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Geology, Temperature, Geophysics, Stress Orientations, and Natural Fracturing in the Milford Valley, UT Informed by the Drilling Results of the First Horizontal Wells at the Cape Modern Geothermal Project

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ABSTRACT

Fervo Energy (Fervo) has completed the drilling of the first deep geothermal wells at Project Cape, including a vertical observation well to 9,844 ft and four 13,000+ ft-MD horizontal wells drilled in a 'wine rack' pattern with 5,000 ft laterals at vertical depths of 8150-8550 ft. These new wells were drilled west of the DOE FORGE project in Milford Valley and were informed by the significant datasets generated by FORGE. New datasets collected through Fervo drilling have substantially increased knowledge of the geology, temperature, state of stress, and natural fracturing in Milford Valley, leading to new 3D basin models with an unprecedented amount of well data collected. A new detailed gravity study combined with density logs from the deep wells enabled a basin-spanning depth to granitic basement model tied to drilling results from existing wells. Smectite clay zones observed in Fervo wells combined with magnetotellurics (MT) data collected by FORGE led to the discovery of an extensive clay body which was modeled in 3D throughout the basin. DTS fiber and wireline temperature logs confirmed average temperatures of 200°C across the laterals. Image logs across the horizontal wells were used to create an integrated fracture density model across the granitic reservoir area. Image logs from vertical portions of new wells confirm a maximum horizontal stress orientation (SHmax) of NNE-SSW with consistent SHmax orientations measured across the basin. Major improvements in drilling performance were gained throughout the drilling program, demonstrating a rapid learning curve to enable fast lateral drilling through granitic basement rock.

1. INTRODUCTION

In this paper we present the geology, temperature, stress field, and drilling results from the first five wells drilled at Fervo Energy's (Fervo) Project Cape next-generation geothermal project at Milford Valley, Utah. We describe the models and results that led to the successful drilling of Fervo's wells at the site, which include a 9,844 ft-TVD deep vertical monitoring well (Delano 1-OB) and four 8150-8550 ft-TVD, 13,272-13,601 ft-MD deep horizontal wells (Frisco 1-I, 2-P, 3-I, 4-T) that will be hydraulically stimulated to support future injection and production. Pre-Cape drilling, three-dimensional geologic and temperature models were built from a synthesis of the existing data from the publicly available Blundell and FORGE wellfields to support targeting of these wells. As each well was drilled, the 3D geologic and temperature models described in this paper were used as a basis for pre-drill prognoses, and then iteratively updated with results. The orientation of the horizontal Frisco wells were informed by SHmax indicators from image logs at the adjacent FORGE wells along with Fervo monitoring well Delano 1-OB, which indicate a consistent SHmax of 10°-15° (NNE) across the field. Significant well-on-well performance improvement was achieved across the four horizontal Frisco wells, with a >60% reduction in drilling days from the Frisco 1-I to Frisco 4-T, with sustained horizontal drilling rates through granitic rocks significantly higher than previously published.

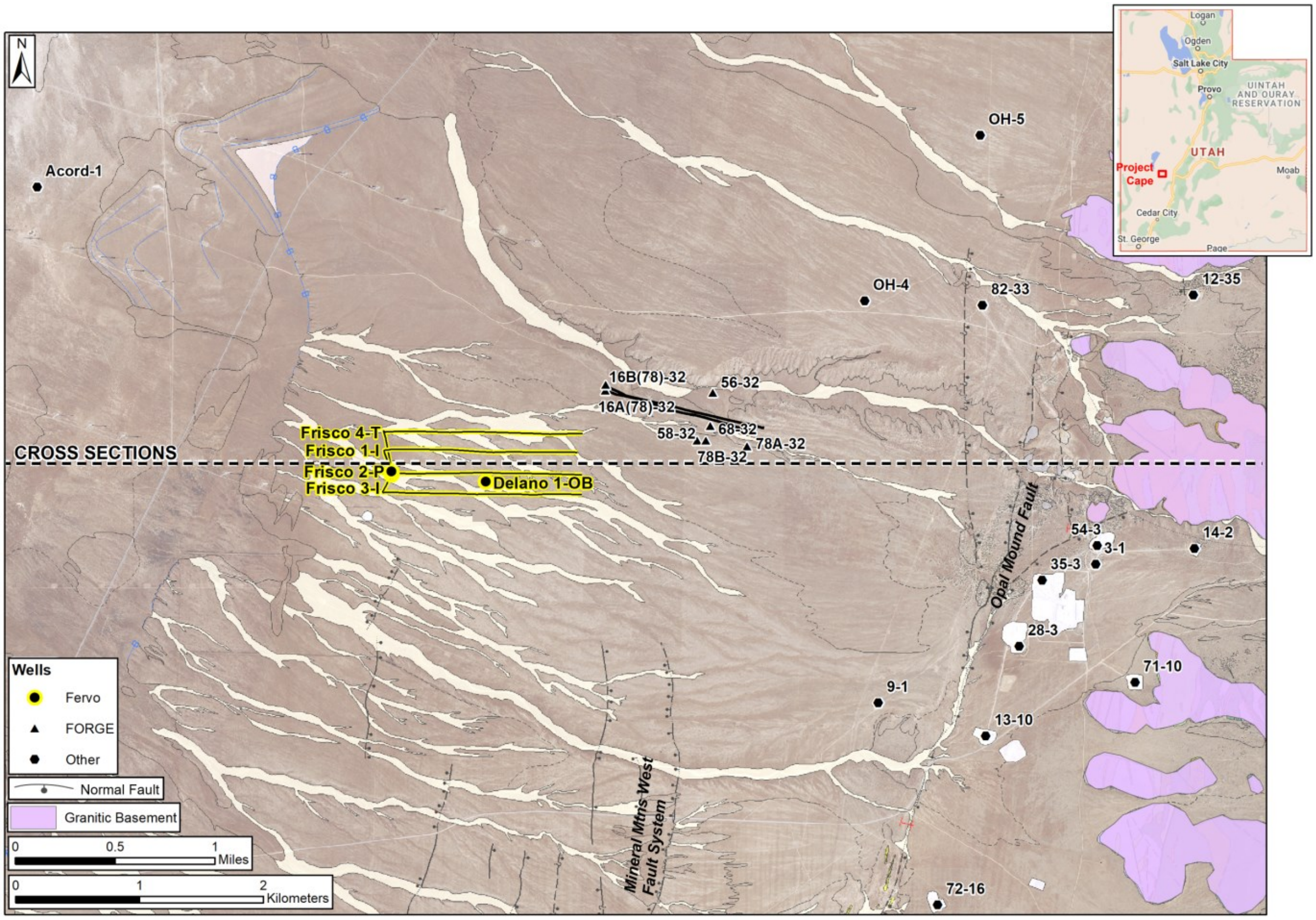

Figure 1: Map of eastern Milford Valley showing Fervo wells (highlighted) and other existing wells in the basin. Geologic map background modified from Kirby et al. (2019).

2. GEOLOGY

2.1 Geologic Model

From youngest to oldest, the overall stratigraphic framework at Cape consists of Miocene to present day basin-fill deposits, Quaternary to late Miocene volcanics and volcaniclastic sediments, and granitic basement comprised of Oligocene and Miocene plutons ranging in composition from granite, granodiorite, diorite, to monzonite, as well as large blocks of Precambrian gneiss (Simmons et al., 2019). The contact between the basin-fill and granitoid dips 25°-35° west. Quaternary faults have been mapped in the region, including the NNE-striking E-dipping Opal Mound fault. The Opal Mound fault forms a hydraulic barrier that separates the Roosevelt Hot Springs hydrothermal system from the low-permeability crystalline rocks at Cape west of the fault (Figure 1). The Mineral Mountains West Fault System of N-striking fault scarps terminate in the southern portion of the field (Miller, 2019).

To better understand the subsurface and help with targeting of Fervo's wells at Project Cape, a 3D geologic model was created using the major formations of Basin-Fill Sediments, Volcanics & Volcaniclastics, and Granitic Basement (Figure 2). After discovering an extensive smectite clay unit in the western portion of the basin, a 4th unit Clay was added to the 3D model (more description on the clay unit can be found in Section 2.2.2). The 3D model was informed by re-interpretation of lithologies from all available well logs in the area as well as gravity profiles (white points) from a high-resolution gravity survey collected by Fervo in 2022. Analyses of the cuttings from the pre-existing wells 58-32, 16A(78)-32, and Acord-1 using X-ray diffraction (XRD) published by Jones et al. (2019 and 2021) were instrumental in informing a thick package of volcanics in the deep portion of the basin which was previously underestimated in both thickness and lateral extent (Figure 4). The initial 3D geologic model created by Fervo was used to predict the expected lithologic depths in the Delano and Frisco wells to estimate casing set points and drilling conditions, and ensure that the wells were targeted with low fault likelihood. Upon drilling and logging each new well, the 3D geologic model was progressively refined and accuracy was improved.

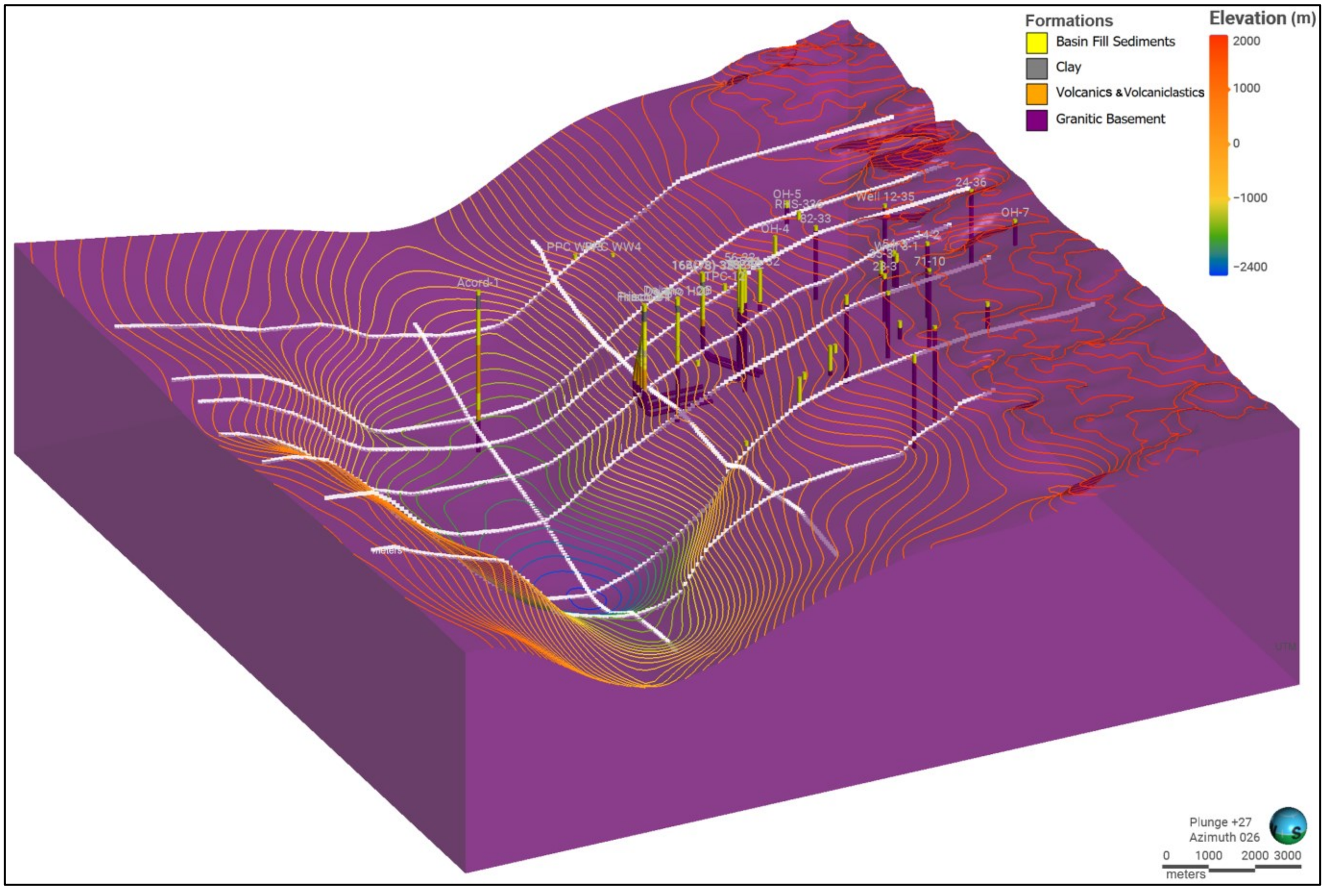

Figure 2: Oblique view of Fervo's 3D granitic basement model looking north-northeast, contoured by elevation. The basement model was informed by well lithologies and gravity profiles (white points) from Fervo's high-resolution gravity survey collected in 2022.

2.2 Geology Results of Fervo Wells

2.2.1 Faults

There are several N-S striking faults mapped at surface by Simmons et al. (2019) as the "Mineral Mountains West Fault System" which appear to terminate 2-3 km south of the Delano and Frisco wells (Figure 1). These faults had never been penetrated by an existing well within basement, so their orientation, degree of permeability, and borehole stability hazard was unknown prior to Fervo drilling operations. It was also unknown how far these surface faults penetrate the granitic basement at depth and if they continue farther than their Quaternary surface expressions to indicate. Upon drilling Fervo's vertical monitoring well (Delano 1-OB) at the center of the future laterals, no mud losses, fault-associated alteration, or brecciated/unstable zones were detected within the formations. Based on the lack of any geologic evidence for these faults at Delano 1-OB, we interpreted that the Mineral Mountains West Faults terminate south of the Frisco pad and proceeded to drill the Frisco laterals. Upon drilling the Frisco wells, the geologic results confirmed that no major faults were encountered. The only signs of permeability encountered in these wells were very minor mud losses (10-20 bbl/hr) in the volcanics above the granitic basement. The losses in volcanics are likely caused by porous beds, microfractures, and contacts between the volcanic layers. Porosity logged in Frisco 1-I log shows a high porosity zone in the bottom 300 ft of the volcanics, where these losses were encountered.

2.2.2 Basin-Fill Sediments and Clay

The pre-drill prognosis for Delano 1-OB predicted two major formations the well would encounter, basin-fill sediments and granitic basement. Based on the FORGE wells it was known that the well would penetrate a thick package of alluvial sediments comprised of sands, gravels and clays before encountering the granitic basement. The clays within most of the FORGE wells were mixed with sands in an alluvial package, rather than a pure clay unit. While drilling Delano 1-OB, the expected sands and gravels were encountered until an interval from 690 ft-MD to 1150 ft-MD, where a nearly pure, sticky smectite clay was encountered that caused issues including plugging the well's riser. The issue was solved by repeated cessation of drilling to clean the riser and setting surface casing to cover the clay hazard. Methylene Blue (MeB) analysis confirmed the high smectite content of this zone.

Subsequent analysis of magnetotelluric (MT) data for the basin revealed a striking correlation between an extensive low-resistivity conductor in the MT and the interval with where clay has been encountered in wells. High quality MT data were acquired at 122 stations by Quantec Geoscience LLC as part of the FORGE project, with additional stations being supplemented by the EGI SubTER project which extends over the Mineral Mountains (Wannamaker et al., 2020). MT station spacing ranges from 0.5 km in the core of the survey area to >3 km at the survey edges. For the analysis of shallow, low resistivity clays, Fervo performed new depth-limited 1D inversions, which were targeted at resolving the shallow resistivity patterns. Previous MT studies of the Milford basin have focused on 3D inversions aimed at resolving deeper, low frequency resistivity patterns (Wannamaker et al., 2020). TE-mode, depth-limited 1D inversions were performed for each of the MT sites in the FORGE and SubTER datasets, and limited to where data were consistent with 1D assumptions indicated by low amplitude of on-diagonal MT impedance elements among other constraints (Chave and Jones, 2012; Cumming and Mackie, 2010). 1D MT resistivity models are reviewed in cross section and compared to well cutting analysis (Figure 3). The 1D inversions resolve a thin and shallow low resistivity zone that correlates well to clays identified in publicly available mud logs from the FORGE wells, Acord-1, and Blundell geothermal wells. The 1D MT interpretation agrees with the well cutting analysis, which indicates that low permeability, low resistivity clays appear to be thicker in the basin to the west, intersect the Delano well, and then pinch out somewhere between FORGE 16A-32 and 58-32. The MT correlation with the clay unit was used to predict its depth and thickness in the Frisco wells with good results, including comparison to methylene blue derived smectite content (Figure 3). Using the MT and the Delano 1-OB results, we predicted clay in Frisco to lie between 500-1400 ft-MD, and upon drilling the Frisco wells it was encountered from 500-1250 ft-MD. This shallow clay zone is interpreted as primary lacustrine clays that were deposited as part of the historic Lake Bonneville and not related to hydrothermal smectite clays associated with alteration in a circulating hydrothermal system. A second, deeper clay zone was also encountered in the Frisco wells from 3315-4135 ft-MD, however the deeper clay is mixed 50/50 with sands and limestones, has a lower smectite content and MeB result, and consequently was not resolved by 1D MT inversions.

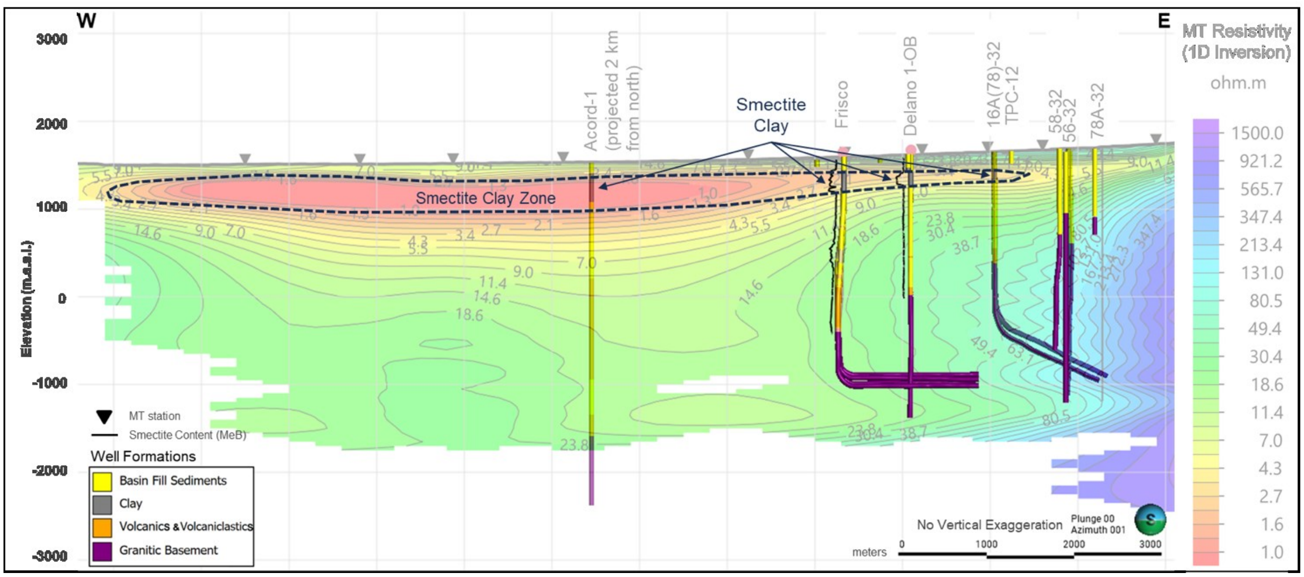

Figure 3: Correlation of 1D MT to clay observed in wells across Milford Valley, including methylene blue analysis of cuttings.

2.2.3 Volcanics and Volcaniclastic Sediments

Upon drilling Delano 1-OB, two volcanic units were encountered that were previously unknown. The first was a thin dacite unit encountered from 3,810 to 3,260 ft-MD. The second, more significant volcanic unit, was a 305 ft thick ash-flow tuff which was encountered above the basement contact at a depth of 4,970 to 5,275 ft-MD. Approximately 4.5 km northwest of Delano 1-OB, the Acord-1 well encountered thick volcanics, however just east of Delano 1-OB at the FORGE wells, there are only 10 ft of volcanics above the basement contact. This finding subsequently led to a revised model, where volcanics are thick in the basin and thin toward Delano 1-OB before they pinch out before FORGE 16A-22 (Figure 4). This model was used to predict the top of volcanics in the Frisco wells, and upon drilling Frisco 1-I the volcanics were found to be thicker and shallower than expected and include a thick package of volcaniclastics and andesites. Additionally, two thin welded tuff units were encountered from 2,630-2,700 ft-MD and 4,205-4,360 ft-MD in Frisco 1-I, which were then tracked across the remainder of the Frisco wells. The shallower welded tuff, encountered at 2,630 ft-MD, appears to be mostly flat across the Frisco wells, while the 4205 ft-MD welded tuff deepens to the south (Figure 5).

2.2.4. Granitic Basement

To constrain the subsurface basin geometry of the Milford Valley, Fervo contracted with Magee Geophysical Services LLC to acquire 1,388 new gravity sites in 2022. Station spacing ranged from 250 m in the core of the survey area to >1 km in the periphery. These new sites were integrated with 283 stations acquired as part of the FORGE project and 425 stations from the Pan-American Center for Earth and Environmental Studies (PACES) database (Hardwick et al., 2018). The gravity data were processed to Complete Bouguer Anomaly (CBA) using a density of 2.45 g/cc. The new resulting CBA map illustrates the trend of a deepening basin west of the Frisco pad and shows the north-south trough of the basin deepens towards the south of the Frisco pad and Acord-1 well (Figure 7).

The pre-drill prognosis for Delano 1-OB provided a granitic basement uncertainty range of 4,840-6,050 ft-TVD based on previous 2D and 3D seismic interpretations by FORGE and Fervo's new endmember 2D gravity forward models. Delano 1-OB was sited farther west and deeper into the basin than any of the FORGE or Blundell wells. Gravity models were calibrated based on FORGE density logs; however, because Delano 1-OB was sited farther west, there was little known about the deeper alluvial packages that were encountered by the FORGE wells. To mitigate this uncertainty a range of density values were used for different 2D gravity forward model endmembers. Upon drilling Delano 1-OB, the granitic basement was encountered at a depth of 5275 ft, very close to the median of our predicted uncertainty range. After drilling Delano 1-OB, a density log was obtained that greatly increased the precision and confidence of the 2D gravity forward model results. The 2D and 3D FORGE seismic data and new 2D gravity forward modeling were used to predict the granitic basement at 6500 ft-MD in Frisco 1-I (Figure 6). Upon drilling Frisco 1-I, the top of granitic basement was encountered at a depth of 6615 ft-MD, which was then used to improve the model and predict the remainder of the adjacent Frisco wells.

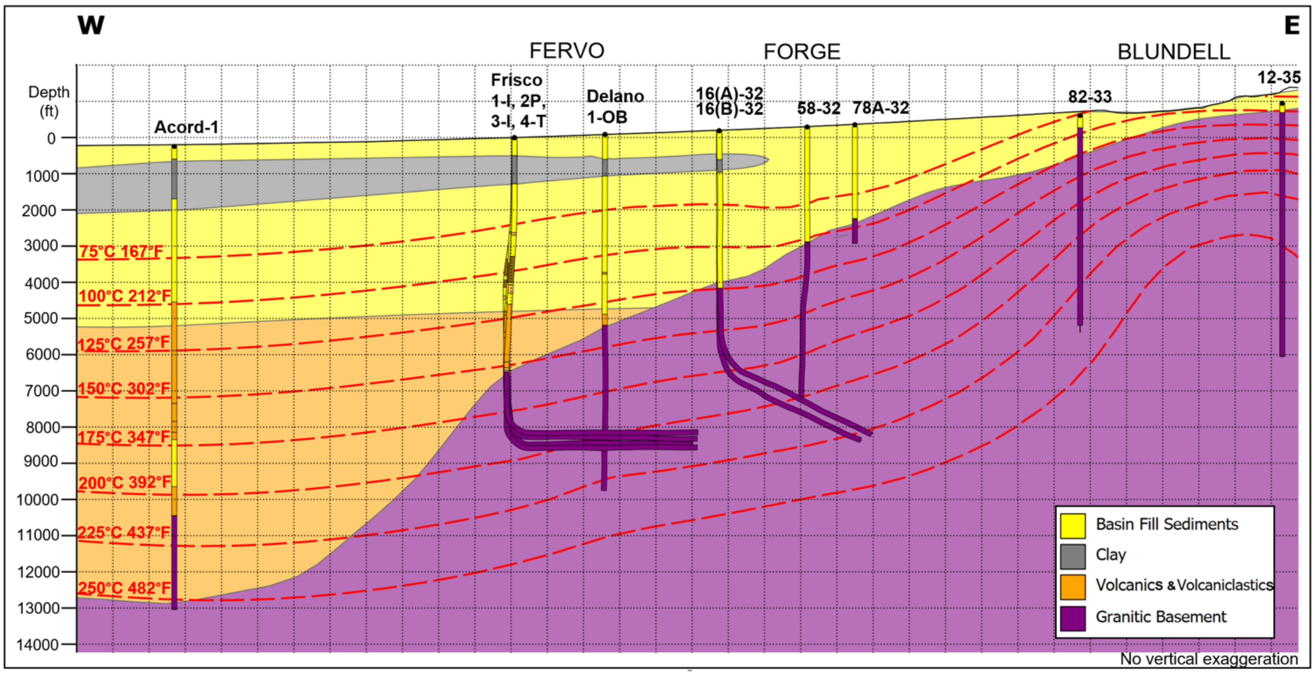

Figure 4: West-East geologic and temperature section across the Fervo Cape area, FORGE area, and Blundell hydrothermal area.

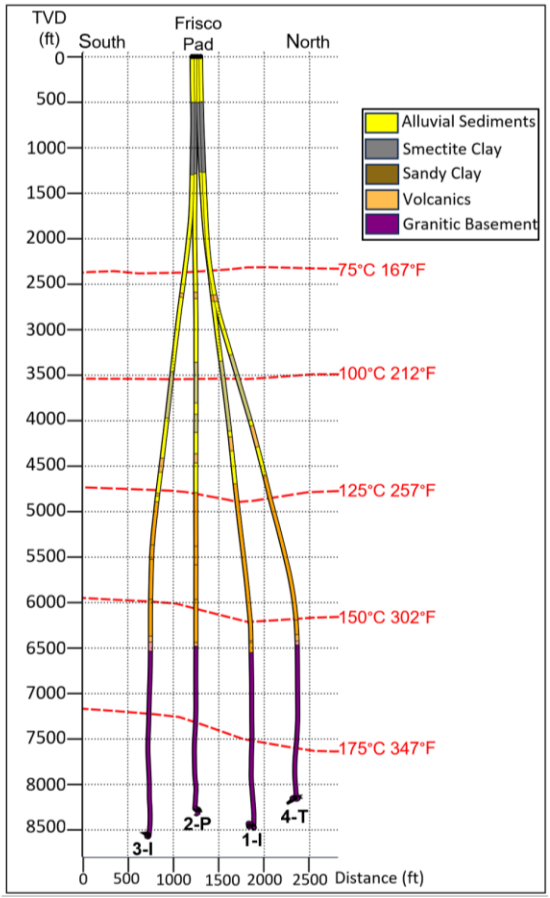

Figure 5: North-South section showing geologic formations and measured temperatures across the Frisco wells.

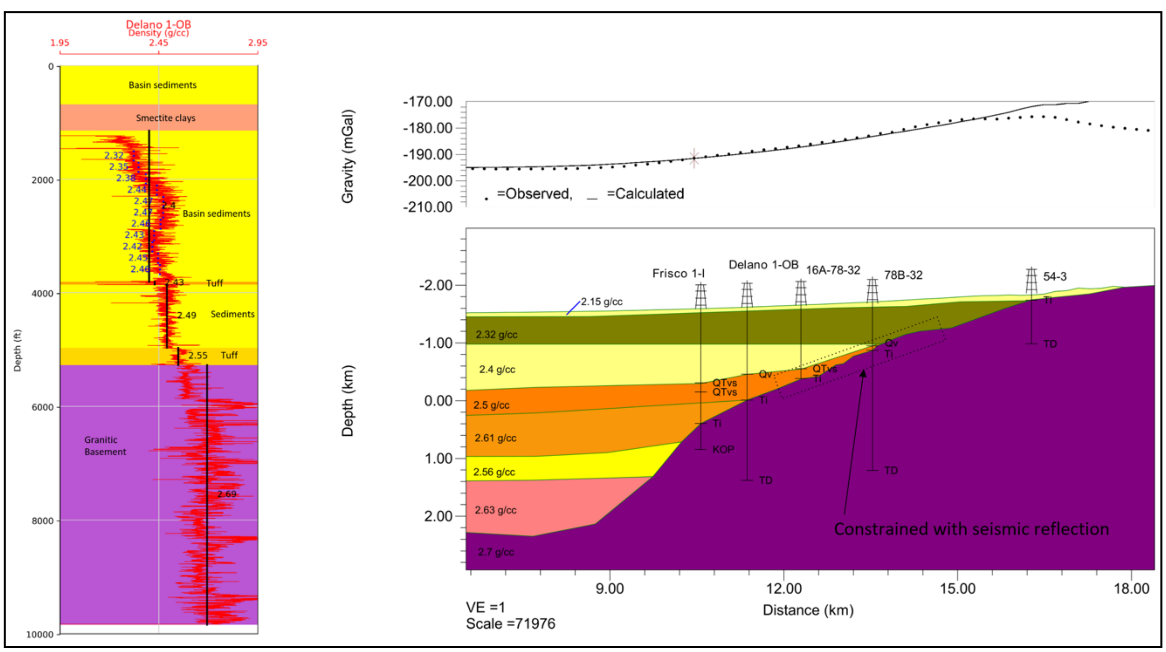

Figure 6: West-East 2D gravity forward model across the Frisco pad using densities logged in Delano 1-OB and Frisco 1-I. Example of density interpretation based on Delano 1-OB is shown to the left. The 2D forward model fit to the observed CBA is shown above the profile.

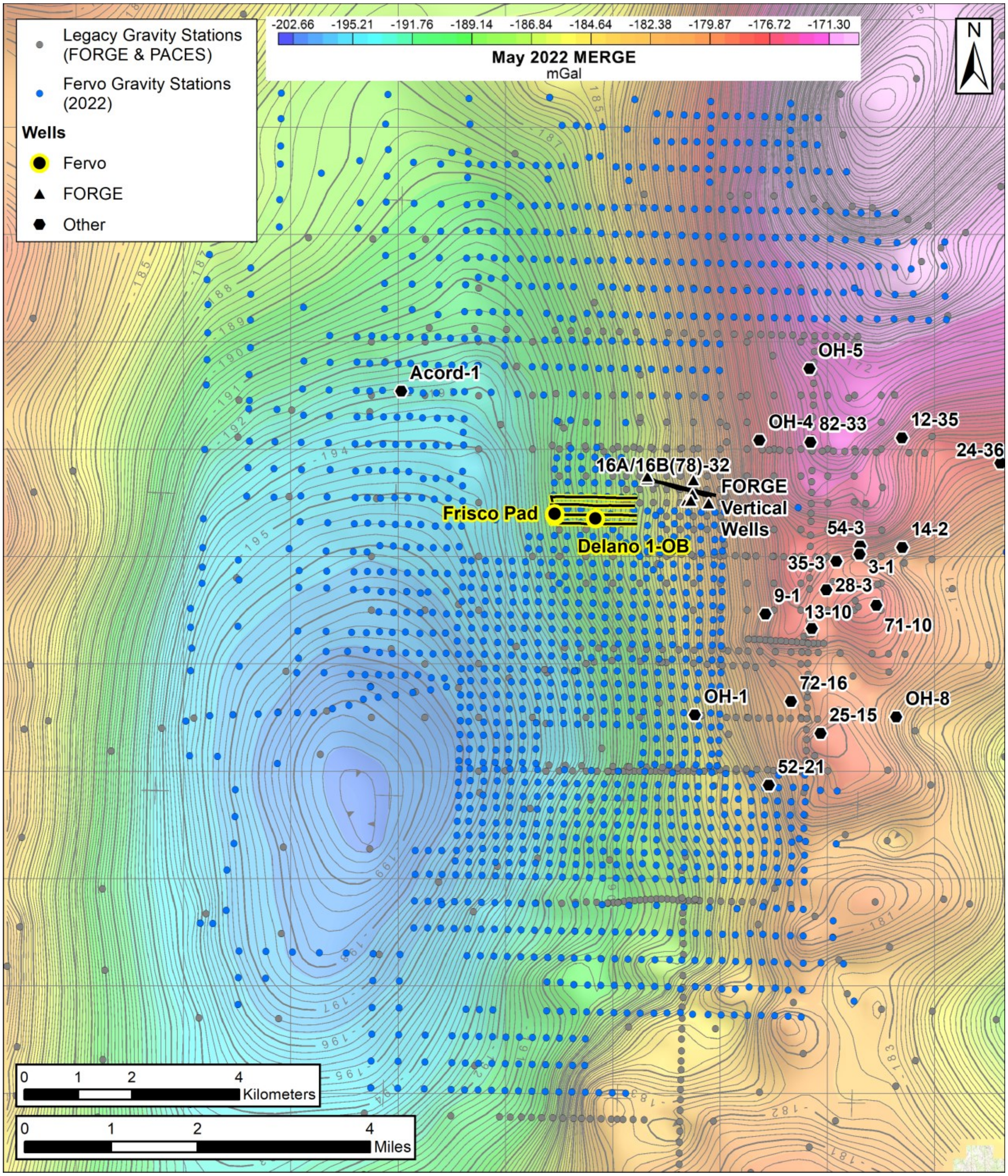

Figure 7: Complete Bouguer Anomaly (reduced at 2.45 g/cc) map of the Milford Valley, Utah.

3. TEMPERATURE

3.1 Temperature Model

The initial Cape P50 temperature model, built before drilling the Fervo wells, used temperature data from existing FORGE, Blundell, and historic exploration wells in the Milford basin combined with statistically derived temperature gradients in areas lacking well data. 3D interpolation of the measured and statistically controlled temperature data was then completed using a Radial Basis Function (RBF) using Leapfrog Energy software. RBF is an algorithm widely used for implicit modeling and is well adapted for temperature distribution modeling. The resulting 3D model (Figure 8) shows that the shallowest, highest temperatures lie at the eastern edge of the basin, where the Blundell conventional hydrothermal system brings hot fluids near surface through convection within deeply connected normal faults. Farther west, at the FORGE and Fervo Cape wells, temperatures are lower but still elevated within the un-faulted basin due to lateral conduction from the Blundell hydrothermal system, low crustal thickness from Basin and Range extension, and thermal insulation from the 5,000-7,000 ft (1.5-2.1 km) thick cover of insulating basin-fill sediments and volcanics. At the most westward extent of the model, the historic Acord-1 well provides measured temperature control for the deepest point of the basin, anchoring 175°C at 9055 ft (2.76 km).

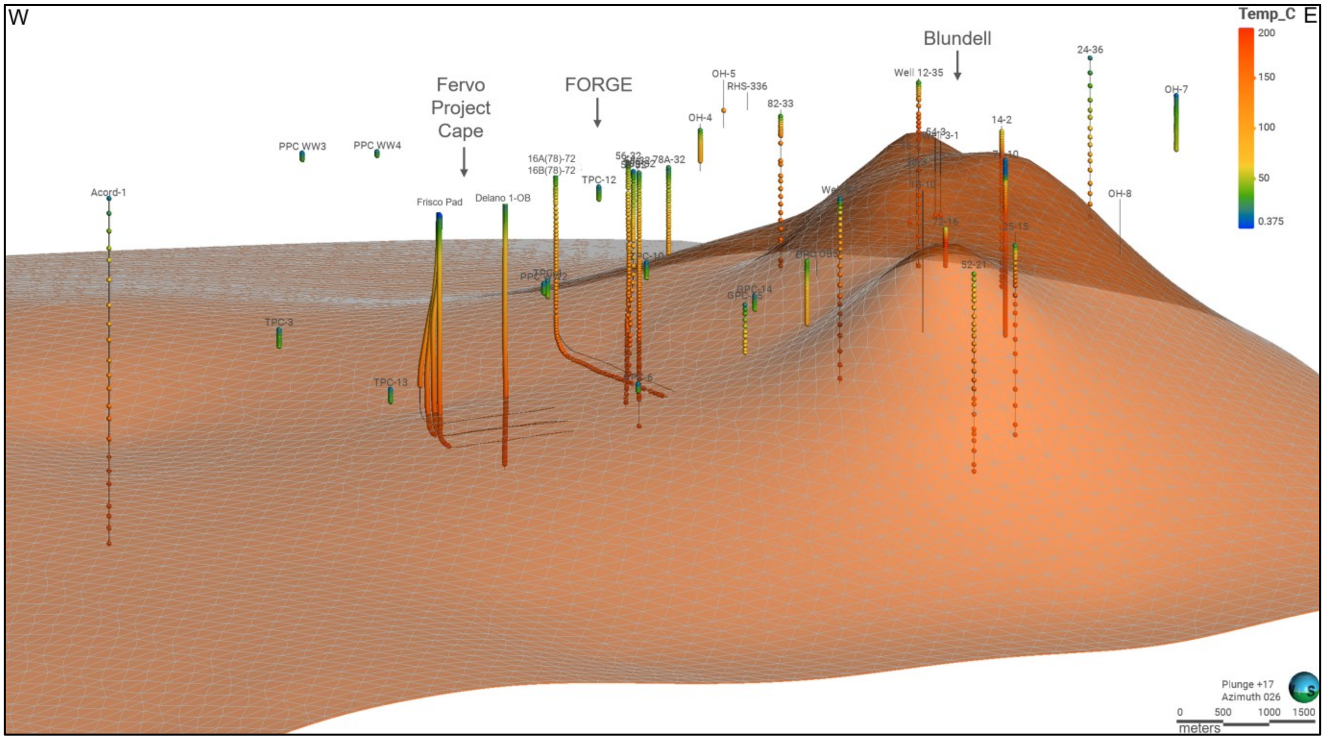

Figure 8: Oblique view of the P50 3D Temperature model constructed for Project Cape showing the P50 175°C isosurface (orange).

3.2 Temperature Results of Fervo Wells

After drilling Delano 1-OB, installing the DTS fiber, and allowing over a month of thermal recovery, the first Fervo measured temperature profile was obtained (Figure 9). The measured Delano 1-OB temperature profile is about 5 degrees Fahrenheit (°F) hotter than predicted on average and was very close to the predicted curve, with a maximum temperature of 444°F at 9,647 ft measured by the DTS fiber where 427°F was predicted in the 3D model. These temperature results for Delano 1-OB were subsequently loaded into the 3D model to improve the Frisco prognoses and help determine the optimal landing depth for the four Frisco lateral wells. After drilling the Frisco pad, all four Frisco wells were temperature logged through the vertical section and partly through the directional build curve of each well using standard wireline tools after 2-4 months of heat up. The logged temperature profiles for all four Frisco wells were very close to what was predicted by Fervo's P50 temperature model, measuring 2-10°F hotter than predicted at depth (Figure 9). Figure 5 shows the measured temperatures contoured across the four wells in a south – north profile, and indicates a slight warming trend towards the southern area of the field. Although the lateral portions of the Frisco wells were not logged, Fervo's temperature model has good constraints from the mid-lateral placement of Delano 1-OB and the deep FORGE wells further east of the lateral toes, which all indicate a trend of increasing temperature along the laterals from west to east.

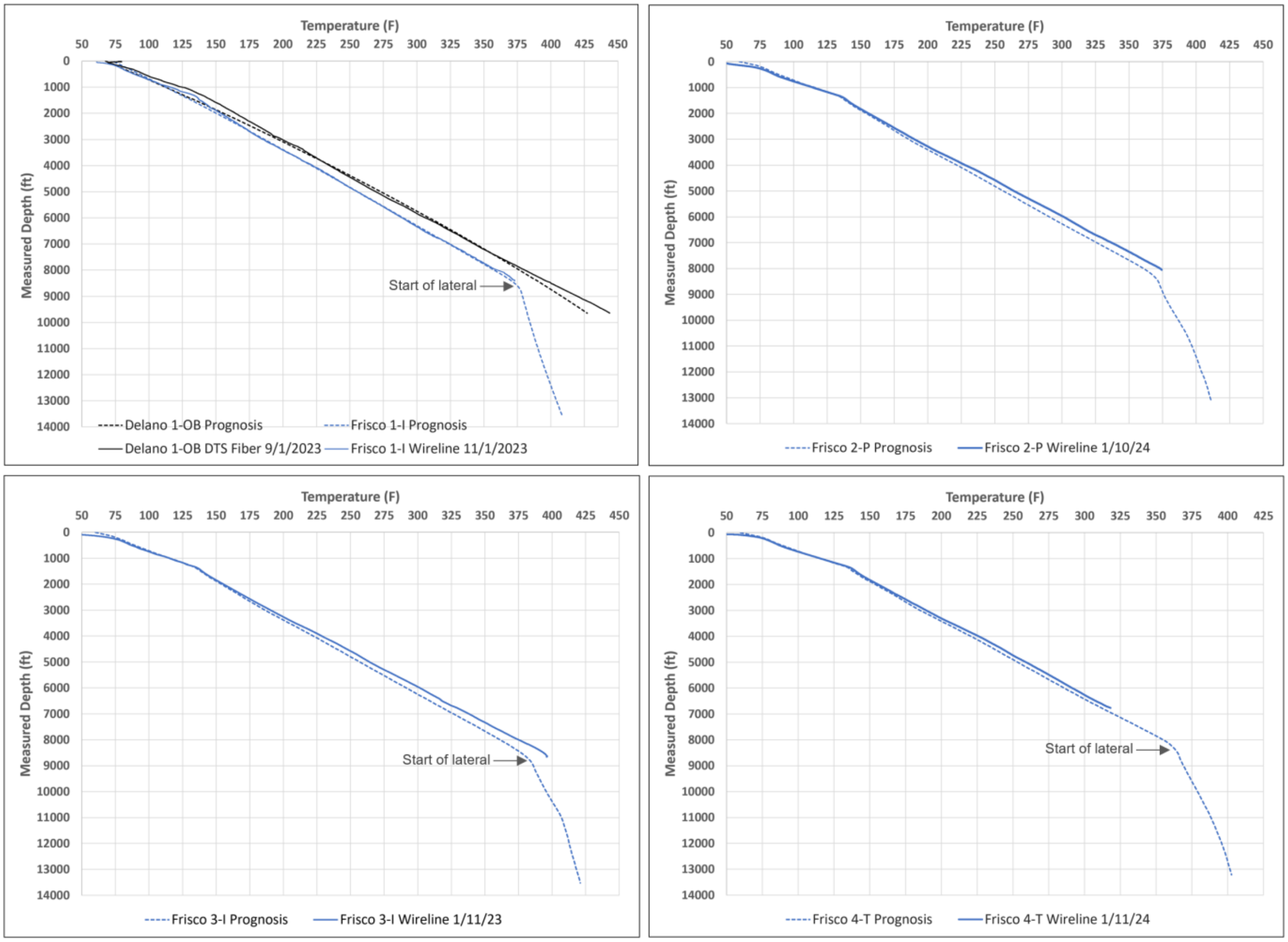

Figure 9: Temperature profiles for Delano 1-OB & Frisco 1-I (top left), Frisco 2-P (top right), Frisco 3-I (bottom left), and Frisco 4-T (bottom right). Dashed lines show pre-drill prognosis predictions based on Fervo's 3D temperature model, solid lines indicate post-drill measured temperatures.

4. IMAGE LOGS AND STRESS FIELD

The primary goals of the image logs in the Frisco wells were to characterize the local stress field and to measure orientations of natural fractures. Prior to drilling Delano 1-OB, There were 4 wells from FORGE with image logs: 16A(78)-32, 78B-32, 56-32, 58-32. The drilling induced fractures (DIFs) measured in FORGE wells were tightly aligned to NNE, indicating ~35° SHmax orientation in 58-32 and 78B-32 and ~15° SHmax in 16A-32 (Simmons et al., 2019). DIFs were found to be well developed in the Fervo Delano 1-OB log, tightly aligned to a 10° SHmax orientation. At the Frisco pad, image logs were collected in Frisco 1-I, 2-P, and 4-T, and DIFs measured in the vertical sections of those wells average ~15° SHmax. The combination of this Fervo SHmax data with FORGE data indicates a very consistent SHmax of 10°-15° across the field, except for FORGE 58-32 and 78B-32 which have a clockwise rotation to more NE (Figure 10).

Natural fractures observed in the Delano 1-OB and Frisco 1-I, 2-P, and 4-T image logs were closely aligned with the stress field, with dominant north strikes and a dominant west dip with a large conjugate east dipping population (Figure 11). The natural fractures have high angle dips, dominantly ranging from 60° to 90°, consistent with Basin and Range normal faulting. With the fracture datasets picked from the image logs, natural fracture density was calculated every 50 ft and average strike orientation was calculated every 500 ft for Frisco 1-I, 2-P, & 4-T (Figure 12). The fracture density, gridded across the Frisco laterals to identify trends, reveal two immediate features: 1: Frisco 1-I has a lower fracture density than Frisco 2-P & 4-T across the heel-side half of the laterals from roughly 8500 to 10,500 ft-MD, and 2: There is a high fracture density zone that seems to correlate between all three wells from approximately 11,500 to 12,200 ft-MD. The lower fracture density along the heel side of Frisco 2-P may be related to lower image quality in that section of the well caused by washouts during drilling. In all three wells, natural fractures consistently exhibit a N-S average strike, with just small variations between NNW and NNE every 500 ft. Table 1 shows key geomechanical properties compiled by Fervo on the granitic reservoir to inform modeling and future hydraulic stimulation using the image logs, sonic logs, FORGE datasets (McLennan, 2019; May and Jones, 2023).

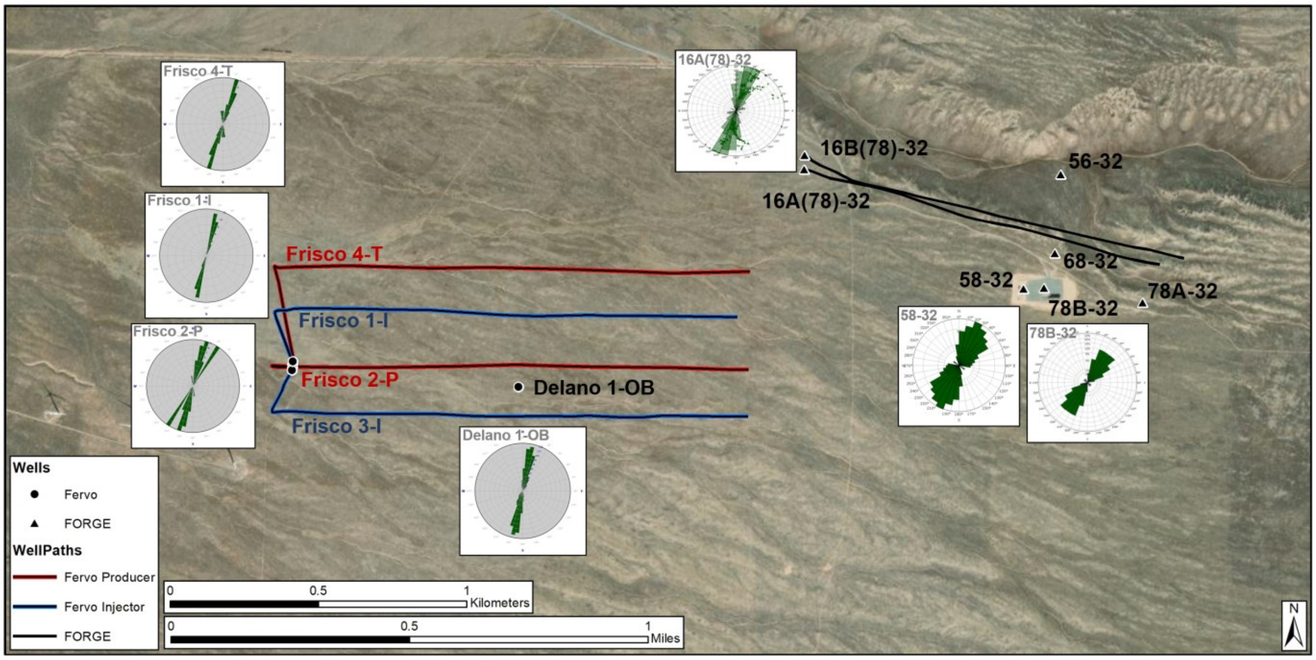

Figure 10: Map of drilling induced fractures measured in image logs collected by Fervo and FORGE.

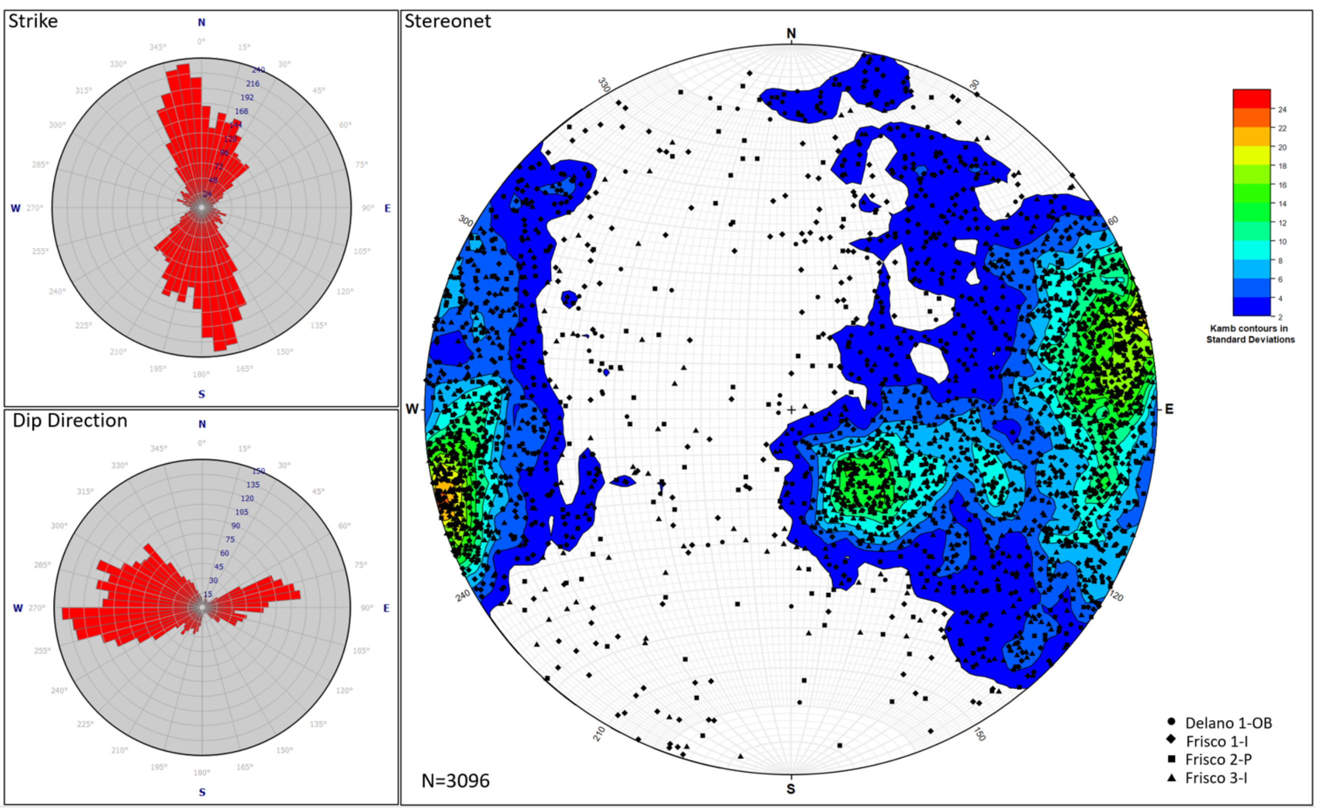

Figure 11: Natural fracture orientation data from all logged Fervo wells.

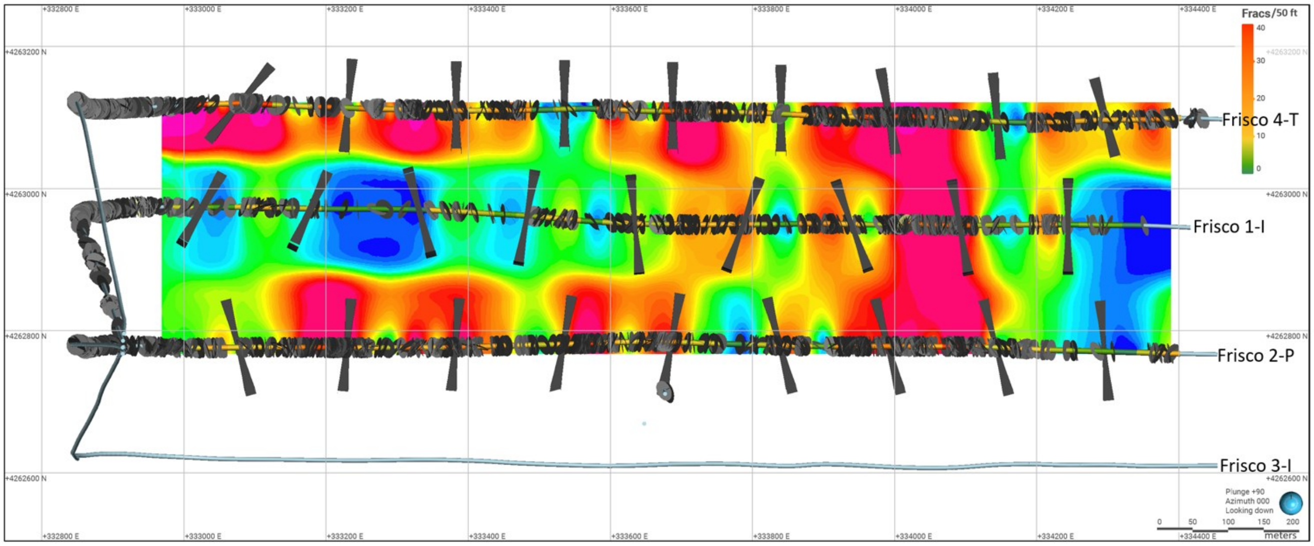

Figure 12: Natural fracture density model across Frisco wells with image logs. Warm colors have higher natural fracture density. The bow ties represent the average natural fracture orientation every 500 ft along each lateral.

Table 1 – Key geomechanical properties from logs collected within the granitoid basement across Fervo and FORGE wells.

Well	Shmax Orientation	Static Young's Modulus	Static Poisson's Ratio	Source
FORGE 58-32	25°	6-7 Mpsi	0.25	McLennan, 2019
FORGE 16B(78)-32	25°	4.70 Mpsi	0.29	May and Jones, 2023
Fervo Delano 1-OB	10°	5.89 Mpsi	0.24	Fervo 2023 Sonic Log
Fervo Frisco 1-I	15°	5.21 Mpsi	0.26	Fervo 2023 Sonic Log

5. CONCLUSIONS

Building on the learnings from Fervo's successful commercial pilot project in Nevada (Fervo et al., 2023, Norbeck et al., 2023) and the adjacent DOE funded FORGE project in Utah, Fervo Energy successfully drilled one vertical deep observation well and four deep horizontal wells that will be hydraulically stimulated to support future injection and production at Project Cape. Significant drilling performance improvements have been achieved which demonstrate that horizontal wells can be drilled quickly and effectively through granitic formations (El-Sadi et al., 2024). Through the drilling of over 52,000 ft of combined horizontal wells, Fervo demonstrated that the granitic reservoir at Project Cape lacks fault-hosted permeability and has temperatures of 190°-210°C (375°-410°F), making it the ideal target for large-scale EGS development. Stress field information collected by FORGE and from Fervo's drilling campaign confirm a near north-south SHmax orientation within an extensional stress environment, informing a west-east lateral direction ideally placed for future hydraulic stimulation of fractures between the wells.

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