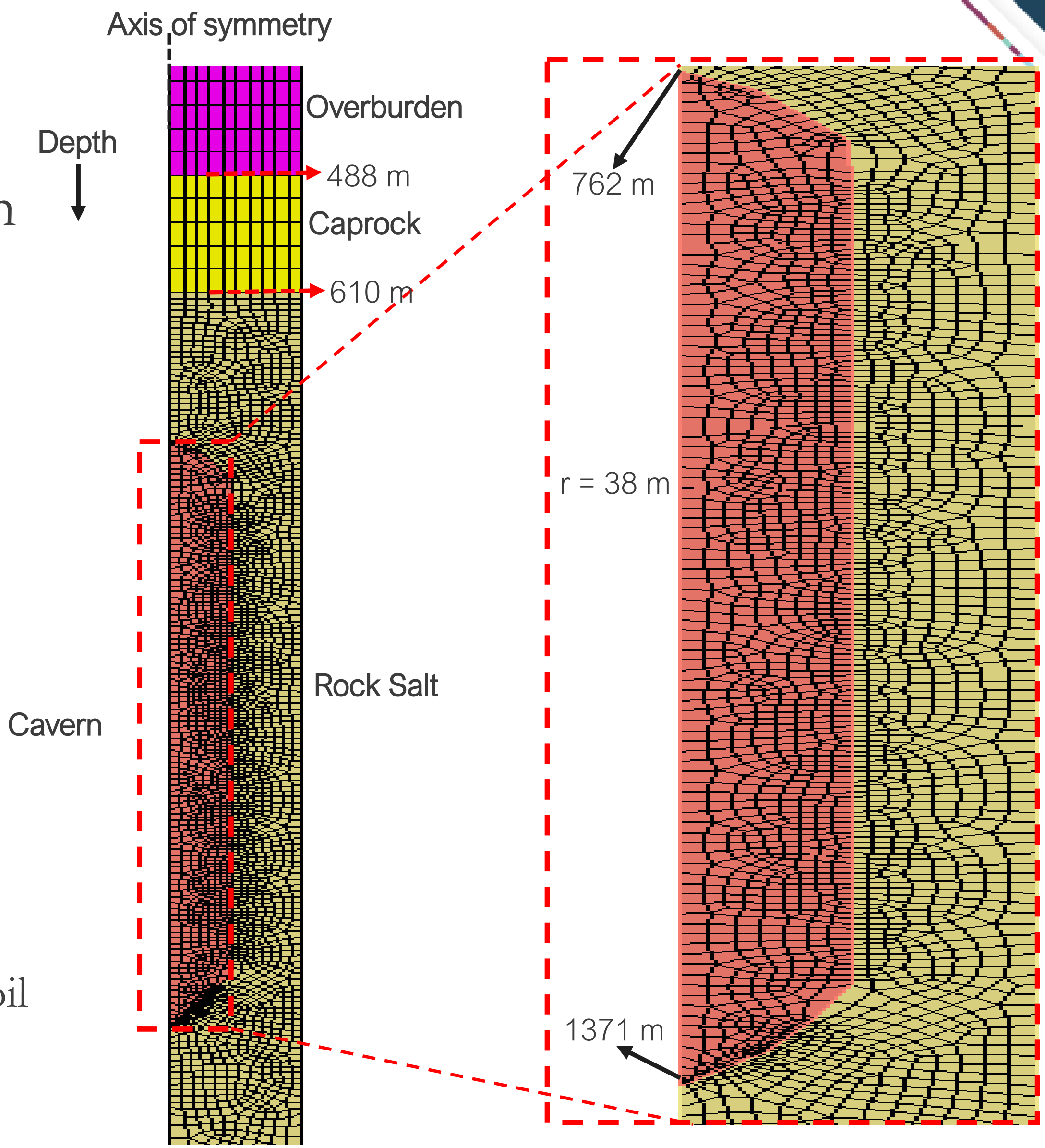


BACKGROUND - MOTIVATION

- Promote **physical understanding of the U.S. SPR (Strategic Petroleum Reserve) salt cavern behaviors** by implementing potential scenarios related to cavern operations and geologic conditions
- **A simple generic salt dome model was developed**
  - Modeled using a similar approach from Brouard et al., 2021 SMRI Fall 2021 Technical Conference paper
  - Modeled using the West Hackberry SPR site properties – stratigraphic layers, material properties
- **Use calculations to analyze and predict effect on structures:**
  - Well integrity (steel casings)
  - Surface subsidence (effect on surface structures)
  - Cavern integrity/volume change (ability of salt to contain oil, allow retrieval)
  - Long-term operational considerations (effect of workovers on cavern integrity)

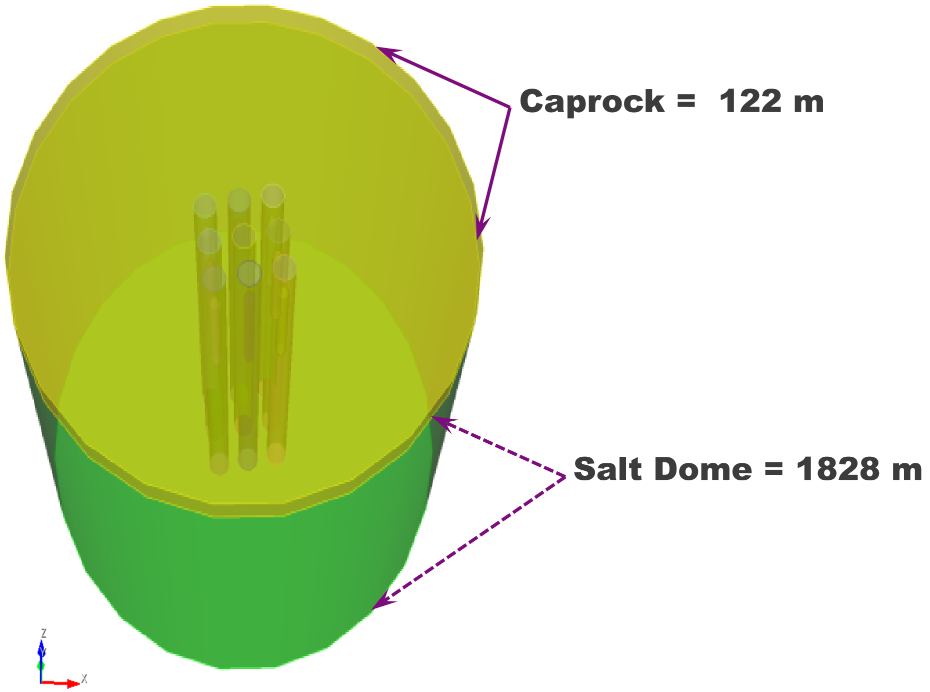
MODEL SETUP

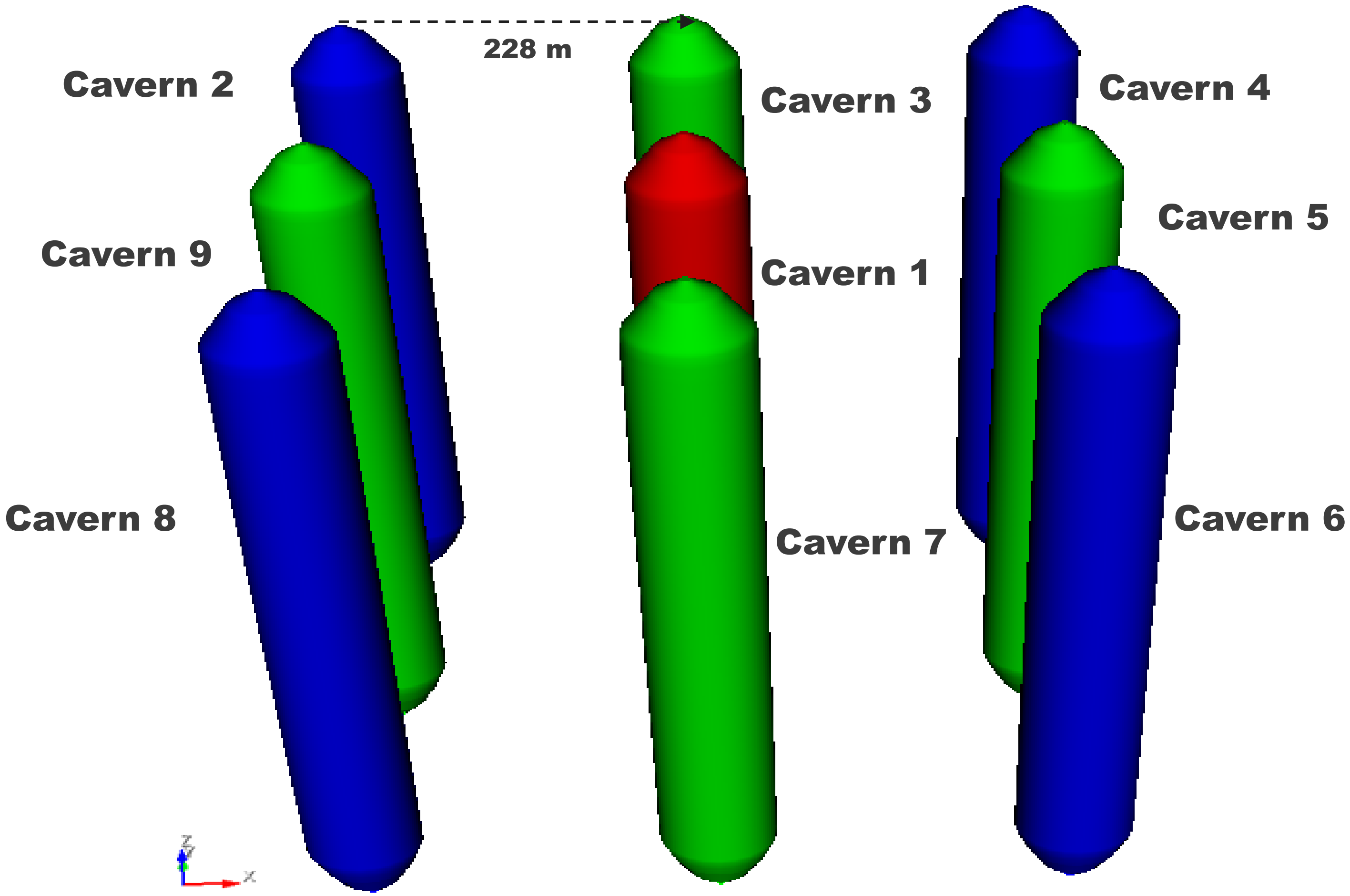
- Axi-symmetric Finite Element (FE) model
- Salt cavern at 762 (2500 ft) – 1371 (4500 ft) m depth
- **Elastic behavior in all layers except salt**
- Simulation timeline – 42 years
  - Equilibration phase – 1 year
  - Leaching phase – 1 year
  - Operation phase – 40 years
- Constant pressure field with 900 psi (~ 6 MPa) is Wellhead Pressure (WHP)
  - Pressure within the cavern is calculated using pressure gradient – oil filled cavern



MODEL SETUP - CAVERN GROUP IN A SALT DOME

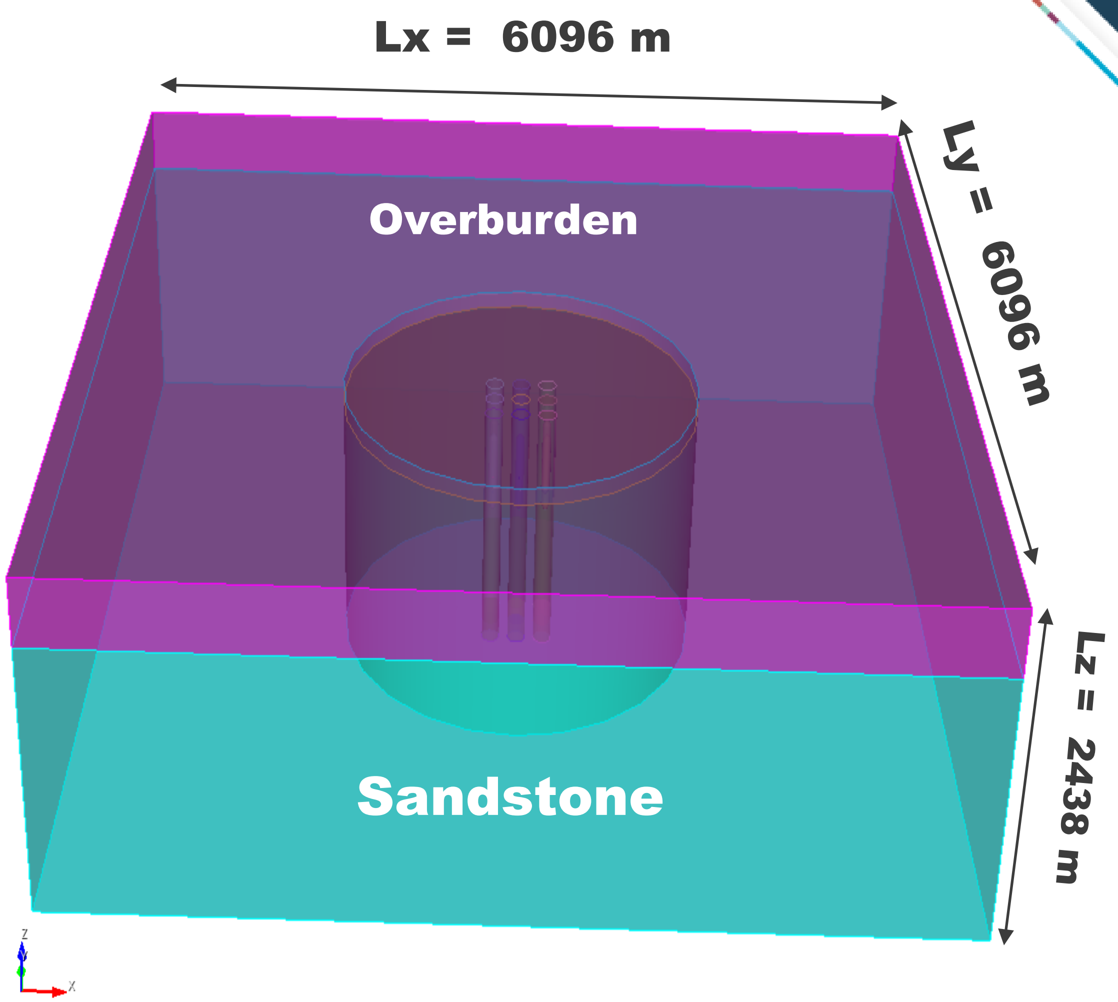
- The salt dome is 1828 m (6000 ft) high, while
- The caverns are spaced 228 m (750 ft) in the x, y from Cavern 1 being at 0, 0 (x, y).





MODEL SETUP- FULL DOMAIN

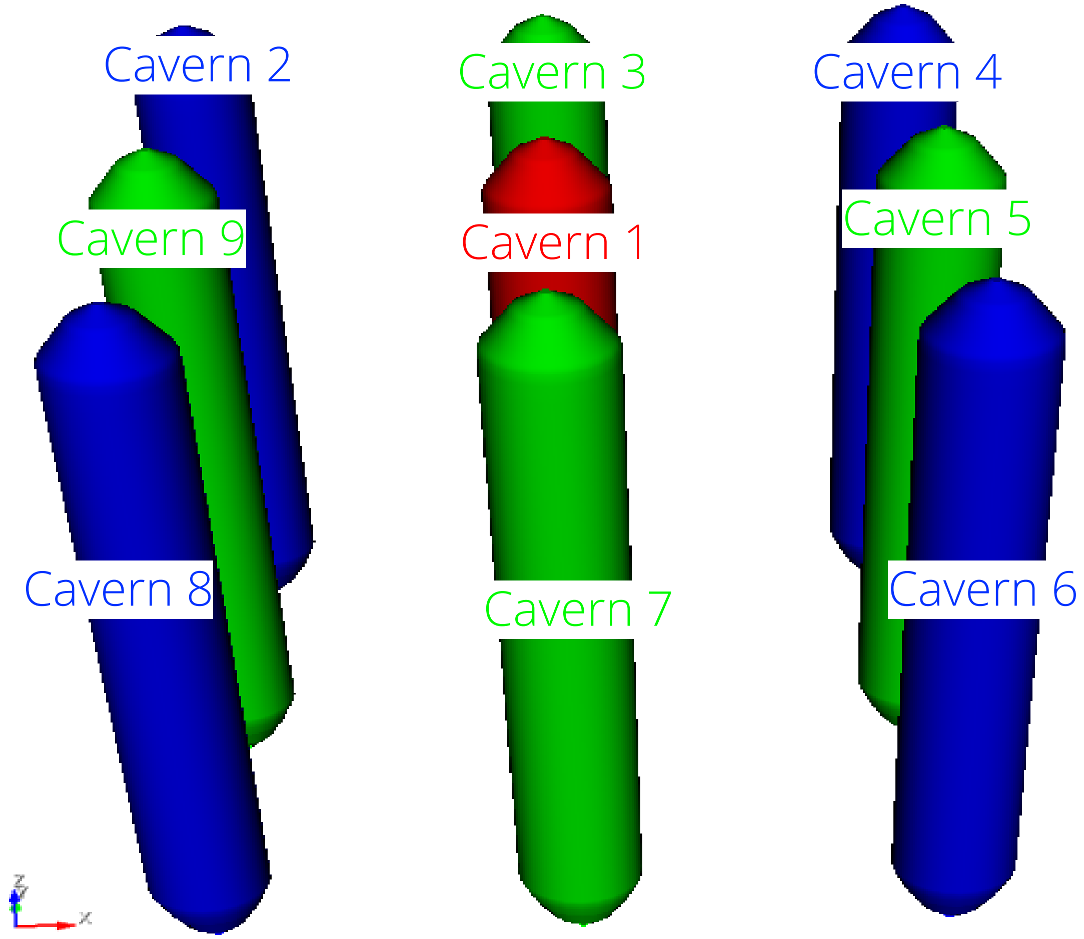
- Meshes were generated using Sandia CUBIT Meshing Program
- Two layers of sandstone and overburden with a cylindrical salt dome
- Hexahedral mesh comprised of **2.21** million nodes and **2.19** million elements
- Simulation runs with SNL's finite element software (SIERRA/SolidMechanics)
- Salt constitutive model (Munson-Dawson)



FEASIBILITY STUDIES

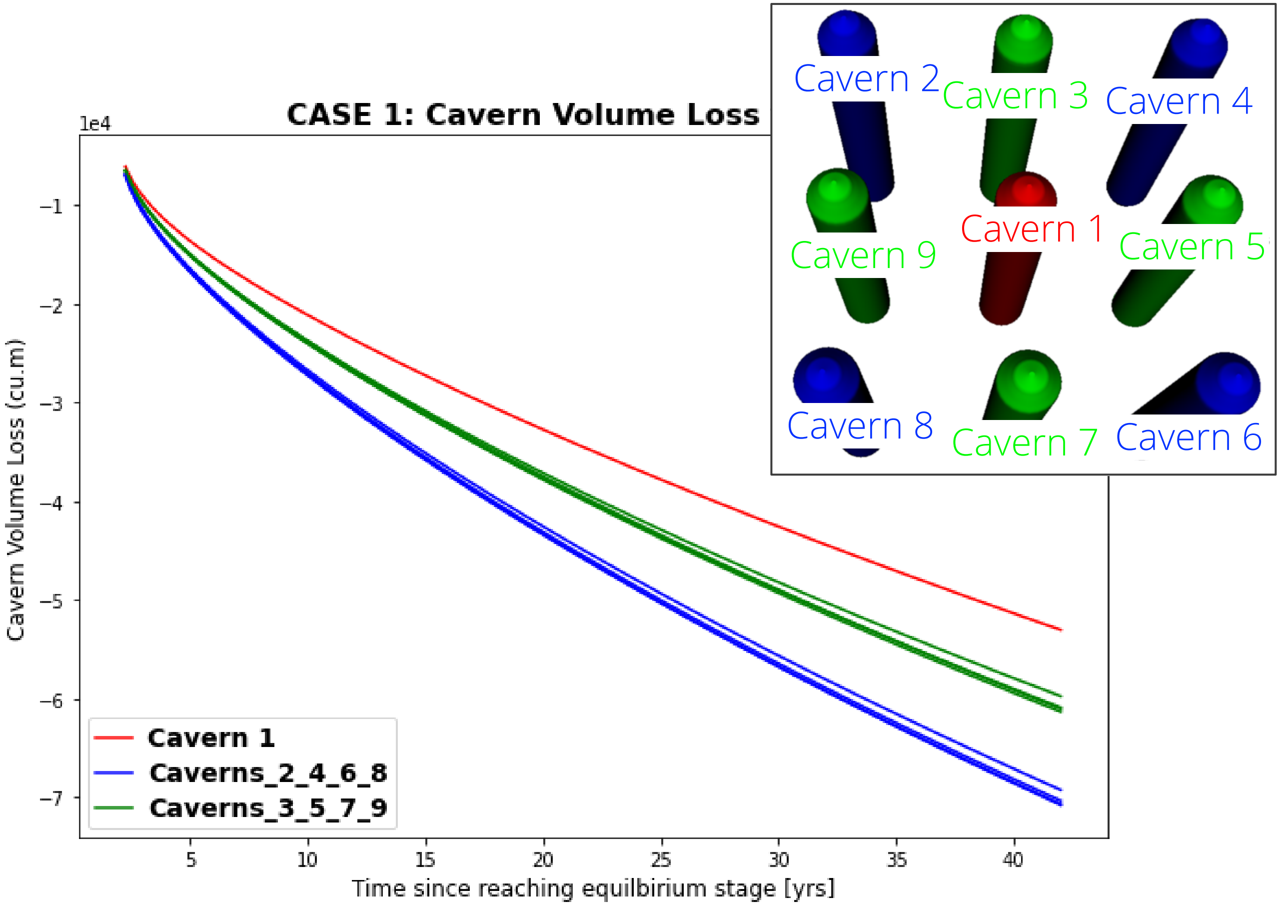
- **CASE1** – Base case analysis
- **CASE2** – Change in M-D creep parameters
- **CASE3** – Caprock compressibility
- **CASE4** – Damaged dome above cavern

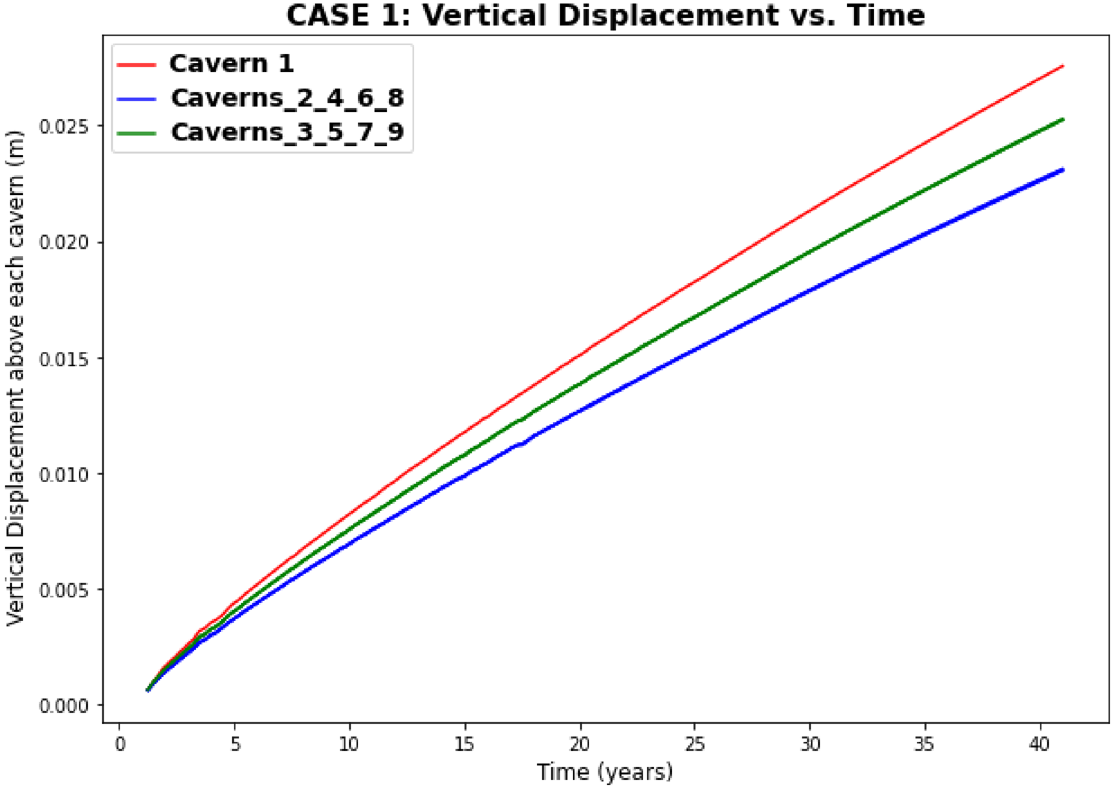
CASE1: BASE CASE ANALYSIS



- **CASE1** – Reference case
  : Constant operation pressure (900 psi)
  : M-D creep model for salt behaviors

CASE1: RESULTS



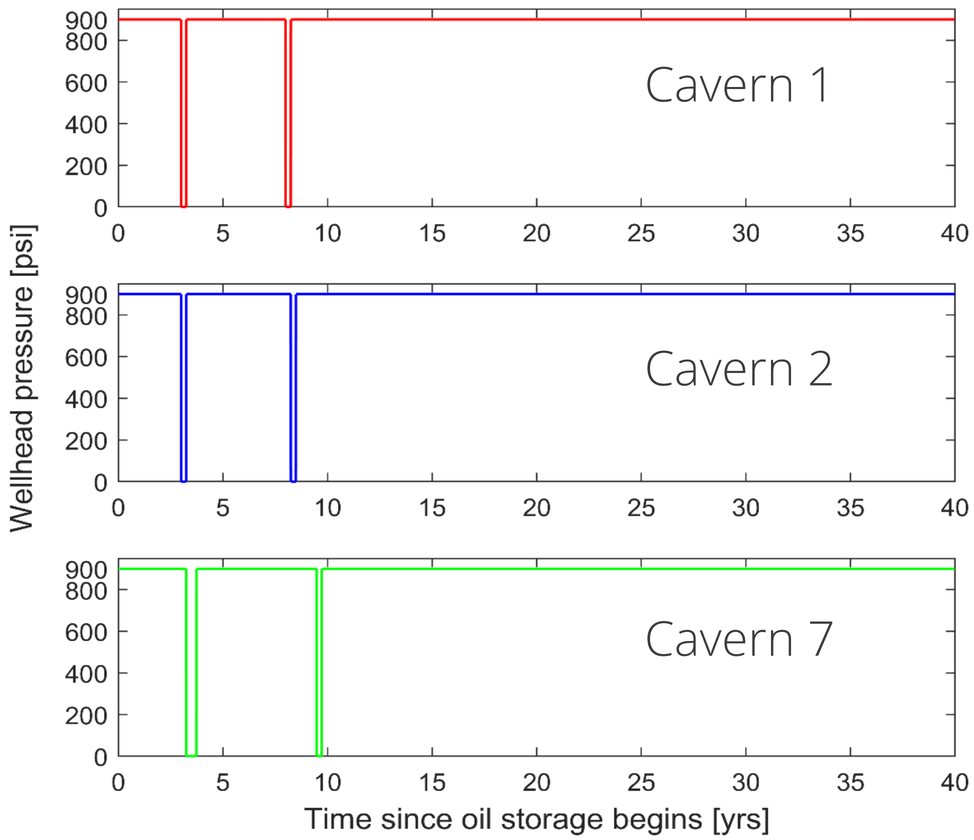


- Less volume closure (cavern creep) and more vertical displacement of the center cavern 1 because of less horizontal displacement.

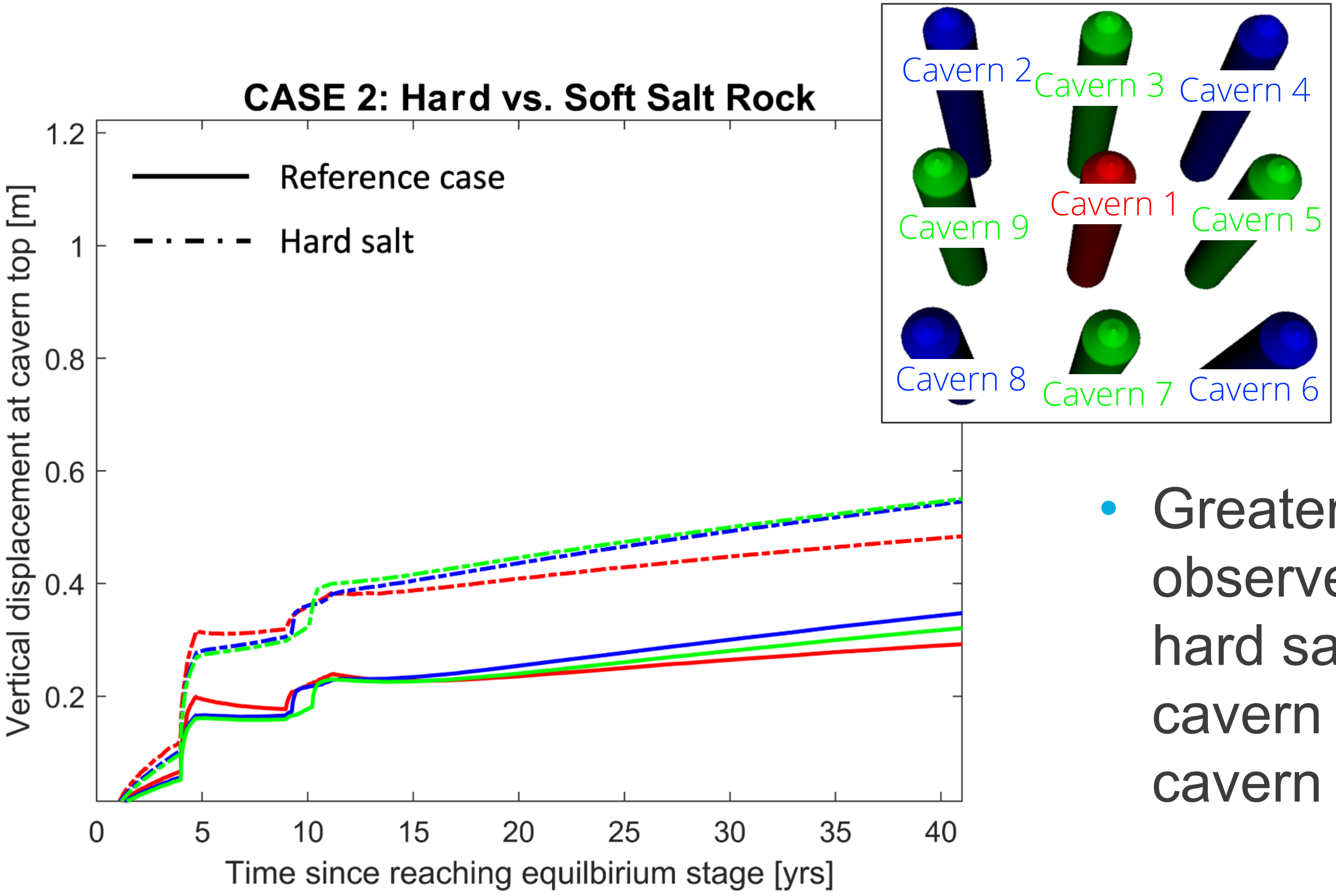
CASE2: CREEP RESISTANCE OF SALT

- **CASE2** – Impact of creep-resistance of salt rock
  : Hard (slow creeping, lower creep rate) vs. soft salt

✓ Note that the sensitivity tests model
  : Maximum/constant operation pressure (900 psi)
  : Two times workover (cavern depressurization to 0 psi)



CASE2: RESULTS OF SALT CREEP RESISTANCE



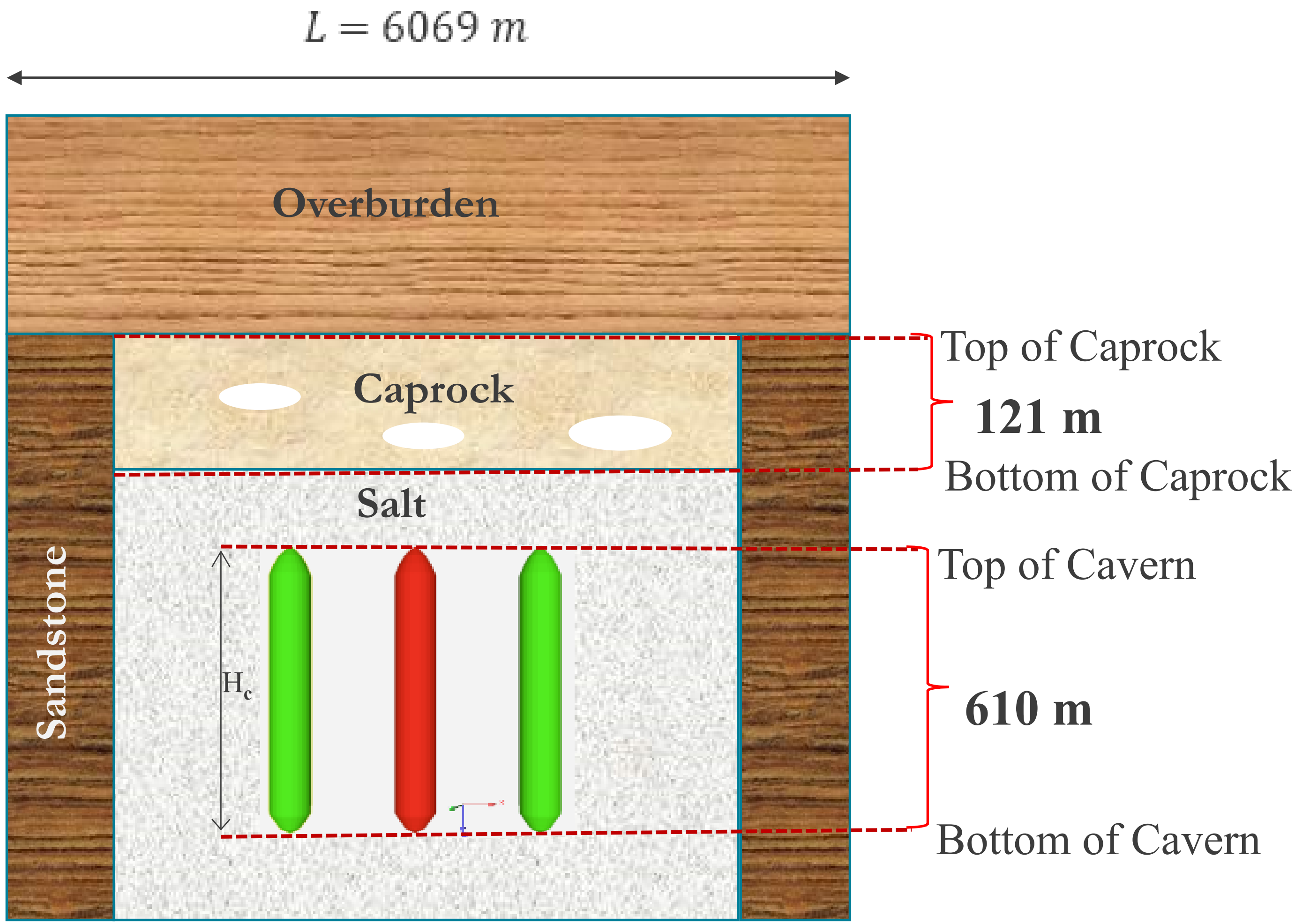
Reference results from CASE1 with twice workovers

- Larger vertical displacement of the cavern top is observed in the case of hard salt (dashed lines).
- Greater impacts of workover are observed at the cavern top in a hard salt dome because of greater cavern volume changes with cavern depressurization.

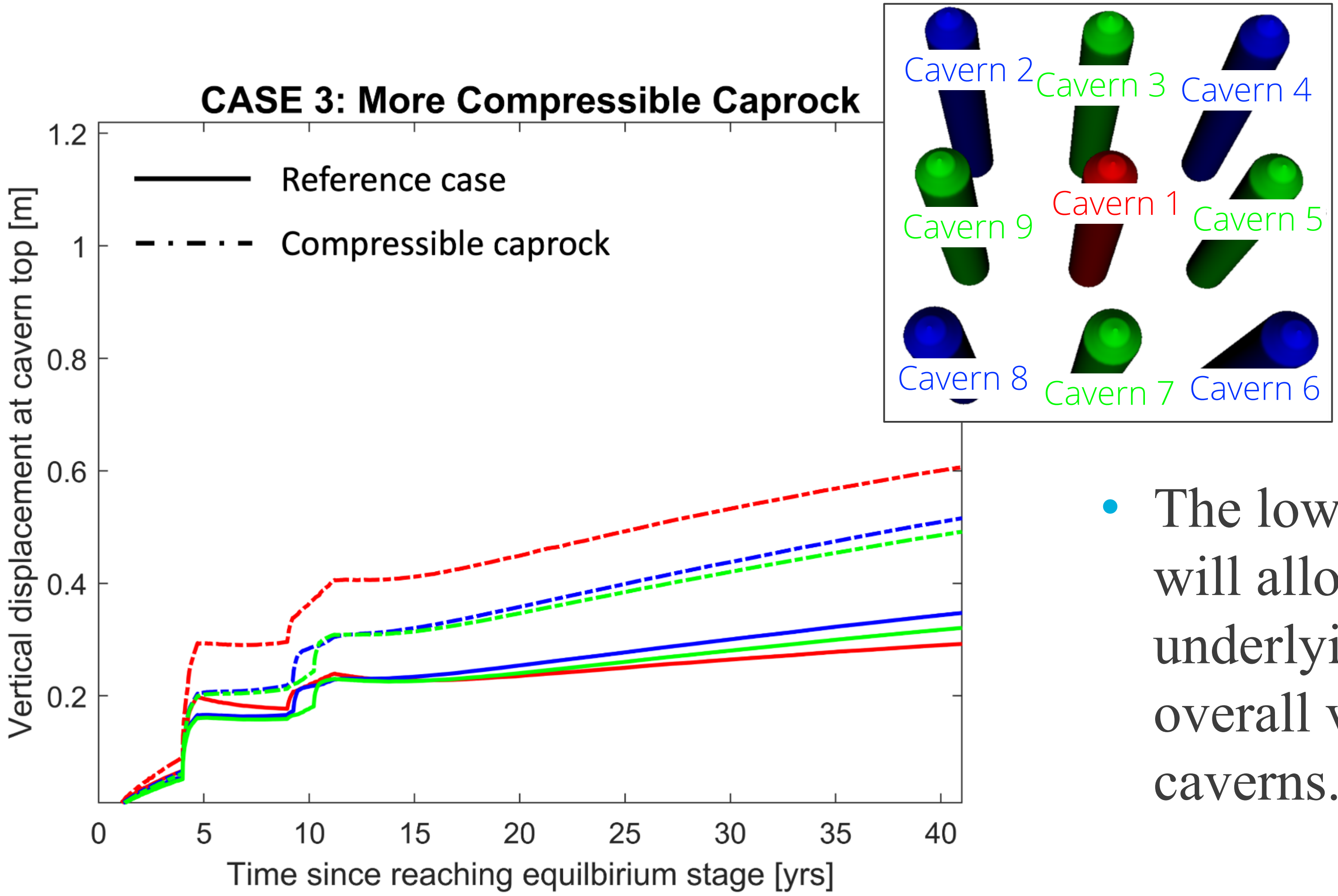
CASE3: CAPROCK COMPRESSIBILITY

- **CASE3** – Impact of damaged caprock

  : Impact of changes in mechanical properties of the caprock (e.g. Young's modulus)



CASE3: RESULTS OF CAPROCK PROPERTY



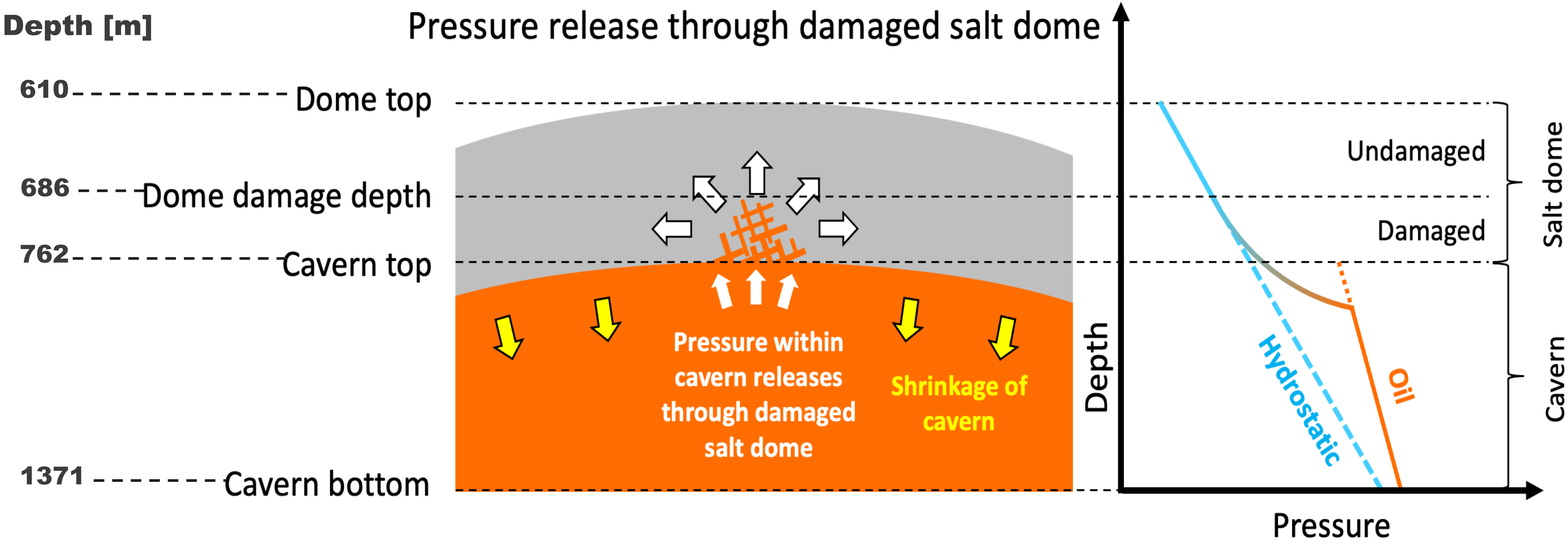
Reference results from CASE1 with twice workovers

- Lower Young's modulus of caprock results in a greater vertical displacement of the cavern top (dashed lines)

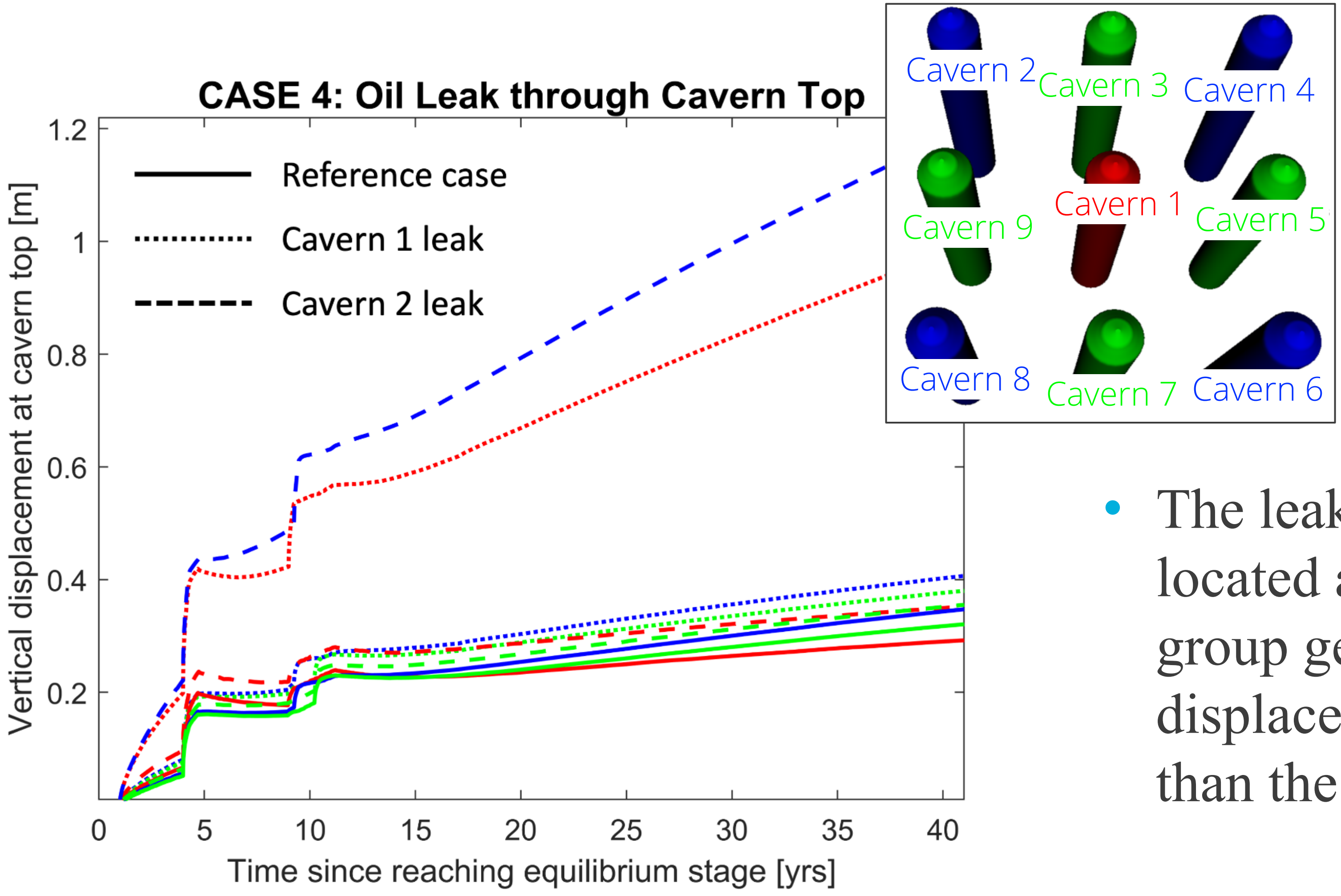
- The lower Young's modulus of caprock will allow it to deform more as the underlying salt creeps, creating more overall vertical movement above the caverns.

CASE4: DAMAGED DOME ABOVE THE CAVERN

- **CASE4** – Leakage through damaged dome above cavern
  : Change vertical pressure profile in a cavern



CASE4: RESULTS OF CAVERN LEAKAGE



Reference results from CASE1 with twice workovers

- Larger vertical displacement of the cavern top is observed at the top of leaking caverns.

- The leakage from cavern 1 (red) located at the center of the cavern group generates less vertical displacement above the leaked cavern than the leakage from cavern 2 (blue).

CONCLUSION

Stability of multiple caverns for underground storage needs to be considered as a function of the geomechanical interaction among caverns corresponding to cavern-specific operations for individual caverns:

- **CASE1:** Caverns location contributed to spatial difference in the cavern volume closure and vertical displacement.
- **CASE2:** Caverns located in a more creep-resistant (hard) salt region are prone to have a higher vertical displacement than caverns located in a softer salt region.
- **CASE3:** Material properties of caprock needs to be considered over time to study time-dependent impact based on cavern operations
- **CASE4:** Location of the leaking caverns will results in different geomechanical behaviour (vertical displacement)

FUTURE WORK

- Update generic model geometry to reflect **wellbore steel casing and cement**
- **Operation pressure effects** on caverns closure, surface subsidence, and strain behavior
- Representation of **damaged caprock region with spatial variation** of material properties
- Implementing **time/stress-dependent mechanical properties** of domal salt
- **Updating a salt constitutive model** based on geomechanical lab testing of salt rocks

THANK YOU FOR YOUR ATTENTION

SALT CONSTITUTIVE MODEL (CREEP)

- Traditional M-D Steady-State Creep Model
  - Mechanism 2 dominated at low temperatures and medium equivalent stresses

$$\dot{\varepsilon}^{ss} = \sum_{i=0}^{3} \dot{\varepsilon}_i^{ss}$$

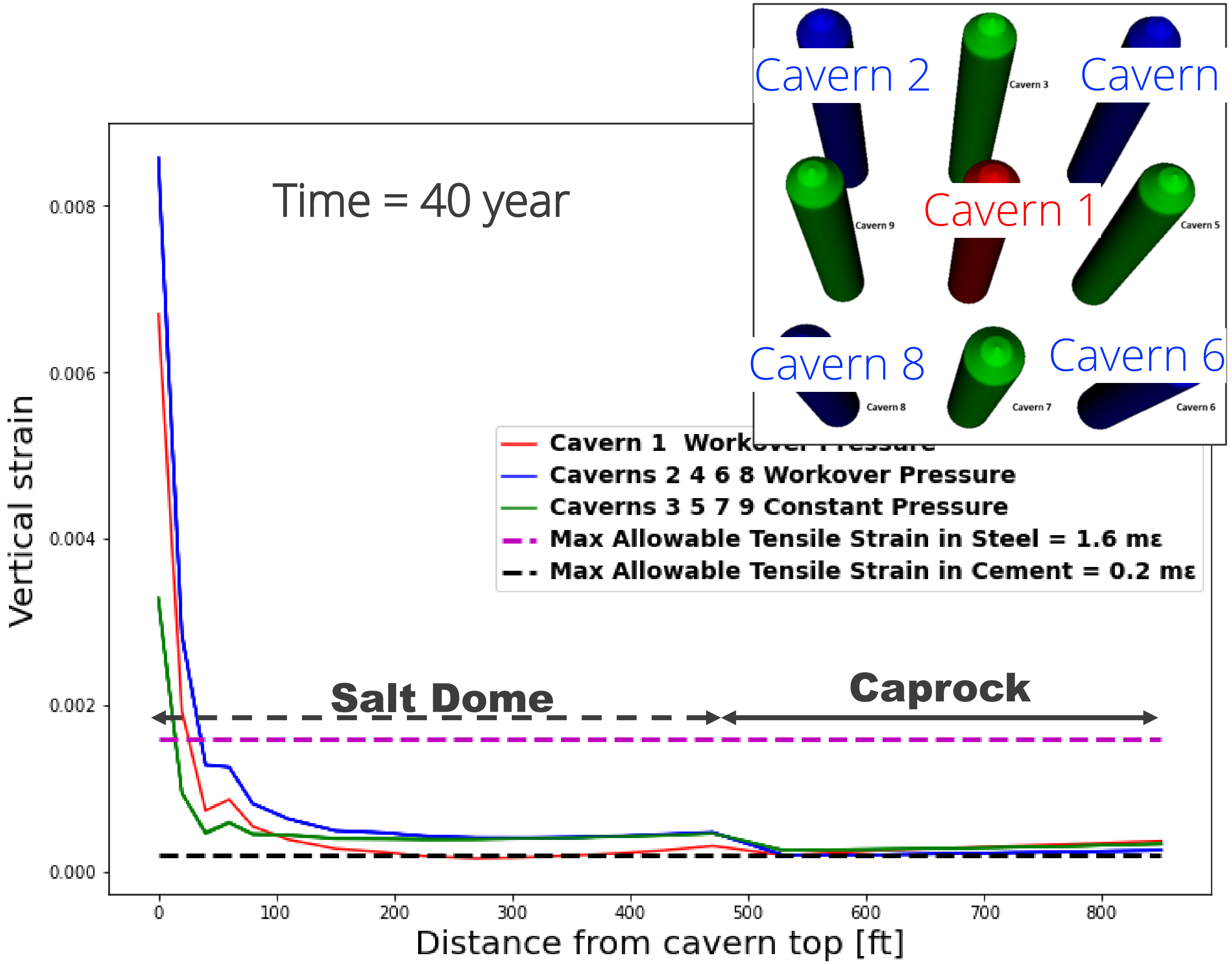
$$\dot{\varepsilon}_i^{ss} = A_i \exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\sigma_{eq}}{\mu}\right)^{n_i} \quad \text{for } i = 1, \text{and } 2$$

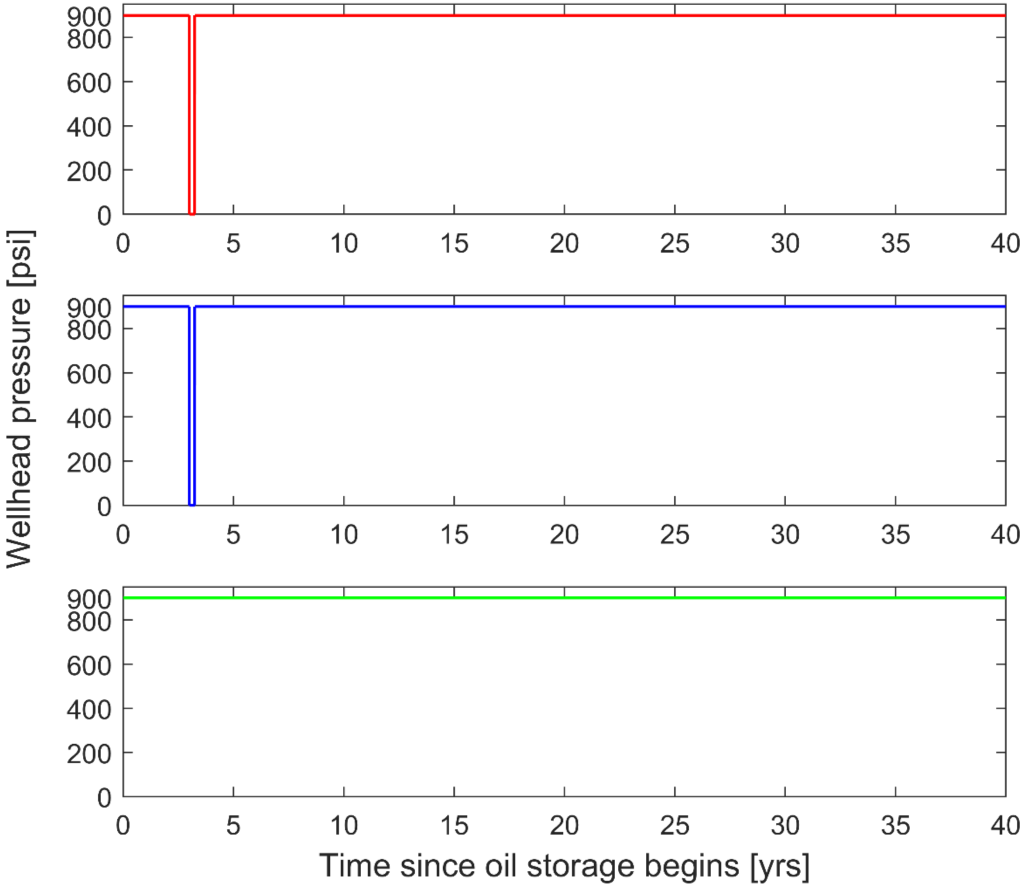
- Extended M-D Viscoplastic Model Parameters
  - Mechanism 0 to capture low equivalent stress behavior

$$\dot{\varepsilon}_i^{ss} = A_i \exp\left(-\frac{Q_i}{RT}\right)\left(\frac{\sigma_{eq}}{\mu}\right)^{n_i} \quad \text{for } i = 0, 1, \text{and } 2$$

- **Sobolik, S.R**. and T.S.A. Ross (2021). "**Effect of the Addition of a Low Equivalent Stress Mechanism to the Analysis of Geomechanical Behavior of Oil Storage Caverns in Salt**" ARMA 21-1127, 55th US Rock Mechanics / Geomechanics Symposium held online in Houston, Texas, USA, 20-23 June 2021

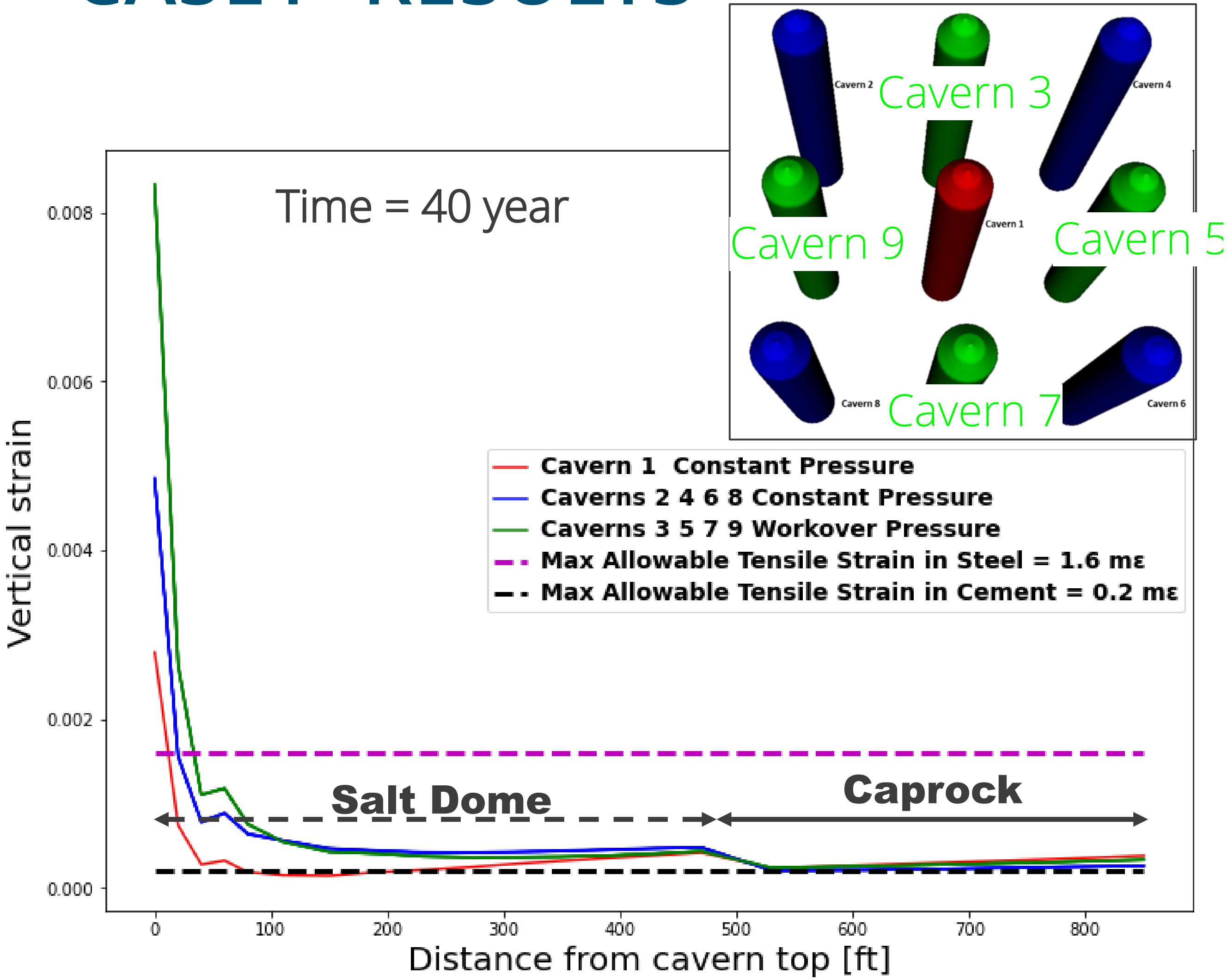
CASE1- RESULTS

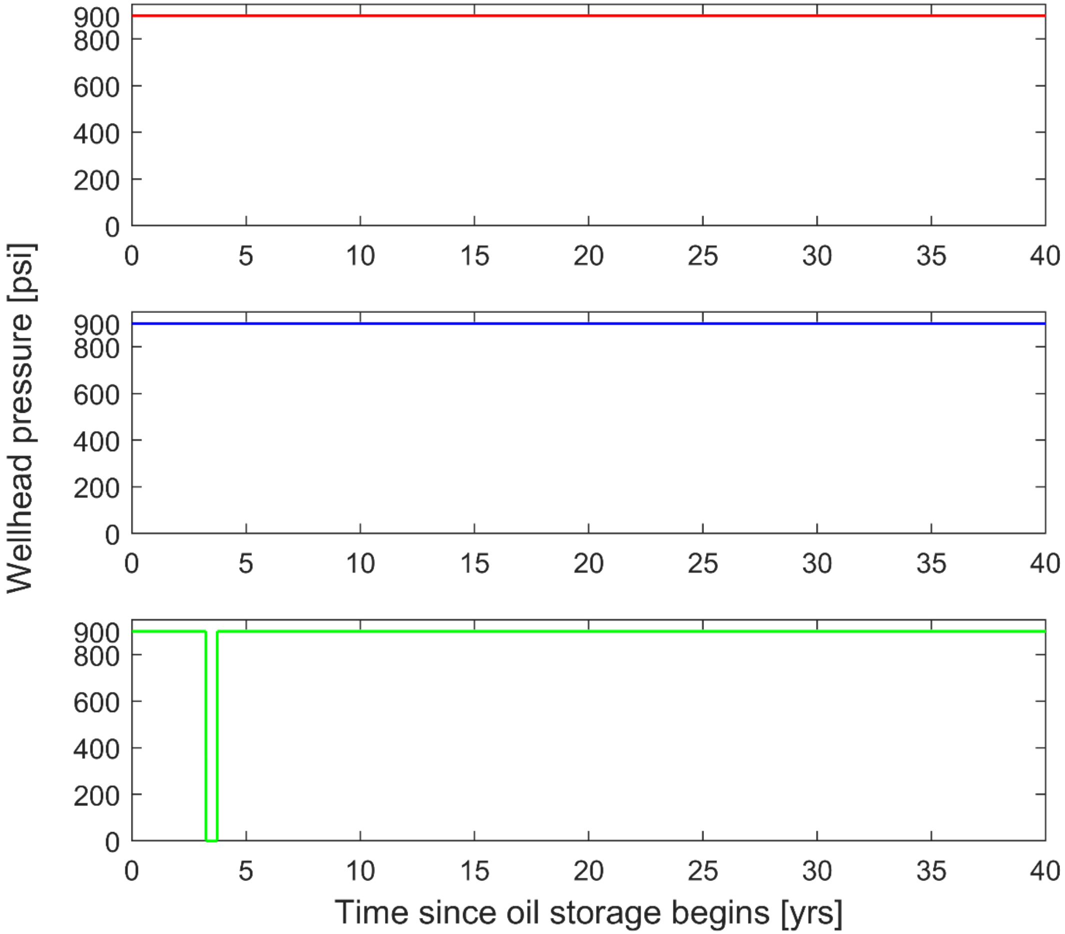




- Larger magnitude of vertical strains are observed at the caverns with workover:
  - Cavern 1 (red)
  - Caverns 2, 4, 6, and 8 (blue)

CASE1- RESULTS

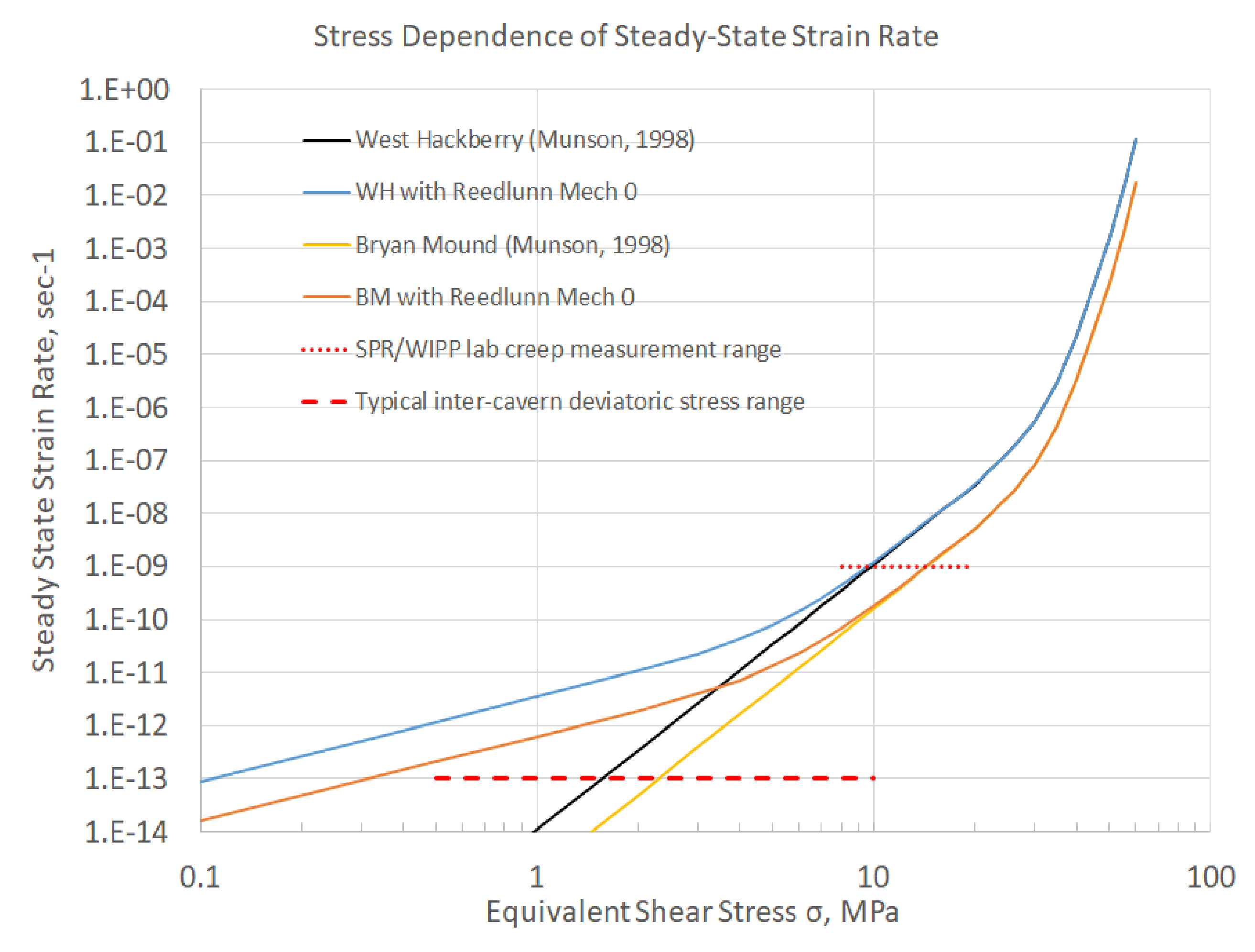




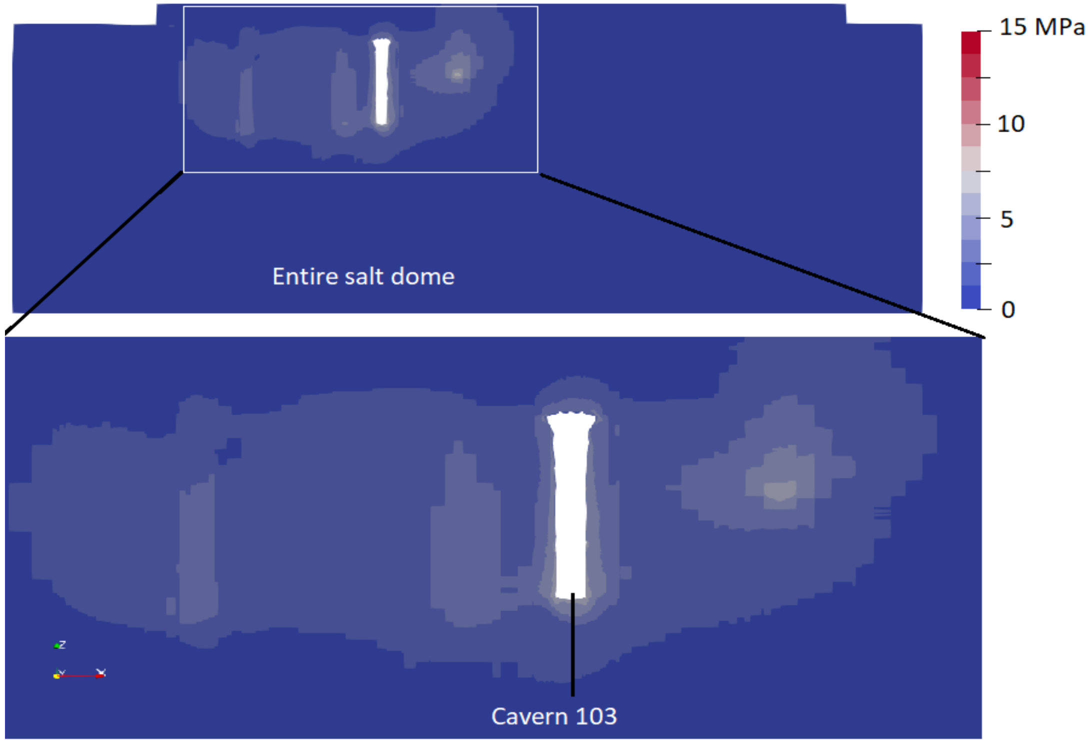
- Larger magnitude of vertical strains are observed at the caverns with workover:
  - Caverns 3, 5, 7, and 9 (green)

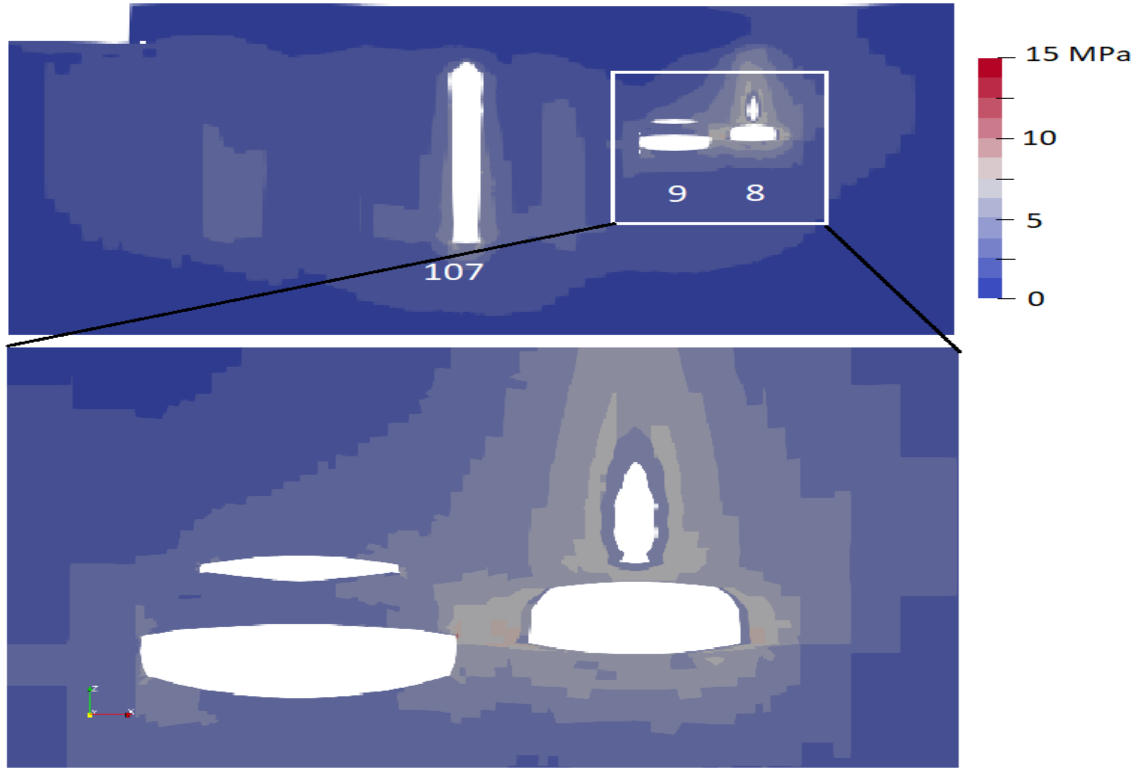
WHAT ARE WE ADDING TO THE M-D VISCOPLASTIC MODEL?

- Reedlunn (2018) added low equivalent stress mechanism (Mech. 0) to MD model (named MD viscoplastic model); used WIPP room closure to develop parameters.
- Note difference in strain rates for stresses less than 8 MPa.
- West Hackberry model was rerun with addition of Mechanism 0, no other changes.
- These runs were done to evaluate the new model. Lab data are required to quantify parameters.



EQUIVALENT STRESSES – WHY IS IT IMPORTANT?





The volume of salt experiencing stress of 10 MPa or greater is significantly small compared to stress less than 10 MPa.

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, $\Delta\sigma$ is difference between horizontal, vertical stresses

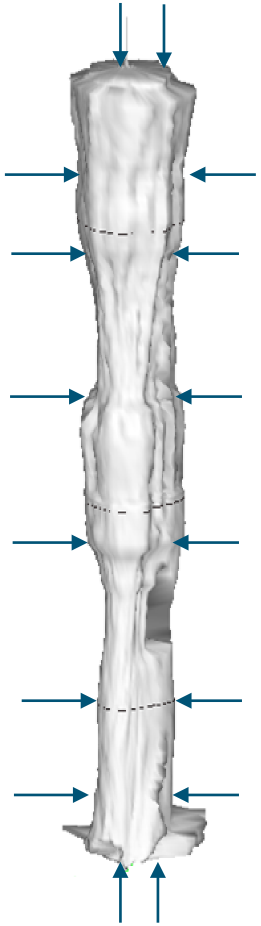
EFFECTS OF CREEP

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



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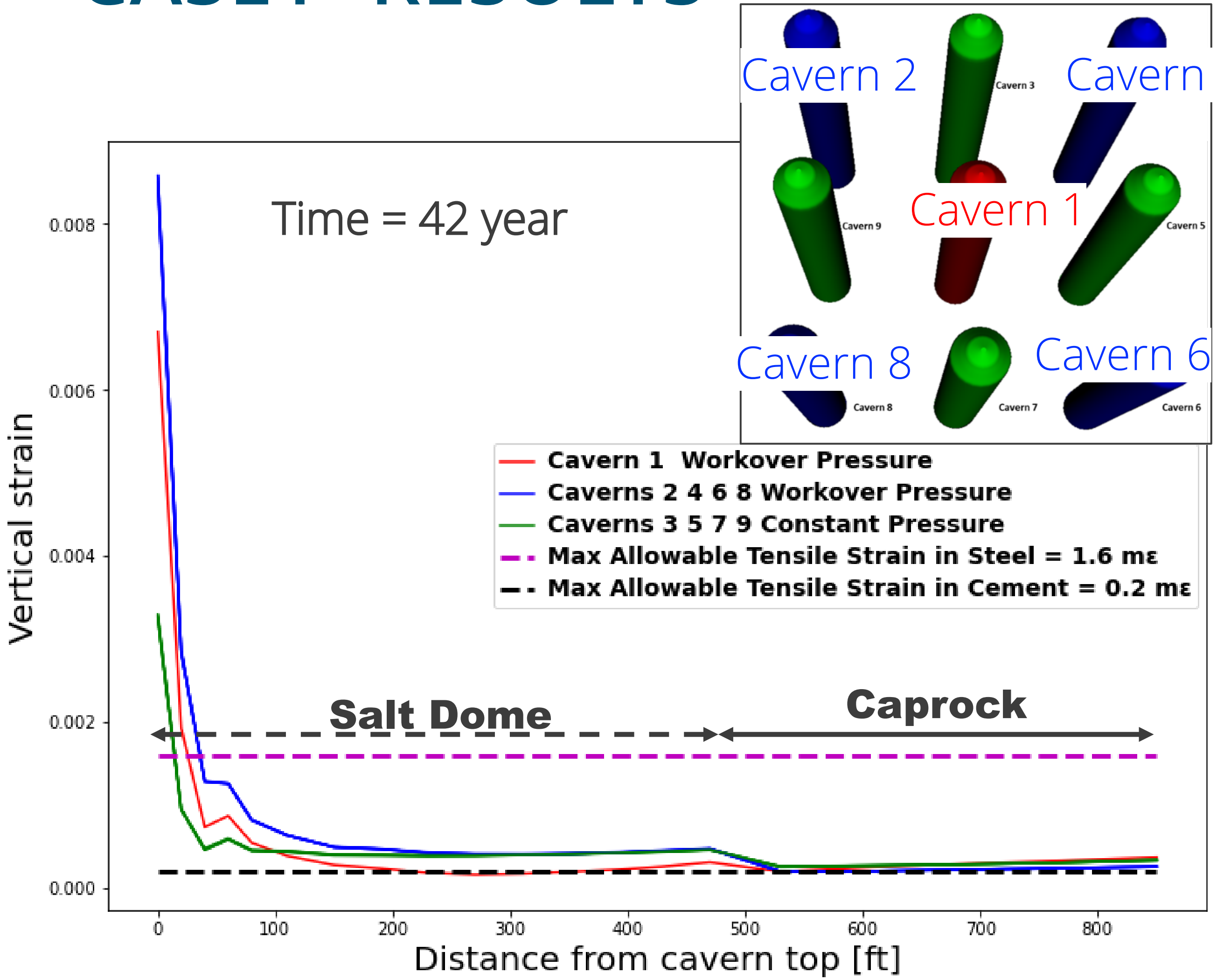

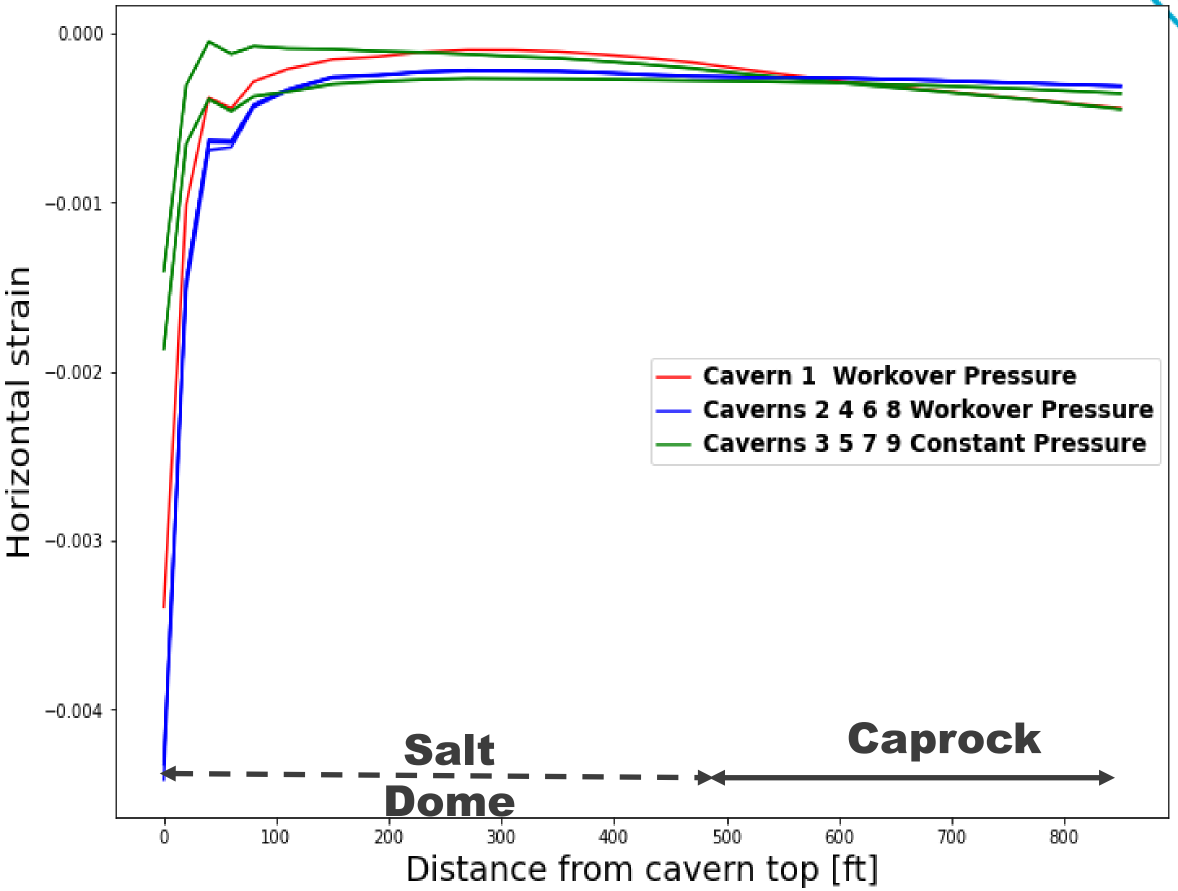

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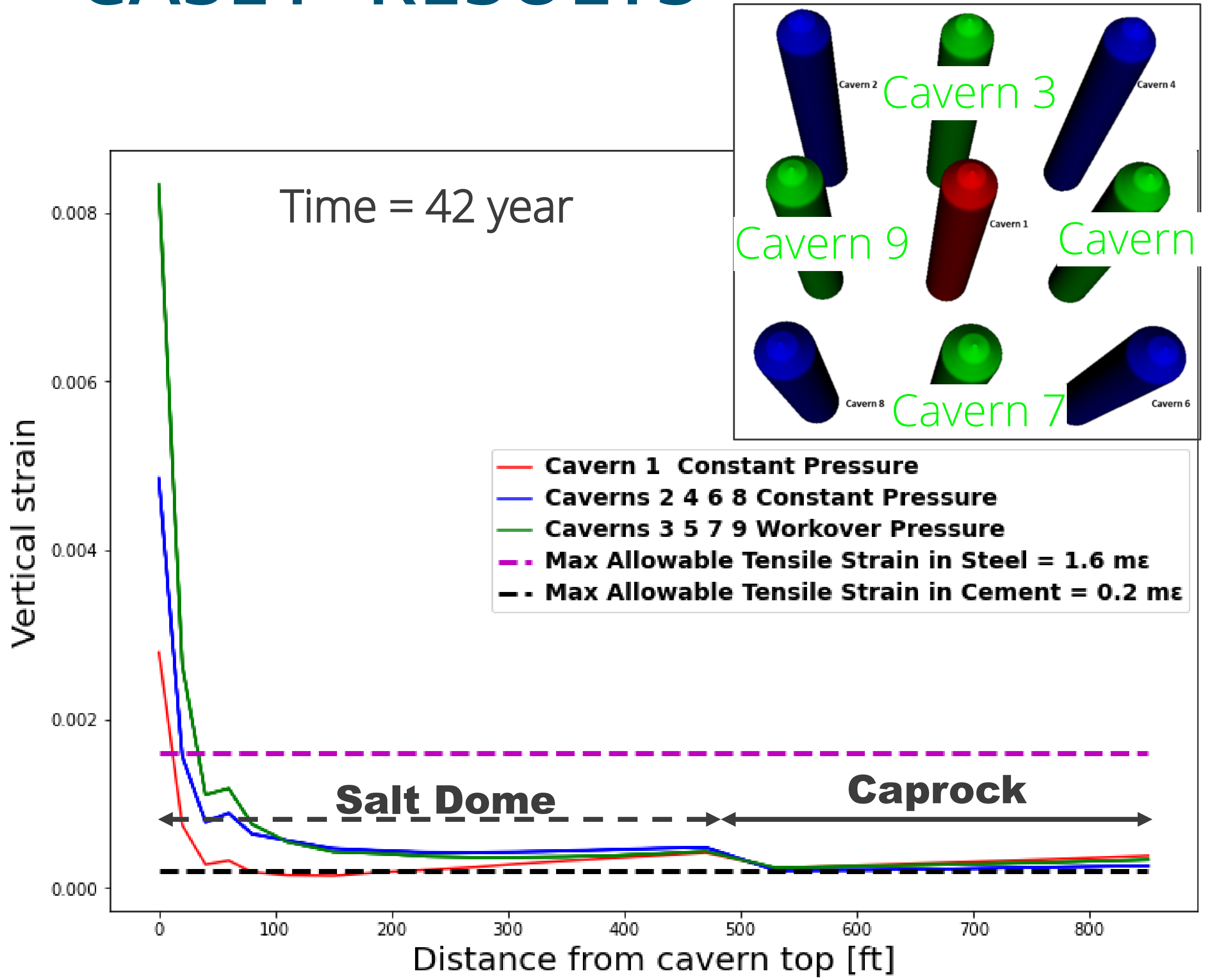

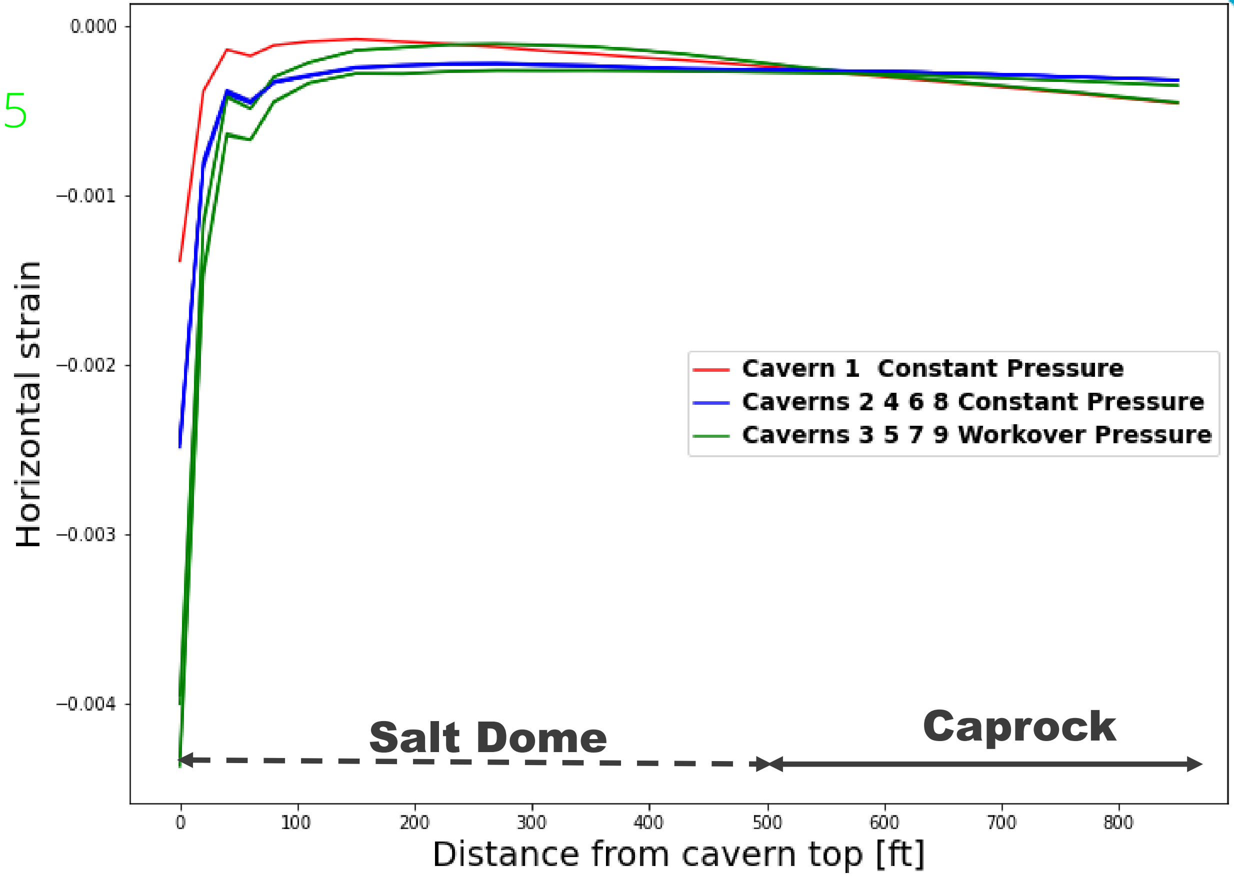

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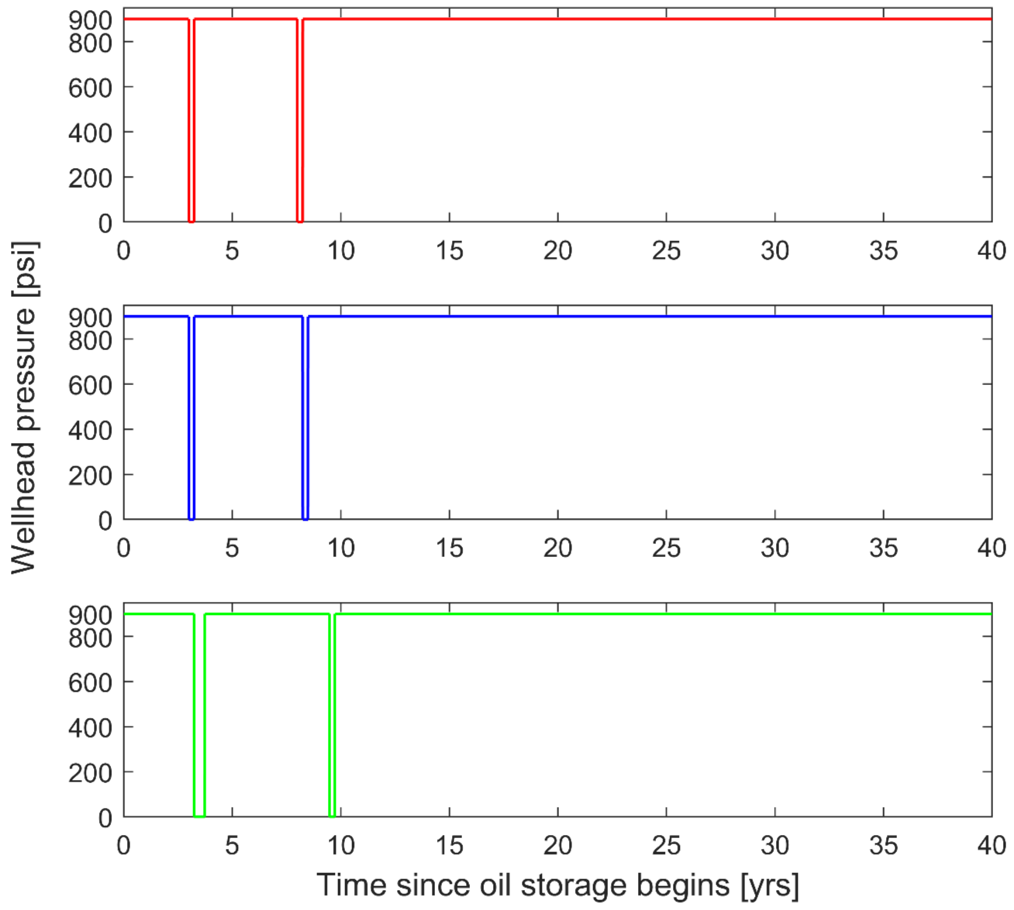
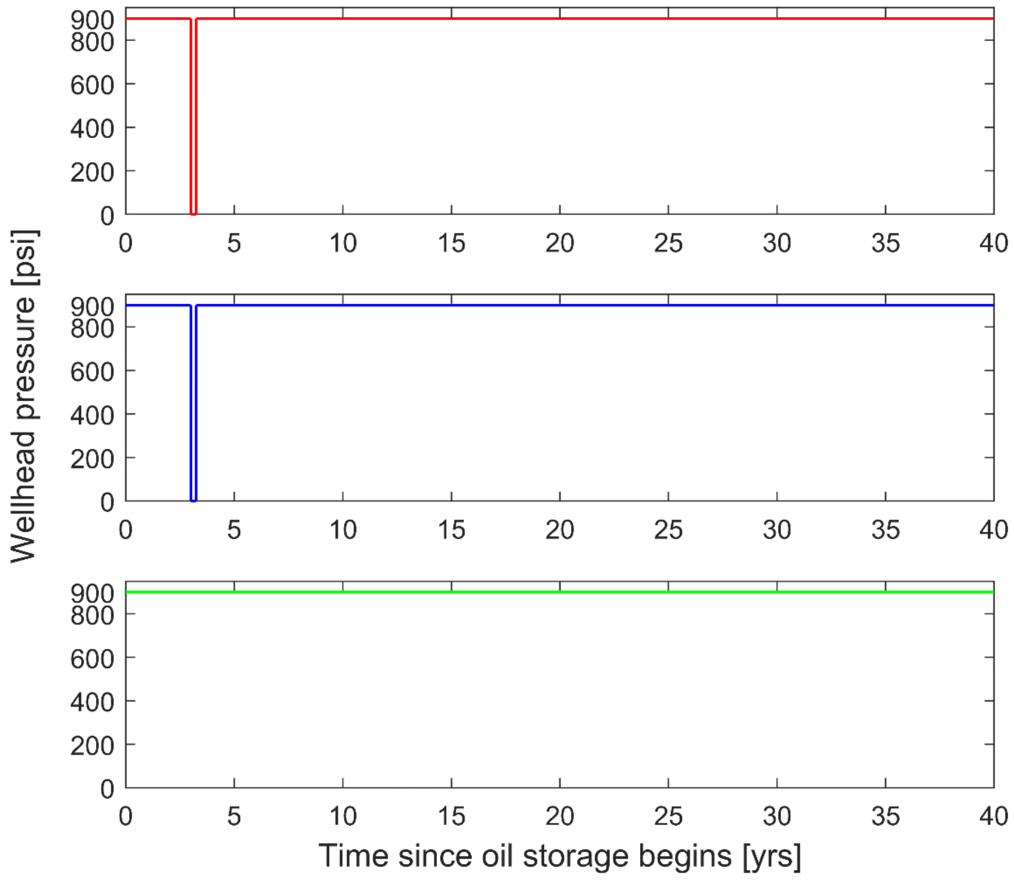
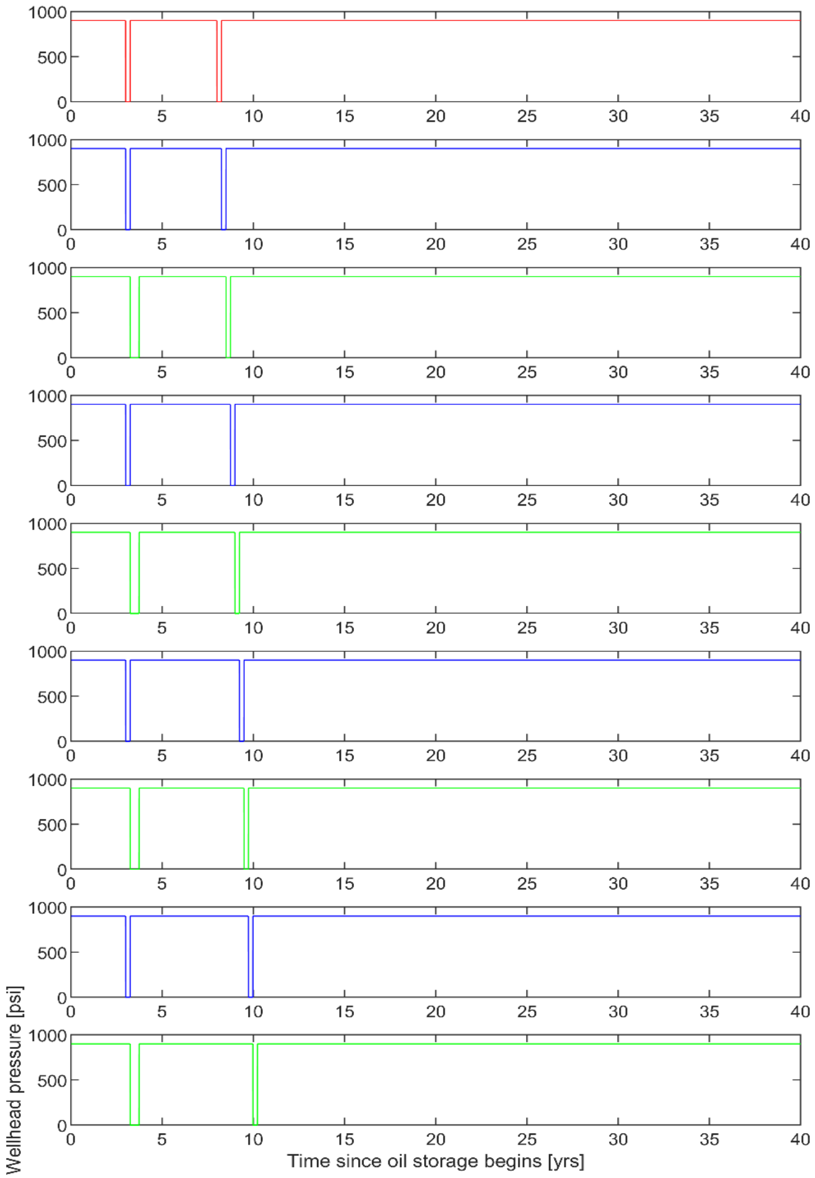
WORKOVER PRESSURE FOR CASE 1 AND CASE 3






Wellhead pressure [psi]
Time since oil storage begins [yrs]