Cavern 007 DFOS Project
Data Analysis and Interpretation

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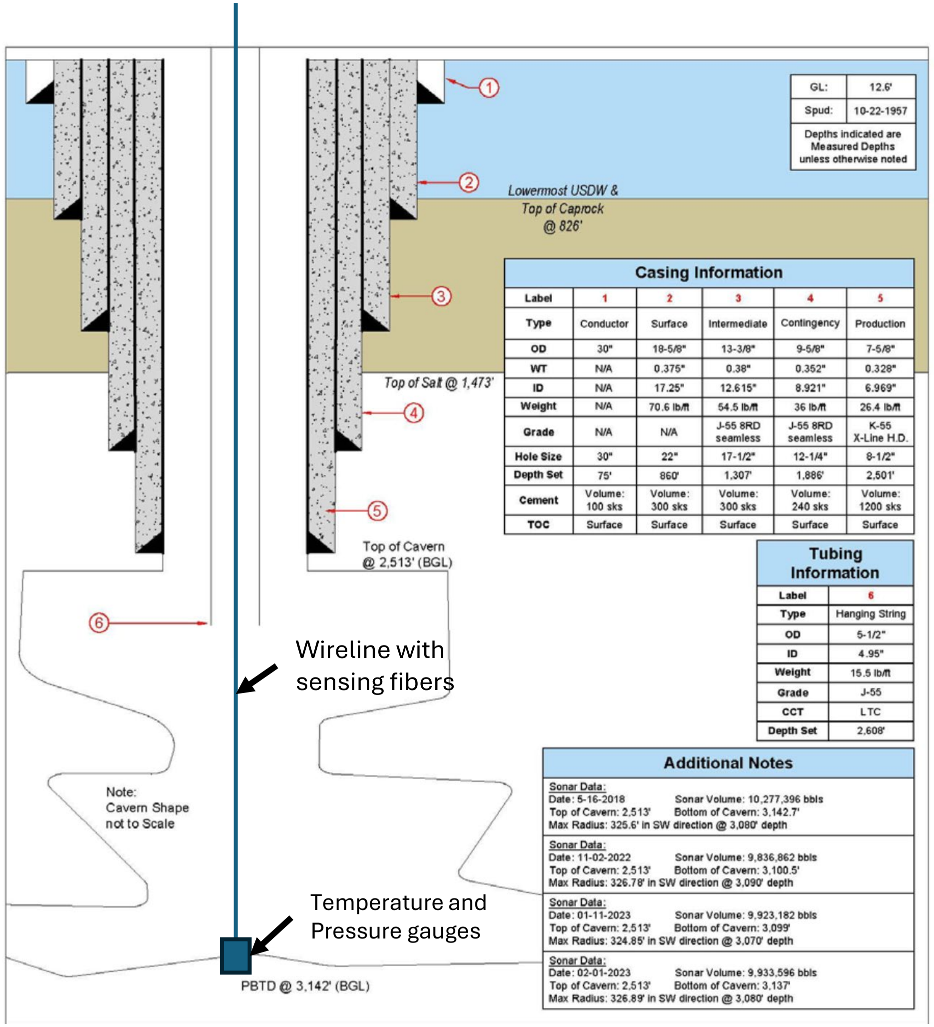
Outline

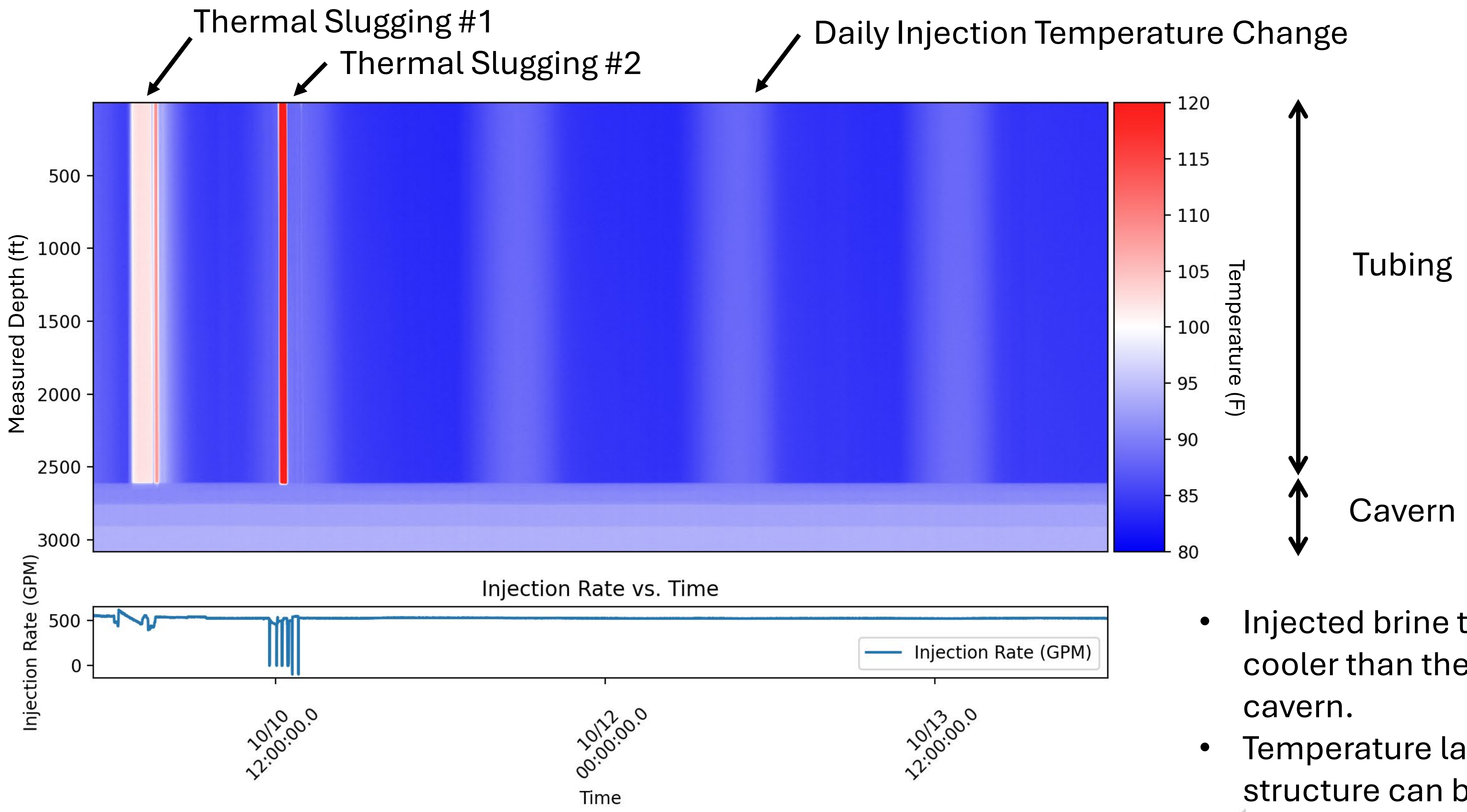
- Introduction
- Temperature logging observations
- Salinity logging and water sample analysis
- Energy balance calculation
- Conclusion

DFOS data acquisition in Cavern 007



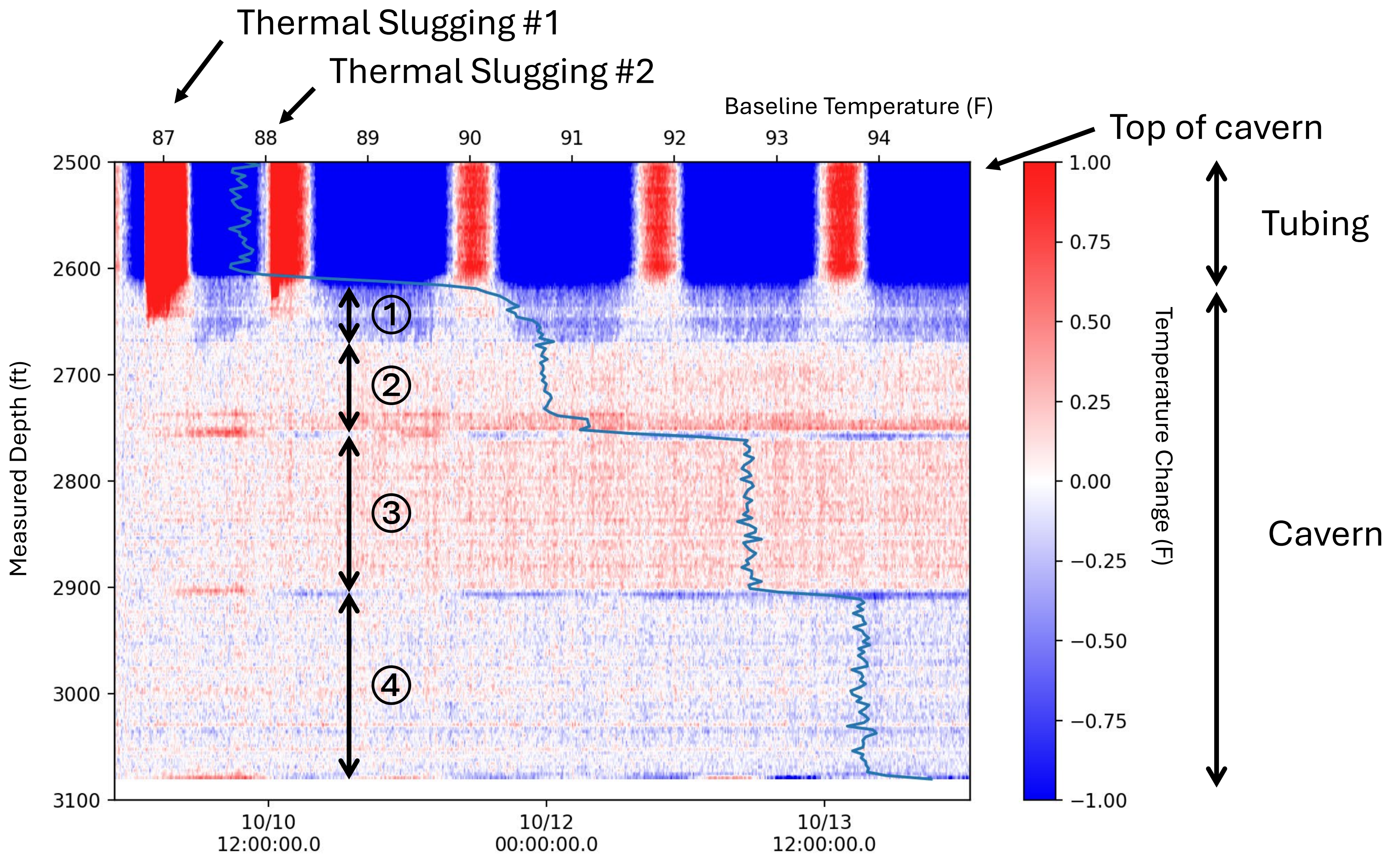
- Data Acquisition Period
  - 2024-10-09 16:00 - 2024-10-14 07:00
- Distributed Temperature Sensing (DTS)
  - Raw data
    - Sampling interval: 1 minute
    - Spatial sampling: 1 m
    - Total data volume: ~400 MB
  - Calibrated data
    - Sampling interval: 10 minute
    - Spatial sampling: 1 m
    - Total data volume: ~11 MB
- Distributed Acoustic Sensing (DAS)
  - Sampling rate: 10 KHz
  - Spatial sampling: 4.78 m
  - Total data volume: ~6 TB

Calibrated DTS data



- Injected brine temperature is cooler than the fluid in the cavern.
- Temperature layering structure can be observed in the cavern.

Temperature Change during data acquisition

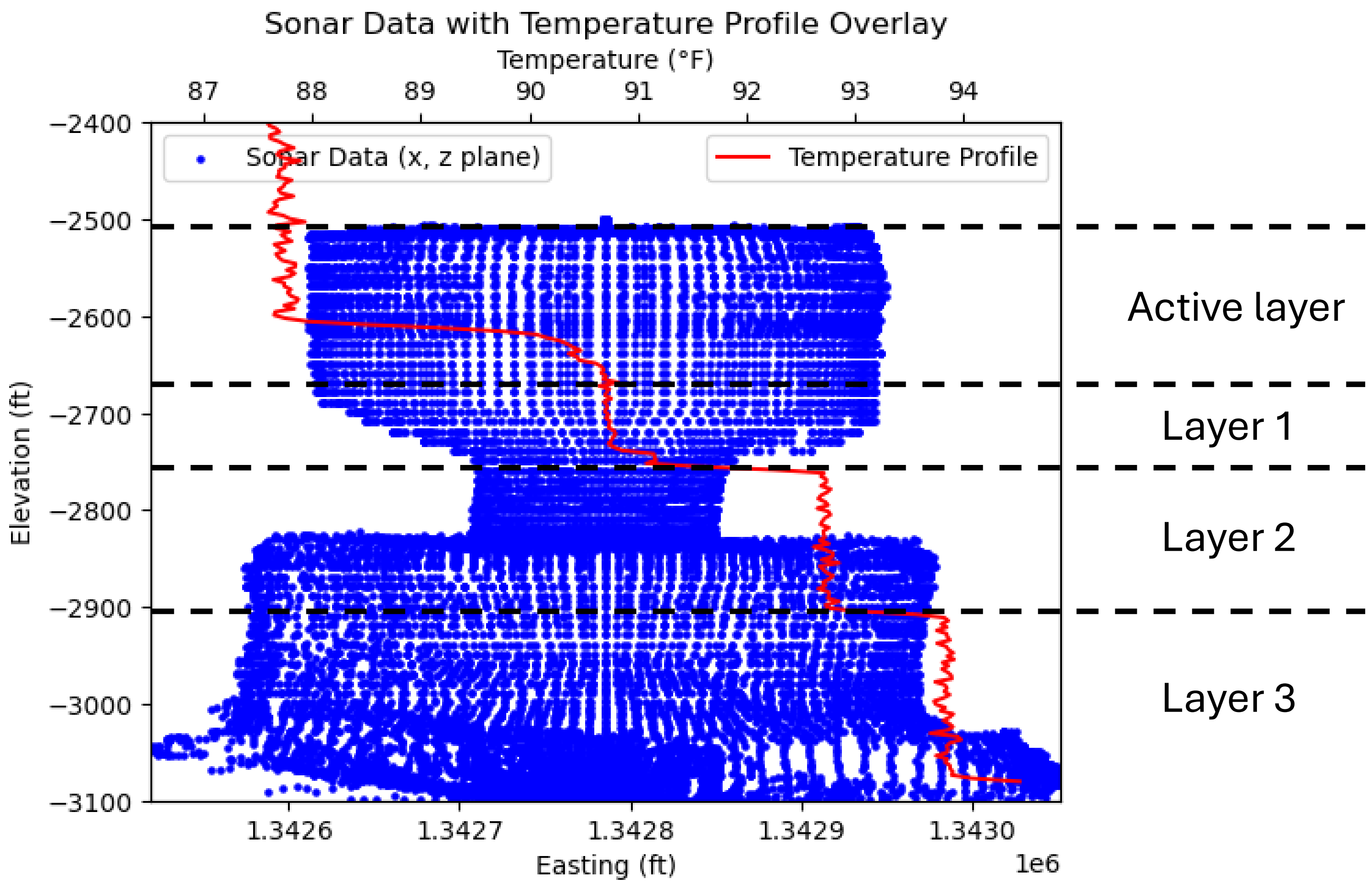


The baseline temperature profile is the average of the first 1.5 hours of DTS data.

Fluid in the cavern formed a stable layering structure.
①: Active layer that is affected by the daily temperature changes of the injected water.
②-④: Stable temperature layer 1,2,3.

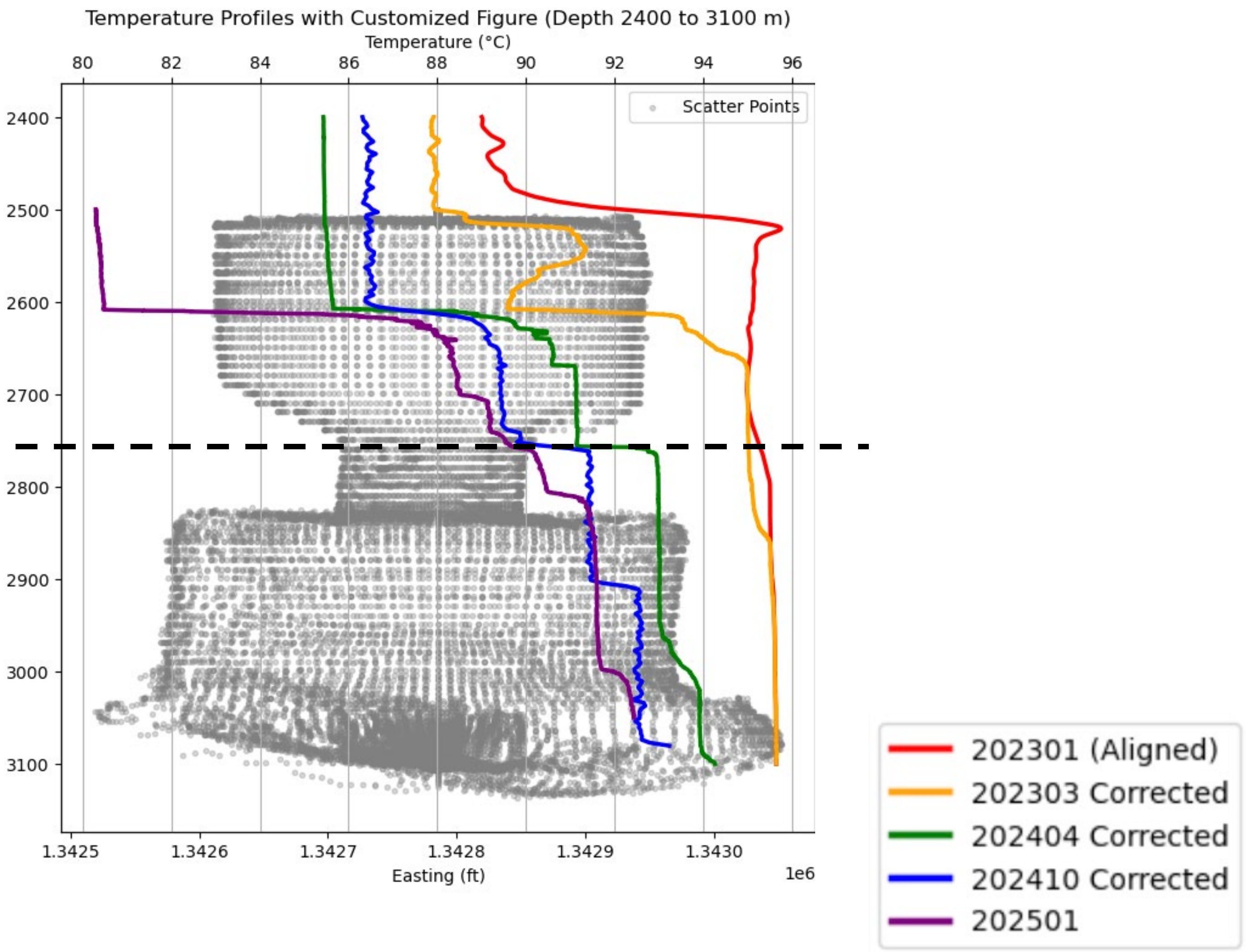
Thermal slug signals vanished in the active layer without impacting stable temperature layers.

Temperature layers with cavern geometry



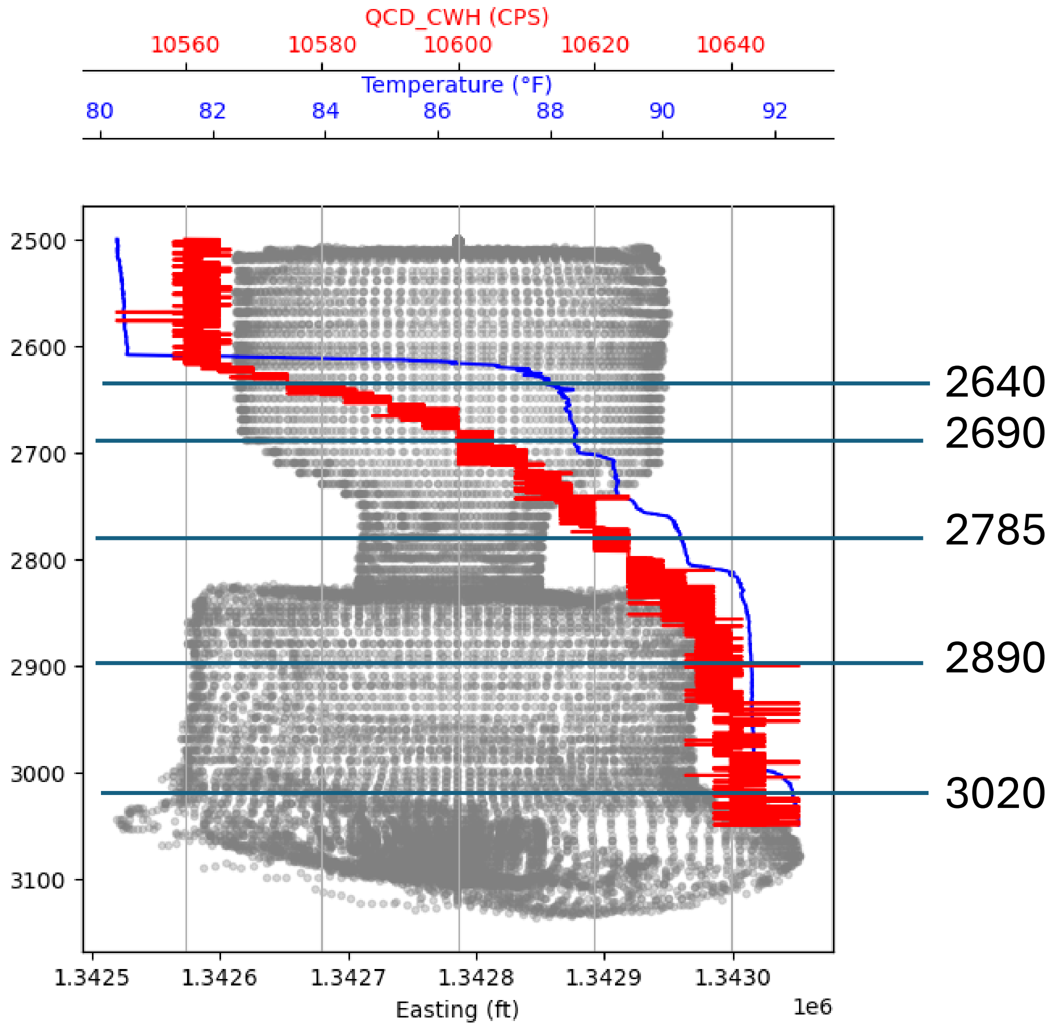
- Several temperature layers have formed within the cavern.
- The temperature interface between layer 1 and 2 seems to be correlated to cavern geometry.
- The active layer is limited to the upper portion of the cavern.

Temperature evolution in the cavern



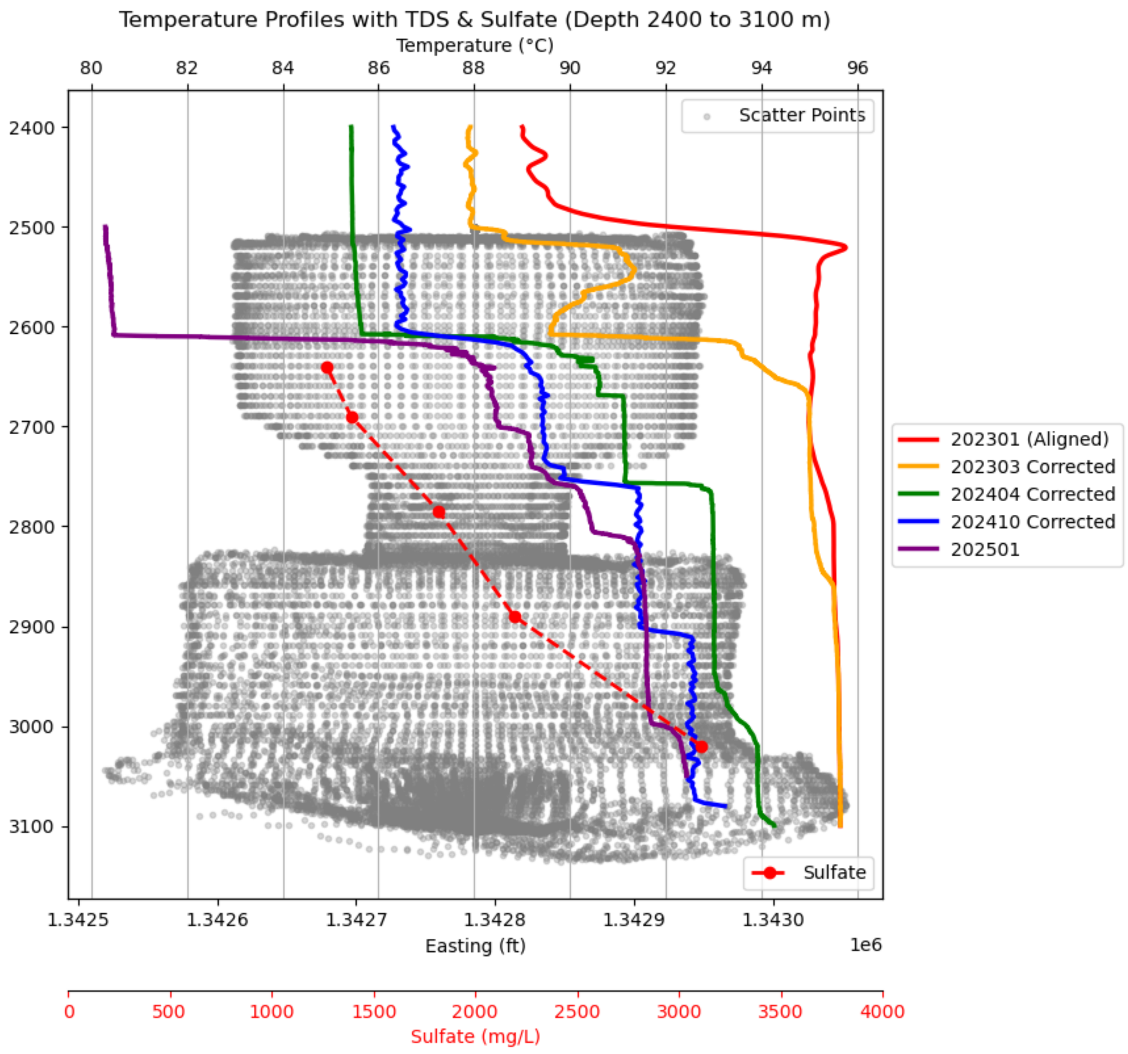
- DTS (202410) and wireline temperature measurements indicate that the temperature of the entire cavern fluid has continued to decrease due to the injection of colder fluid from the surface since 2023.
- However, the cooling process is not uniform across the cavern depth. Due to the complex relationship between the density and temperature of saturated brine, and the heat exchange between the cavern wall and fluid, the cooling process results in the formation of several temperature layers that vary with time.
- The temperature boundary around 2760 feet correlates with the sudden narrowing of the cavern geometry and appears stable in depth over time.
- Temperature profiles before 202410 are calibrated using borehole gauge measurements.

Temperature and Salinity Logging



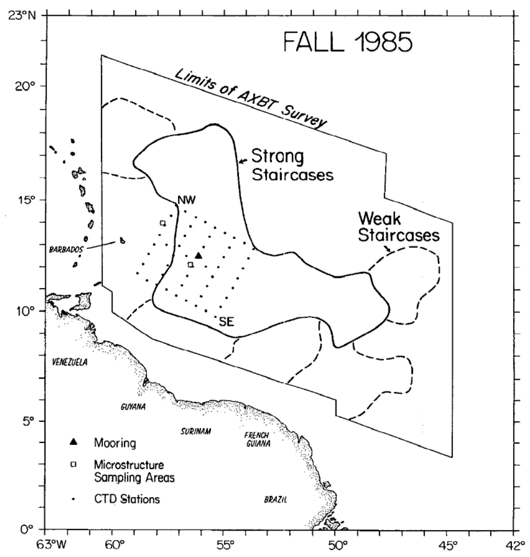
- In order to validate the stability of the temperature layering structure, a salinity log was performed utilizing quantum chromodynamics tools in January, 2025. Although the log encompasses a degree of uncertainty, it confirms that salinity increases with depth, thus creating the density gradient that enables cooler fluid to remain above the warmer fluid within the cavern.
- Water samples were collected at five distinct depths to confirm the trend of increasing density.
- Water samples were also analyzed for their chemical compositions.

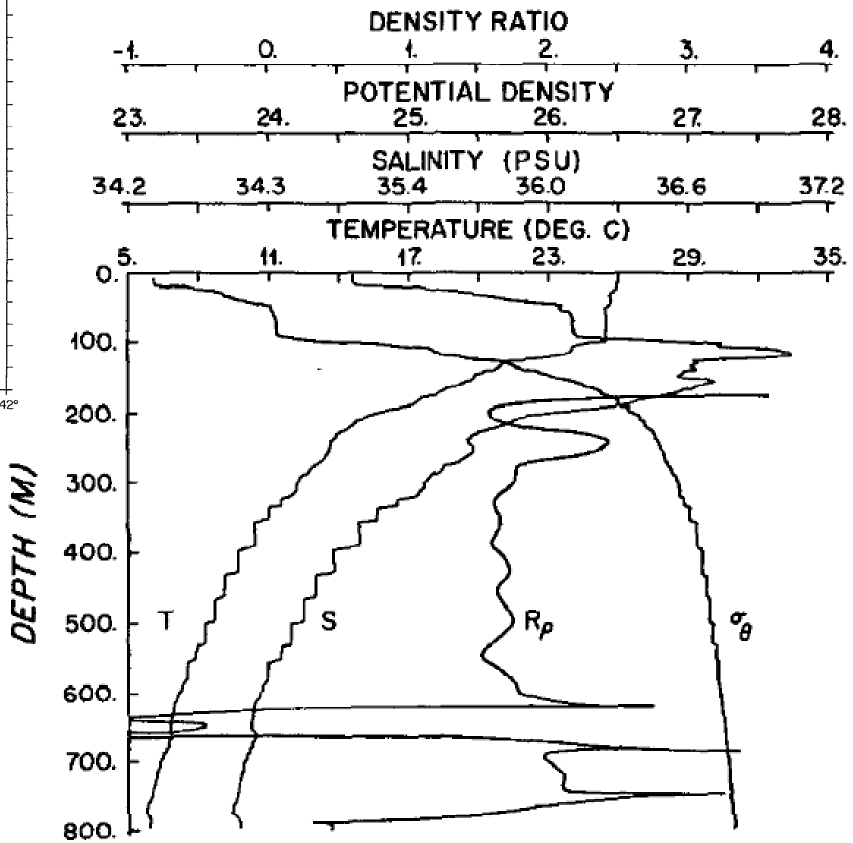
Chemistry of Water Samples



- The chemical analysis of the water samples indicates that sulfate, along with a group of components, increases significantly with depth.
- The analysis of water samples suggests that the fluid inside the cavern is stratified and does not mix vertically, likely due to the density contrast between different temperature layers.

Literature Review

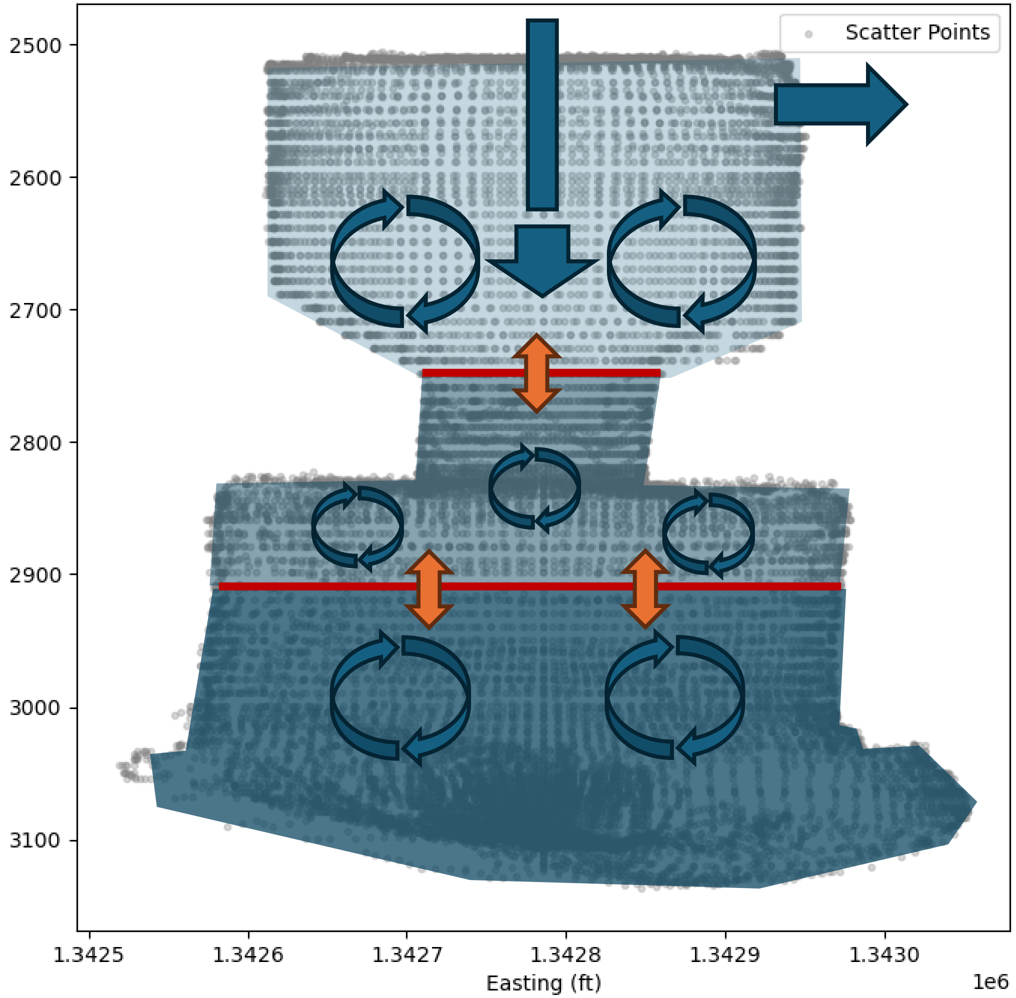




Schmitt, R. W. (1994). Double diffusion in oceanography. *Annual Review of Fluid Mechanics*, *26*(1), 255–285.

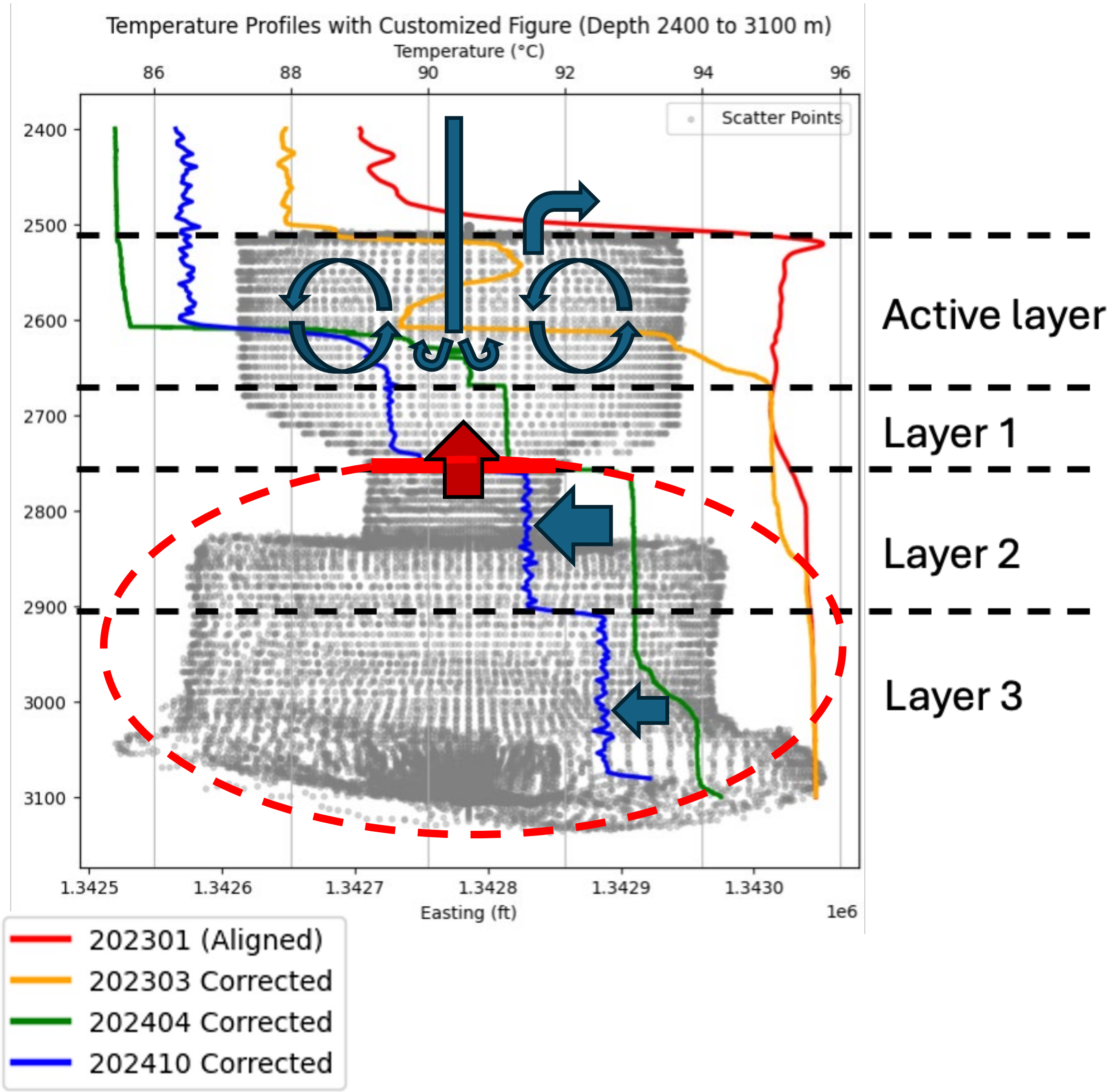
- Although the temperature layering structure had not been previously observed in any cavern environment, similar phenomena have been recorded in oceans for several decades. The layering structure in the ocean is predominantly attributable to significantly different diffusion coefficients of salinity and temperature, a matter that has been extensively studied in the field of oceanography.
- These temperature layering structures can be extremely stable and can remain constant for many years.

Energy Balance Calculation – Top Leakage Model



- If the leakage point is at the top of the cavern, due to the density contrast, the diffusion process across the temperature boundaries, both thermally and chemically, is likely to happen through molecular diffusion instead of natural convection.
- In this case, the heat loss of the lower cavern fluid must be conducted through thermal diffusion across the temperature boundaries.
- By calculating the thermal balance and energy exchange of the lower cavern, we can determine whether it is possible to have the leakage at the top portion of the cavern.

Energy Balance Calculation – Top Leakage Model



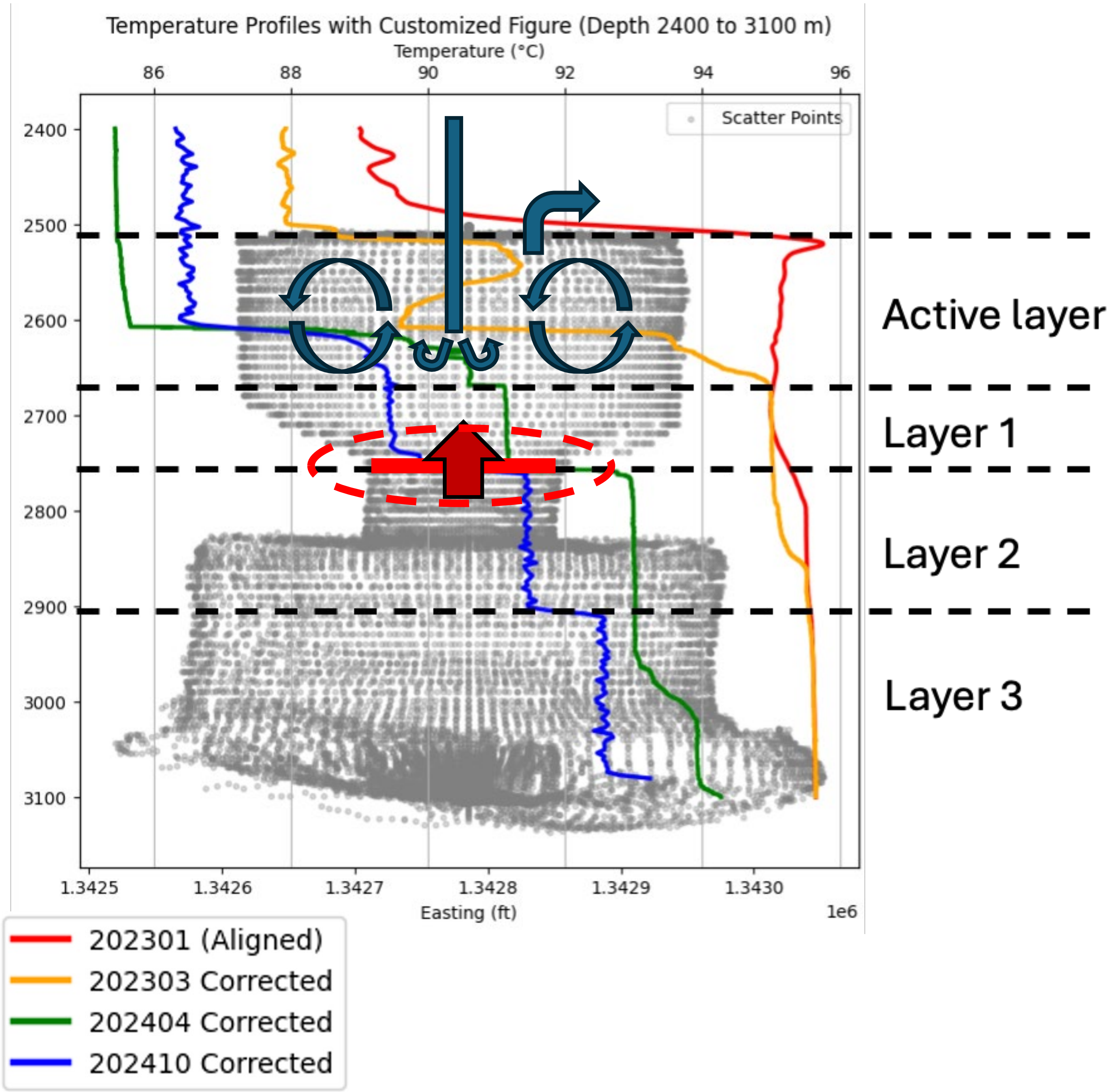
- We can focus our analysis between April 2024 and October 2024 due to their similar temperature layering structure.
- The volume-averaged temperature decrease in the lower cavern (layer 2 and 3) is about 1.1 °F, and the total volume below the temperature boundary at 2755’ is about 6 million barrels.
- The total energy loss in the lower cavern is:

$$E = \rho C_p V dT \sim 2{,}520{,}000 \text{ MJ}$$

Density ρ: 1200 kg/m3
Heat capacity C_p: 3600 J/K
Volume V: 6 Mbbl
Temperature change dT: 1.1 °F

Since the fluid in the cavern is cooler than the original geothermal energy, the energy loss must occur at the top of the lower cavern through the temperature boundary.

Top Leakage Model



- If leakage occurs at the top, due to insufficient forced circulation, heat can only transfer through diffusion at the temperature boundary between layers 1 and 2.
- Heat transfer rate through a boundary with constant temperature difference can be calculated by:

$$q = kS\frac{\Delta T}{L} = 548\ \mathrm{W}$$

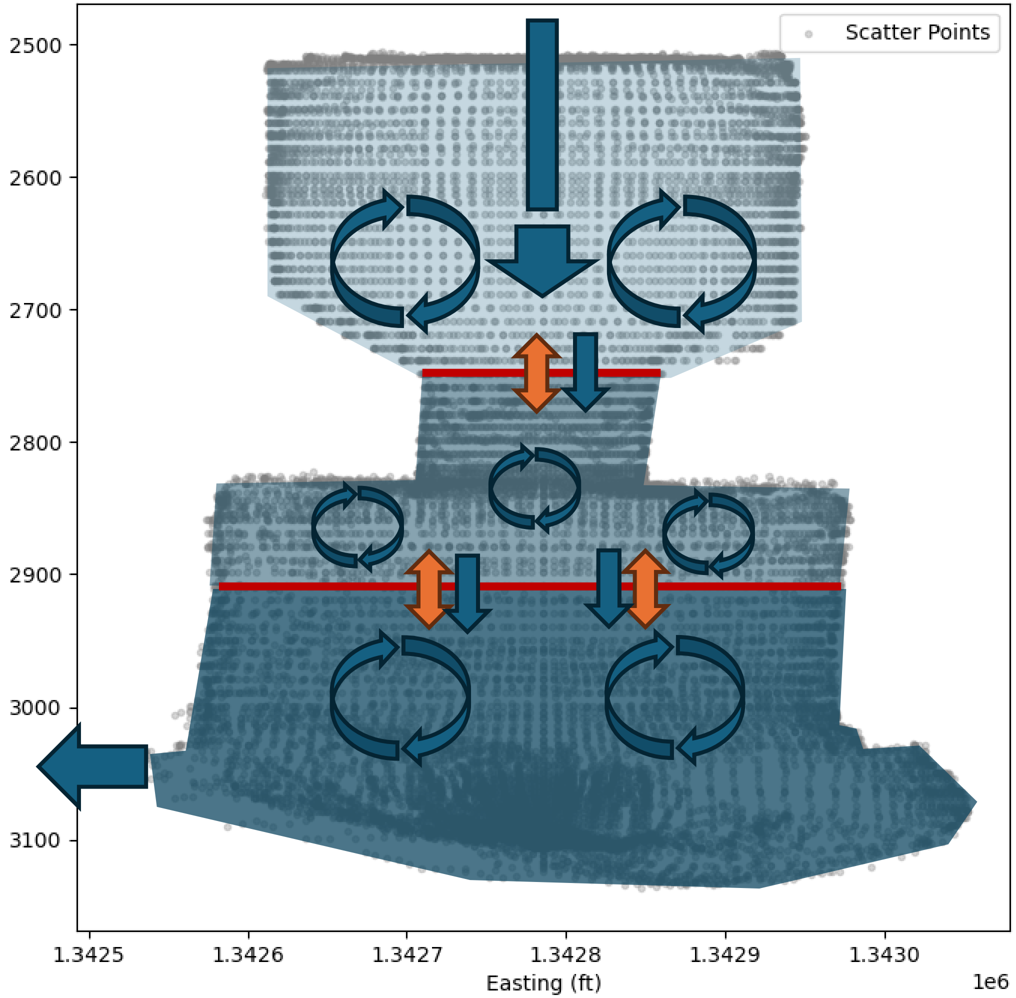
Where

Thermal conductivity k: 0.6 W/(mK)
Surface area S: 30000 ft^2 at 2755'
Temperature difference ΔT: 1.8 °F across the boundary
Boundary layer thickness L: 10 ft from DTS measurement

- From 04/2024 to 10/2024, the total heat transfer is
  548 W × 6 months = 8,500 MJ

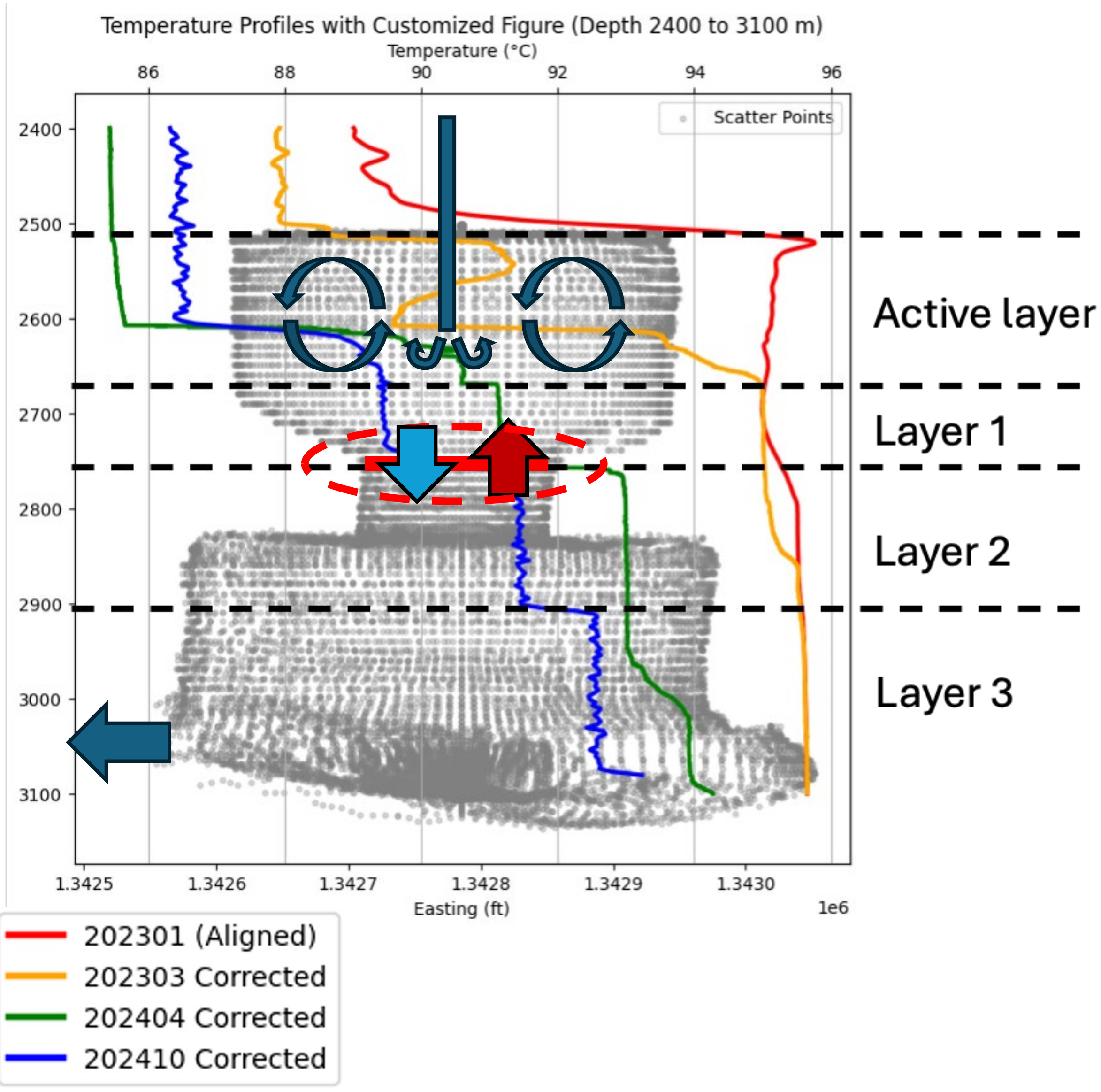
This accounts for only 0.3% of the total heat loss in the lower cavern. The energy balance shows nearly three orders of magnitude difference, making the top leakage model highly unlikely.

Energy Balance Calculation – Bottom Leakage Model



- On the other hand, if the leakage occurs at the bottom, to maintain mass balance, an amount of fluid equal to the leakage volume (and injection volume) is continuously forced to convect through the thermal boundary
- Theoretically, this should push the temperature boundary to a deeper depth over time. However, some temperature boundaries, especially the one at the bottom neck around 2740', are mainly controlled by the cavern geometry and heat and chemical transfer across the cavern wall. As a result, their depth can be maintained over time.

Bottom Leakage Model



- If leakage occurs at the bottom, heat transfer at the layer 1/2 boundary can occur through forced convection.
- From April to October 2024, around 2.8 Mbbl of salt water was injected. If the leakage occurs at the bottom, an equal volume of fluid must pass through the temperature boundary and be heated by 1.8 °F.
- The total energy loss of the lower cavern due to the forced convection is:

$$E = \rho C_p V dT \sim 1{,}920{,}000 \text{ MJ}$$

Density ρ: 1200 kg/m3
Heat capacity C_p: 3600 J/K
Volume V: 2.8 Mbbl
Temperature change dT: 1.8 °F

- This is less than the calculated total energy loss, but in the same order of magnitude.
- Energy balance can be achieved by shifting one of the temperature logs by 0.3 °F. Since the borehole gauge and temperature logging were not conducted simultaneously, there is a potential error of calibration that can explain the difference.

Conclusion

- Temperature logs and Distributed Temperature Sensing (DTS) measurements along the center line of the cavern confirm that a temperature layering structure is developed within the cavern as a result of the injection of cooler and slightly lower salinity water as compared to the cavern fluid.
- The salinity log and water samples indicate that the observed layering results from the density contrast attributed to variations in salinity.
- The chemical analysis of water samples suggests minimal vertical mixing occurring throughout the depth of the cavern.
- The calculation of energy balance necessitates that the leakage be positioned near the bottom of the cavern. This positioning enables forced convection across the temperature layers, facilitating the cooling of the lower portion of the cavern, as indicated by historical temperature measurements.