BASELINE GEOMECHANICAL EVALUATION OF HYPOTHETICAL LOW-PRESSURE CONDITIONS IN WESTLAKE CAVERNS 7B AND 6X AT THE SULPHUR MINES SALT DOME, CALCASIEU PARISH, LOUISIANA

RESPEC

MINING & ENERGY

CAVERN GEOMECHANICS

RAPID CITY, SD, USA

AUGUST 10, 2023

RSI(RAP)-M0170.23004

PROJECT CONTROL NO. M0170.23004

CONFIDENTIAL

OUTLINE

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- Technical Approach
  - 3D Numerical Model Overview
  - Key Assumptions
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- Phase 1 - Baseline Modeling Results
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- Recommended Path Forward

INTRODUCTION

- RESPEC was engaged to perform a geomechanical analysis of hypothetical low-pressure conditions in Caverns 6X and 7B to assess the stability of the caverns assuming several depressurization scenarios.

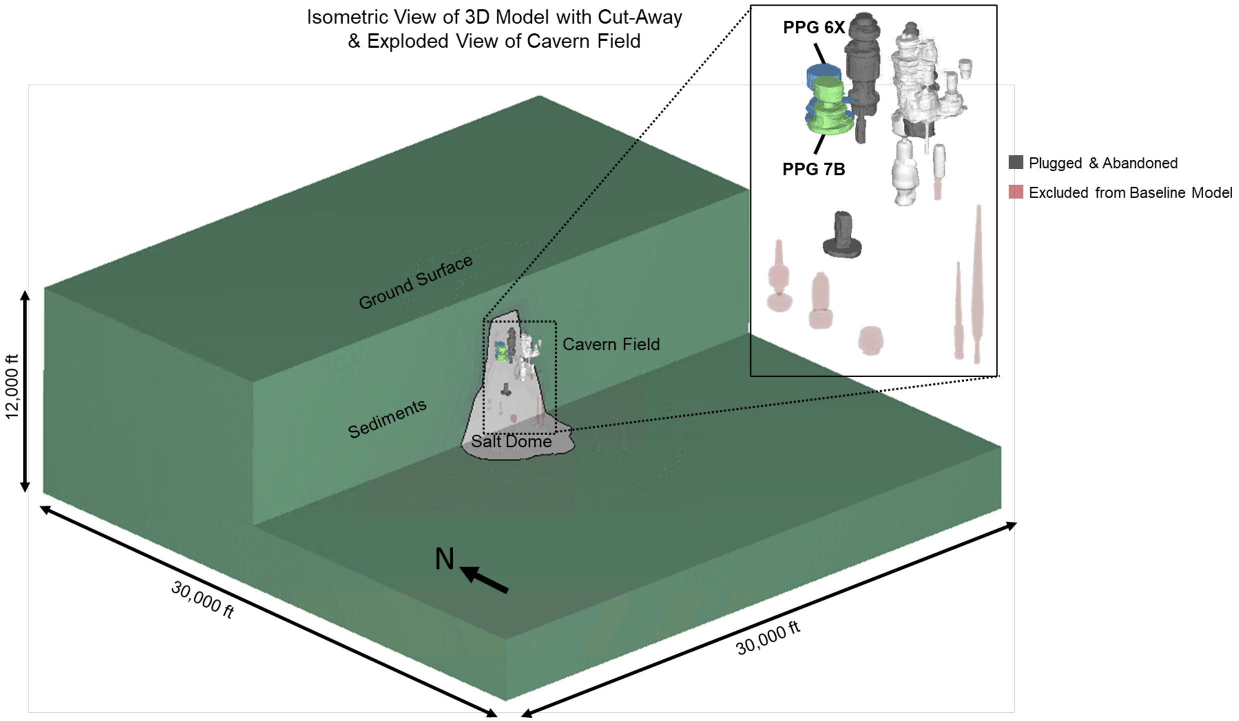
- The planned geomechanical study is being executed in a phased approach.
  - Phase 1 – Baseline Assessment (draft results presented herein)
    - Adopted material properties from a previous RESPEC geomechanical study [Heiberger, 2015]
    - Employed typical modeling methods
    - Focused on the immediate, or near-term stability of Caverns 6X and 7B at low pressures

- Planned future modeling phases will investigate the key assumptions employed in Phase 1
  - Primary objectives will focus on,
    - Salt strength in the web between Cavern 7B and the dome flank
    - Characteristics of the contact between the salt stock and the adjacent formations
    - Characteristics and influence of the nonsalt formations next to the salt dome
    - Long-term stability of all caverns in the dome

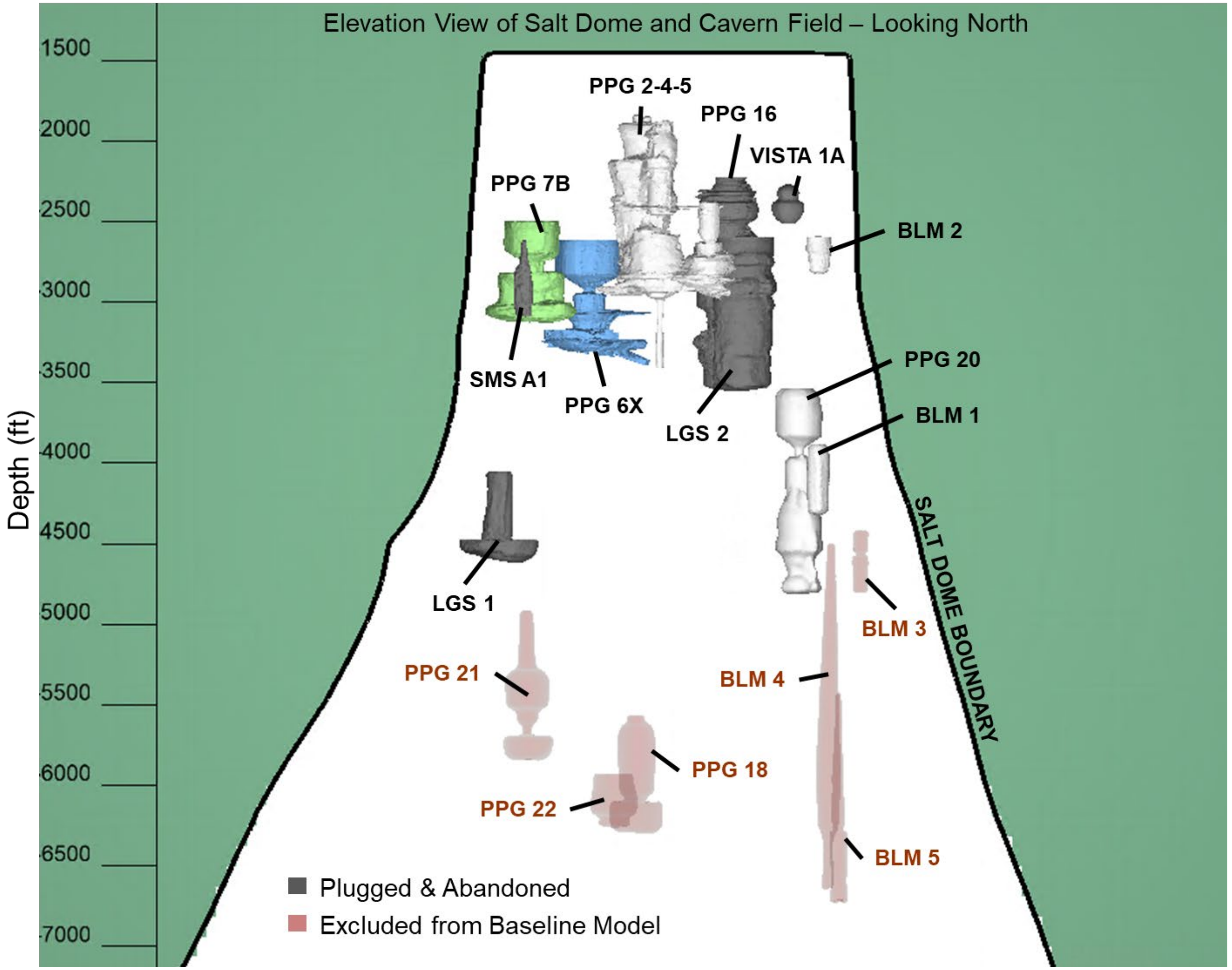
TECHNICAL APPROACH OVERVIEW

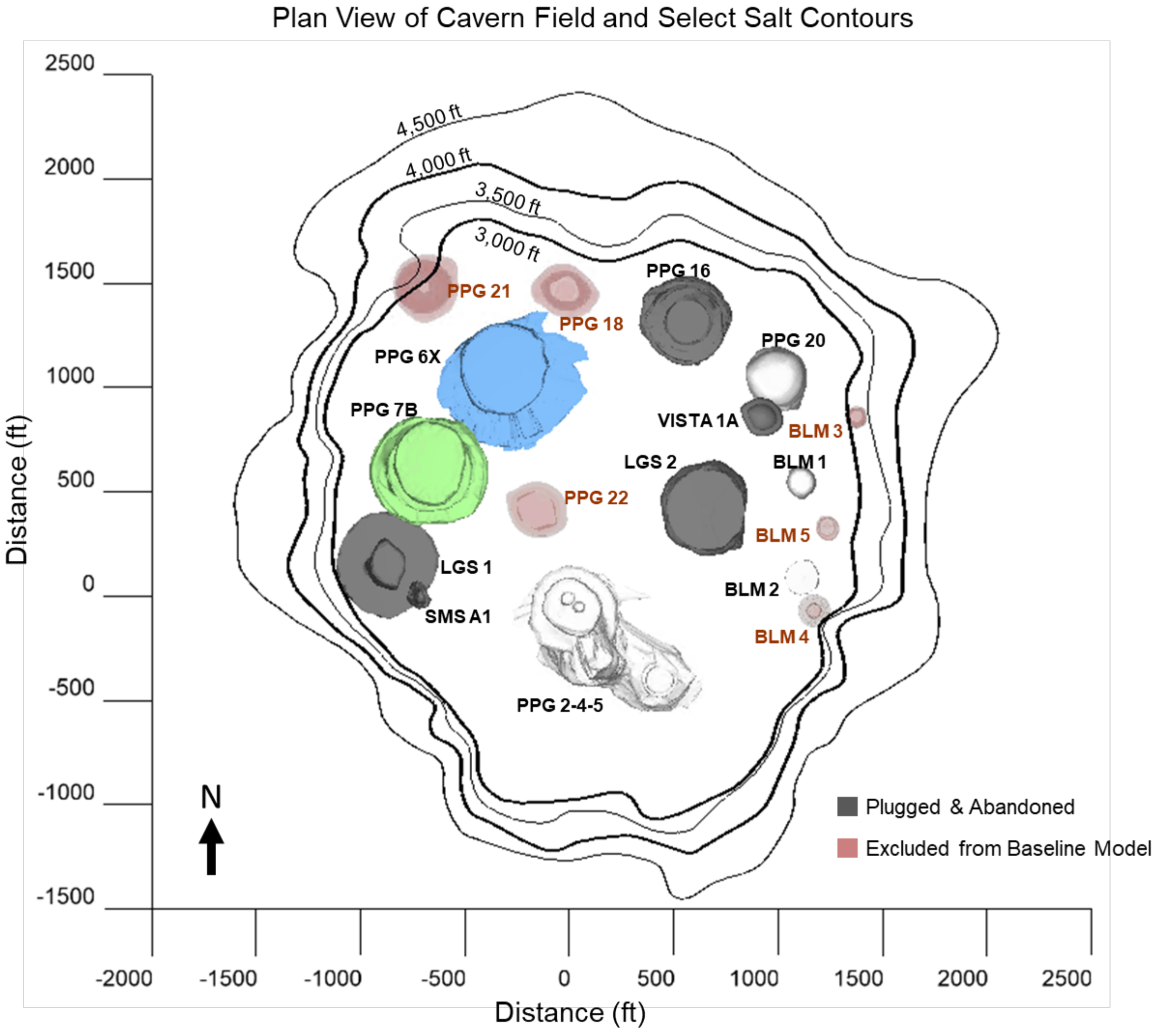
- Large-domain three-dimensional (3D) numerical model to predict the geomechanical response of the caverns to various hypothetical low-pressure operating conditions.
- Included Westlake Caverns 6X and 7B and the surrounding caverns within the area of influence.
- Approximated the historical cavern development and operations to estimate the stress state in the salt.
- Simulated several hypothetical low-pressure conditions and two depressurization rates.
- The model-predicted stresses were post-analyzed to determine factor-of-safety (FS) values for salt dilation (or damage).

Isometric View of 3D Model with Cut-Away & Exploded View of Cavern Field



3D NUMERICAL MODEL OVERVIEW

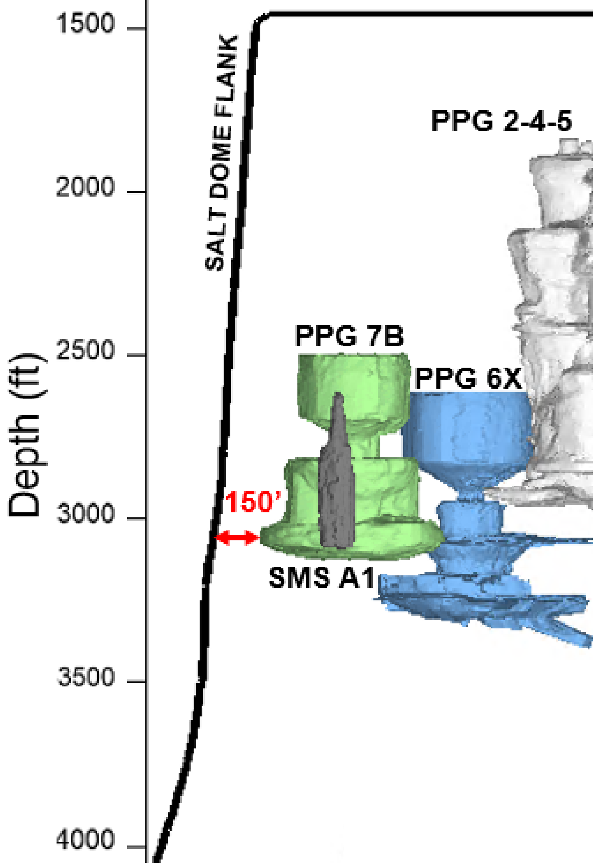




KEY ASSUMPTIONS IN PHASE 1 MODELING

- The salt dome flank is approximately 150 feet from the perimeter of Cavern PPG 7.
- The web between Cavern PPG 7 and the dome flank consists entirely of rock salt, with homogenous strength and deformation properties.
- The rock salt between Cavern PPG 7 and the dome flank is perfectly bonded to the adjacent nonsalt rock formations.
- Mechanical properties of the salt surrounding Caverns PPG 6 & 7 can be accurately characterized by the RESPEC testing of salt core recovered from Well No. 22 [Arnold, 2015].
- The potential leak path from Cavern PPG 7 is undefined, and therefore, it is omitted from the model.
- The potential hydraulic connection between Caverns PPG 6 & 7 is undefined, and therefore, it is omitted from the model.
- Adjacent formation pressures are neglected in the model; therefore, they do not affect the stresses within the salt stock.
- Extensive sulphur mining in the caprock has significantly degraded the caprock stiffness and strength, therefore it is omitted from the model.
- Cavern PPG 6 will maintain a +100 psi pressure differential compared to the pressure in PPG 7

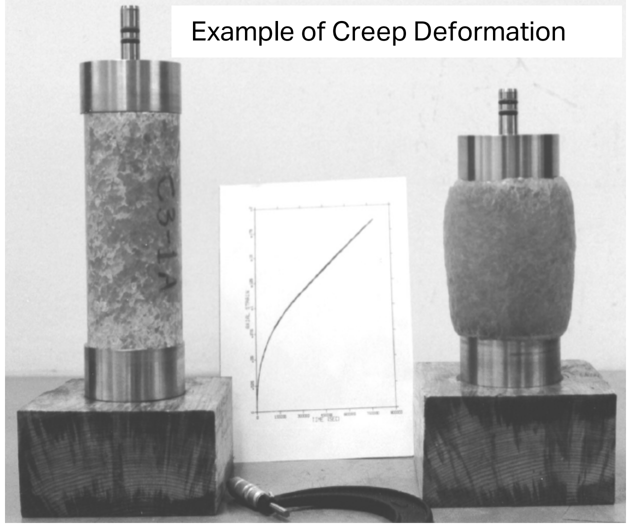
Cropped Elevation View of Salt Dome and Cavern Field – Looking North

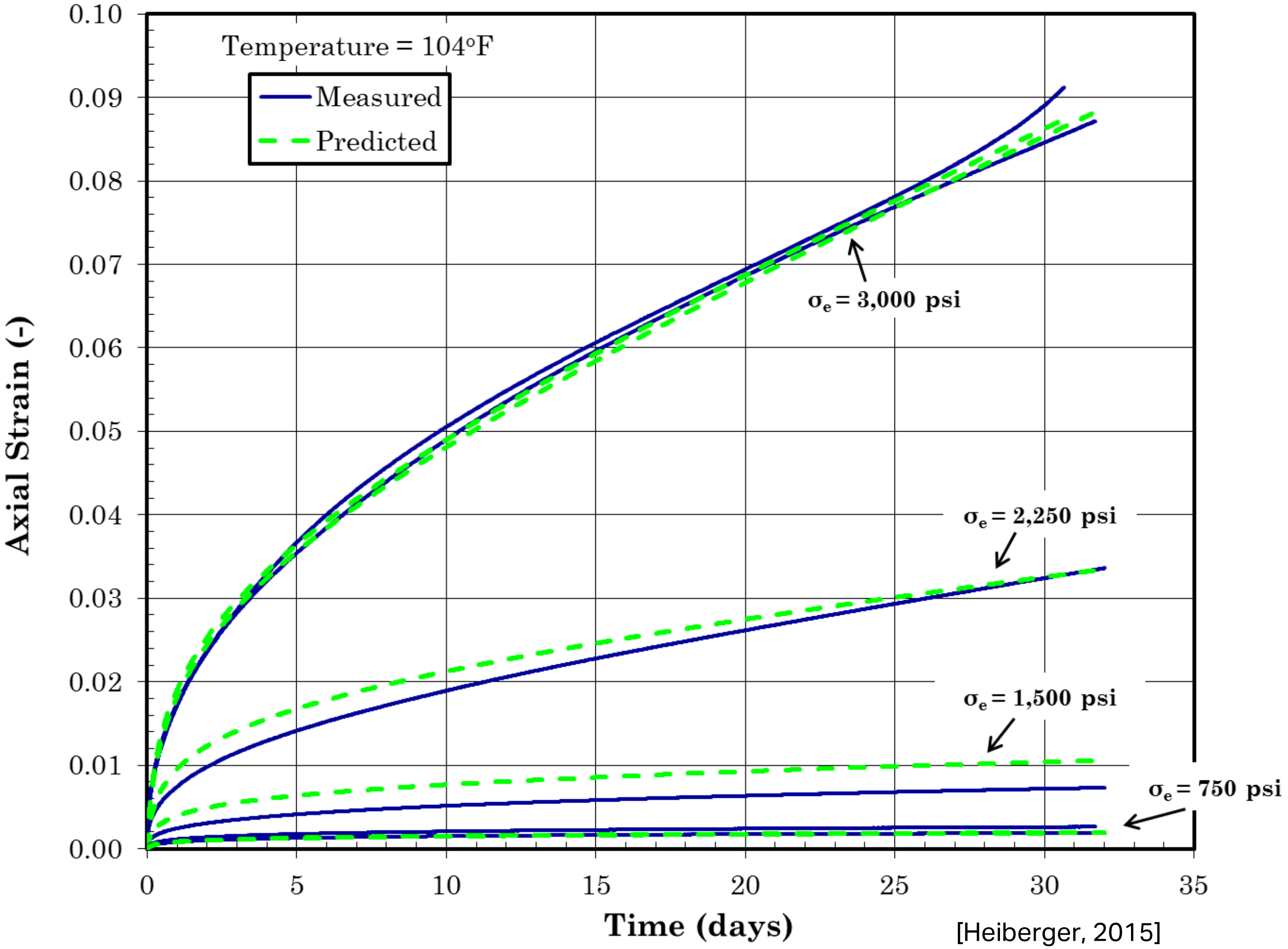


SALT CREEP PROPERTIES

- The Sulphur Mines salt creep behavior was modeled based on RESPEC testing of salt core recovered from Well 22 (S/N 974245) [Arnold, 2015]

- Good agreement is shown between the creep model fit (i.e., predicted strain) and the measured strain from the creep tests

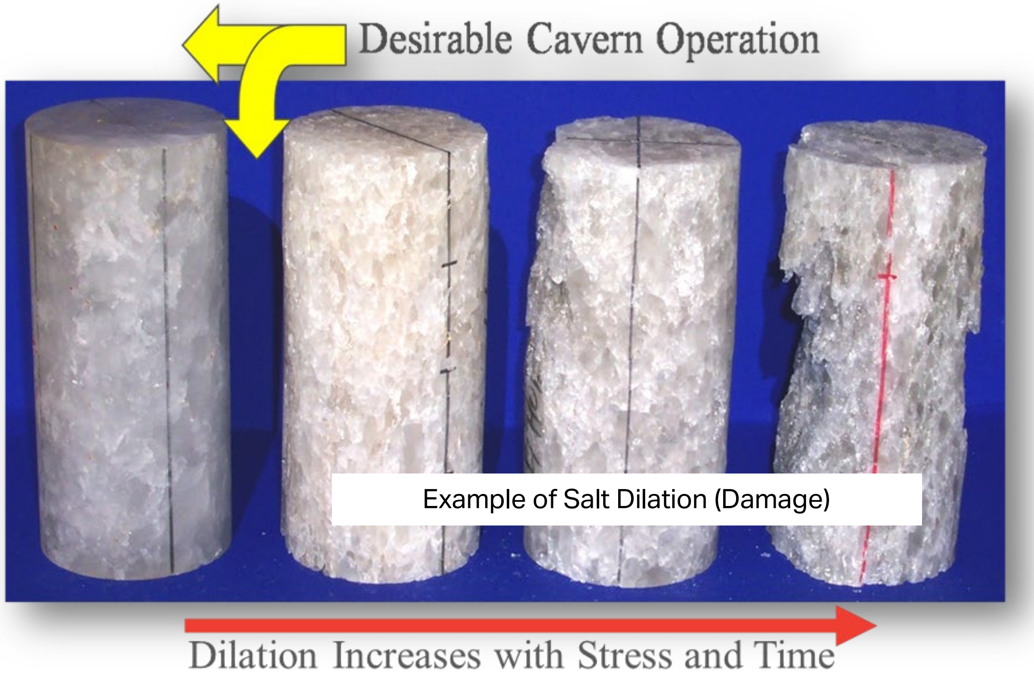


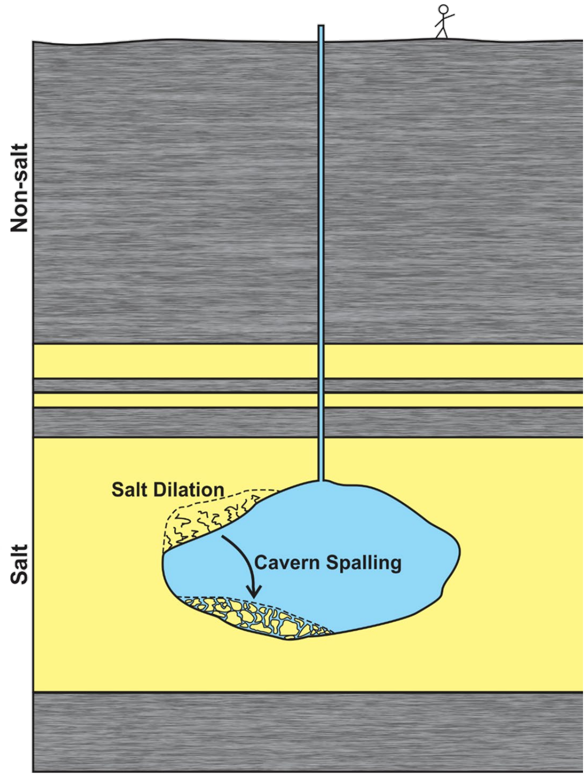


[Heiberger, 2015]

SALT DILATION STRENGTH

- Unlike brittle rock types that fail suddenly, rock salt around a solution-mined cavern will typically begin to fail through microfracturing along the grain boundaries, which is a process referred to as dilation (or damage). If damaging states of stress are maintained, the microfractures will increase and coalesce.
- Salt damage is a progressive process that can lead to the salt spalling from the roof and walls of the cavern and may lead to salt-web failure or roof collapse.



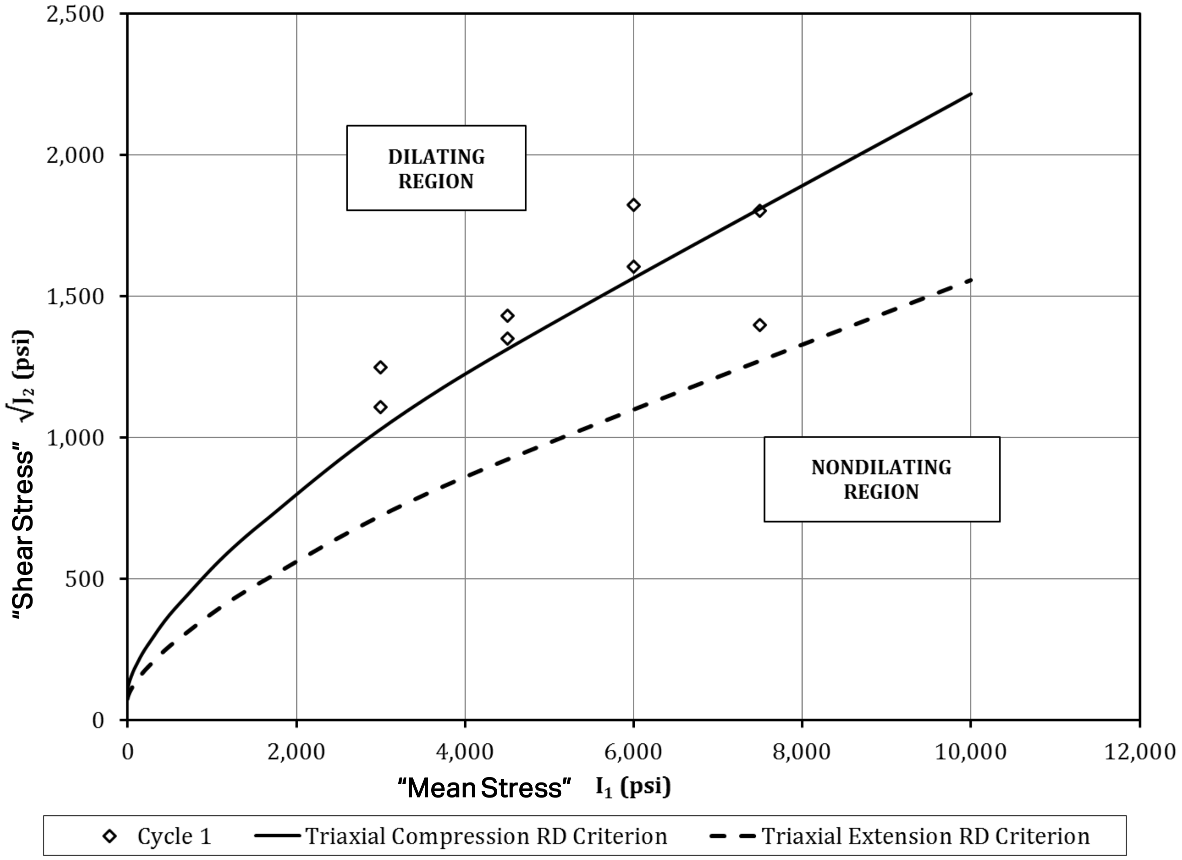


SALT DILATION STRENGTH

- The salt dilation strength was estimated based on RESPEC testing of salt core recovered from Well 22 (S/N 974245) [Arnold, 2015]
- The potential for salt damage was assessed using the RESPEC Dilation (RD) Criterion [DeVries et al., 2005]
- The dilation factor of safety (FS) is the ratio of the salt's dilation strength ($\sqrt{J_{2,dil}}$) to the model-predicted shear stress ($\sqrt{J_2}$)

$$FS = \frac{\sqrt{J_{2,\mathrm{dil}}}}{\sqrt{J_2}}$$

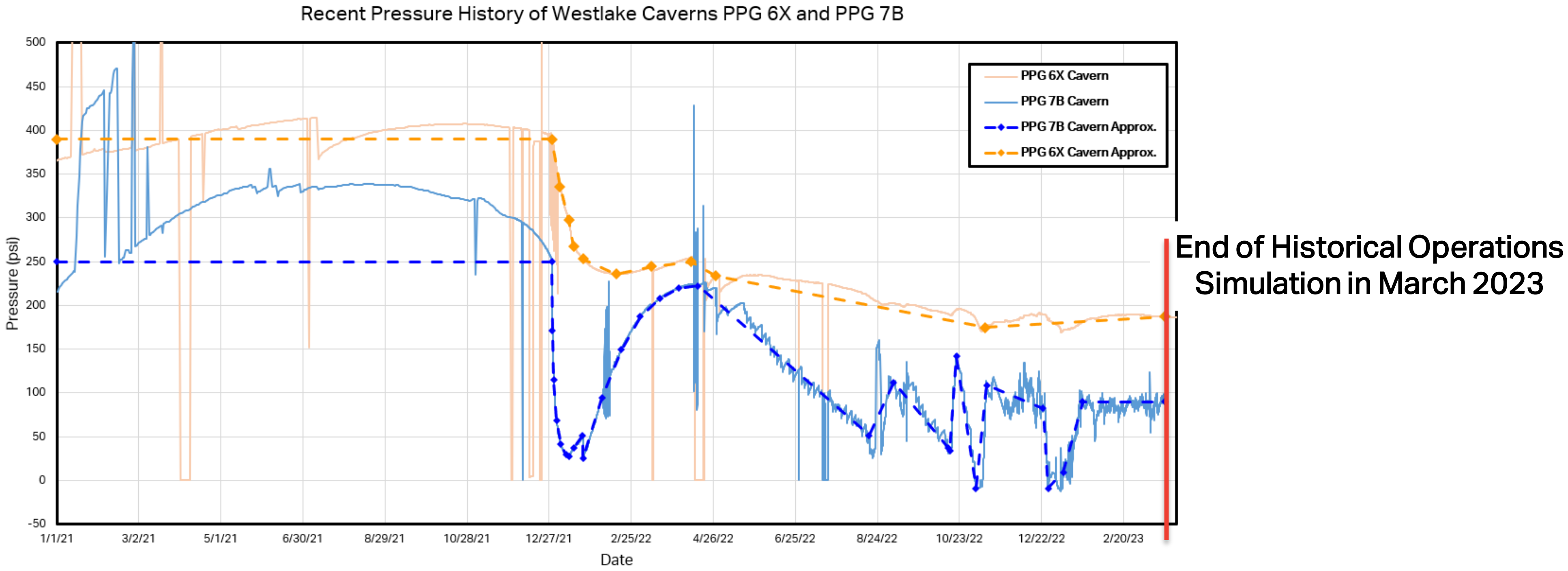
- Salt dilation (or damage) is predicted when FS ≤ 1.0



[Heiberger, 2015]

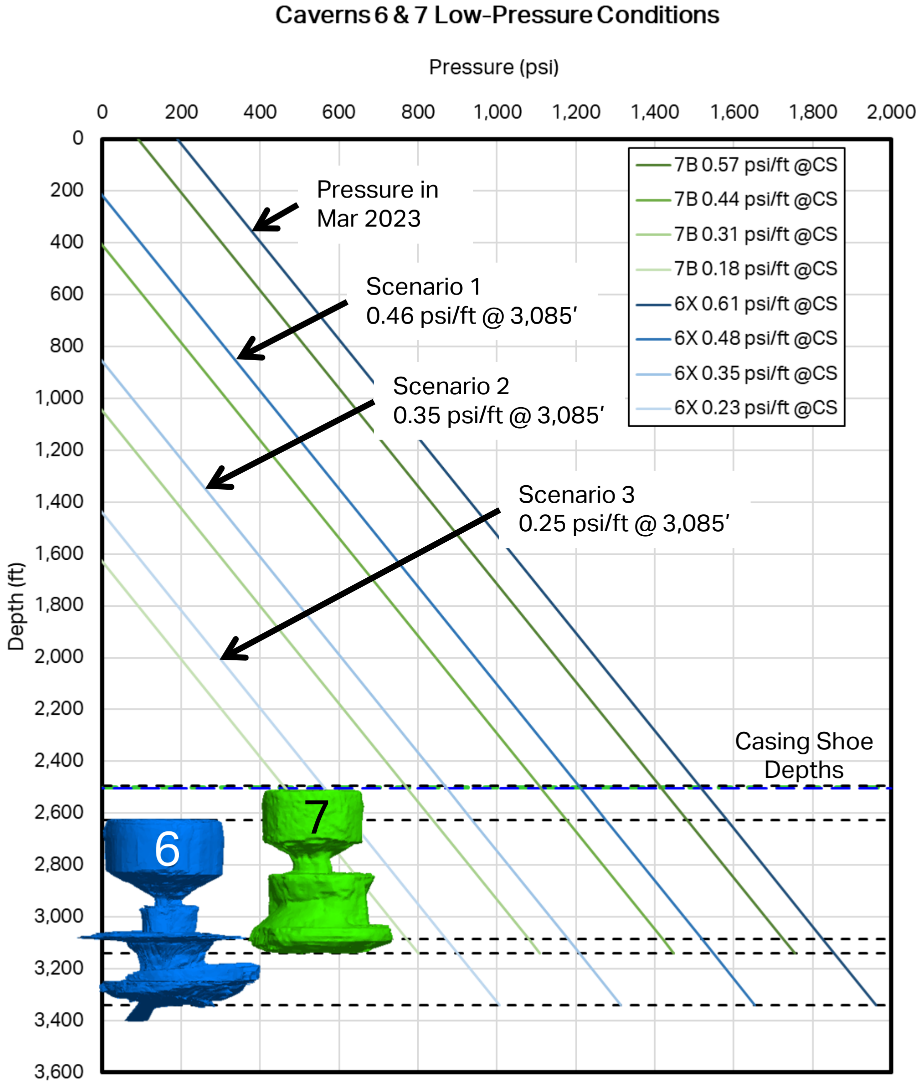
HISTORICAL CAVERN OPERATIONS

- Historical cavern operations were approximated in the model by simulating each cavern at a constant brine pressure gradient with minimal wellhead pressure.
- The P&A caverns were modeled as plugged wells beginning at the P&A date for each well.
  - The pressure was gradually increased in each P&A cavern, based on the model-predicted creep closure.
- The caverns were modeled at static pressure conditions up until Jan 2021, at which time the pressures in PPG 6X and PPG 7B were adjusted to more closely approximate the recent pressure histories in these caverns up until March 2023.



HYPOTHETICAL LOW-PRESSURE CONDITIONS

- The low-pressure conditions were specified for caverns PPG 7B and PPG 6X as a pressure gradient at a depth of 3,085 ft.
  - The approximate depth of the minimum salt web thickness
  - Possible depth of the hydraulic connection between the two caverns
- Three hypothetical low-pressure conditions were evaluated in Phase 1
  - Scenario 1 : 0.46 psi/ft at 3,085 ft depth
  - Scenario 2 : 0.35 psi/ft at 3,085 ft depth
  - Scenario 3 : 0.25 psi/ft at 3,085 ft depth
- It was assumed that PPG 6X will maintain a +100 psi pressure differential compared to the pressure in PPG 7B.



HYPOTHETICAL LOW-PRESSURE CONDITIONS

- The depressurization rate of the caverns was simulated for two different scenarios
  - Controlled pressure reduction rate at 25 psi/day
  - Uncontrolled pressure reduction rate at 211 psi/day

Cavern PPG 7B					
		Normal Ops.	Scenario 1	Scenario 2	Scenario 3
Gradient at 3,085 ft (psi/ft)		0.56	0.46	0.35	0.25
Gradient at Casing Shoe (psi/ft)		0.57	0.44	0.31	0.18
Brine Depth (ft)		0	407	1,048	1,630
Uncontrolled Duration (days) [211 psi/day]			1.5	3.1	4.5
Controlled Duration (days) [25 psi/day]			12.2	25.8	38.2
	Depth (ft)	(psi)	(psi)	(psi)	(psi)
Surface	0	90	-216	-555	-864
Casing Shoe	2,501	1,416	1,110	770	462
Cavern Roof	2,495	1,412	1,106	767	459
Min. Web Thickness	3,085	1,725	1,419	1,080	771
Cavern Floor	3,140	1,754	1,448	1,109	800

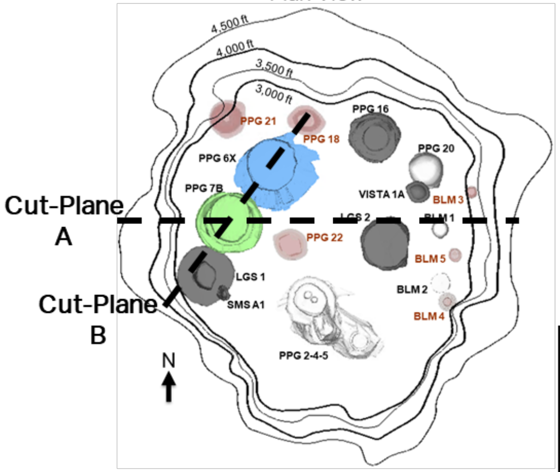
Cavern PPG 6X					
		Normal Ops.	Scenario 1	Scenario 2	Scenario 3
Gradient at 3,085 ft (psi/ft)		0.59	0.49	0.38	0.28
Gradient at Casing Shoe (psi/ft)		0.61	0.48	0.35	0.23
Brine Depth (ft)		0	219	859	1,441
Uncontrolled Duration (days) [211 psi/day]			1.5	3.1	4.5
Controlled Duration (days) [25 psi/day]			12.2	25.8	38.2
	Depth (ft)	(psi)	(psi)	(psi)	(psi)
Surface	0	190	-116	-455	-764
Casing Shoe	2,505	1,518	1,212	872	564
Cavern Roof	2,628	1,583	1,277	938	629
Min. Web Thickness	3,085	1,825	1,519	1,180	871
Cavern Floor	3,340	1,960	1,654	1,315	1,006

BASELINE MODELING RESULTS

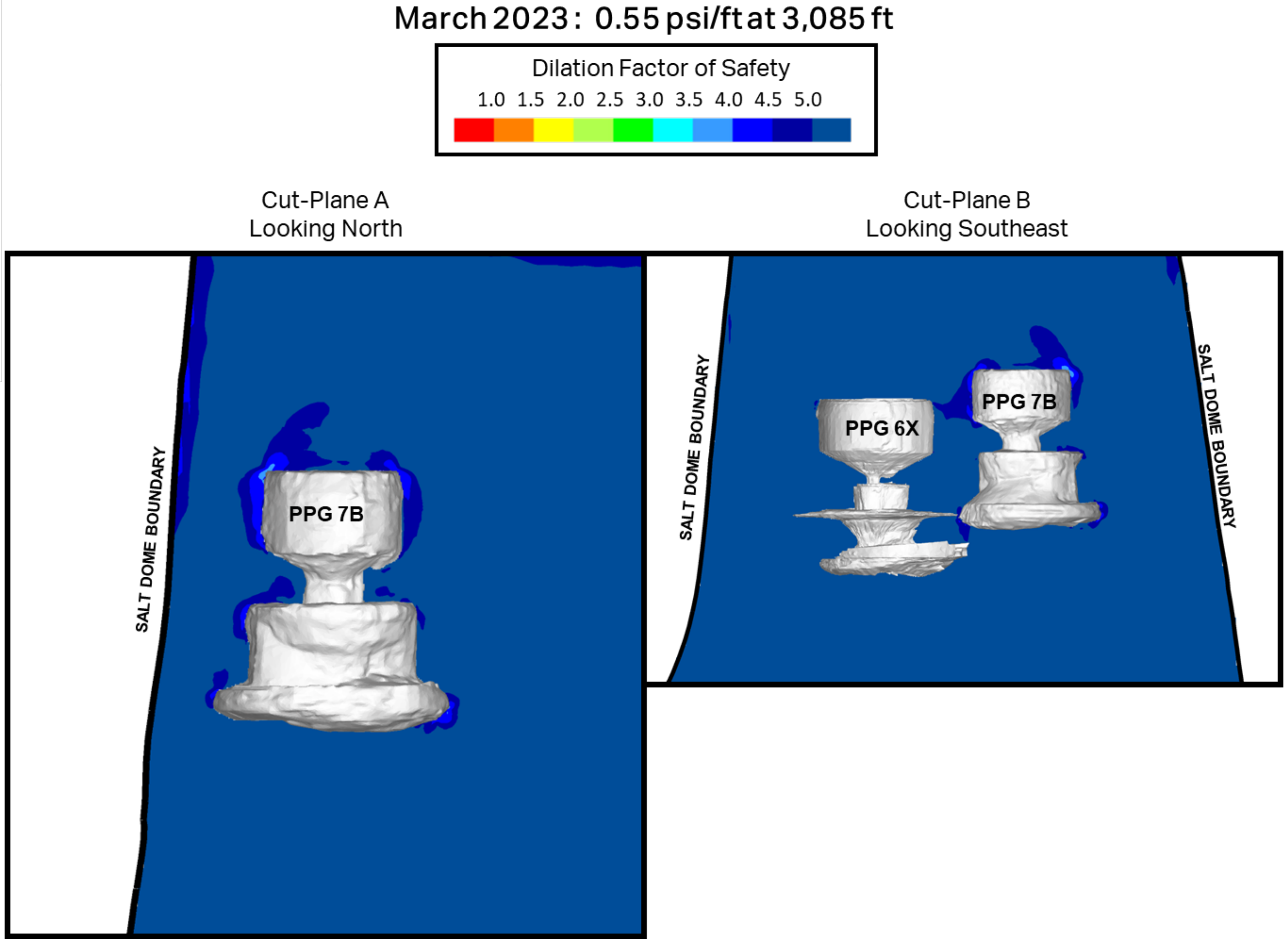
SALT DILATION FACTORS OF SAFETY FOR THREE HYPOTHETICAL LOW-PRESSURE CONDITIONS AND TWO DEPRESSURIZATION RATES

MARCH 2023 : 0.55 PSI/FT AT 3,085 FT

Plan View

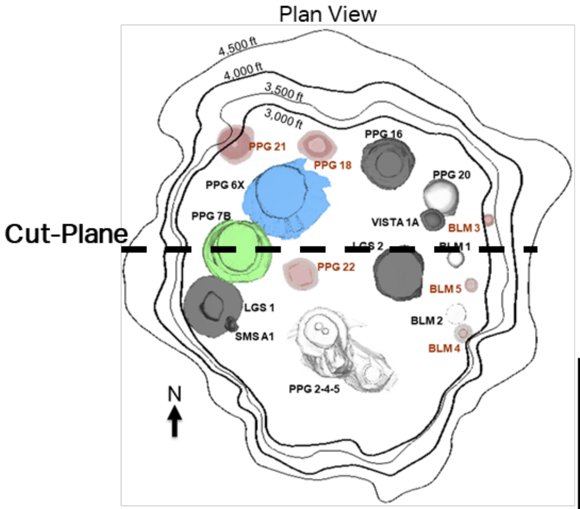


- Dilation FS contours surrounding PPG 6X and PPG 7B prior to simulating the hypothetical low-pressure scenarios
- Min. FS values of 3.0-3.5 at perimeter of PPG 7B roof
- Dilation FS values greater than 5.0 for much of the salt stock surrounding the caverns

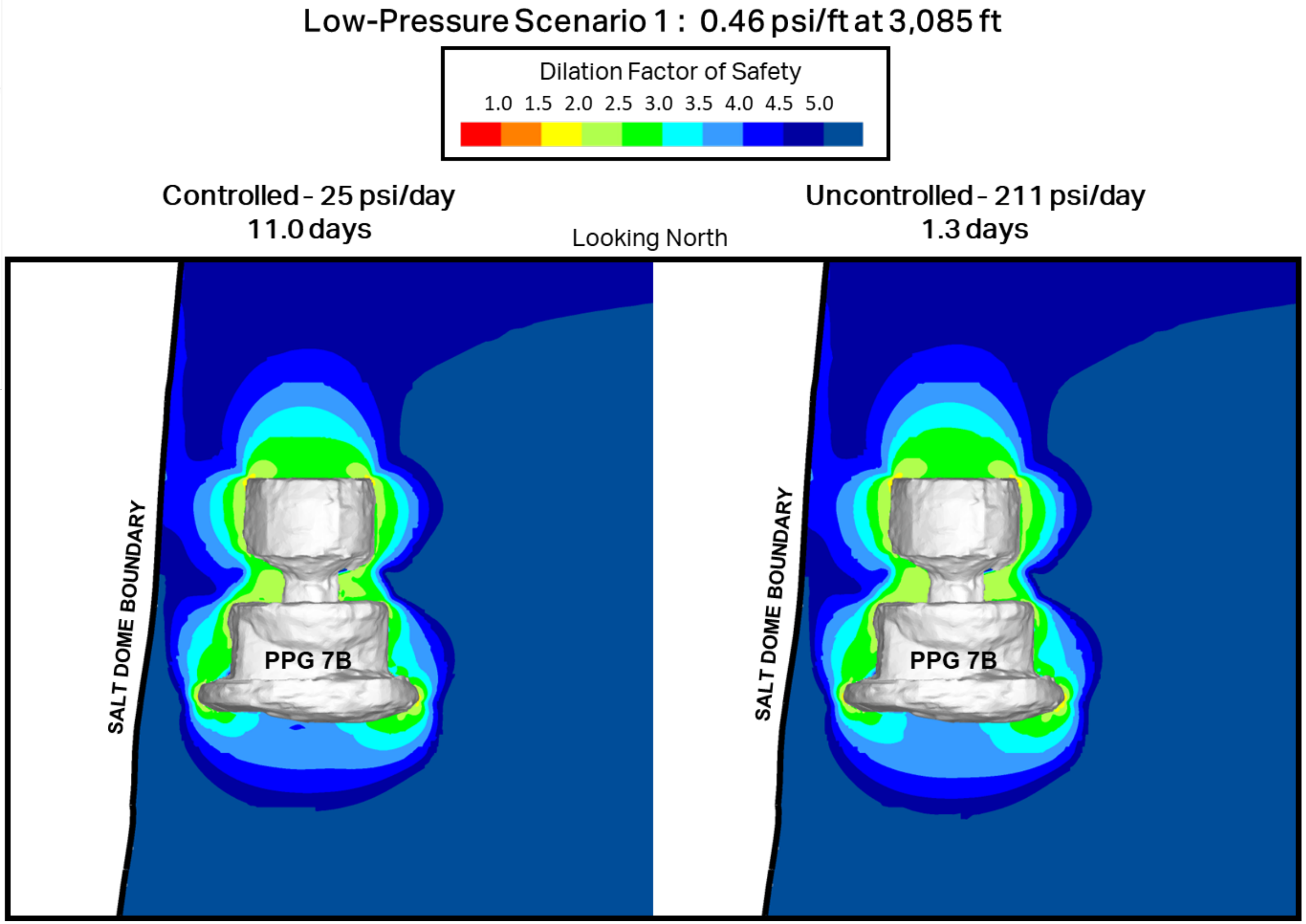


Low-Pressure Scenario 1 :
0.46 psi/ft at 3,085 ft

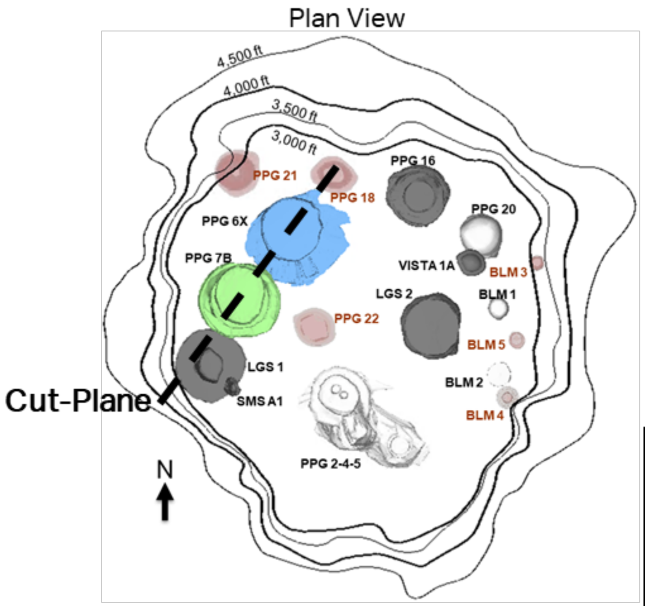
SCENARIO 1 : 0.46 PSI/FT AT 3,085 FT



- Min. FS values of 1.5-2.0 at perimeter of PPG 7B roof
- Uncontrolled depressurization results in slightly lower FS values near the caverns



SCENARIO 1 : 0.46 PSI/FT AT 3,085 FT



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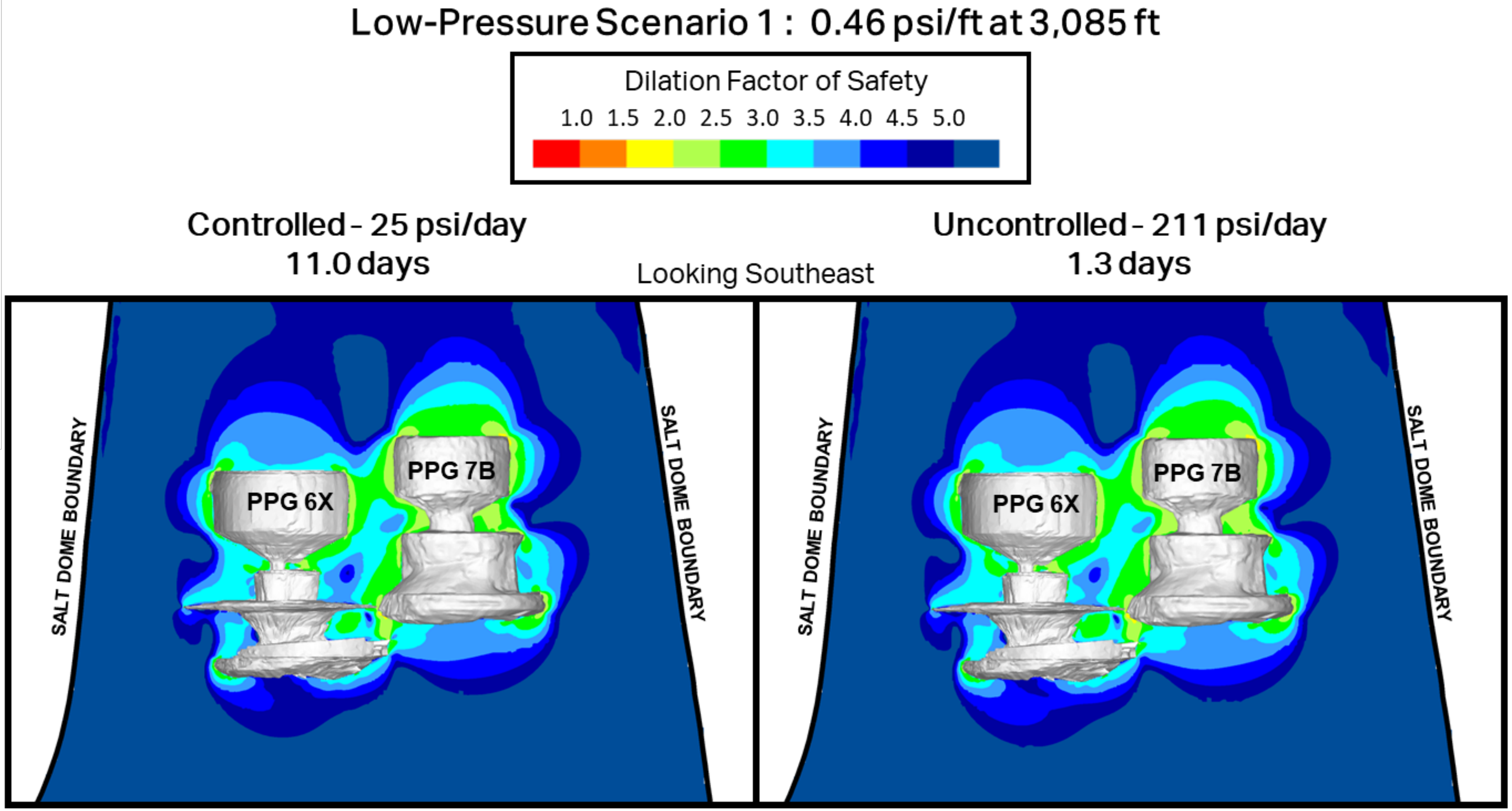
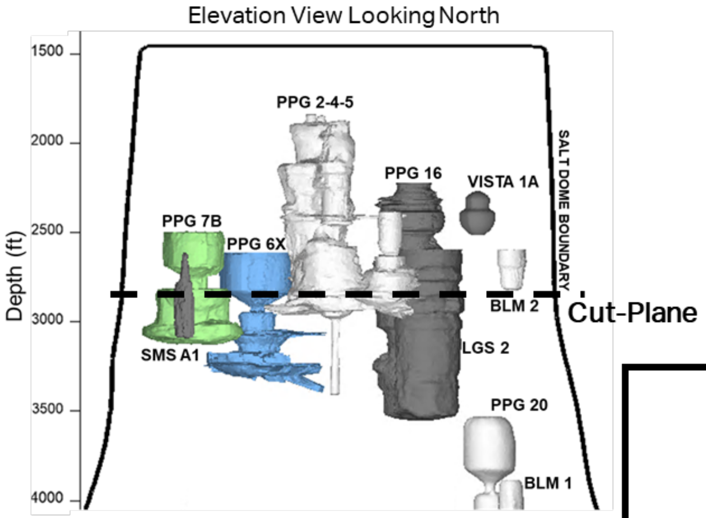
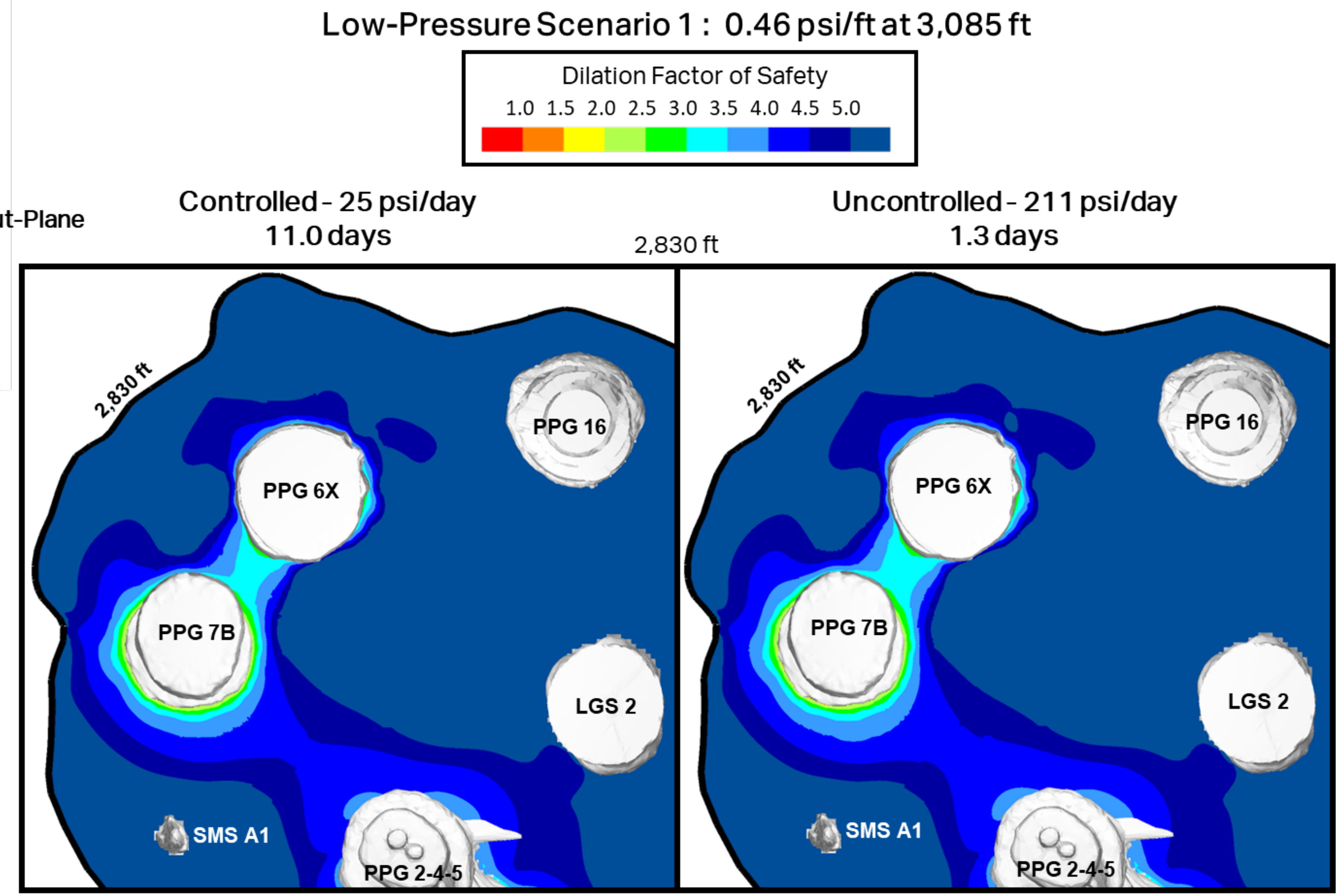


SCENARIO 1 : 0.46 PSI/FT AT 3,085 FT

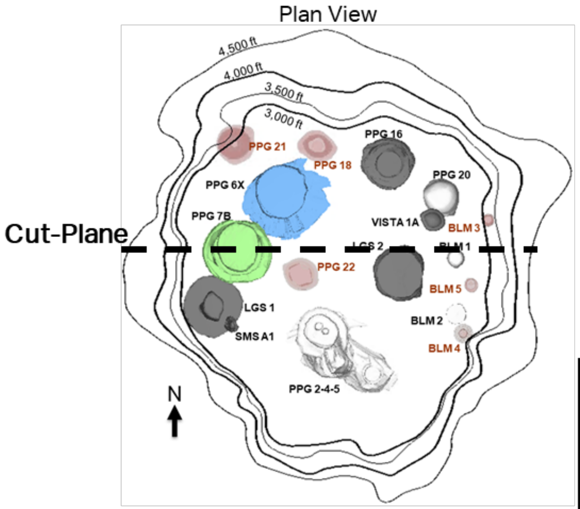




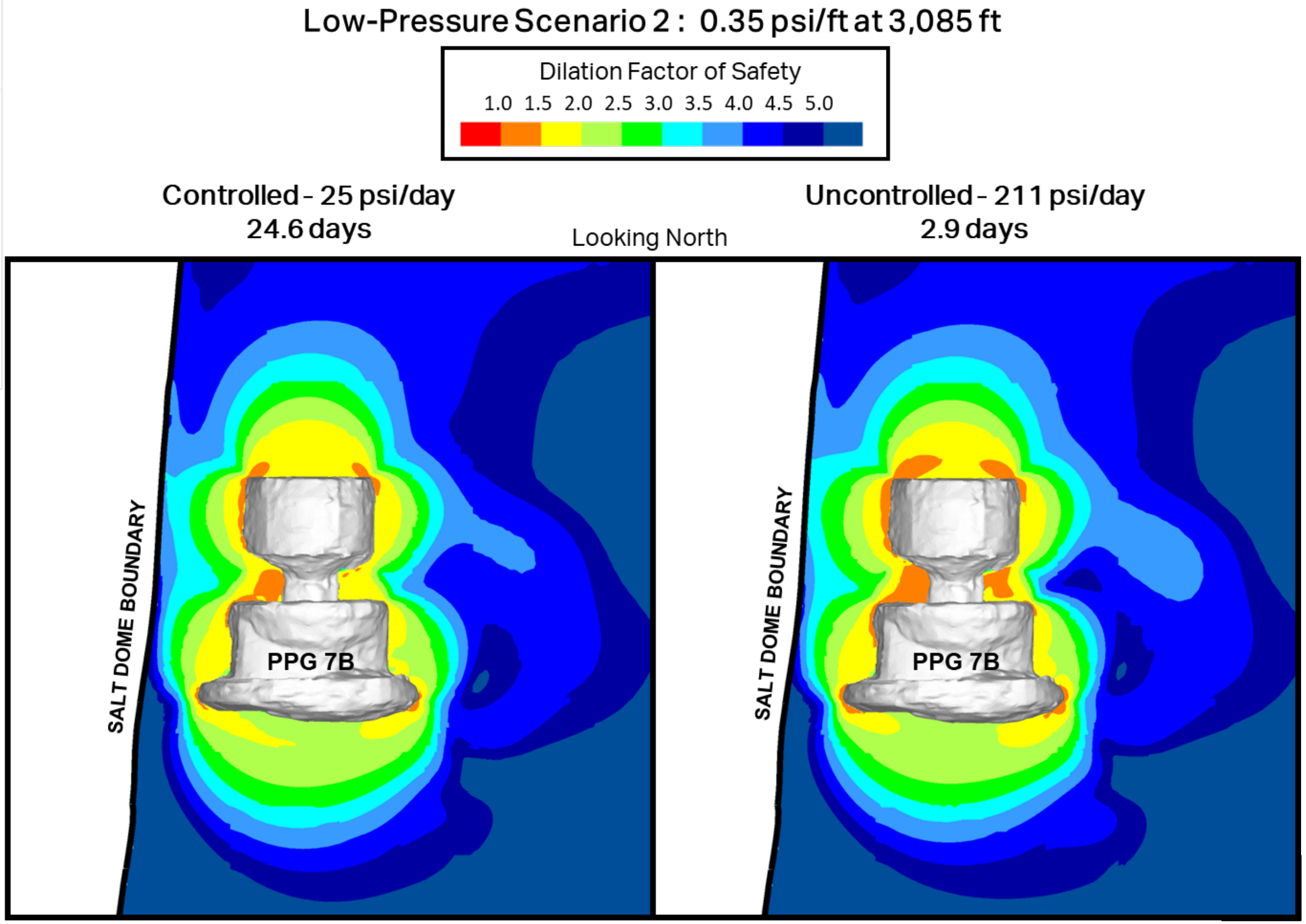
- FS values in salt webs surrounding PPG 6X & 7B range from 4.0 to 5.0+, suggesting low-potential for salt web instability

Low-Pressure Scenario 2 :
0.35 psi/ft at 3,085 ft

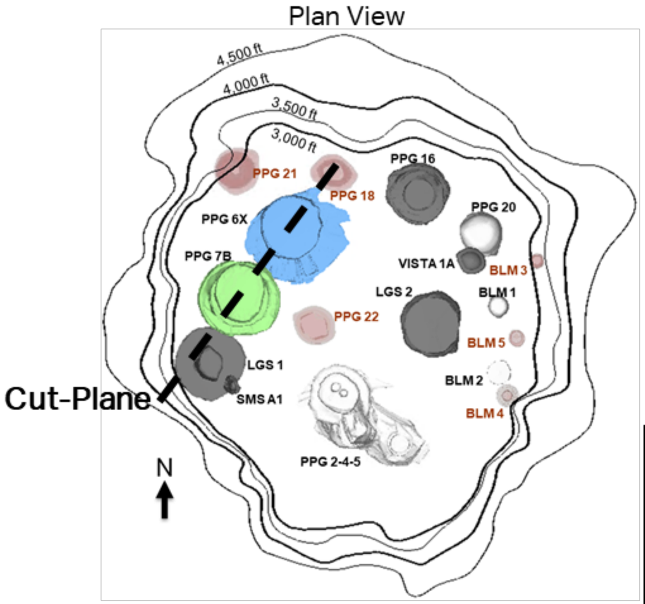
SCENARIO 2 : 0.35 PSI/FT AT 3,085 FT



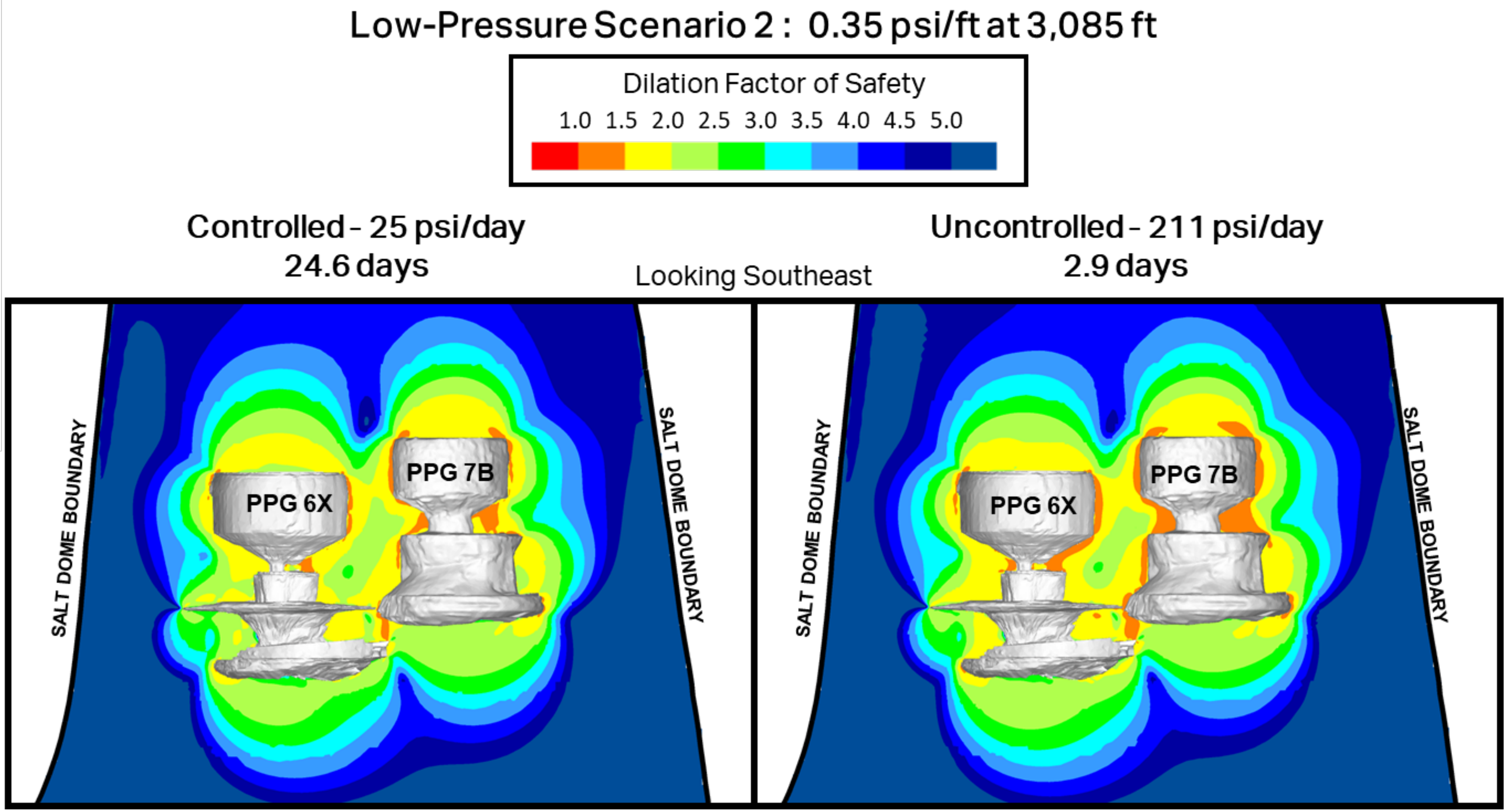
- Significant areas of low FS values between 1.0-1.5 around the caverns suggest the loading conditions are near the dilation strength of the salt
- Greater extent of low FS values (1.0-1.5) predicted for uncontrolled depressurization scenario



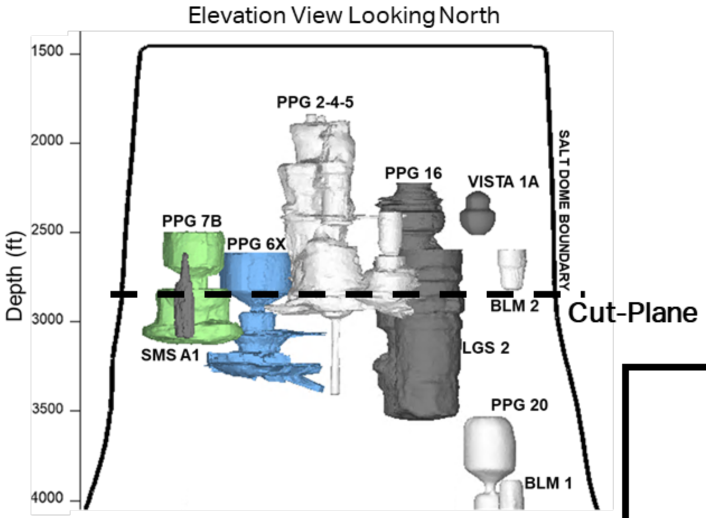
SCENARIO 2 : 0.35 PSI/FT AT 3,085 FT

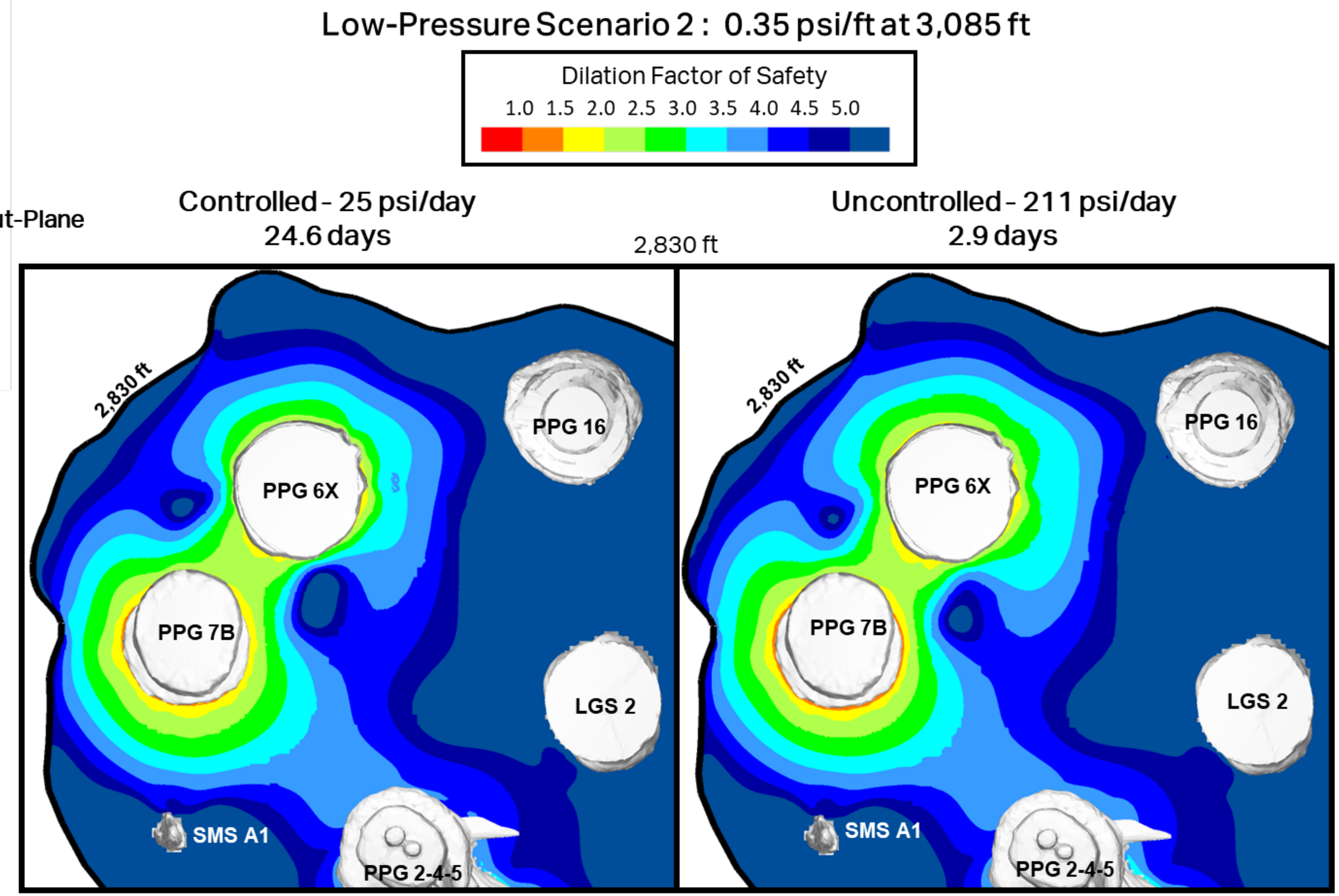


- Significant areas of low FS values between 1.0-1.5 around the caverns suggest the loading conditions are near the dilation strength of the salt
- FS < 2.0 through the salt web suggest risk for salt web instability



SCENARIO 2 : 0.35 PSI/FT AT 3,085 FT

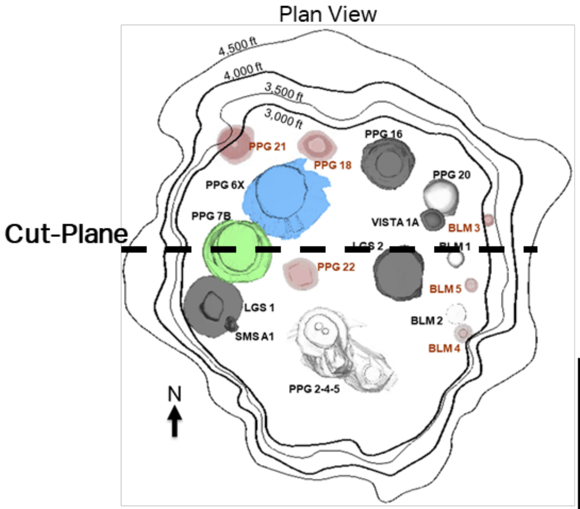


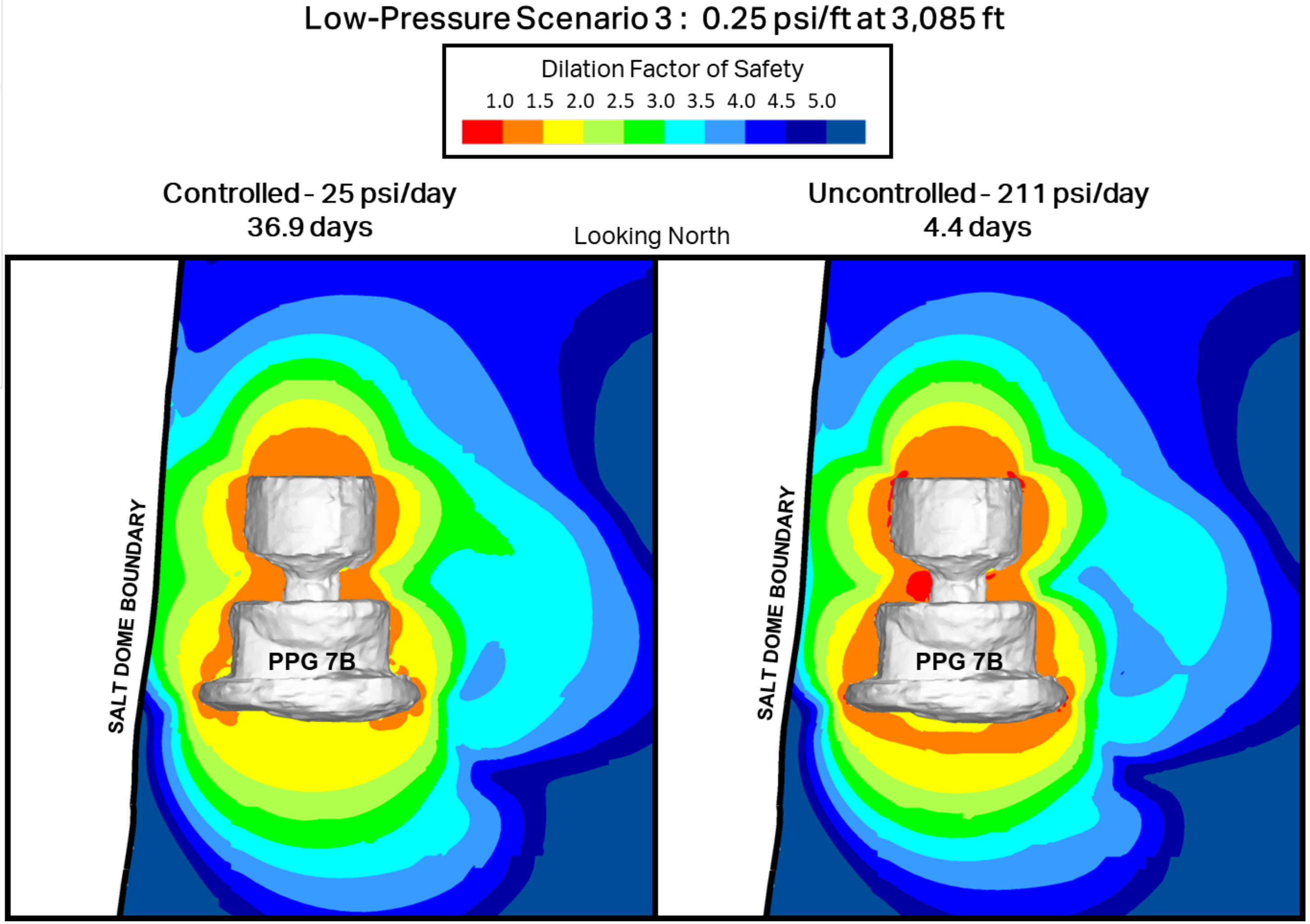


- FS values in salt webs surrounding PPG 6X & 7B ranging from 3.0 to 4.5 suggest low potential for salt web instability

Low-Pressure Scenario 3 :
0.25 psi/ft at 3,085 ft

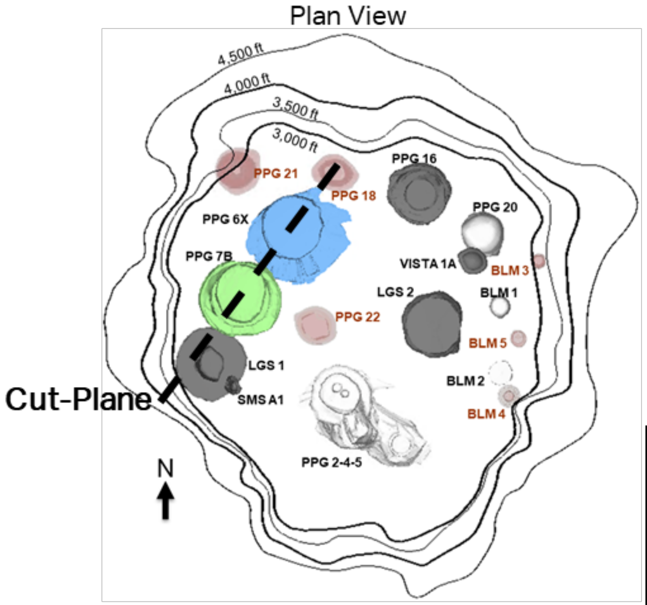
SCENARIO 3 : 0.25 PSI/FT AT 3,085 FT



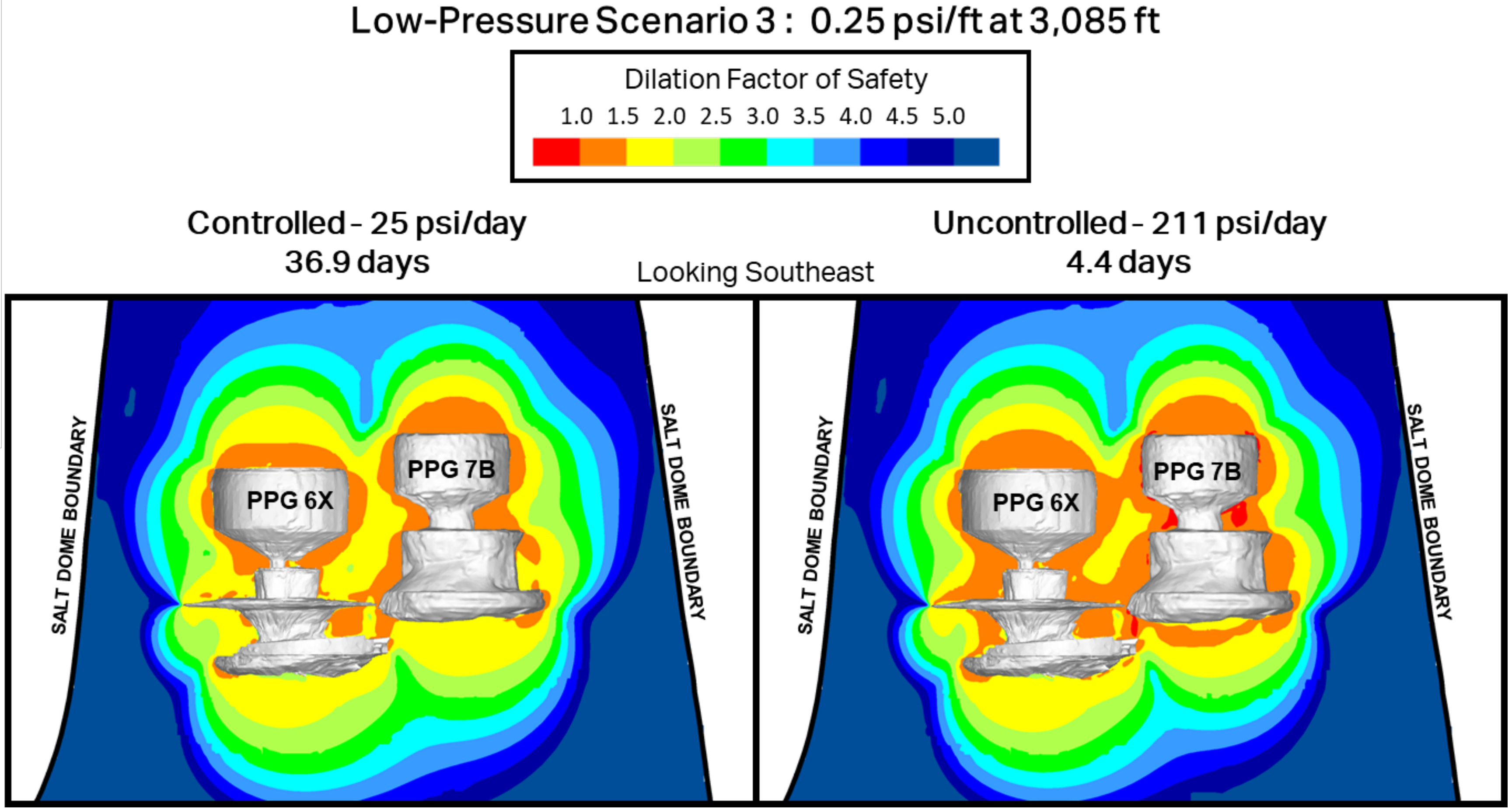


- Large extent of low FS values (1.0-1.5) suggests the loading conditions are very near the dilation strength of the salt
- Areas of dilating salt (FS<1.0) around PPG 7B predicted for uncontrolled scenario may result in spalling and instability

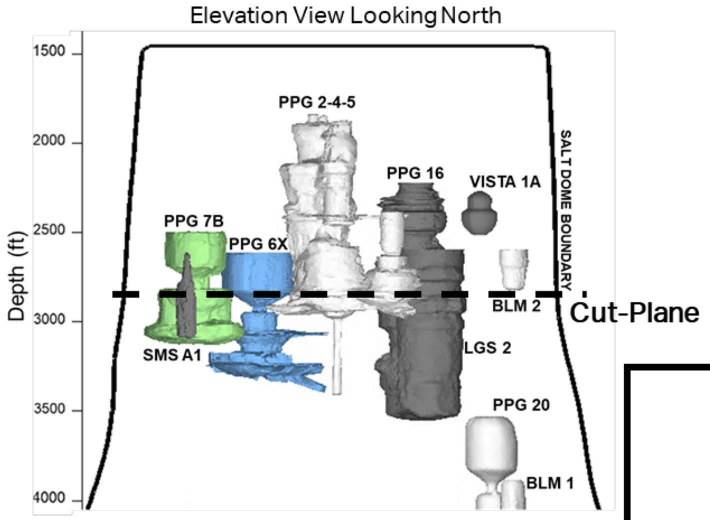
SCENARIO 3 : 0.25 PSI/FT AT 3,085 FT

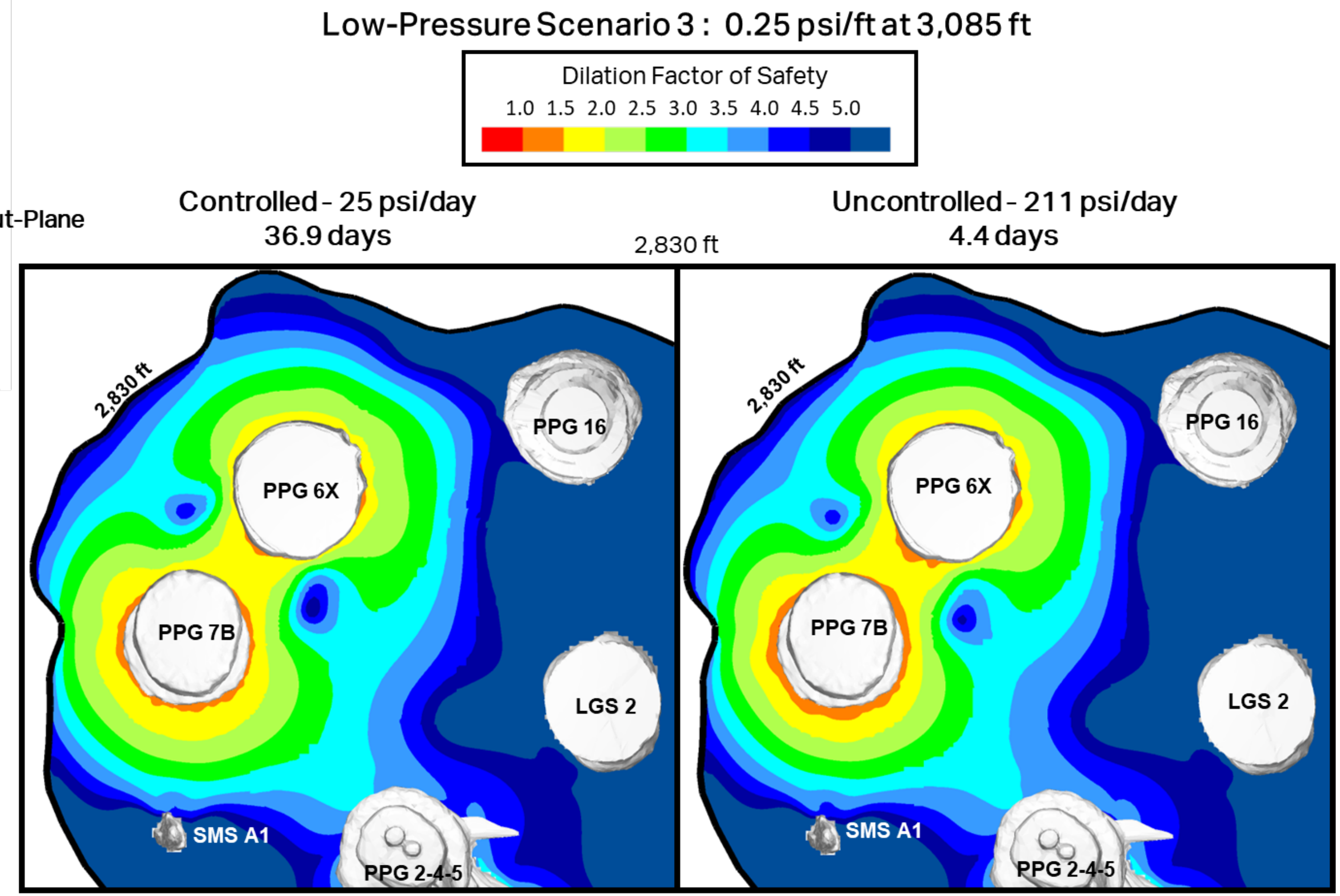


- Large extent of low FS values (1.0-1.5) suggests the loading conditions are very near the dilation strength of the salt
- Areas of dilating salt (FS<1.0) around PPG 7B predicted for uncontrolled scenario may result in spalling
- Consistent low FS values (1.0-1.5) through the salt web suggest potential for salt web instability



SCENARIO 3 : 0.25 PSI/FT AT 3,085 FT





- Large extent of low FS values (1.0-1.5) suggests the loading conditions are near the dilation strength of the salt
- Dilation FS values in cores of the salt webs surrounding PPG 6X & 7B are significantly reduced to values ranging from 2.5 to 3.5

NEAR TERM FUTURE EVALUATION

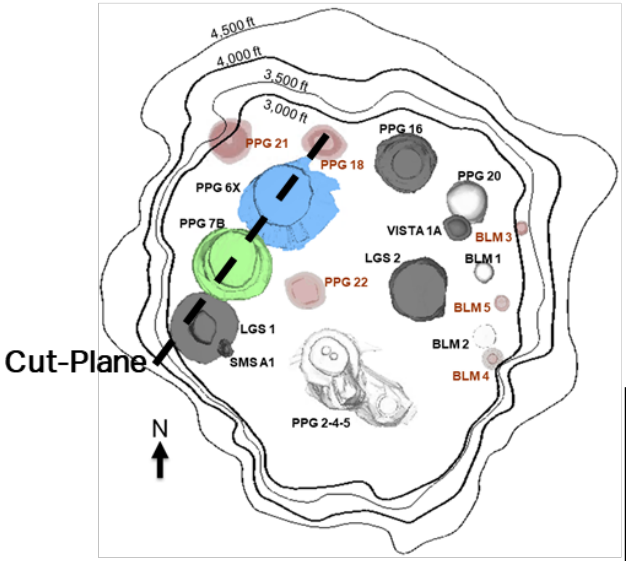
- Assuming the cavern pressures stabilize at one of the hypothetical low-pressure conditions, the salt will continue to creep at a relatively high rate and redistribute the stress through the surrounding salt stock, changing the dilation FS values over time

- Two cases are presented to assess dilation FS values after 1 year of future creep deformation at constant low-pressure conditions to illustrate how the FS values may evolve over time

  1. Controlled Low-Pressure Scenario 1 – “Best Case”
  2. Uncontrolled Low-Pressure Scenario 3 – “Worst Case”

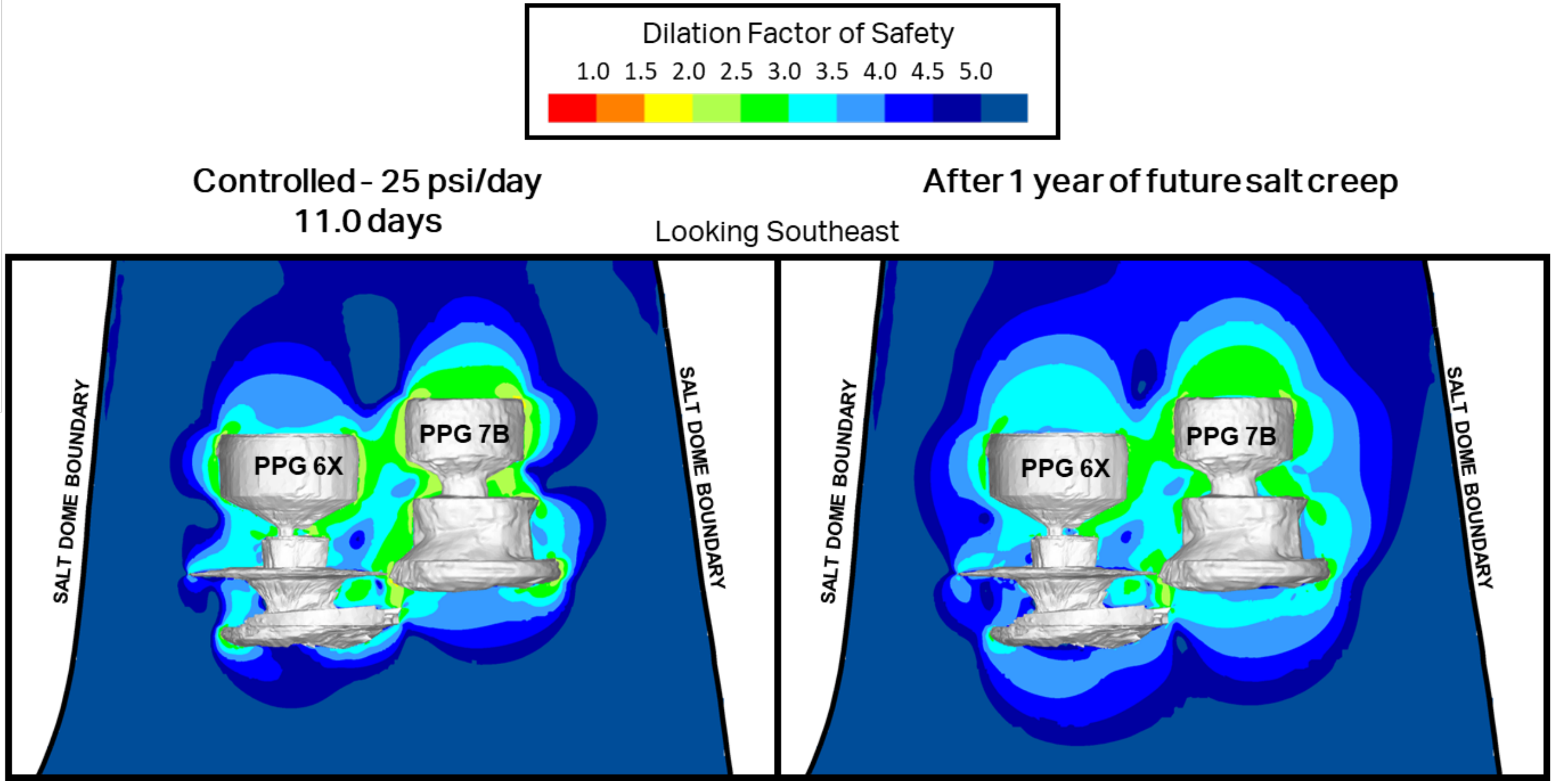
SCENARIO 1 : AFTER 1 YEAR OF FUTURE CREEP

Plan View

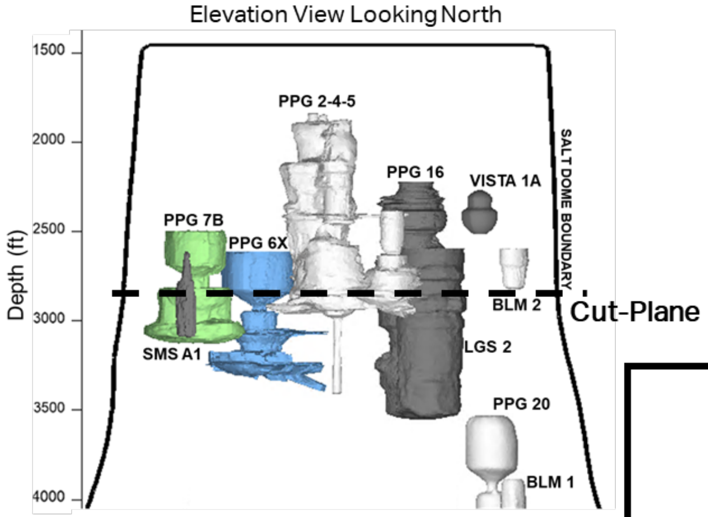


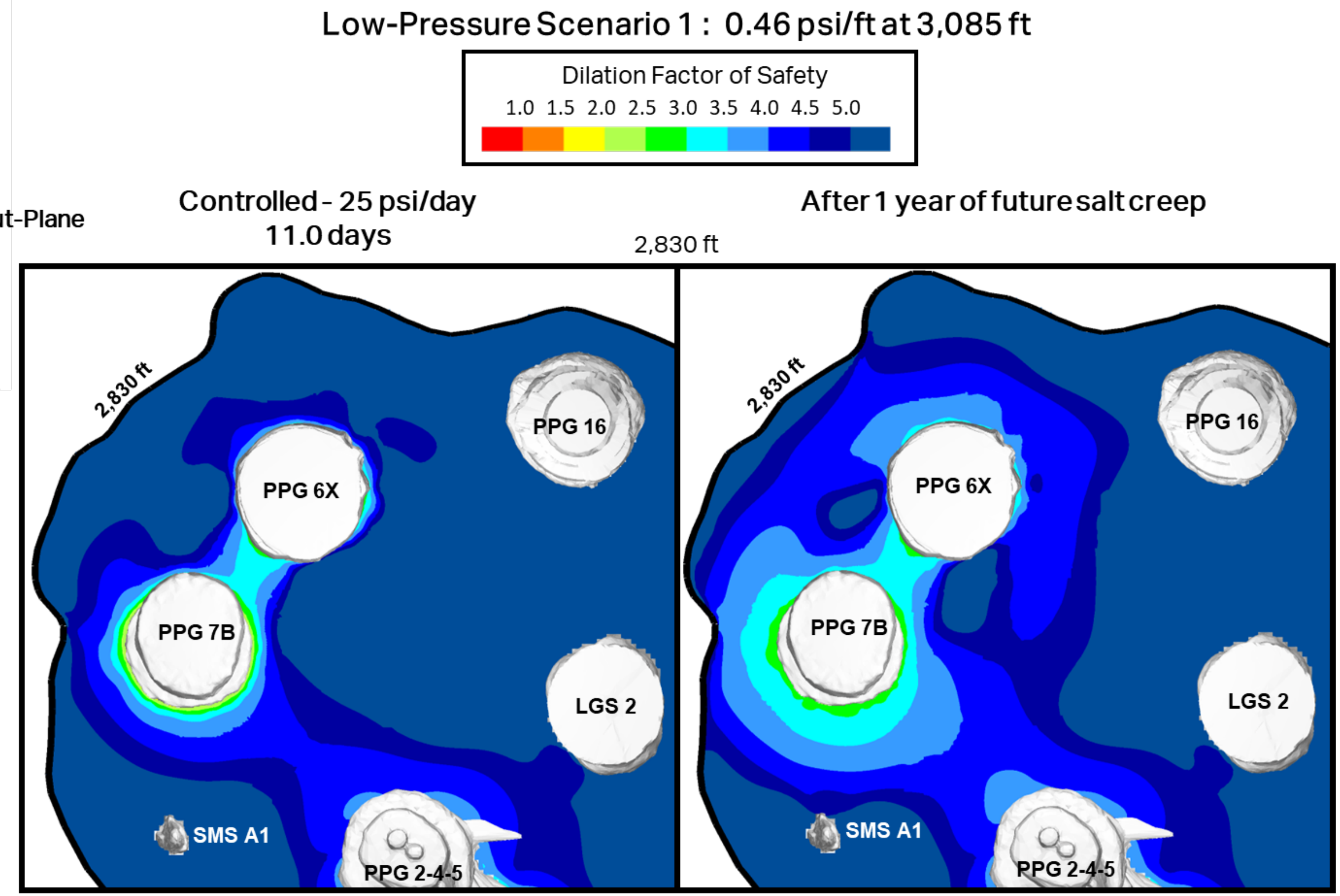
- FS values near the caverns' surfaces improve slightly
- FS values further away from the caverns decrease over time

Low-Pressure Scenario 1 : 0.46 psi/ft at 3,085 ft



SCENARIO 1 : AFTER 1 YEAR OF FUTURE CREEP

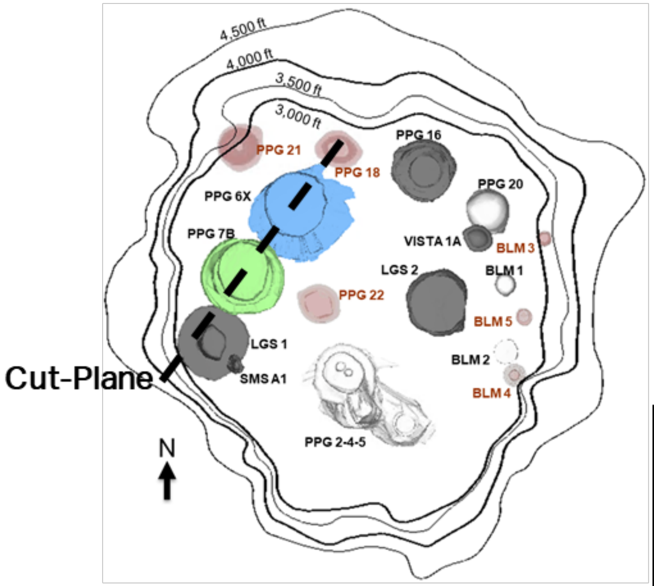




- FS values near the caverns' surfaces improve slightly
- FS values further away from the caverns decrease over time

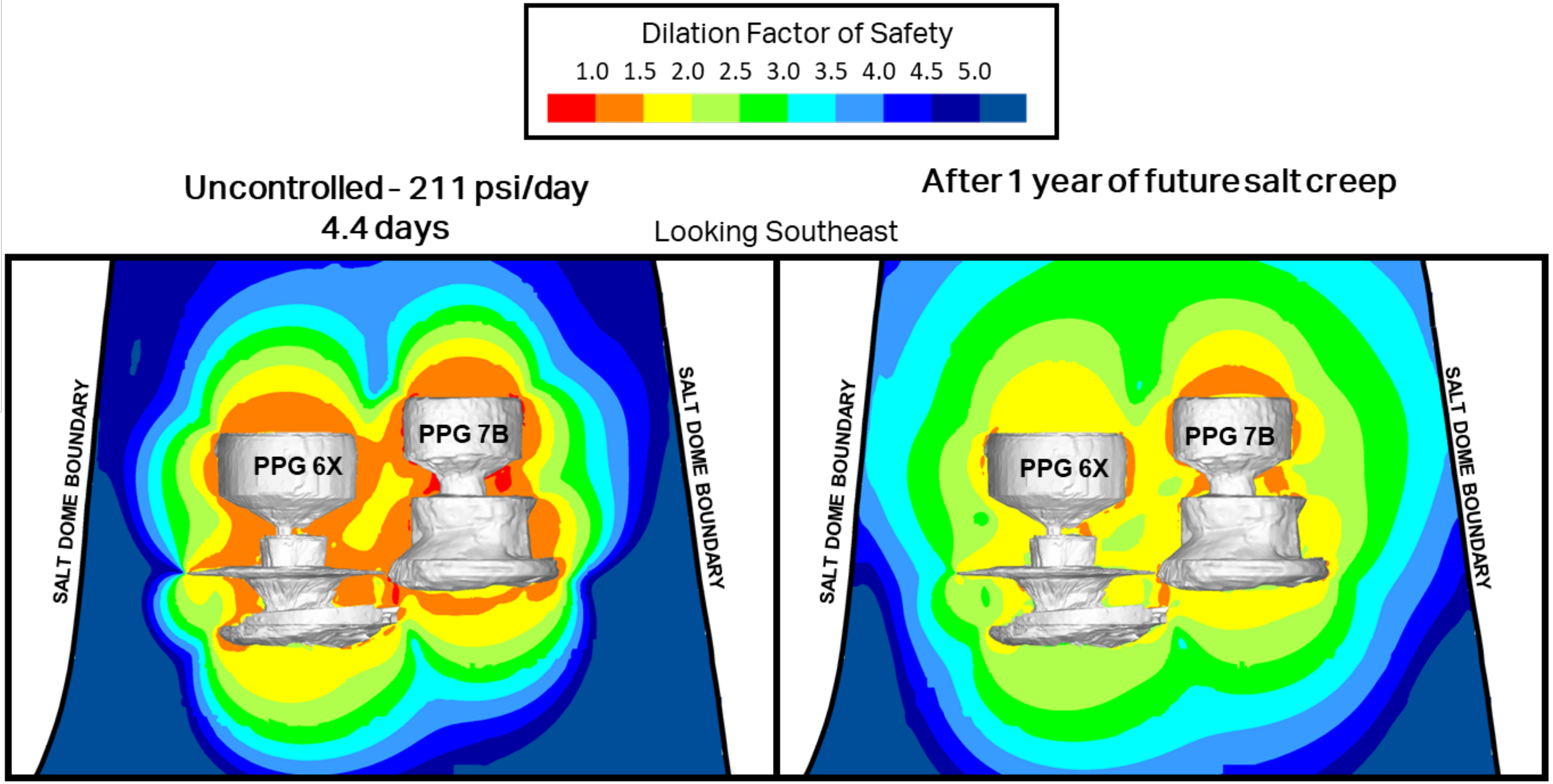
SCENARIO 3 : AFTER 1 YEAR OF FUTURE CREEP

Plan View

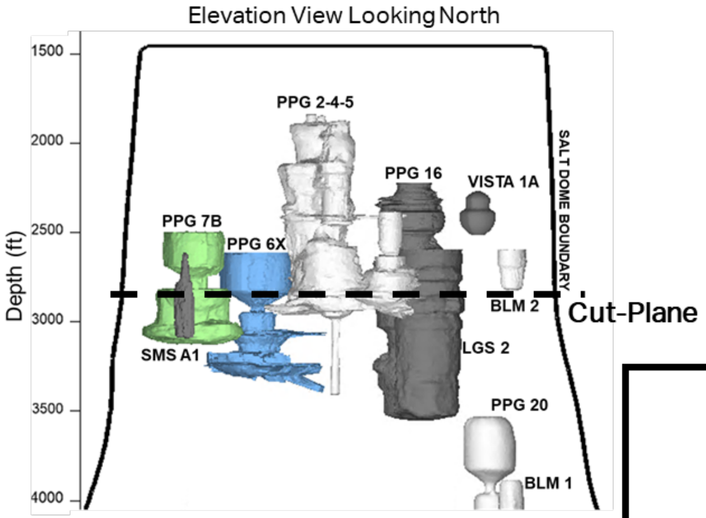


- FS values near the caverns' surfaces improve slightly
- FS values further away from the caverns decrease over time

Low-Pressure Scenario 3 : 0.25 psi/ft at 3,085 ft



SCENARIO 3 : AFTER 1 YEAR OF FUTURE CREEP



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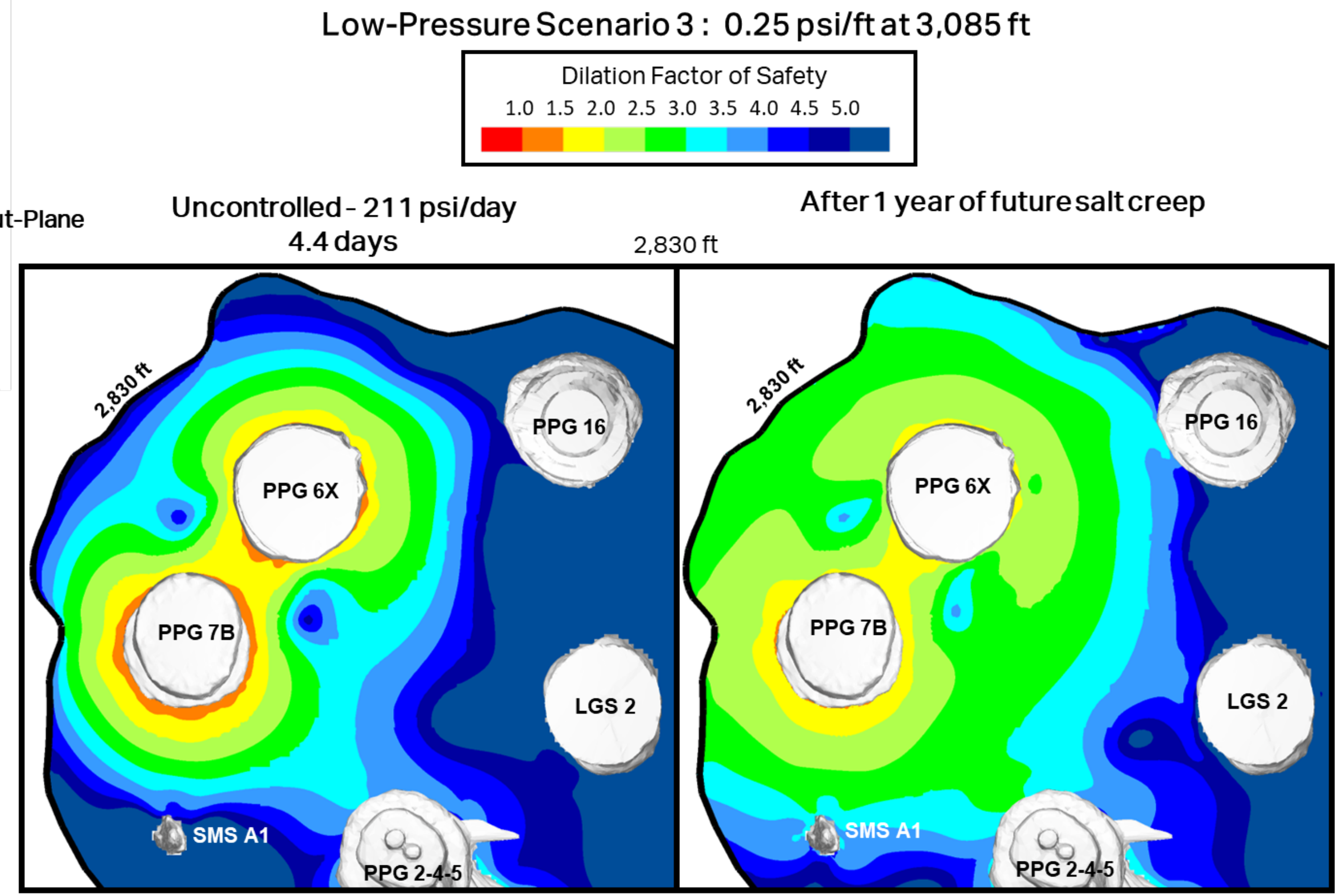

SUMMARY OF RESULTS & CONCLUSIONS

- Scenario 1 : 0.46 psi/ft @ 3,085 ft
  - Salt dilation FS values suggest the caverns and salt webs should remain stable (near-term).
- Scenario 2 : 0.35 psi/ft @ 3,085 ft – Not Recommended
  - Significant areas of low FS values (1.0-1.5) suggest the loading conditions are near the dilation strength of the salt. Low FS values (1.5-2.0) in the core of the salt web between 6X & 7B are less than the minimum 2.0 typically recommended for salt web stability.
- Scenario 3 : 0.25 psi/ft @ 3,085 ft – Not Recommended
  - Large areas of dilatant stress states were predicted near PPG 7B for the uncontrolled depressurization scenario. Large extents of low FS values (1.0-1.5) predicted near the caverns suggest the loading conditions are very near the dilation strength of the salt. Low FS values (1.0-1.5) across the thickness of the salt web between 6X & 7B suggest the potential for salt web instability.
- The depressurization rate of the caverns should be controlled as much as possible to reduce the impact on the salt webs.
- The simulated future salt creep deformation with the caverns at constant low-pressure conditions causes a redistribution of the stresses, resulting in an evolution of the model-predicted salt damage FS values
  - The potential for damage generally decreases near the caverns – an increase in FS values
  - The potential for damage generally increases at distances further away from the caverns – a decrease in FS values

CONCLUSIONS – CONTINUED

- The baseline modeling results and conclusions presented above were based on assuming that the salt properties in the webs can be accurately characterized by the salt from Well No. 22 [Arnold, 2015]. If the properties of the salt forming the webs differ significantly from the salt in Well No. 22 , the conclusions presented here may be impacted. Furthermore, if the contact between the salt web and the nonsalt formations outside of the dome is not perfectly bonded as assumed in this study, the conclusions presented here may be impacted.
- Because salt variability or the presence of anomalous features in the salt webs is not possible to determine, an appropriate factor of safety should be considered. The relatively recent sidewall spalling in PPG 7B evidenced by sonar surveys may indicate that the salt in the web between PPG 7B and the dome flank exhibits lower strength than what was assumed in this Phase 1 of the study. It may also indicate that the salt web contact with the adjacent nonsalt formations is weaker than assumed, or that the distance from the dome flank is less than what was assumed in this Phase 1 of the study.
- Subsequent modeling efforts will investigate these assumptions and the sensitivity of the modeling results to a reasonable range of strength characteristics for the dome flank and adjacent rock formations. An attempt to history match the observed rock falls in PPG 7B could assist in determining an appropriate minimum pressure that precludes instability of the caverns or the salt web between PPG 7B and the dome flank.

PATH FORWARD

- Phase 2 – History Matching to Estimate the In Situ Salt Dilation Strength
  - Attempt to history-match the recent rock falls evidenced in PPG 7 sonar surveys through adjustment of the salt dilation strength
    - Estimate an in situ salt strength for the web between PPG 7 and the dome flank
  - Assess effects of adjacent formation pressures and a weak contact at the dome flank
  - Re-establish baseline conditions for current cavern and web stability (prior to low-pressure scenarios)
- Phase 3 – Assess Near-Term Impact of Hypothetical Low-Pressure Conditions
  - Use the estimated in situ salt strength for the web between PPG 7 and the dome flank
  - Simulate pressure drawdown scenarios and assess near-term impacts
- Phase 4 – Potential Web Failure Risk Analysis
  - Model hypothetical web failure scenarios
    - Web between PPG 7 and dome flank
    - Web between PPG 6 & 7
  - Assess potential impacts on surrounding wells, caverns, and surface structure
- Phase 5 – Long-Term Stability Evaluation of All Caverns
  - Simulate long-term sustained low-pressure conditions in PPG 6 & 7
  - Assess potential impacts on surrounding wells, caverns, and surface structure

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BASELINE GEOMECHANICAL EVALUATION OF HYPOTHETICAL LOW-PRESSURE CONDITIONS IN WESTLAKE CAVERNS 7B AND 6X AT THE SULPHUR MINES SALT DOME, CALCASIEU PARISH, LOUISIANA

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MINING & ENERGY

CAVERN GEOMECHANICS

RAPID CITY, SD, USA

AUGUST 10, 2023

RSI(RAP)-M0170.23004

PROJECT CONTROL NO. M0170.23004