New data yield new geologic insights at the Fallon FORGE site, Carson Sink Region, Nevada

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ABSTRACT

The geologic structure beneath the Fallon Frontier Observatory for Research in Geothermal Energy (FORGE) site represents a record of the Mesozoic through Cenozoic tectonism, volcanism, and sedimentation that has affected the Carson Sink local to Fallon, NV. A robust dataset confirms that the lithologic sequence consists of Quaternary through Miocene sedimentary and volcanic rocks resting non-conformably on Mesozoic crystalline basement. The basement consists of four lithologic units; 1) Triassic-Jurassic low-to-medium grade meta-rhyolites, 2) Jurassic low-to-medium grade quartzites and other metamorphosed marine sedimentary rocks, and 3) Jurassic low-to-medium grade meta-basalt and -basaltic-andesite lavas, all intruded by 4) Jurassic-Cretaceous quartz monzonite. The geologic section dips ~20-25° west, tilting that was accommodated by a predominant system of north-to-north-northeast striking, east and west moderately-to-steeply dipping normal faults. The above, relatively broad-scale characteristics of the geologic framework of the Fallon site have been developed throughout the ~3 year duration of the project. With the collection of new data and re-analysis of existing data in Phase 2B of the Fallon FORGE project, our detailed understanding of the relatively finer-scale aspects of the geologic framework, including aspects of the stratigraphic sequence and the locations and attitudes of individual faults have evolved and an updated 3D geologic map has been developed. Here, we compare the Phase 1 3D geologic map to the Phase 2B 3D geologic map and demonstrate the evolution of our understanding of the geologic framework of the Fallon site and the value of the new data that was collected in Phase 2B in developing this updated framework.

1. Introduction

An essential aspect of the Frontier Observatory for Research in Geothermal Energy (FORGE) initiative is the necessity that Enhanced Geothermal Systems (EGS) research activities at FORGE take place in a well-characterized geological environment. Detailed geologic characterization of the site provides crucial constraints to the drilling, numerical modeling, EGS stimulation, and other activities that will occur at the site. Characterization of the geologic framework also helps to constrain to what extent and in what environments EGS technologies developed at FORGE can be applied to other locations in the future.

2. Data

Beginning with Phase 1 in Spring 2015, the Fallon FORGE team commenced, along with many other activities associated with FORGE, characterization of the Fallon site utilizing an extensive set of existing data (Table 1). Phase 1 data (Figures 1) concerning the geologic setting consisted of; two 2D seismic reflection data sets (total of 287 line km crossing and adjacent to the Fallon FORGE site), regional gravity data, detailed gravity data covering the eastern portion of the site, detailed magnetic data covering the eastern part of the site, 1:24,000 and 1:31,680 scale geologic maps covering and adjacent to the site (Morrison, 1964; Bell et al., 2009; Bell and House, 2010; Hinz et al., 2010, 2011), down hole lithologic data and drilling logs from six wells on the site (four into Mesozoic crystalline basement) and dozens of wells adjacent to the site (eight into Mesozoic crystalline basement), equilibrated temperature logs from eight wells on and directly adjacent to the site, and downhole induced and natural fracture data from image logs in four wells on the site (two into Mesozoic crystalline basement) (Blake and Davatzes, 2012; Blake et al., 2015). These data were integrated into a 3D geologic map of the Fallon site completed in Spring 2016 (Faulds et al., 2015; Blankenship et al., 2016; Siler et al., 2016).

In Winter 2016-2017, amongst many activities associated with other aspects of FORGE, the Fallon FORGE team began collection of data that would supplement the existing data set, fill data gaps, and allow us to refine the Phase 1 geologic framework. The data collected and activities completed in Phase 2B (Table 1 and Figure 2) associated with refinement of the geologic framework were: re-processing and re-interpretation of one of the two 2D seismic reflection data sets (total of 110 line km, 56 line-km within the Fallon site; Faulds et al., this volume), collection of 900+ new gravity stations, 475 line-km of new ground magnetic data, and analogue outcrop studies of the four primary Mesozoic crystalline basement units defined in Phase 1. The analogue studies allowed for detailed analysis of the lithologic and structural character of these units. Density and magnetic rock property measurements collected as part of the analogue studies constrained 2D forward modeling (magnetic and gravity data) and 3D inversion (gravity data) of these new, more comprehensive potential field data sets (Siler et al., 2018; Witter et al., this volume). Equilibrated temperature data from two wells directly adjacent to the site were also added in Phase 2B. Well 21-31 was drilled in February-March of 2018 on the Fallon FORGE site and lithologic data, temperature data, and drilling data from 21-31 were incorporated in order to refine the 3D geologic framework. These data were integrated with the Phase 1 data in construction of a new 3D geologic map in the Spring of 2018 (Blankenship et al., 2018; Siler et al., 2018).

Table 1. Data used in construction of the Phase 1 and Phase 2B geologic framework at Fallon FORGE.

		Phase 1 Data	Phase 2 Data	Change from Phase 1 to Phase 2
Geophysical Data				
	Gavity	8000+ station regional data set, including ~250 Ormat Survey over eastern side of FORGE	903 gravity stations collected Oct-Nov 2017. ~300 x 300 m grid spacing within and adjacent to FORGE. 100 m spacing along reflection profiles	903 new gravity stations
	Magnetic	116 line km collected by Ormat (data covers only the eastern 0.75 km of FORGE site	~475 line km collected April 2017. ~250 m line spacing within and adjacent to FORGE site	475 line km magnetic data
	Seismic Reflection	1994 Navy GPO Survey (original processing). 7 lines, 110 line km. 6 lines within geologic model, 56 line km; SEI data circa 1970-80s. 9 lines, 177 line km. 6 lines within geologic model, 31 unique line km (9 km duplicated Navy Data).	1994 Navy GPO Survey (reprocessed) 7 lines. Lines are slightly different than Phase 1 due to crooked line reprocessing. 110 line km. 6 lines within geologic model, 56 line km	110 line km of re-processed data, along slightly different profiles
	2D and 3D geophysical modeling		2D forward modeling of gravity and magnetic data along 5 profiles through the site. 3D inversion of gravity data	All data new in Phase 2B
Surface Geological Data				
	Geologic Maps	Lahanton Mountains Quadrangle, Bell et al., 2010; Grimes Point Quadrangle, Bell and House, 2010; Bunejug Mountains Quadrangle, Hinz et al., 2011; Lee-Allen geothermal area, Hinz et al., 2010		No change
	Analogue Outcrop Studies		Lithologic, structural mapping, and sample collection of all lithologic units present in the crystalline basement in the West Humboldt range, Stillwater range, and Humboldt range	All data new in Phase 2B
Well Data Located on Fallon FORGE site				
	FOH-3D	Lithologic data: 2728 m of well cuttings, crystalline basement Temperature data: Equilibrated temperature log Structural data: FMI and ABI logs, natural and driling induced fractures		No change
	21-31 (Drilled Feb-Mar 2018)		Lithologic data: 2480 m of well cuttings and 45 spot cores Temperature data: Equilbrated temperature log Structural data: Borehole televiewer log	All data new in Phase 2B
	61-36	Lithologic data: 2137 m of well cuttings, crystalline basement Temperature data: Equilibrated temperature log Structural data: FMI log, natural and driling induced fractures		No change
	82-19	Temperature data: Equilibrated temperature log		No change
	82-36 (FOH-1A)	Lithologic 2890 m of well cuttings, crystalline basement Temperature data: Equilibrated temperature log		No change
	84-31	Lithologic data: 1804 m of well cuttings, crystalline basement Temperature data: Equilibrated temperature log		No change
	86-25	Lithologic data: 932 m of well cuttings Temperature data: Equilibrated temperature log Structural data: FMI log, natural and driling induced fractures		No change
	88-24	Lithologic data: 1530 m of well cuttings Temperature data: Equilibrated temperature log Structural data: UBI log, natural and driling induced fractures		No change
Well data located adjacent to Fallon FORGE site				
Distance				
0.5 km	13-36		Temperature data: Equilibrated temperature log	New equilbrated temperature log
0.5 km	78-36		Temperature data: Equilibrated temperature log	New equilbrated temperature log
1 km	84-31	Lithologic data: 1804 m of well cuttings, crystalline basement Temperature data: Equilibrated temperature log		No change
4 km	17-16	Lithologic data: 2201 m of well cuttings, crystalline basement		No change
5.5 km	51A-20	Lithologic data: 3170 m of well cuttings, crystalline basement		No change
6 km	62-15	Lithologic data: 2667 m of well cuttings, crystalline basement		No change
6.5 km	35A-11	Lithologic data: 3048 m of well cuttings, crystalline basement		No change
7 km	86-15	Lithologic data: 2134 m of well cuttings, crystalline basement		No change
9 km	34-33	Lithologic data: 3048 m of well cuttings, crystalline basement		No change
11 km	14-36	Lithologic data: 2591 m of well cuttings, crystalline basement		No change

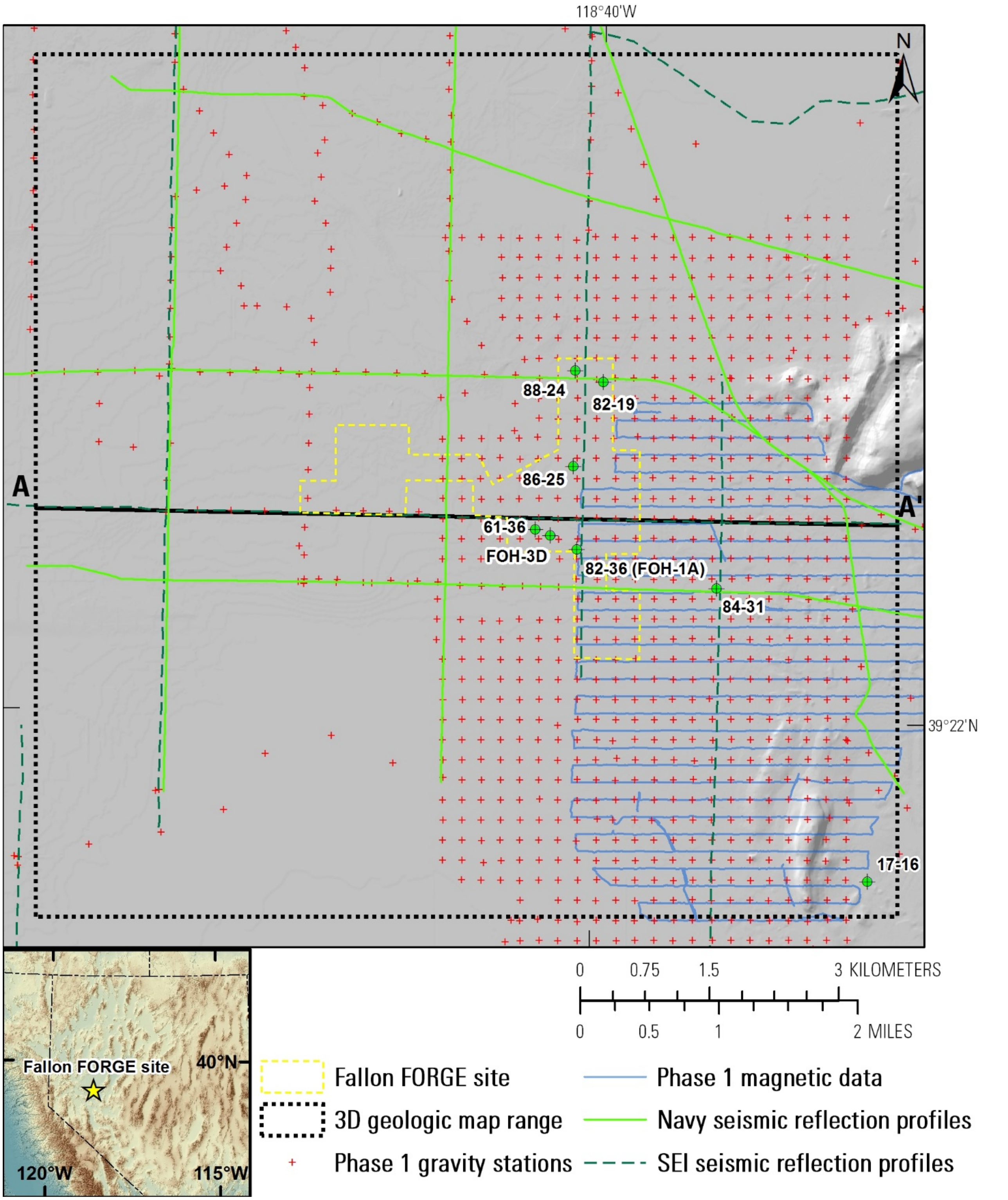

Figure 1. Map of data used in construction of the Phase 1 geologic framework at Fallon FORGE

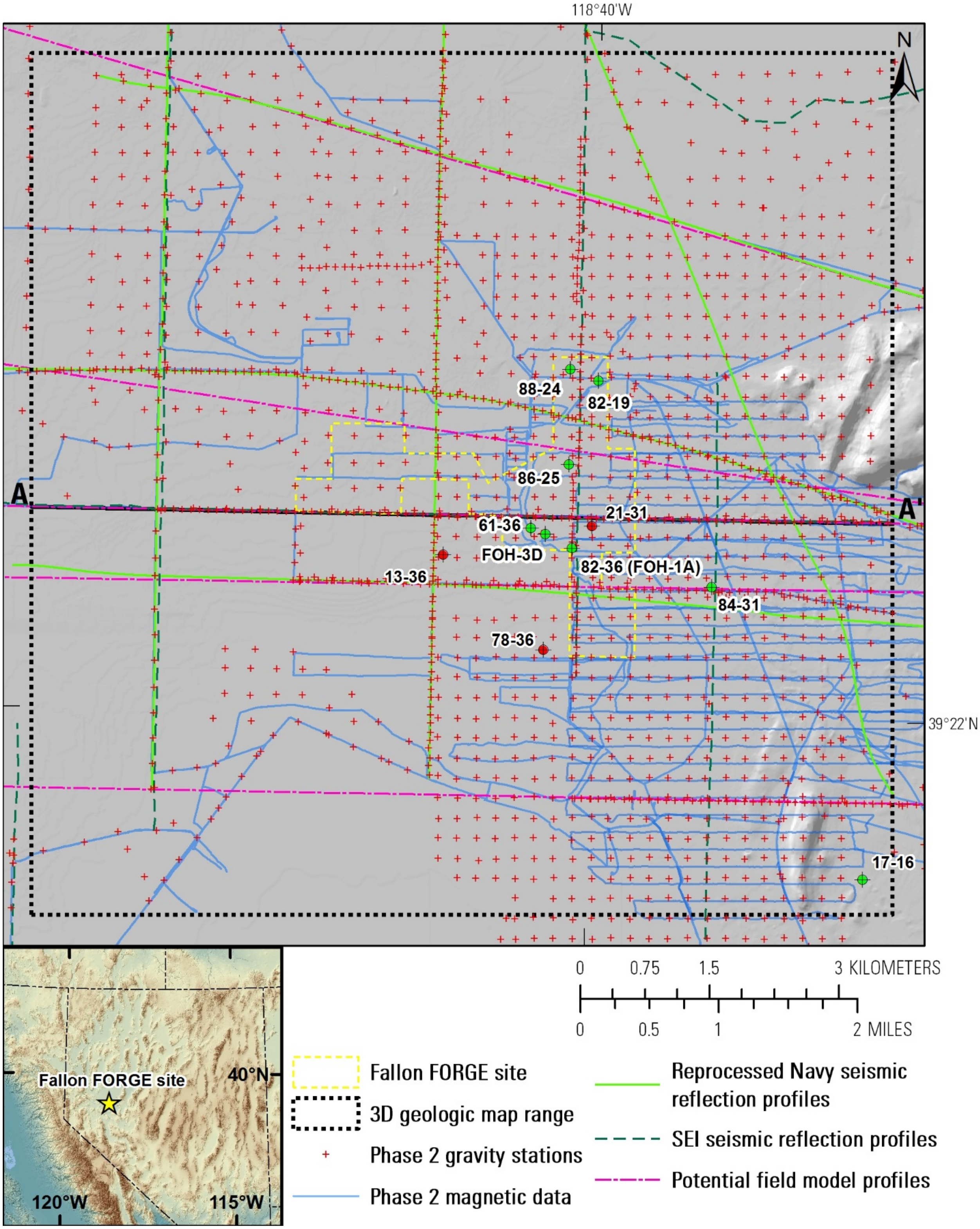

Figure 2. Map of data used in construction of the Phase 2B geologic framework at Fallon FORGE

The relative density, resolution, and quality of data used in construction of the Phase 2B geologic framework is greatly increased relative to Phase 1 (Figures 1 and 2). The increase in density and coverage of magnetic and gravity data, especially with regards to the ~100 m gravity station-spacing along the seismic reflection profiles allowed for precise 2D forward modeling of the potential field data and therefore a stronger framework to interpret the seismic reflection data. Similarly, the greatly increased resolution of the re-processed seismic reflection data, allowed for more confident interpretation of stratigraphic contacts and faults, which were utilized in construction of the 2D potential field models and interpretation of magnetic and gravity gradient maps. In this way the Phase 1 geologic framework has been iteratively refined, culminating in construction of the Phase 2B 3D geologic map. The additional lithologic constraints derived from well 21-31, in conjunction with the analogue outcrop studies, and supported by the density and magnetic property data, allowed for a more precise definition of the stratigraphy in the Mesozoic basement section.

3. Results

3.1 Structure and Stratigraphy of the Fallon FORGE site

The lithologic sequence at Fallon FORGE consists of Quaternary through Miocene sedimentary rocks overlying undivided Miocene predominantly mafic volcanic rocks and interbedded sedimentary rocks. The Miocene volcanic rocks rest non-conformably on Mesozoic crystalline basement. The basement consists of four lithologic units; 1) Triassic-Jurassic low-to-medium grade meta-rhyolites, 2) Jurassic low-to-medium grade aeolian quartzites interlayered with lesser phyllite and marble, and 3) Jurassic low-to-medium grade meta-basaltic and -basaltic-andesite lavas, all intruded by 4) Jurassic-Cretaceous quartz monzonite.

This lithologic sequence lies in a west-tilted half graben on the western limb of an extensional anticline. The axis of the extensional anticline is situated east of the FORGE site and just east of the eastern margin of the 3D map. There is a relatively high density of normal faults in the hinge zone of the anticline, as compared to beneath the FORGE site. The geologic contact between the Miocene volcanic section and the Mesozoic crystalline basement within the half graben dips ~20-25° west. The primary fault system cutting the section strikes north-to-north-northeast and dips moderately (~40-60°) to the east, with secondary, north-to-north-northeast striking, moderately west-dipping antithetic faults (Figure 3). North-to-north-northwest and east-west striking faults are also present, though the latter are statistically very minor. Vertical separation across faults is generally very minor, on the order to 10s-100s of meters. It follows that the westward tilting of the strata, rather than significant vertical separation across faults, accommodates the majority of the east-to-west deepening (from ~1.5 to 2.2 km) of the Mesozoic crystalline basement section.

3.2 Variation between Phase 1 and Phase 2B geologic framework

Several aspects of the subsurface stratigraphy and structure at Fallon were very well constrained by Phase 1 data and did not change with the addition of Phase 2B data, including the details presented in the previous two paragraphs. The gently west-tilted geometry of the half graben, the general geometry of the extensional anticline and location of its hinge zone to the east of the site, the 20-25° westward dip of Neogene strata, the widely spaced normal faults with minor offsets, and the relative high density of faults in the hinge zone of the extensional anticline relative to the FORGE area are all well constrained and are consistent between the Phase 1 and Phase 2B geologic maps (Blankenship et al., 2016, 2018, Siler et al., 2016, 2018). Furthermore, the locations of the stratigraphic contacts along the wellbores were well constrained by lithologic logging in Phase 1 and did not change between Phases 1 and 2B. The locations of the stratigraphic contacts in the newly drilled well 21-31, as identified from analysis of well cuttings and spot cores, are located within 10s of meters of their expected positions based on the Phase 1 analysis and Phase 1 3D geologic map. The new lithologic data from 21-31 therefore confirmed, rather than significantly changed, the major subsurface stratigraphic interpretations.

3.2.1 Stratigraphy

The reprocessed seismic reflection data (Faulds et al., this volume), 2D potential field profile modeling (Siler et al., 2018) (from new, more detailed gravity and magnetic data), and the 3D gravity inversions (Witter et al., this volume) refine (on the order of ~10s of meters vertically) the position of the lithologic contacts throughout the Phase 2B 3D geologic map relative to the Phase 1 map. For example, an inferred late-Pliocene contact within the basin-fill sedimentary section that is evident in Phase 2B reprocessed seismic reflection data was not evident in the SEI or original Navy reflection data (Faulds et al., this volume, Figure 3). Additionally, the reprocessed Phase 2B seismic reflection data do not clearly show the Oligocene ash-flow tuff unit to the northeast of the FORGE site (Faulds et al., this volume) that was interpreted based on the SEI reflection data and original processing of the Navy reflection data in Phase 1 (Blankenship et al., 2016; Siler et al., 2016). In addition, the 2D and 3D potential field models do not require a low-density ash-flow tuff unit between the Miocene volcanic rocks and the Mesozoic basement (Blankenship et al., 2018; Witter et al., this volume). Coupled with the fact that no wells encountered significant thickness of ash-flow tuff beneath the Miocene basalts, no Oligocene ash-flow tuff unit is incorporated into the Phase 2B 3D geologic map.

The analogue lithologic studies and the lithologic data from well 21-31 collected in Phase 2B allowed for more precise definition of the stratigraphy in the Mesozoic basement that was not evident from the Phase 1 data. With the addition of data from well 21-31, we correlate the basement stratigraphy across an area ~2.5 km-wide in the east-west direction, ~1 km-wide in the north-south direction, and to a depth of ~2.9 km as defined by the coverage of the wells which penetrate the Mesozoic basement section (Figure 2-3). The Phase 2B 3D geologic map consists of a ‘nested-scale’ 3D geologic map spanning only the area of the deep wells with the basement stratigraphy divided, within the 10 x 10 km 3D map with the basement undivided (Figure 3). The Mesozoic crystalline basement consists of, from oldest to youngest; Triassic-Jurassic low-to-medium grade meta-rhyolites within interbedded meta-basalt and -basaltic-andesite lavas, Jurassic low-to-medium grade quartzites and other metamorphosed marine sedimentary rocks with interbedded meta-basalt and basaltic-andesite lavas, Jurassic low-to-medium grade meta-basalt and -basaltic-andesite lavas, all intruded by Jurassic-Cretaceous quartz monzonite (Figure 3). As evidenced by km-scale folding documented in the analogue outcrop studies, stratigraphic correlations in the basement section outside of the area defined by the deep wells and ‘nested-scale’ 3D map are highly uncertain.

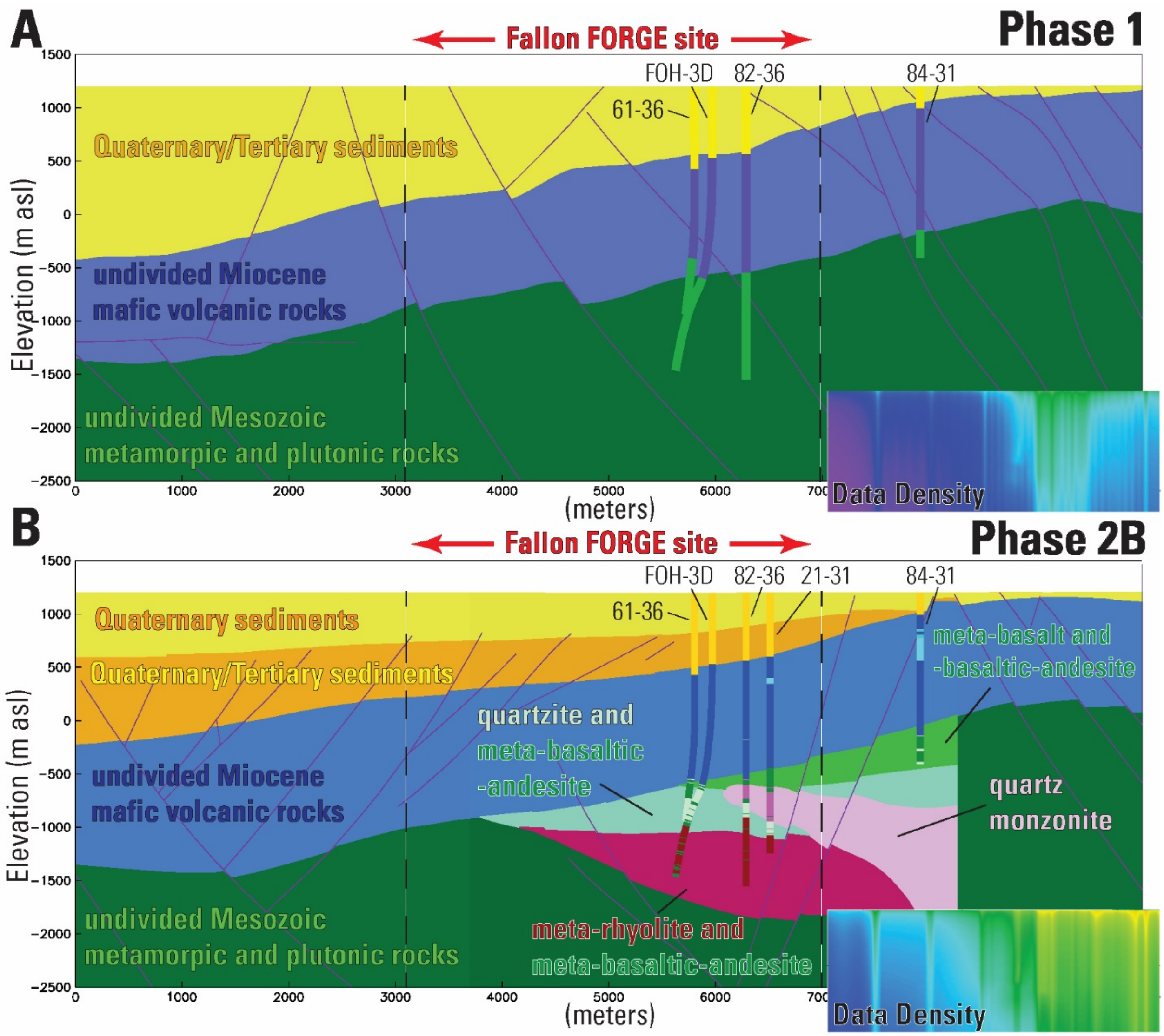

Figure 3. A) Cross-section along A-A' through the Phase 1 3D geologic map. Undivided lithologic logs for the four wells reaching Mesozoic crystalline basement are shown. Inset in bottom right of (A) is the logarithm of the summed spatial density of the Phase 1 data along A-A' section line, warm colors represent a relatively high spatial density of data, cool colors a relatively low spatial density of data. B) Cross-section along A-A' through the Phase 2B 3D geologic map. The lithologic logs for the five wells reaching Mesozoic crystalline basement are shown. The basement stratigraphy shown is from the 'nested' scale 3D geologic map which encompasses the area surrounding five deep wells. Inset in the bottom right of (B) shows the logarithm of the summed spatial density of the Phase 2B data along A-A' section line, warm colors represent a high spatial density of data. Color-scale is equivalent for the A and B insets.

3.2.1 Structure

The new seismic reflection and potential field data better constrain the geometry and relative age of faults. The reprocessed seismic reflection data, in particular, illustrate that vertical separation across faults in very minor, bordering on sub-seismic in many cases (Faulds et al., this volume). Additionally, the late-Pliocene contact within the basin-fill sedimentary section that is evident in the Phase 2B reprocessed seismic reflection data constrains the relative ages of recent faulting in the Phase 2B geologic framework. Of the forty-seven faults in the Phase 2B 3D geologic map, only seven show clear evidence of offset across the late Pliocene contact and no faults are observed to cut reflectors associated with the youngest near the surface (Figure 3), further constraining that the Fallon site lies in a locally quiescent area with respect to young tectonism. The offset across most faults in the Phase 2B 3D map is smaller relative to the Phase 1 3D map (Figure 3). This is because the resolution of the reprocessed seismic reflection data was sufficient to better constrain relative offset in the Phase 2B map in most cases, whereas the offsets interpreted from the Phase 1 seismic reflection were generally over-estimated (Figure 3).

The generally wide (0.5-2.0 km) spacing of faults at the Fallon FORGE site is comparable between the Phase 1 and Phase 2B geologic frameworks. The strike-distribution of the fault system in both the Phase 1 and Phase 2B 3D maps are both consistent with the natural fracture system as identified through analyses of image logs from five wells, and natural fracture systems present in outcrop in analogous lithologic units (Blankenship et al., 2018; Siler et al., 2018). Even so, the location and geometry of individual faults have been greatly refined, with several new faults identified, several negated, and the geometry and/or location of several faults modified. The east-dipping normal fault set that controls the westward tilting of the half graben remains the dominant fault system. The Phase 2B analyses indicate the presence of several west-dipping normal faults that were not resolvable prior to reprocessing the seismic reflection data and the acquisition of the more detailed gravity and magnetic data. Specifically, two west-dipping faults were interpreted in Phase 2B that were not interpreted in Phase 1 project beneath the FORGE site at ~2500-3000 m depth. The geometry and location of the western-most of the two west dipping faults, evident as a high amplitude, laterally continuous gradient in the gravity and magnetic data, and on the seismic reflection data, was confirmed via minor mud losses (97-113 bph) at ~2400 m, near the bottom of well 21-31.

Conclusions

Data collected in Phase 2B of the Fallon FORGE project have helped to refine our understanding of the 3D geologic framework. The new data constrain key details within the general geologic framework that was developed in Phase 1. The Phase 2B data have helped to define the stratigraphy of the Mesozoic crystalline basement section. The key lithologies are from oldest to youngest; Triassic-Jurassic low-to-medium grade meta-rhyolites within interbedded meta-basalt and -basaltic-andesite lavas, Jurassic low-to-medium grade quartzites and other metamorphosed marine sedimentary rocks with interbedded meta-basalt and -basaltic-andesite lavas, Jurassic low-to-medium grade meta-basalt and -basaltic-andesite lavas, all intruded by Jurassic-Cretaceous quartz monzonite. The relatively widely-spaced east-dipping and west-dipping faults cutting through the Fallon site have relatively minor offset, on the order of a few 10s to 200 m, and none of these faults have ruptured surficial Quaternary deposits at or proximal to the site.

The igneous, meta-sedimentary, and meta-volcanic lithologies present at Fallon ensures that new EGS insights gained from future FORGE activities will be directly applicable to a variety of analogous basement sections throughout the United States for future EGS development.

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