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IN-SITU STRESS TESTING
CORE HOLE ZEV-CH-03-23

WILLOW ROCK - DAWN ROAD PROJECT SITE, ROSAMOND CALIFORNIA

Prepared for:

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1 INTRODUCTION

In September 2023, Agapito Associates, Inc. (Agapito) performed downhole in-situ stress testing for Lane Power and Energy Solutions at the Willow Rock – Dawn Road Project site near Rosamond, California. The purpose of the work was to measure the in-situ stress field within the quartz monzonite rock at target cavern construction horizons. A total of four tests were attempted in the quartz monzonite. Two of the tests were unsuccessful, owing to one oversized pilot hole and one attempt, in which the IST tool did not set into the pilot hole correctly; two of the tests were successful and provided usable stress relief data.

Testing was conducted in core hole ZEV-CH-03-23 between the depths of 2,027.4 and 2,037.4 feet (ft). The overcore testing was conducted by Agapito in cooperation with Crux Subsurface, Inc. drilling personnel, who performed the core drilling for all the stress tests.

The measurements were obtained using the in-situ stress measurement tool (IST2D) and downhole technique developed by Sigra, Pty. (Sigra) of Brisbane, Australia. The IST technique measures the rock stresses in the plane perpendicular to the core hole, and because core holes are generally vertical, this technique provides the principal stresses in the horizontal plane at the testing depth.

Rock samples from the two successful overcores were tested in Agapito's laboratory in Grand Junction, Colorado, to determine the unconfined compressive strength (UCS), Young's modulus € (in the axial direction), and Poisson's ratio (*v*). The horizontal stresses were determined based on the elastic properties and the measured changes in hole diameter resulting from stress relief during overcoring.

The effects of horizontal stress on structural stability have been identified as potentially important design factors at the project site. The orientation, magnitude, and ratio of the maximum and minimum components of the pre-mining stress field, along with the intact rock mass strength and jointing characteristics, determine the extent of the impacts of horizontal stress.

2 TESTING METHODOLOGY

The IST2D tool is a pilot hole overcoring device that automatically measures the deformation across the diameter of a 25 to 27 mm pilot hole at six locations during overcoring. It is used with the Boart Longyear HQ wireline coring system. The tool's orientation is determined by triaxial magnetometers and accelerometers which are read when the tool is locked in the pilot hole and the drill rods are withdrawn 6 meters (m) above the tool, so as to free it from the effects of magnetic field.

The overcore samples are tested to determine the core's mechanical properties relating to Young's Moduli and Poisson's Ratios as well as uniaxial compressive strength. The analysis is in terms of axisymmetric anisotropic elastic, though not necessarily linearly elastic behavior. The derivation of core properties is described by Gray, Zhao, and Liu (2018).

There is one solution for six diameter change measurements, six solutions for five diameter change measurements, fifteen solutions for four diameter change measurements, and twenty solutions for three diameter change measurements. Thus, there exists forty-two potential solutions. The best solution is one that uses the most diameter change measurements, provided the traces of diameter changes are consistent throughout the overcore process.

The solution to the sets of equations describing the stress and deformation is arrived at by using a least squares procedure. A value of the RMS (Root Mean Square) error between the theoretical best fit and actual measurements is presented with each solution.

3 FIELD TESTING PROGRAM

Testing was conducted using a specially modified set of wireline coring components (setting tools) and the IST stress tool. The setting tools were brought to the site in conjunction with Agapito's field work and assembled immediately prior to testing. Testing was conducted by one Agapito employee with the assistance of the drillers and other project personnel.

The data measured by the IST and used for analysis consisted of the measurement time and voltages for the six measurement pins, three magnetometers, and three inclinometer accelerometers. The datalogger contained within the IST was configured to record the hole diameter at 4-second intervals and orientation data at 20-second intervals for each overcore test. The response of the stress tool measurement pins was calibrated prior to the field program to determine the (linear) relationship between voltage and diameter. The pin response was checked periodically to verify proper operation. The magnetometers and accelerometers determined the orientation of the tool with respect to Magnetic North and the tool inclination within the hole. Each overcore test was performed in the following sequence, as shown in Figure 1.

1. After coring proceeded to a pre-determined depth (Figure 1 [a]), the core was pulled and a special counterbore assembly was lowered down the hole by wireline (Figure 1 [b]). The counterbore bit grinds any core stump left at the bottom of the hole and makes a counterbore to center the 25-mm-diameter pilot hole within the HQ (100-mm) bore. The counterbore bit is locked into the outer barrel such that thrust is transmitted to the bit, and an adapter, installed in the drill string, permits the counterbore bit to rotate with the rods.

2. Once the counterbore was drilled, the counterbore assembly was removed from the hole by wireline, and the pilot hole assembly (thruster) was lowered down the hole (Figure 1 [c]). Thrust on the pilot hole bit is provided by a water-pressure-actuated piston within the assembly, and rotation is transmitted to the assembly through the special adapter installed in Step 1. Thus, the rods rotate during drilling of the pilot hole, but do not provide thrust. Completion of the 500-mm-deep pilot hole is accompanied by a drop in water pressure as the piston advances past water-bypass ports at the end of its stroke.
3. Upon completion of the pilot hole, the hole was flushed for several minutes to clear cuttings. The thruster assembly was then removed, and the IST tool was carefully lowered down the hole by wireline (Figure 1 [d]). The IST was guided into the pilot hole by the shape of the counterbore, and wedges on the end of the IST secured it within the pilot hole as the downward load of hydraulic pressure acted on the IST. The launching tool was then pulled out of the hole, and the inner core barrel lowered down the hole by wireline.
4. After the inner core barrel latched, the rods were pulled up 20 ft so that magnetometers within the IST could stabilize without magnetic interference from the metallic rods

(Figure 1 [e]). The rods were held in this position for a minimum of 5 minutes to ensure that a satisfactory data sample was recorded.

5. With the inner barrel latched in and directional orientation assured, overcoring of the IST proceeded (Figures 1 [f] and 1 [g]). Rotation and feed rate were somewhat lower than in normal coring operations to minimize vibration as the IST was overcored.
6. At the completion of the overcore run, the inner barrel was pulled out of the hole by wireline, and with it, the core and IST. The core was extracted from the inner barrel into a core tray, and the core around the IST pins was photographed. Finally, the IST was removed from the core and the battery powering the IST was removed. The IST was then connected to a laptop computer and the pin, magnetometer, and accelerometer data were downloaded and reviewed (Figure 1 [h]). Depending on the expected competence of the strata in the next core run, the process was immediately repeated, or further coring was undertaken to locate a suitable test horizon.

Stress testing in core hole ZEV-CH-03-23 began on September 4, 2023, at a depth of 2027.4 ft. A total of four tests were attempted in the core hole to a depth of 2037.0 ft. A summary of the overcoring test attempts is given in Table 1. Two tests were successful: overcores 0052-70 and 0054-70. When possible, the recovered cores for each test were photographed to document rock type and condition, particularly cores that contained fractures which may have influenced the overcore data. Photographs of the recovered core for the two successful tests, including the relative location of the measurement pins are shown in Figures 2 and 3.

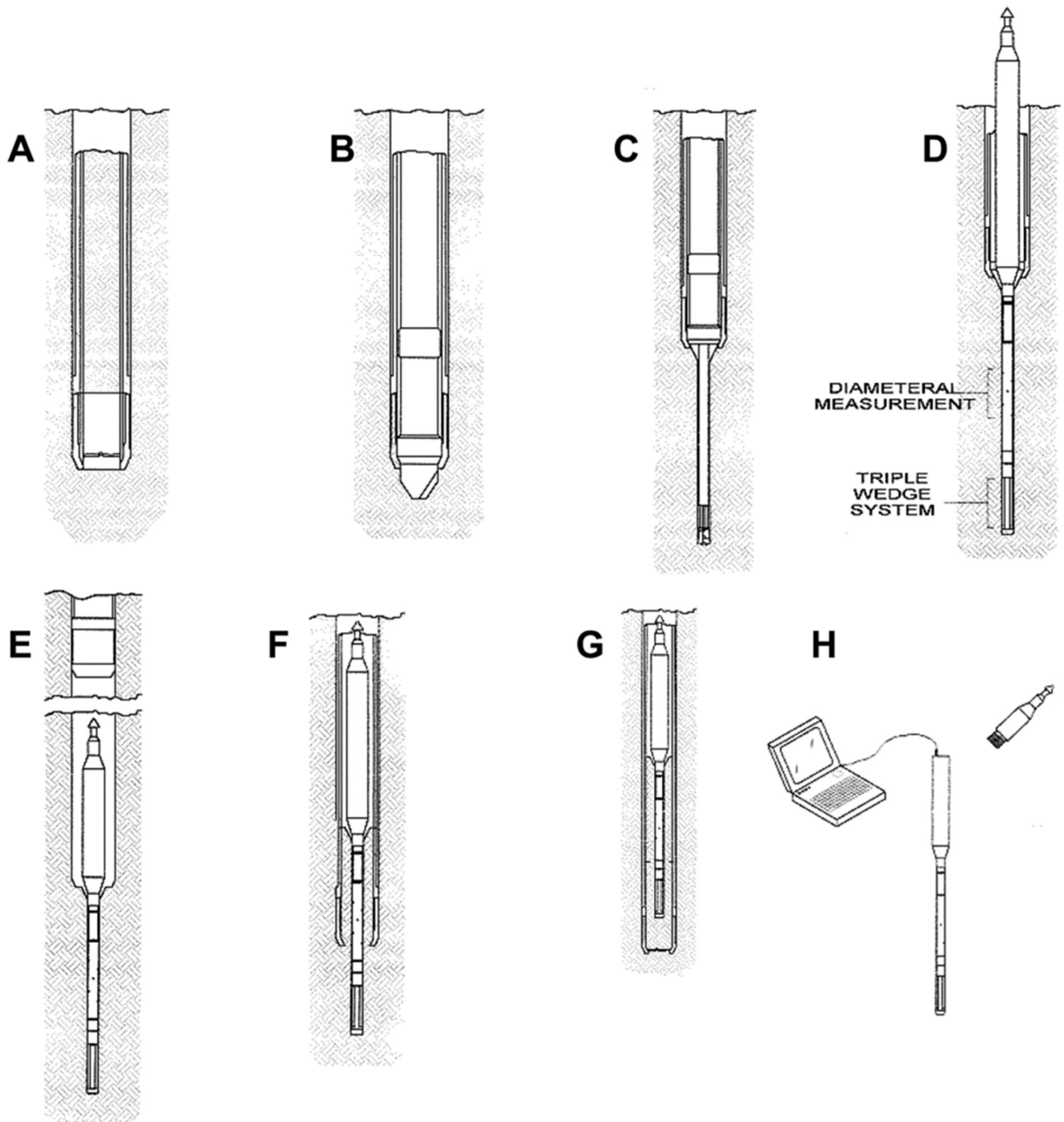


Figure 1. IST Field Stress Testing Sequence

Table 1. Summary of IST Test Attempts

Test Number	Overcore Number	Test Date	Successful Unsuccessful	Rock Condition	Depth (ft)
1	0036-076	9/5/2023	Unsuccessful	Solid	2027.4
2	0052-070	9/5/2023	Successful	Solid	2030.0
3	0054-070	9/5/2023	Successful	Solid	2033.4
4	0056-070	9/6/2023	Unsuccessful	Solid	2037.0

Figure 2. Photograph of Recovered Core from Overcore 0052-070

Figure 3. Photograph of Recovered Core from Overcore 0054-070

4 Physical Property Testing

4.1 Physical Property Testing

Rock samples from both successful overcores were tested in Agapito's laboratory in Grand Junction, Colorado, to determine unconfined compressive strength (UCS), Young's modulus, and Poisson's ratio (in the axial direction).

4.2 Axial Testing

A summary of the laboratory test results is included in the Appendix following this report. The Appendix also contains the stress-strain plots for each test. Tests Run-0052-070 and Run-0054-070 correspond to overcores 0052-070 and 0054-070, respectively. The calculated values of Young's modulus (E) were 10.38×10^6 psi for overcore 0052-070, and 9.31×10^6 psi for overcore 0054-070. The Poisson's ratio was 0.32 for overcore 0052-070 and 0.19 for overcore 0054-070. The UCS was 26,468 psi for overcore 0052-070 and 12.696 psi for overcore 0054-070.

4.3 Radial Testing

Ideally, the value of E should be determined in the plane (generally horizontal) of the measurement direction, perpendicular to the borehole axis. However, because of the core size and geometry, samples used for conventional compression tests in the laboratory must be loaded along the borehole (vertical) axis. Additionally, the granitic rock being tested is presumed to be isotropic, with similar elastic properties in directions parallel and perpendicular to the plane of testing. Therefore, it was determined that radial testing was unnecessary for this project.

5 Calculation of Horizontal Stresses

Plots of the pin data versus time were examined to determine the change in diameter that occurred during overcoring. In general, the diameter decreases slightly just before overcoring due to a stress concentration ahead of the core bit, then increases significantly and stabilizes as the bit relieves the horizontal stress acting on the core. The diametral change is calculated as the difference between the diameter measured just before the stress concentration decreases and the stable diameter just after the stress relief increases. Because the pins are offset, the overcore responses for the six pins occur in sequence at different times, depending upon the bit advance speed. Most of the pin traces for the successful tests showed normal response during the approximately 5-minute interval, while the core bit drilled past the pins, and could be used to calculate the stresses. The data for some pins were inconsistent and were excluded from the calculations.

Periodically, dummy runs were conducted on the surface to ensure that the tool, communication box, and laptop computer were all functioning properly. During dummy runs, data was collected while an aluminum standard cylinder was fitted over the pin zone. The data was downloaded and reviewed to confirm each pin was recording the correct diameter. In this manner, typical problems such as sticking pins and poor battery connections could be identified and corrected before lowering the IST tool into the pilot hole and attempting the actual overcore test.

The elastic properties and changes in the pilot hole diameter during overcoring are used to calculate the rock stresses in the plane (horizontal) normal to the borehole axis. The stresses can be determined using data from a minimum of three pins; however, the additional data obtained using all six pins provides a measure of redundancy and permits the evaluation of the relative accuracy of the measurement. The stress calculation software, provided by Sigra, evaluates each combination of three or more pins and calculates an error value, or goodness-of-fit measure, for those combinations with four or more pins. An exact solution can be determined for any three-pin combination; however, a least-squares curve-fit technique is required to solve the combinations involving four or more pins.

The analysis software determines values for the mean effective stress (σ_m) and the deviatoric stress (σ_d). The major (σ_1) and minor (σ_2) principal stresses in the horizontal plane are calculated as follows:

$$\sigma_1 = \sigma_m + \sigma_d \quad \text{(Eqn. 1)}$$

$$\sigma_2 = \sigma_m - \sigma_d \quad \text{(Eqn. 2)}$$

For gravitational loading, the vertical stress (σ_v) is based on the density of the rock and the depth of the test. The stress gradient of the overburden material was calculated assuming a specific gravity of 2.69, or 1.17 psi-per-foot of depth (psi/ft). Assuming elasticity and that the rock is laterally constrained so there is no allowable strain in the horizontal plane, the lithostatic stress, or horizontal stress due to self-loading (σ_{hsw}) caused by the Poisson's effect, is:

$$\sigma_{hsw} = \sigma_v \times \frac{v}{(1-v)} \quad \text{(Eqn. 3)}$$

Recent research (Mark and Gadde 2008) into the expected levels of horizontal stress worldwide has shown the classic assumption of passive pressure (σ_{hsw}) may not be applicable and horizontal stresses are typically much higher. It was found that horizontal stresses varied linearly with depth and rock stiffness, and a constant excess stress was present, regardless of depth.

Figures 4 and 5 show plots of the best-fit stress calculations for each successful test (overcore runs 0052-070 and 0054-070). The data is considered valid and provides clear indications of stress relief and accurate relief displacements. The least-squares curve fits are generally good, and the stress orientations are consistent. Overcore 0052-070 was slightly biaxial, though overcore 0054-070 showed minimum and maximum horizontal stresses with similar magnitudes. This low biaxiality in the two overcore results means further testing may be required to determine a more accurate bearing of maximum horizontal stress at depth at the project site. The orientation of the instrument and the calculated principal stresses relative to Magnetic North are determined using the magnetometer and inclinometer data recorded by the IST. The data obtained during the measurement periods when the rods were raised were stable and are considered valid.

Using the axial modulus values derived from the laboratory tests, the average maximum horizontal stress (σ_1) is 1.2 times the minimum horizontal stress (σ_3) and 1.62 times the estimated vertical stress (σ_v). Thus, the ratio between the major maximum horizontal stress and vertical stress indicates a reasonably high horizontal stress regime. The successful tests were located at similar depths, so it was not possible to predict the variation of stress with depth. However, since the increase in vertical stress is typically linear, vertical stress levels should be expected to increase with depth. The horizontal stresses are presumed to be caused by the tectonic stresses related to the San Andreas Fault system and, therefore, not a function of the depth.

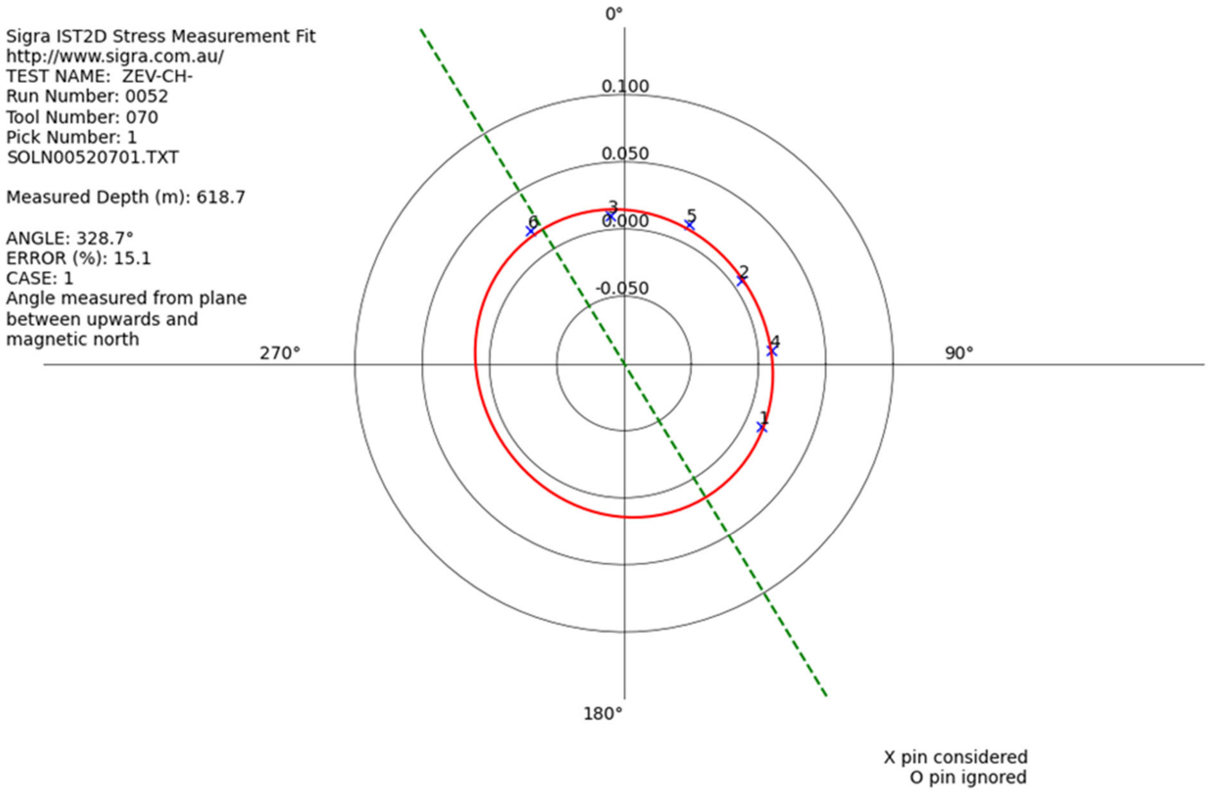


Figure 4. Best-Fit Stress Calculation for Overcore 0052-070

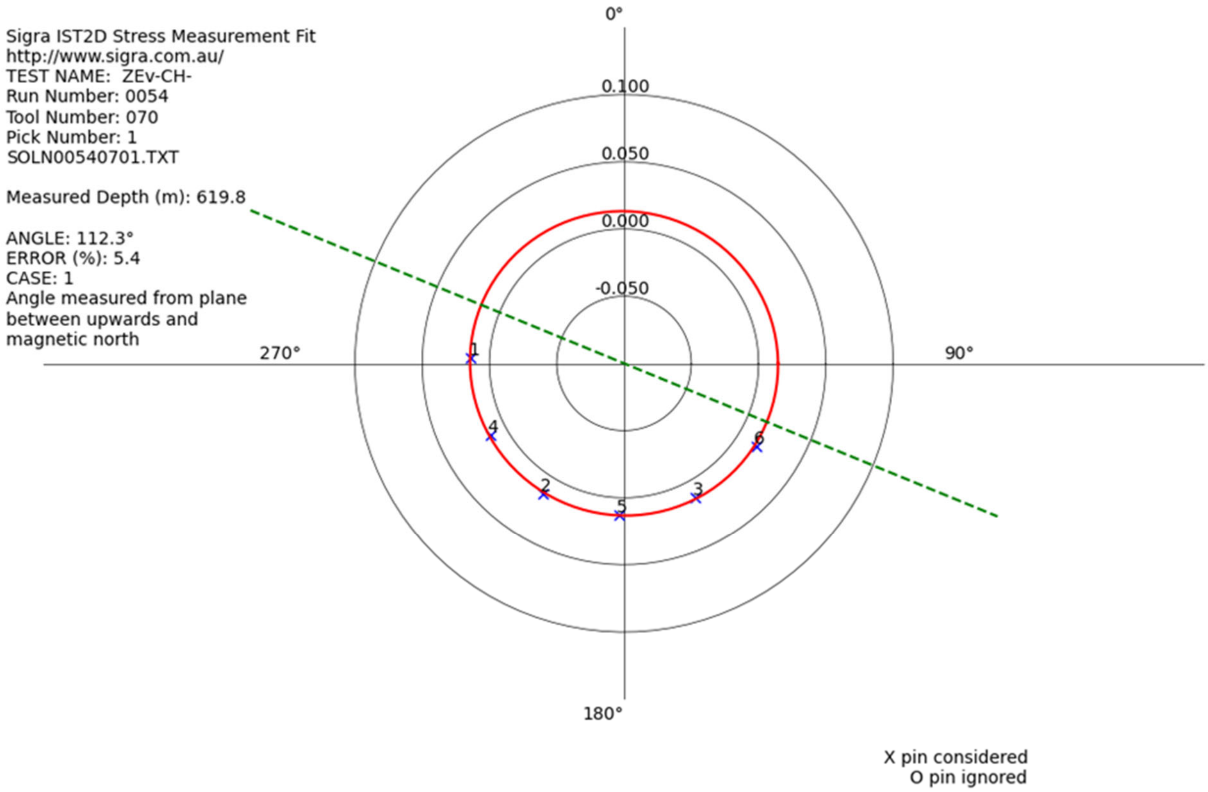


Figure 5. Best-Fit Stress Calculation for Overcore 0054-070

Table 2. Calculated Principal Stresses in ZEV-CH-03-23

Hole Name	ZEV-CH-03-23	
Overcore Number	**0052-070**	**0054-070**
Date Tested	9/5/2022	9/5/2022
Depth (ft)	2,030.0	2,033.4
Unconfined Compresive Strength (psi)	26,468	12,696
Young's Modulus ($\times 10^6$ psi)†	10.38	9.31
Poisson's Ratio †	0.32	0.19
Estimated Vertical Stress (psi)	2,368	2,373
Self-loading Horizontal Stress σ_{hsw} (psi)	1,114	557
Maximum Horizontal Stress σ_1 (psi)	4,098.8	3,611
Minimum Horizontal Stress σ_3 (psi)	3,115.4	3,446
σ_1:σ_3 Ratio	1.3	1.0
True Bearing of Maximum Horizontal Stress	340.38°	303.98°
Maximum Horizontal Strain ϵ_1 (microstrain)	226.8	269.8
Minimum Horizontal Strain ϵ_2 (microstrain)	101.6	248.6

psi = pounds per square inch; ° = degree; E = East
† Tangent Calculation Method
magnetic declination of 11.68° E

6 Discussion and Conclusions

The testing program resulted in two successful tests out of four attempts. The first unsuccessful attempt was caused by an unforeseen incompatibility between the rock and the type of drill bit used to drill the pilot hole for the tool. This caused the pilot hole diameter to be oversized and outside of the measurable range of the tool for run 0036-076. The cause of the second failed attempt was unclear. Upon retrieval of the core run containing the deployed tool for test 0056-070, the tool was set approximately 4 inches into the pilot hole instead of the ~16 inches required for a proper deployment. The tool's pins were not placed inside the pilot hole in the rock and, therefore, recorded no usable data. The successful overcores generally produced consistent results with respect to stress levels and orientation. The variability between stress magnitudes is attributed to the typical variations associated with geological materials and environments.

The calculated magnitudes and orientation of the stresses are considered reasonable and indicate the tectonic strain of the San Andreas Fault system influences the in-situ horizontal stress of the project area.

The average maximum horizontal stress was 3,855.1 psi and the average minimum stress was 3,280.1 psi. Of the two successful tests run, 0052-070 provided an azimuth of the maximum horizontal stress of 340.4° (clockwise from North). Run 0054-070 provided maximum and minimum horizontal stresses of similar magnitude, causing lower confidence in the azimuthal data for run 0054-070.

7 References

Bickel, D. L. (1993), "Rock Stress Determinations from Overcoring—An Overview," U.S. Bureau of Mines Bulletin 694, 146 pp.

Gray, I. (2000), "The Measurement and Interpretation of Stress," *Bowen Basin Symposium on Seam Gas*, pp. 321–324.

Mark, C. and M. Gadde (2008), "Global Trends in Coal Mine Horizontal Stress Measurements," Proceedings of the *27th International Conference on Ground Control in Mining*, Morgantown, WV, July 29–31, pp. 319–331.

APPENDIX A

LABORATORY COMPRESSION TESTING

Table A-1. Uniaxial Compressive Strength Test Results

Specimen No.	Hole ID	Depth From (ft)	Depth To (ft)	Rock Type	Weight (oz)	Average Diameter (inch)	Axial Length (inch)	Density (pcf)	Failure Load (lb)	UCS (psi)	Young's Modulus† ($\times 10^6$ psi)	Poisson's Ratio†	Young's Modulus‡ ($\times 10^6$ psi)	Poisson's Ratio‡
Run-0052-070	ZEV-CH-03-23	2026.30	2026.75	Granite - IST Test at 2030.0 ft	37.10	2.39	5.29	168	118,940	26,468	10.38	0.32	10.64	0.17
Run-0054-070	ZEV-CH-03-23	2036.30	2036.75	Granite - IST Test at 2033.4 ft	38.37	2.40	5.49	168	57,195	12,696	9.31	0.19	8.94	0.05

†Tangent calculation method.

‡Secant calculation method.

Run-0052-070—Before

Run-0052-070—After

Run-0054-070—Before

Run-0054-070—After

Figure A-1. Before and After Photographs of Uniaxial Compressive Strength Test Specimens

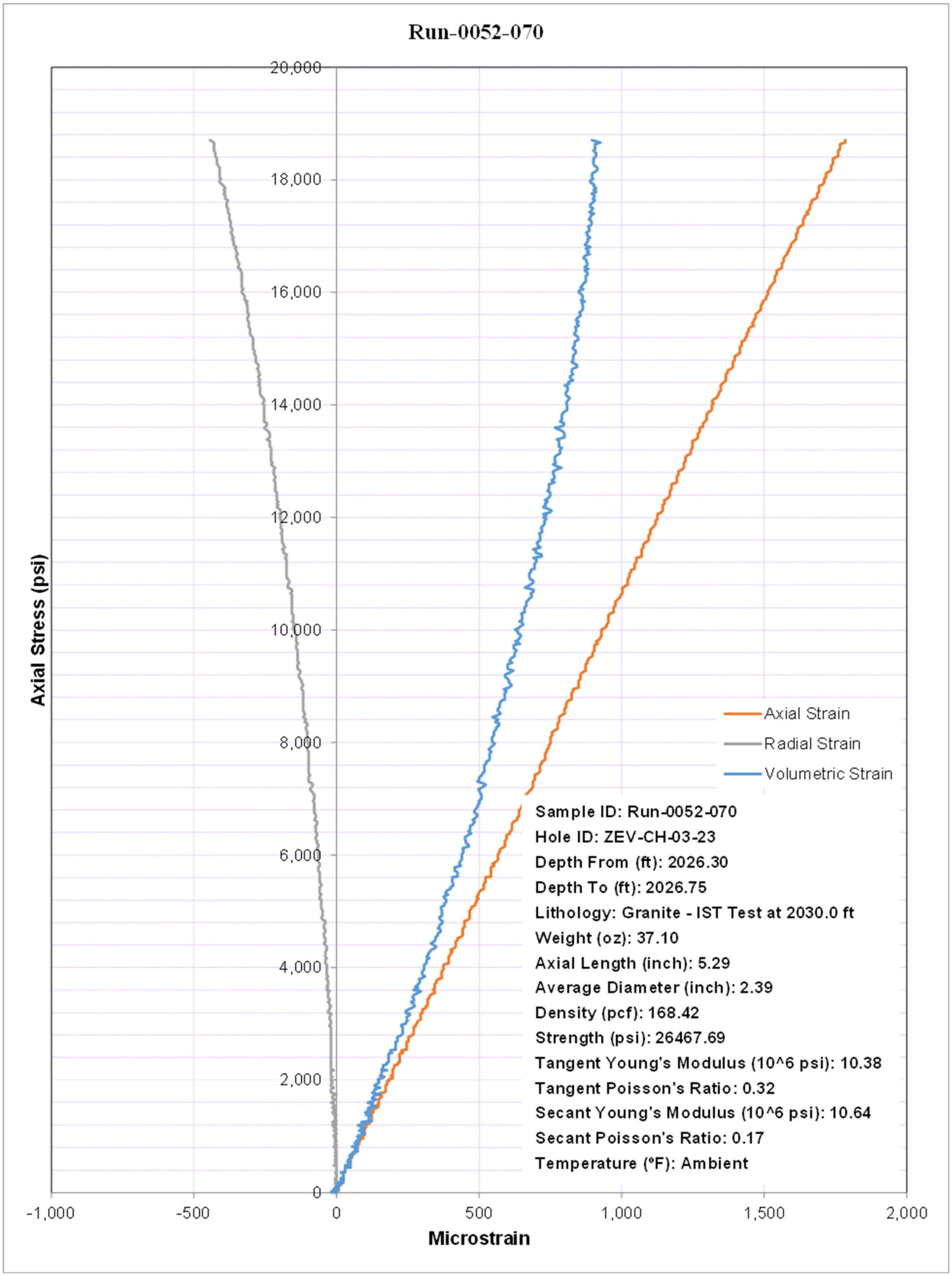
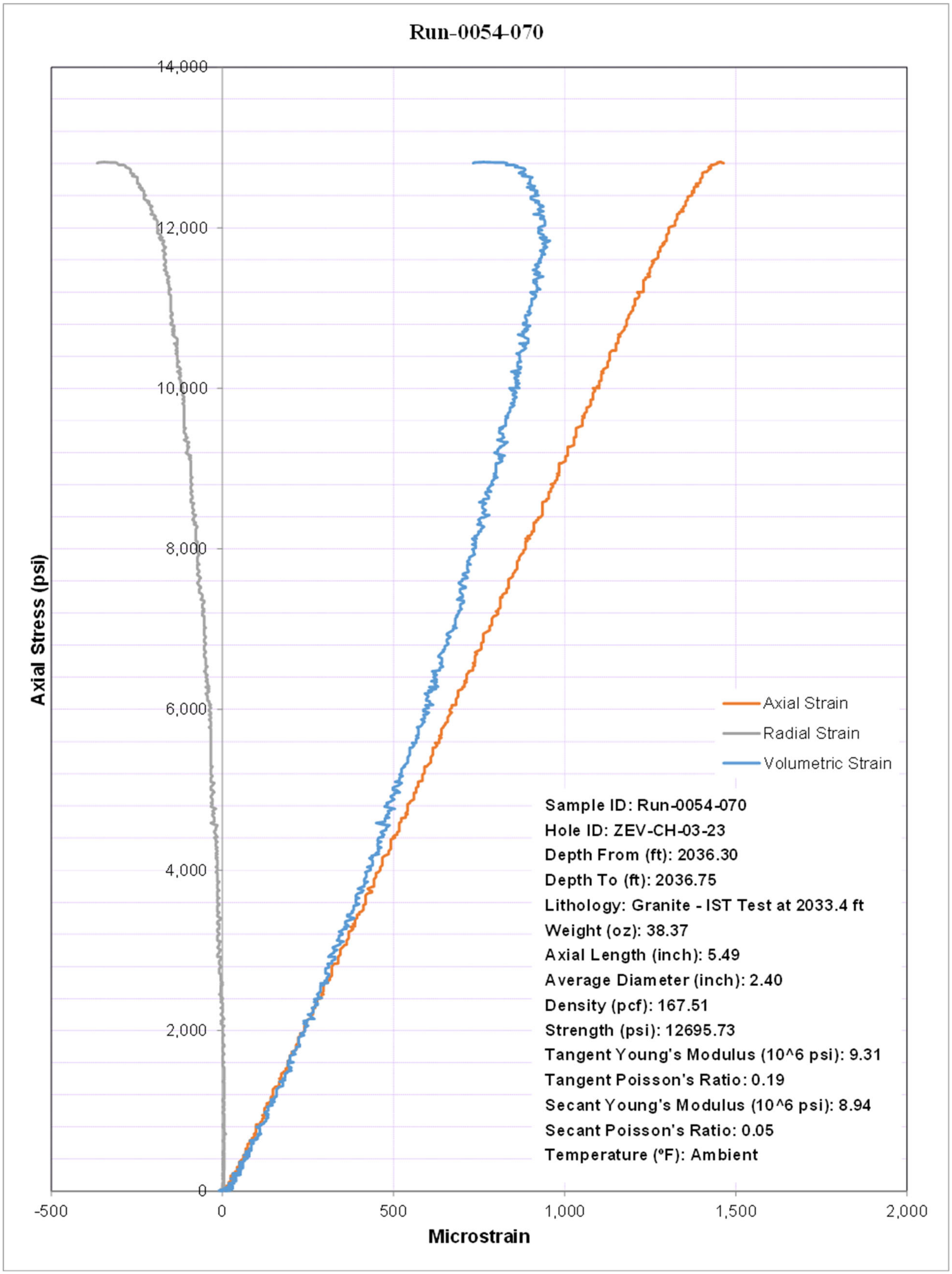


Figure A-2. Stress-Strain Plots of Uniaxial Compressive Strength Test Specimens



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