

# Analysis of a Comprehensive Suite of Microgravity Measurements Conducted over the South Y Brine Operation Site

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SMRI Spring 2017 Technical Conference  
23 – 26 April, 2017  
Albuquerque, New Mexico



24 April 2017



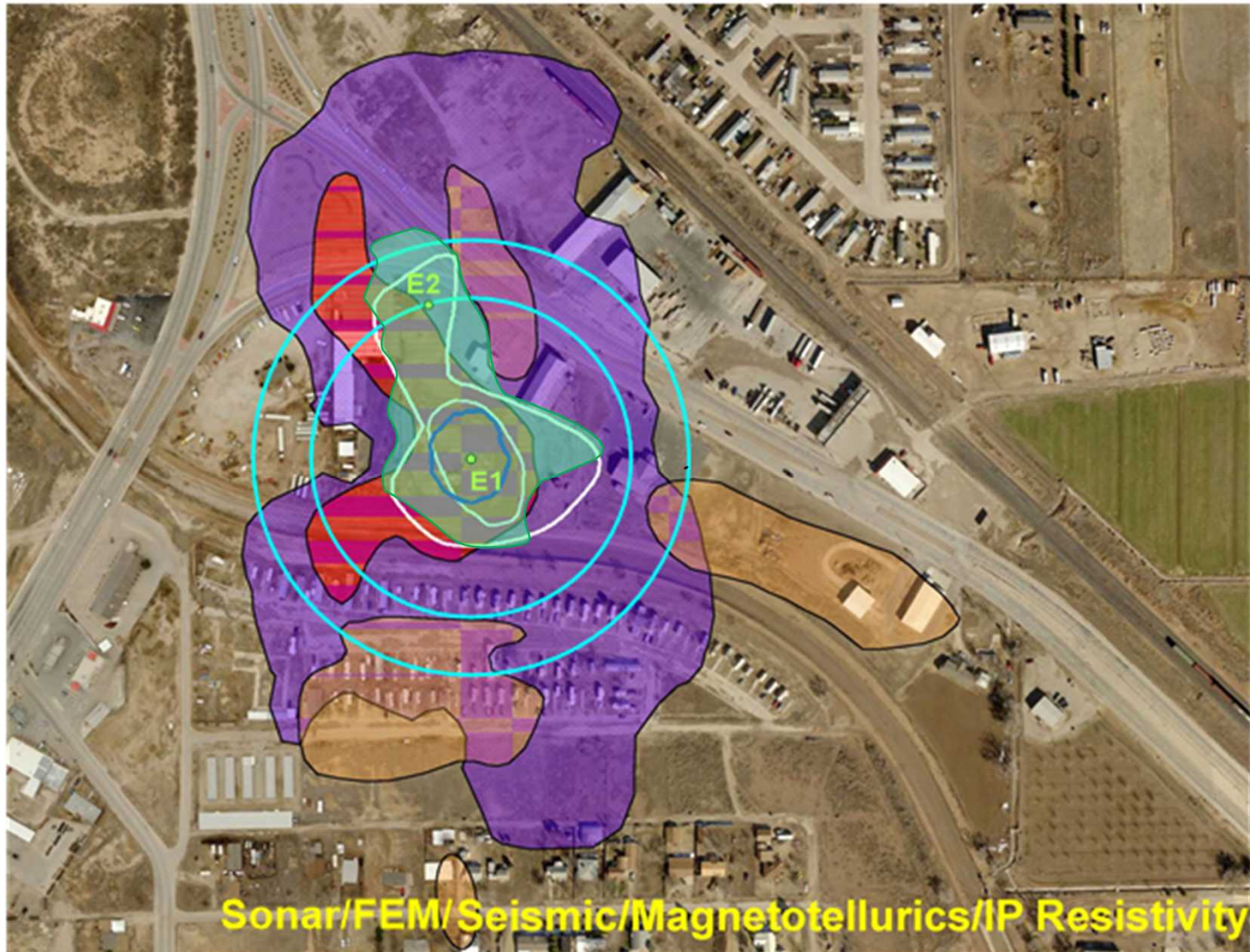
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# The South Y Site

- Similar in estimated brine production and depth to two NM brine caverns that collapsed
- Within the city limits of Carlsbad
- Eugenie 2 plugged in 1999; Eugenie 1 plugged in 2008



# Overview of Characterization Studies



# Microgravity Measurements

- Very high resolution gravity mapping method
- Highly sensitive to subsurface density changes
- Differing subsurface materials results in density changes
- Subsurface voids/cavities have most extreme density changes.
- These changes in density result in measurable anomalies in the Earth's gravitational field
- Microgravity is a geophysical method that measures these minute changes in the force of the Earth's gravity due to subsurface density variations (1 part in 1,000,000,000)

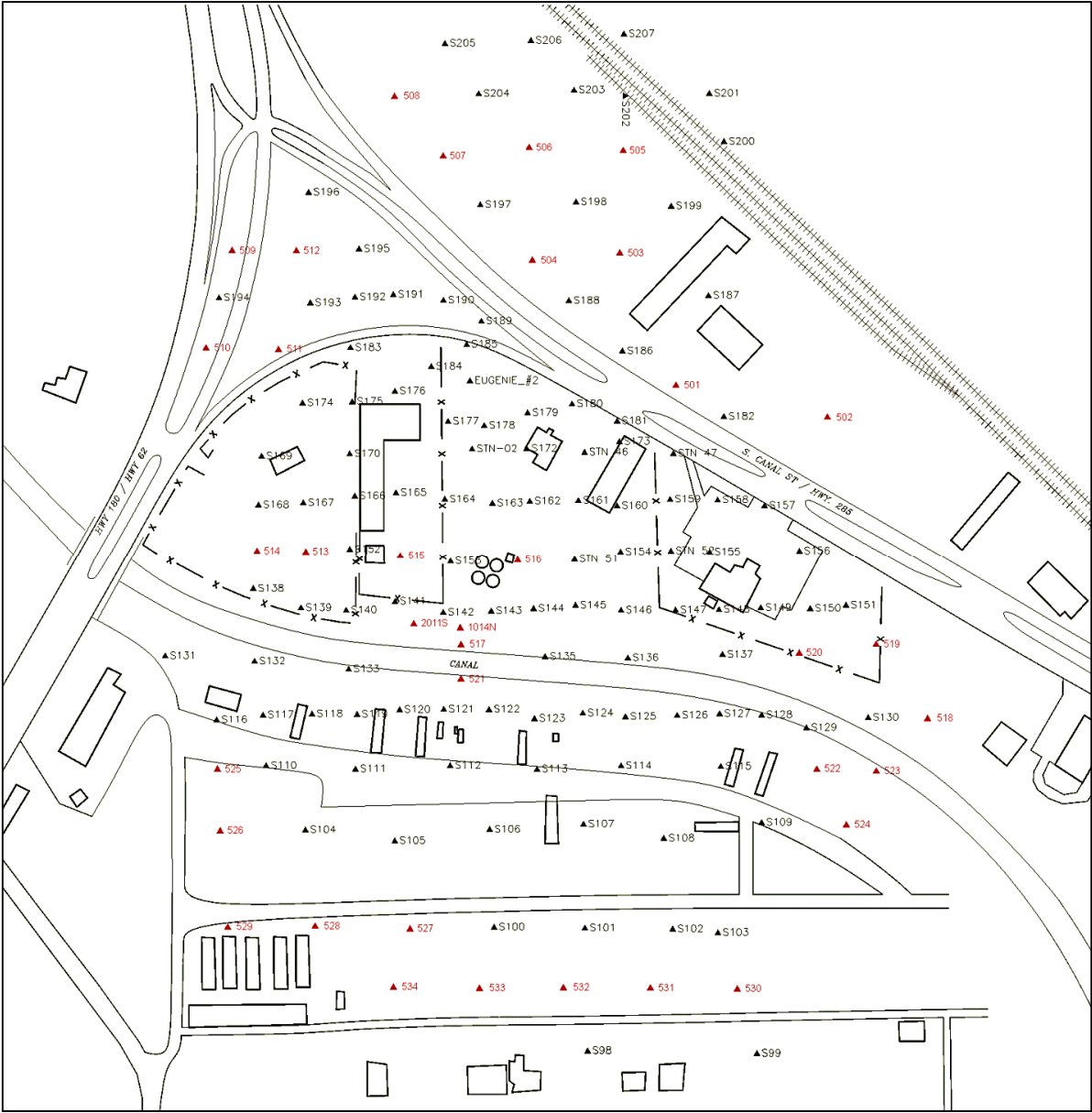
# Scintrex CG-5 Gravity Meter

- Sensor Type: Fused Quartz using electrostatic nulling
- Reading Resolution: 1 microGal
- Standard Deviation: < 5 microGal
- Residual Long-Term Drift (static): < 0.02 mGal/day
- Tares: Typically less than 5 microGals for shocks up to 20 G.
- Automated Corrections: Tide, Instrument Tilt, Temperature, Noisy Sample Filter, Seismic Noise Filter
- Compared to five absolute gravity base stations pre- and post- our South Y measurements



# Measurement Grid

- Based principally on furthest extent of possible cavern disturbance from first magnetotelluric survey
- ≈ 150 points
- High resolution GPS survey by Madron Surveying, Inc. (thanks to AMEC and the State of NM)
- Microgravity measurements performed August – September 2013



# Measurement Procedure

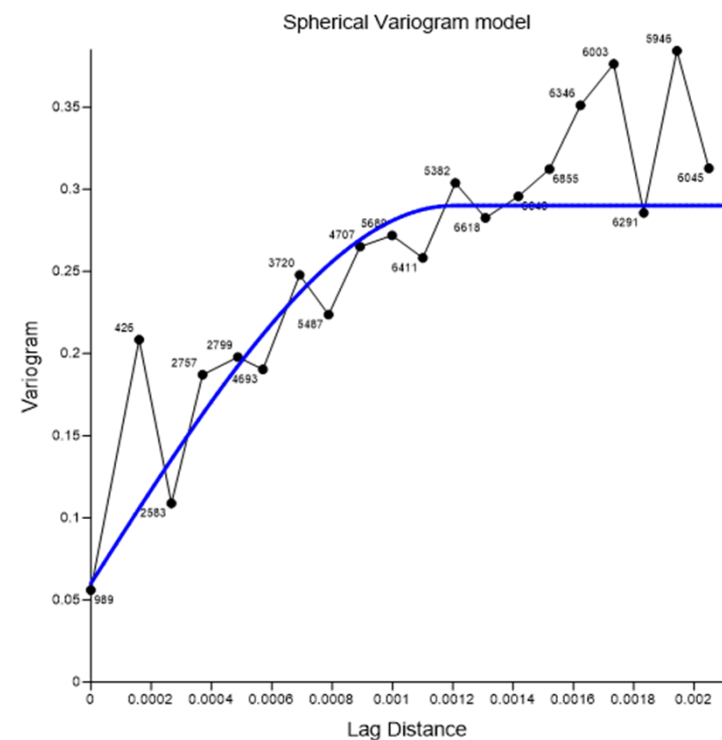
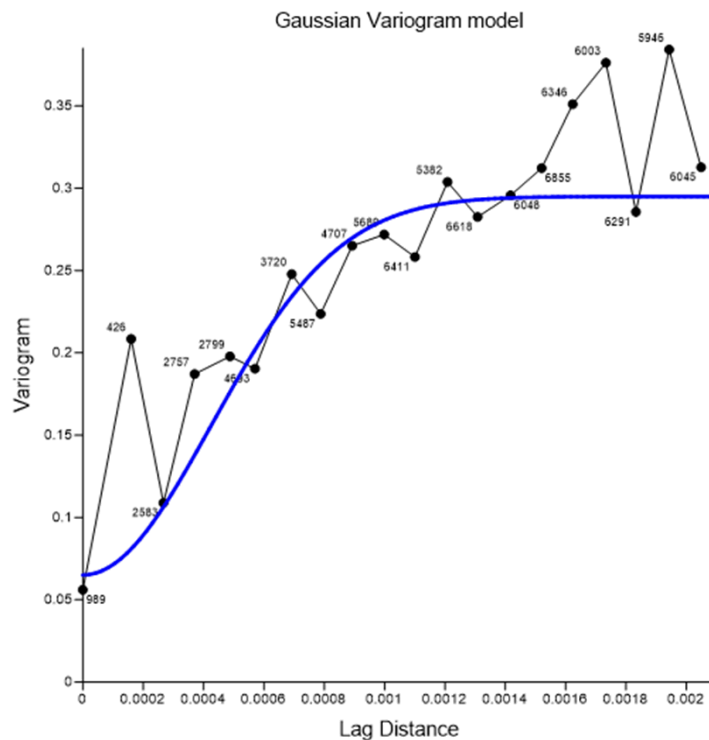
- Started and ended each day with base point gravity measurements in the SNL Soil and Sediment Laboratory
- A second base point at South Y site was checked at the beginning, every 1-3 hrs, and at the end of the day (change < 1  $\mu\text{Gal}$ )
- Gravity meter was carefully positioned and leveled at each measurement point, location coordinates entered
- At each location, three measurements were taken
  - During each measurement, the waveform and data were reviewed for noise and transients (wind, traffic, train, other disturbance). Measurement rejected if stnd. dev. > 5  $\mu\text{Gal}$
  - If the difference between any two measurements was greater than 5  $\mu\text{Gal}$ , additional repetitions of the measurements were performed

# Bouguer and Instrument Drift Corrections

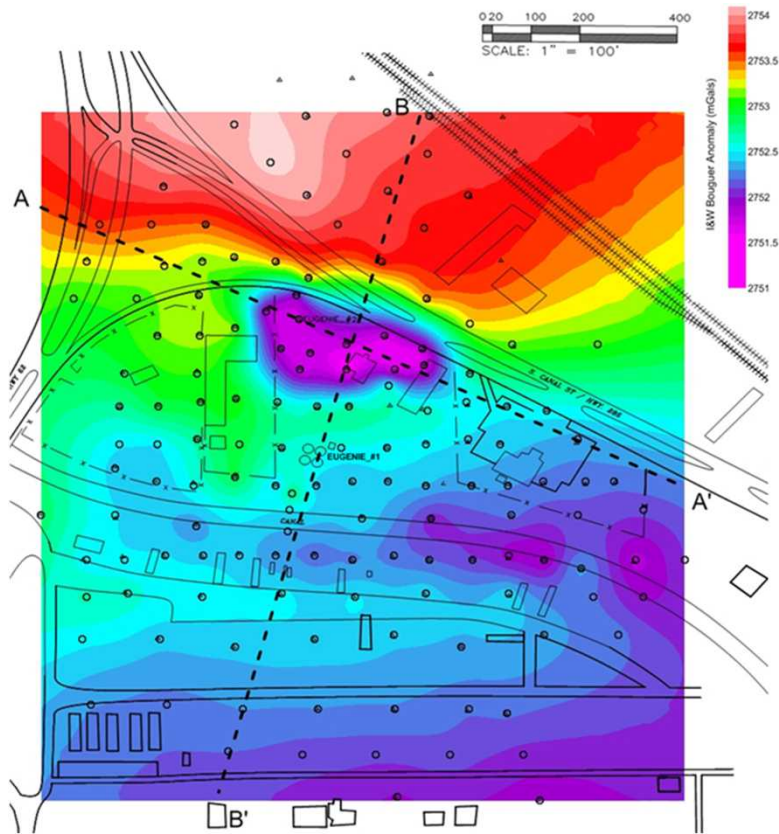
- CG-5 Automated Corrections: Tide, Instrument Tilt, Temperature, Noisy Sample Filter, Seismic Noise Filter
- Latitude correction is needed to account for the change in gravity with latitude
- Free-air correction corrects for the reduction in gravity with height above the reference geoid
- Bouguer correction accounts for the attraction of the rock mass between the station height and geoid that was ignored in the free air correction
- Instrument drift is largely due to stress relaxation in the elastic system

# Kriging

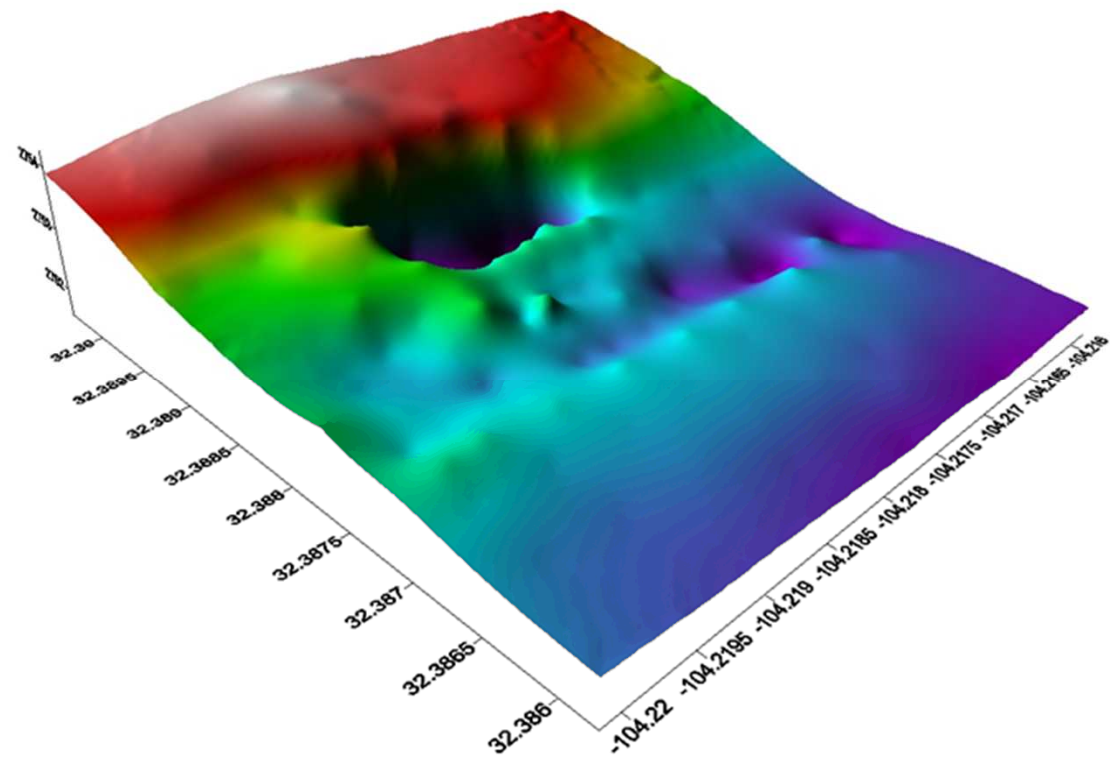
- Kriging is a geostatistical linear interpolation scheme used to generate the contour plots of the Bouguer anomalies
- A variogram is determined from the data and is used to compute the weights used in Kriging



# Contour Maps of the Bouguer Anomaly Over the South Y Site



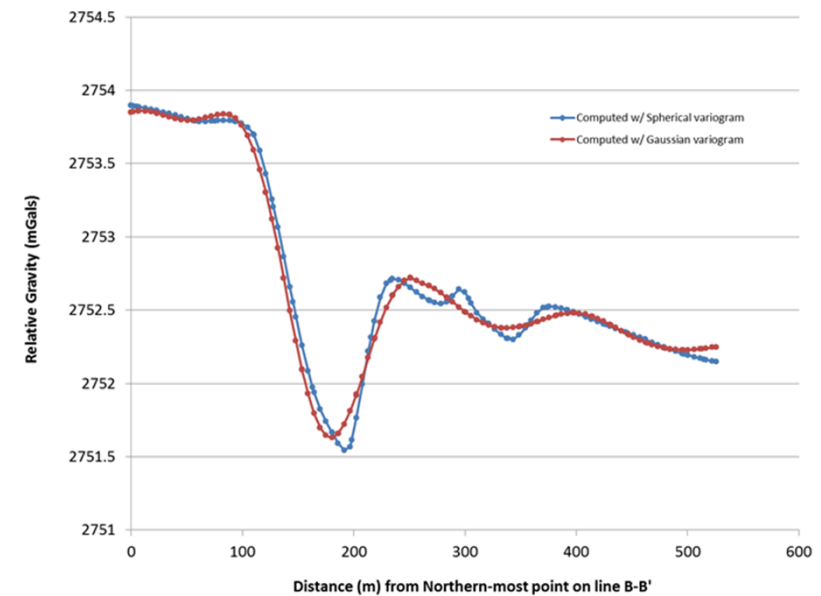
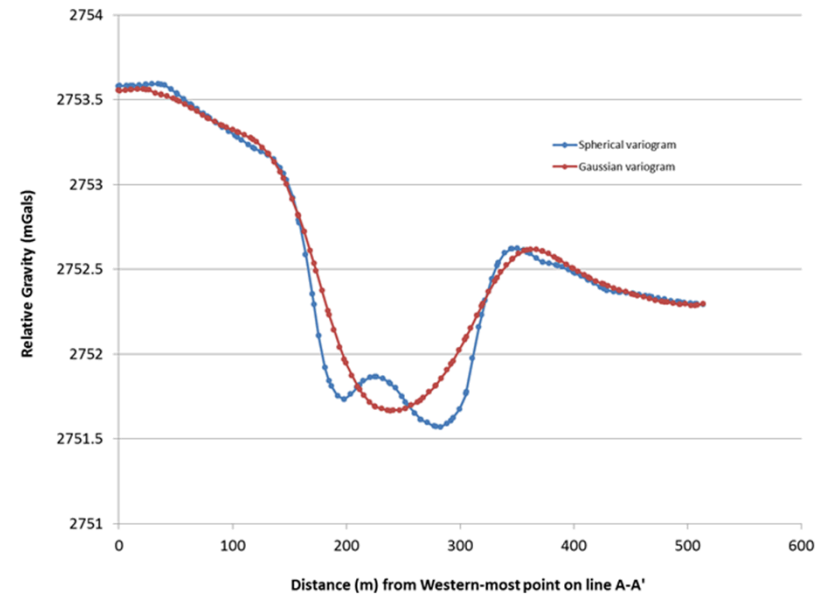
spherical variogram



A singular low gravity anomaly centered in the vicinity Eugenie 2 10

# Estimate of Cavity Depth and Volume

- Depth to center of mass ( $z$ ) can be obtained from a plot of the interpolated relative gravity along the major and minor axes of an ellipse bounding the anomaly
  - $z = 114$  m
  - Top of Salado = 140 m
- Use idealized ellipsoid subsurface body as the cavity model to estimate a bounding volume of the cavity
  - $V_{\text{Bouguer anomaly}} = 187,000 - 244,000 \text{ m}^3$
  - $V_{\text{prod. data}} = 145,000 - 190,000 \text{ m}^3$



# Comparison to AMEC Void (Plan View)



# Why a Cavern in the Vicinity of Eugenie 2

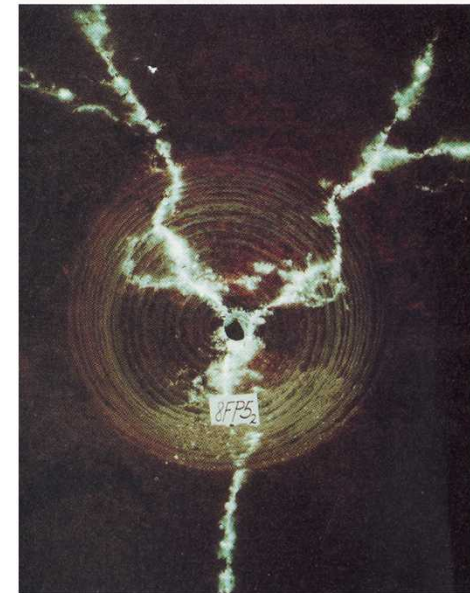
- Eugenie 2 was drilled one year after Eugenie 1
- Eugenie 2 hydraulically fractured (1979) in the lower section of salt between 576 ft (175 m) and 592 ft (180 m) to connect to Eugenie 1
- Freshwater injection in the well dipole was conducted in Eugenie 2 for close to 20 years (1979 – 1999)
  - Accounting for over 75% of the brine production performed
- The hydraulic connection was
  - Difficult to make
  - Required excess wellhead pressure during freshwater injection into Eugenie 2 to produce brine out of Eugenie 1
  - Did not open up further with time

# Why Eugenie 2 (continued)

- Hydraulic fractures in salt are not preferentially oriented
  - Propagate in any/all directions
  - Bifurcate quickly
  - Produce more surface area with increased permeability
- Restricted flow led to longer residence time for fresh or under-saturated water
- Eugenie 1 was primarily an abstraction well for saturated brine
  - Sonar surveys from within Eugenie 1 were unable to discern a cavity that accounts for more than about 5% of the estimated dissolved salt



FRACTURE PATTERNS



# Some Thoughts on Our Shallow Depth Prediction

- No provisions were made to preserve a layer of salt in the roof
- No provisions were made to control the cavern growth in any direction, including laterally
- We expect an inverted cone-shaped cavity, most likely having flaring at the top
- Produces a wide, unsupported roof beam which could be susceptible to collapse
- Eugenie 2 failed a mechanical integrity test which may indicate well damage due to roof rock failure
- We used simple model approximations which produce only very rough estimates of cavity characteristics
  - One would have to solve the inverse problem for more accurate and definitive determinations

# Conclusions

- The Bouguer anomaly indicates a dramatic and precipitous decrease in the gravity about well Eugenie 2
- Indicates this is the probable location of the solution cavity attributable to brine production
- This hypothesis is supported by historical freshwater injection and hydraulic fracturing activities

# Acknowledgements

This work was supported by the New Mexico Small Business Assistance (NMSBA) Program. The companies that partook in this leverage project are Custom Farming, Calvani Farms, Tidwell Farm, and Coley Burgess. AMEC and the State of New Mexico (NMOCD) provided assistance in the GPS surveying. Wes DeYonge and Phil Finley of RESPEC performed the onsite data collection. Kris Kuhlman of Sandia National Laboratories helped with data presentation. We thank these people and companies for facilitating these additional scientific and/or engineering studies concerning the South Y brine site.