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Geologic setting of the West Flank, a FORGE site adjacent to the Coso geothermal field

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ABSTRACT

The West Flank FORGE (Frontier Observatory for Research in Geothermal Energy) site is located immediately west and outside of the Coso geothermal field, eastern California. Coso is a fluid-dominated, high temperature geothermal system that has been producing power continuously since 1987. The reservoir is composed of highly faulted, fractured and hydrothermally altered Cretaceous and Jurassic plutonic basement rocks. The heat source is a shallow, silicic magma chamber associated with overlying, Quaternary rhyolites and basalts of the Coso volcanic field. Over 30 years of development drilling and associated investigations demonstrates that several well-defined boundaries exist at Coso beyond which there is no commercial, hydrothermal geothermal potential. The West Flank is just west of one of these boundaries and it meets all required FORGE temperature (175-225˚C), host rock (crystalline rock), and depth (1.5-4.0 km) criteria.

It has been hypothesized that the Coso volcanic field exists within a right-releasing step-over between two NW-striking, dextral fault systems. Two distinct fault populations yield high permeability drilling targets in the geothermal field. The first population contains WNW-trending with antithetical, NE-trending strike-slip faults and the second includes N- to NNE-trending normal faults. The West Flank appears to be separated from the geothermal field by one such northerly trending fault bounded by a felsic dike swarm. The West Flank's 83-11 well suggests that the West Flank is comprised of weakly altered, leucogranite and diorites typical of the Jurassic to Cretaceous basement. The stress field in the West Flank has been rotated to 81˚ in contrast to the minimum principal stress orientations within the geothermal field which range from 103˚ to 108˚. Limited drilling, geophysics and other data sets are being assessed and synthesized to develop a working, 3d conceptual geologic model of the West Flank for FORGE.

1. INTRODUCTION

The Department of Energy's (DOE) Frontier Observatory for Research in Geothermal Energy (FORGE) project is designed to successfully test and report on techniques needed to make enhanced geothermal systems (EGS) a commercially viable electricity generation option. The objective of FORGE is to establish and manage a dedicated site where the scientific and engineering community can develop, test, and improve new technologies in an ideal EGS environment.

DOE selected five Phase 1 FORGE sites, two of which are on Navy-managed ground. These sites are referred to as the West Flank and Fallon, located respectively at Naval Air Weapons Station (NAWS) China Lake, CA, and Naval Air Station (NAS) Fallon, NA. The West Flank site is within the <1.0 Ma Coso Volcanic Field (CVF) in eastern California (Fig. 1). It occupies about 1,100 acres of the North Ranges of NAWS China Lake (Fig. 2). In addition to being entirely within the fence line of a Navy research and development facility, another attribute of the West Flank site is that it is adjacent to one of the largest producing geothermal fields in North America, the Coso geothermal field. The FORGE area heat source is the Coso geothermal field's heat source. And as a practical matter, infrastructure associated with the Coso geothermal field (water, staging areas, equipment, office space) in this remote region of NAWS China Lake is also available for FORGE activities.

This report describes the geologic setting of the West Flank. It also presents the geological attributes that make the West Flank an ideal location for the multi-year, EGS testing and evaluation program called FORGE.

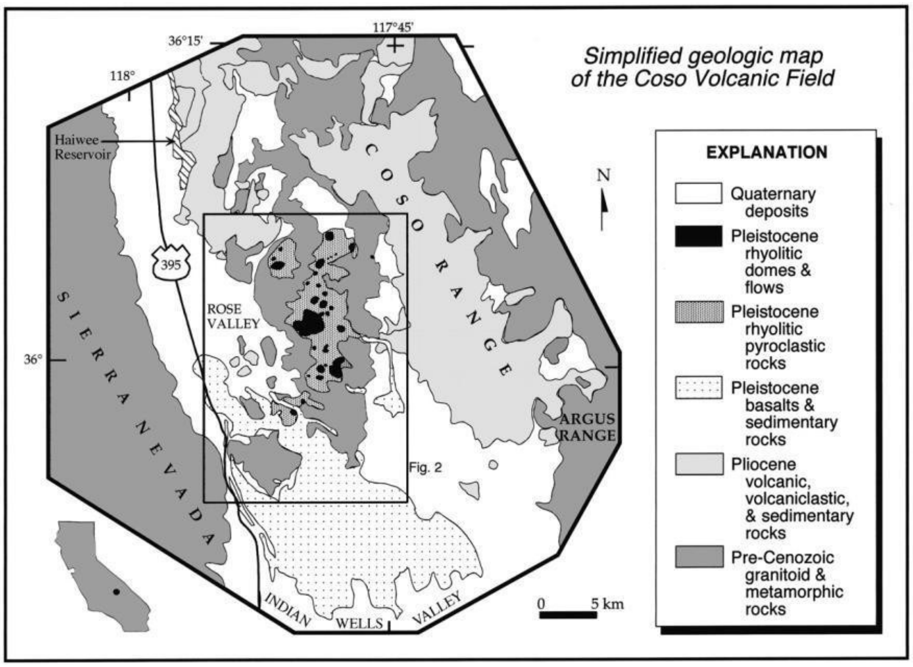

Figure 1: Location and generalized geologic map of the Coso volcanic field, inside the black polygon. The eastern margin of the West Flank is bounded to the east by the largest rhyolite dome in the field (in black) seen in the center of this image. Rose Valley is the source of Hay Ranch water for FORGE. From Duffield and Bacon (1981).

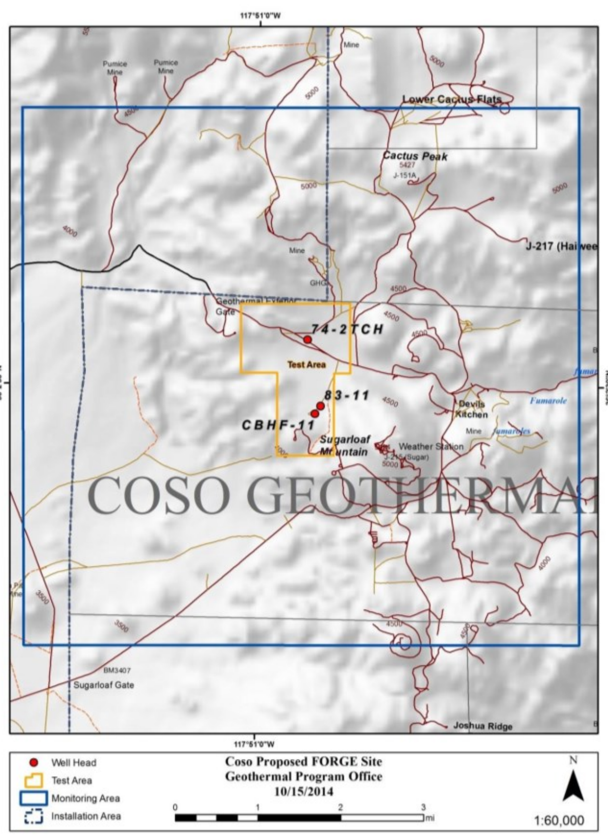

Figure 2.Proposed FORGE test area, West Flank. Gold polygon encompasses the 1,100 acre FORGE site and is where drilling, stimulation and other downhole activities will take place. The blue polygon of 27,860 acres and is where FORGE-related instrumentation (e.g., seismometers) can be placed and larger-scale geophysical surveys may occur. Red lines are dirt tracks.

2. GEOLOGIC SETTING

The West Flank FORGE site is located within the Coso Range, about 50 km north of Ridgecrest, CA, on NAWS China Lake. The West Flank area consists of thin Quaternary sedimentary cover, Pliocene and younger basaltic to rhyolitic volcanic rocks, and Mesozoic plutonic basement. Locally the Cretaceous to Jurassic plutons intrude felsic metavolcanic and other metamorphic rocks ranging from Mesozoic to Precambrian in age (Duffield et al., 1980; Whitmarsh, 1998b).

Pliocene volcanism persisted from 4.0 to 1.5 Ma. Over 30 km^3 of largely mafic to intermediate composition lava flows flank the Coso Range to the east and south (Duffield et al., 1980). After a brief volcanic hiatus, a period of bimodal volcanism began in the Coso Range at < 1.0 Ma and generated what is locally referred to as the Coso volcanic field (CVF). The 3-5 km^3 of CVF material unconformably drape Mesozoic basement rocks in the central Coso Range. Rhyolite domes and associated volcaniclastic and epiclastic successions dominate the CVF landscape. $^{40}Ar/^{39}Ar$ dates and zircon geochronology from select domes suggests that at least 5 distinct periods of rhyolite dome growth began around 625 ka (e.g., Devils' Kitchen dome) (Fig. 3). The youngest cluster of domes is dated at ~85 ka (e.g., Sugarloaf) and based on their roughly NNE alignment, these domes may have been derived from a NNE-aligned dike system (Bacon et al., 1980; Simon et al., 2009). The volcanism is a product of mafic intrusion at the base of the crust, brought on by east-west directed, Basin and Range-style lithospheric extension and associated partial melting of the crust (Duffield et al., 1980). Elevated heat flow in the West Flank FORGE area is a product of conductive heating associated with a silicic magma chamber that fed the Pliocene and younger volcanism, which is estimated to lie below ~8-10 km (Duffield et al., 1980). The Pliocene and younger volcanic rocks lie uncomformably on Jurassic and Cretaceous granitic to dioritic basement rocks, which are correlative with the Sierra Nevada Batholith (Duffield et al., 1980; Reasenberg et al., 1980; Wilson et al., 2003; Hauksson and Unruh, 2007; Simon et al., 2009) .

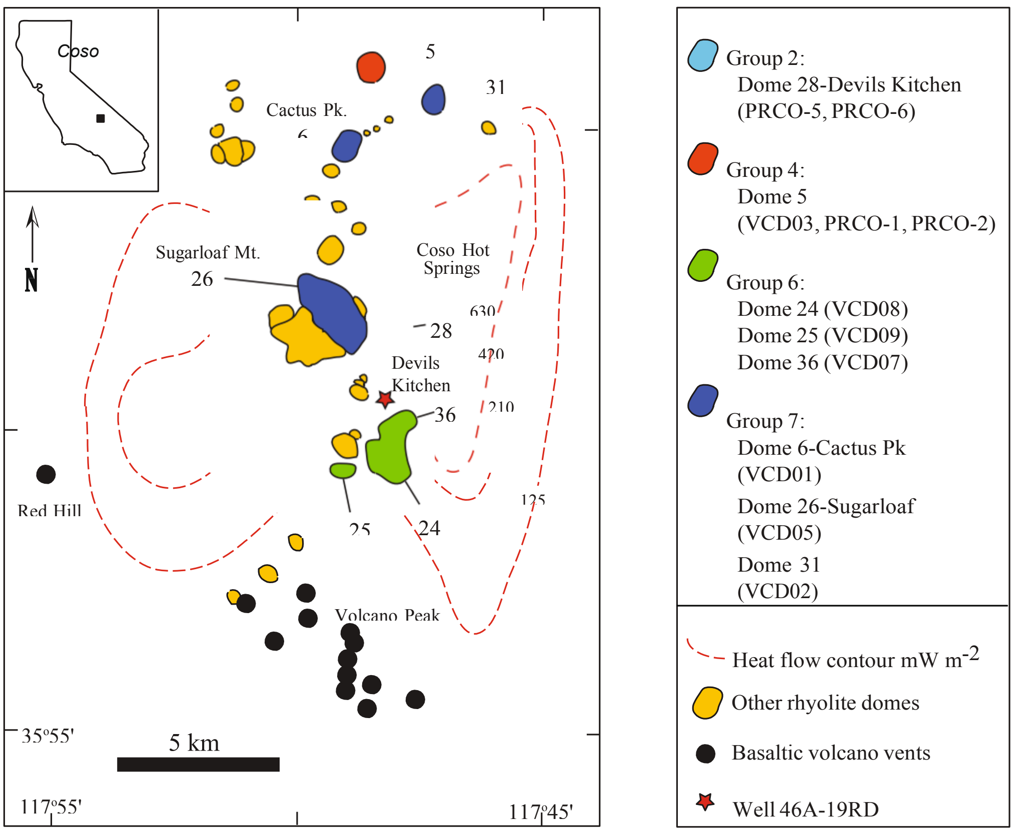

Figure 3. Map of rhyolite domes, cinder cones of Coso volcanic field and shallow heat flow measurements. Domes color- coded by age as determined by 40Ar/39Ar and zircon dates. From Simon et al., (2009).

The Mesozoic basement and proposed host rock to the FORGE work is composed largely of Jurassic age (165 Ma) plutons ranging compositionally from gabbro to quartz porphyritic granite (Whitmarsh, 1998b). WNW-striking intermediate and felsic composition Independence dikes (~148 Ma) and north-striking, Cretaceous age dikes are the two dike sets mapped in the West Flank region (Whitmarsh, 1998). Cretaceous age granites are also abundant in the Coso Range. The Cactus Flat Granite (Kcf), north of the proposed West Flat FORGE site, is the closest mapped Cretaceous age pluton to the West Flank area (Whitmarsh, 1998).

The CVF is within a right-releasing step-over between the dextral Airport Lake (ALF) and Little Lake fault zones (LLFZ) to the south and the Wild Horse Mesa and Owens Valley faults to the north (Fig. 4). Two distinct fault populations have been identified within the CVF, WNW and antithetical, NE trending strike-slip faults and N to NNE trending normal faults. These faults are both high permeability drilling targets and they locally segment the field into distinct hydrothermal regimes. The West Flank is separated from the rest of the field by one such northerly trending fault, evident through pressure data and downhole stress measurements.

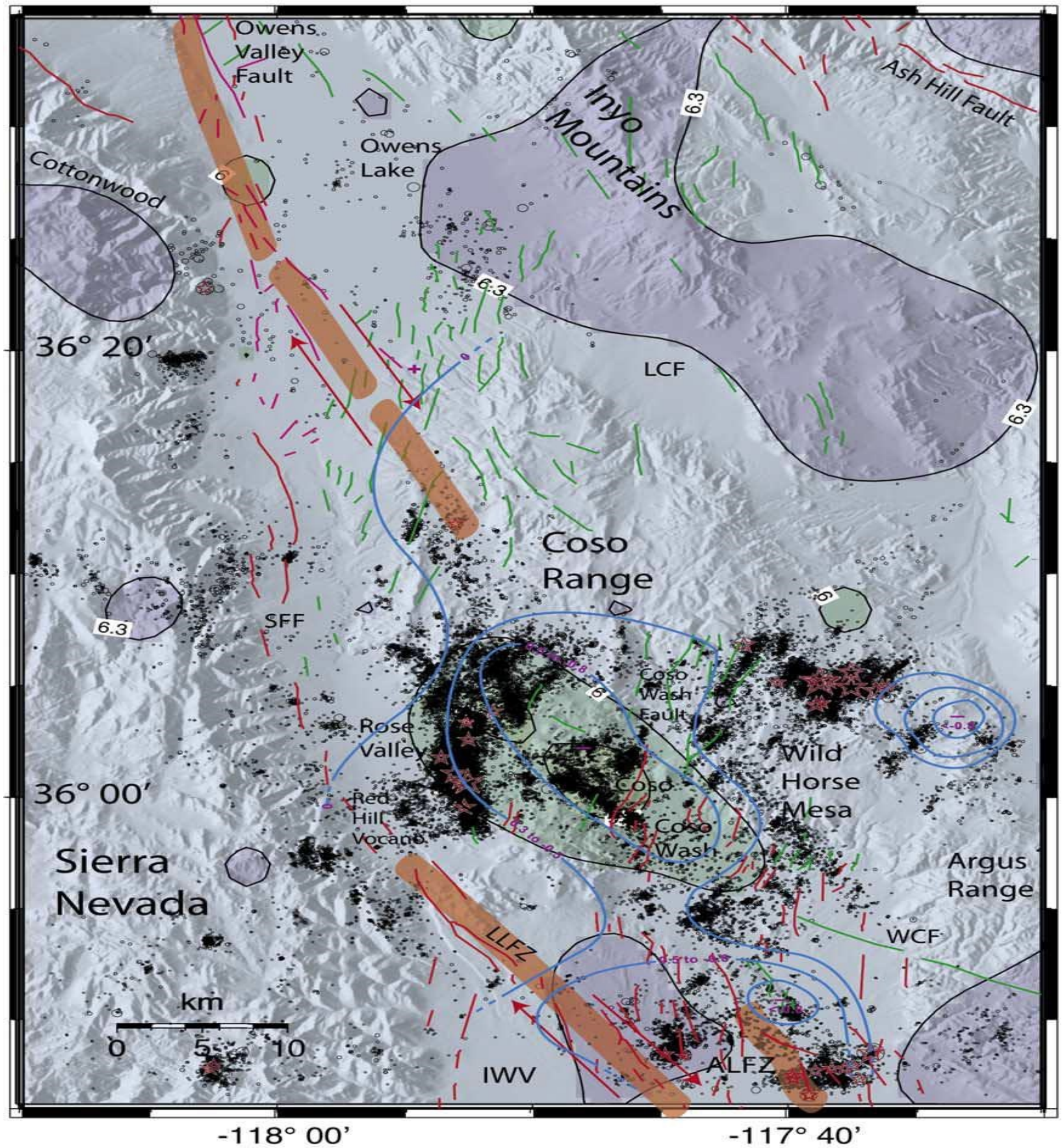

Figure 4. Schematic view of transtensional tectonics of the Coso region. Extensional faulting within the Coso Range occurs in a releasing right step-over between the Owens Lake fault to the north and the Airport Lake fault zone to the south. The region with low P-wave velocities (shown with black contours) beneath the central Coso Range coincides with the releasing step and locus of transtensional crustal thinning, which are shown as (blue) contours. Superimposed on the background topography is relocated seismicity and mapped faults. Red, Holocene; green, late Quaternary. ALF, Airport Lake fault zone; IWV, Indian Wells Valley; LLFZ, Little Lake fault zone; SFF, Sierran frontal fault; WCF, Wilson Canyon fault; LCF, Lower Centennial Flats (from Unruh and Hauksson, 2007).

Upper crustal faults overlie a NW-trending zone in the 5-10 km depth range beneath the Coso Range which is characterized by high heat flow and low P-wave and S-wave velocities (Fig. 4) (Unruh and Hauksson, 2005). The brittle-ductile transition zone is bowed up from ~11 km depth over the low velocity zone as evidenced by shallowing of the base of seismicity to 4-5 km depth beneath the Coso geothermal field. At the latitude of the geothermal field, the traces of active normal faults dip west and likely terminate against or sole into the brittle-ductile transition zone as it deepens westward toward Rose Valley. The velocity signature at the depth range of 11-16 km is interpreted to be a tabular, sill-like magma body 20 km long and 3-5 km thick (Unruh and Haukkson, 2005).

3. COSO GEOTHERMAL FIELD

The Coso geothermal field became operational in 1987 after more than a decade of exploration and development. It is comprised of four power blocks housing nine 30-MW turbine-generator sets. Steam is provided from a well-gathering system connecting over 140 production and injection wells distributed over almost 15,000 acres within the CVF. With a capacity of 270 MW, Coso is one of the largest geothermal systems in North America.

All wells at Coso are completed in the intrusive basement rocks or felsic dikes and hypabyssal rhyolites of the CVF. The field is principally a liquid-dominated system. High fluid temperatures (200°-328°C) permit the use of double-flash technology for steam extraction. Production fluids are moderately saline chloride brines with total dissolved solids ranging from 7,000 ppm to 18,000 ppm. Non-condensable gases make up six percent of the gas fraction, with 98 percent of that amount being carbon dioxide. The heat source is a magma chamber, the top of which may be as shallow as 8-10 km below an upwarped, brittle-ductile zone (Wicks et al. 2001; Manley and Bacon, 2000; Unruh et al., 2002; Monastero et al., 2005).

4. WEST FLANK FORGE SITE

The proposed 1,100 acres of the West Flank FORGE site is situated in relatively flat terrain west of the Coso geothermal field. FORGE requirements are characterized in the West Flank by the 83-11 well which was drilled in 2009 west of the Sugarloaf rhyolite dome for production purposes (Fig. 2). It was drilled to 9,480 ft below ground surface (bgs). Its temperature profile indicates a bottom hole temperature of 580˚F (>300˚C). Static temperature logs illustrate that the required FORGE temperature range of 175˚C (347˚F) to 225˚C (437˚F) exists between 5,000 ft (~1.5 km) bgs and 7,500 ft (~2.3 km) (Fig. 5). All but the top few hundred feet of this well was completed in crystalline basement rock. The conductive profile of the static surveys and the lack of any significant perturbations in the spinner survey demonstrate that this well is noncommercial. An injection test demonstrated this well has very low permeability.

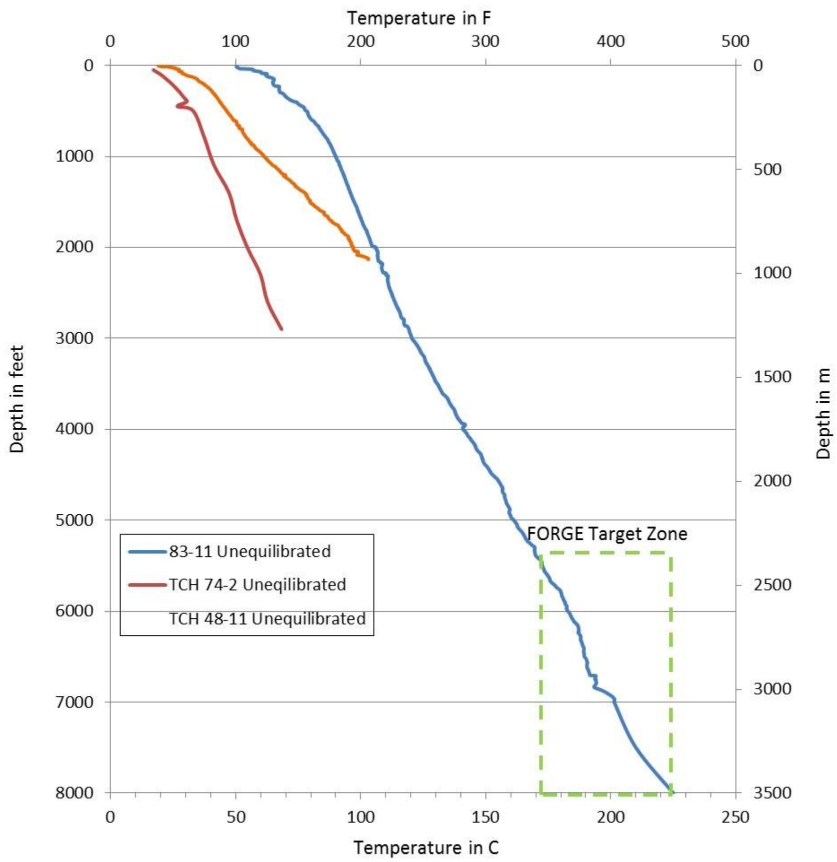

Figure 5. Temperature profiles of well 83-11, temperature core hole (TCH) 74-2 and TCH 48-11. Driller's logs indicate basement (granite) was encountered at ~600 ft bgs in 83-11. Static temperature profiles in 83-11 were run from July through November 2009 and an injection test was conducted in August 2009. T emperature profiles are thick blue, red and orange lines (TCH 48-11). Note that all of the curves are conductive. Interpretations of the injection test on 83-11 suggested that there are no productive (i.e., high permeability) zones in this hole. The green dashed box outlines ideal FORGE temperature and permeability conditions in 83-11 between ~5,300 ft (~1.6 km) and 8,000 ft (~2.4 km) bgs.

Permeability calculations conducted within the Coso geothermal field suggest that brittle zones with temperature profiles indicative of convective heat and fluid flow have permeabilities in the 10^{-13} m^2 range, whereas shallower, clay-rich conductive cap-rock zones have permeabilities in the 10^{-17} m^2 range (Davatzes and Hickman, 2010). Based on its conductive temperature profile, it is inferred that the permeability near well 83-11 is on the order of $<10^{-16}$ m^2.

Pressure records from well 83-11, when compared to wells several km to the east over a two-year span, show that there is no pressure communication with productive areas of the main geothermal field to the east and the proposed FORGE site (Fig. 6). Between

November 2012 and October 2014 steady pressure drops were seen in the Navy II and BLM wells in the main geothermal field, whereas (aside from seasonal fluctuations) pressure in well 83-11 remains unchanged. This demonstrates that well 83-11 is not in pressure communication with the Coso geothermal field. The non-commercial status of well 83-11 coupled with the lack of pressure communication with other wells to the east demonstrates that the western margin of the permeable Coso geothermal field is a northerly trending line that effectively runs through the middle of the Sugarloaf rhyolite dome.

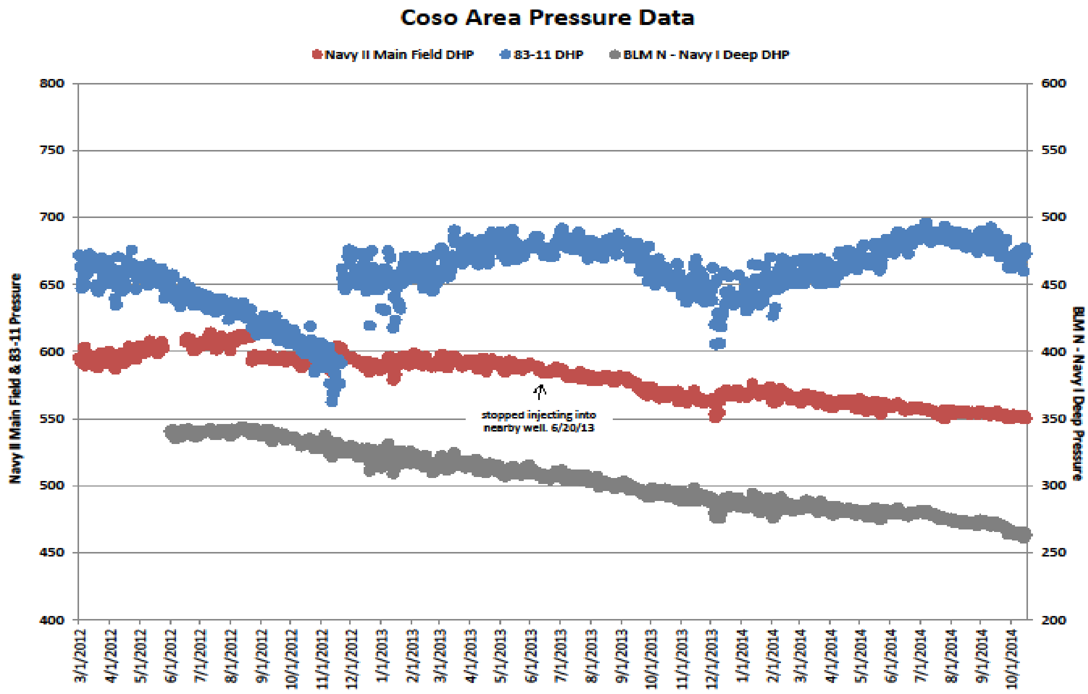

Figure 6. Downhole time-series pressures in well 83-11 (blue) compared to other portions of the Coso geothermal field (red and grey). Note how with the exception of seasonal cycling resulting in a downward trend of pressures from Nov., 2012 through Oct. 2014, pressures in well 83-11 remain relatively unchanged while wells from the Navy II portion of the field (red) and BLM north portion of the field (grey) show a steady decline. This absence of pressure communication demonstrates that well 83-11 is not part of the active Coso geothermal field. The pressure decline measured in well 83-11 from March 2012 through Nov. 2012 was due to faulty equipment.

Along with pressure and permeability data demonstrating that the FORGE area is not connected to the Coso geothermal field, image log analyses of borehole induced structures from wells in the producing geothermal field as well as wells outside the field like well 83-11 show a stress variation from the main field to the West Flank. Schoenball et al. (2015) demonstrates a significant change in principal stress orientation from the main area of the Coso field to the West Flank. This change in principal stress orientation continues to suggest that while rocks in the FORGE area are the same rocks that host the geothermal field to the east, the stress state and therefore the active structures (i.e., active faults or fluid pathways) and associated alteration varies from the FORGE area to the geothermal field.

5. WEST FLANK GEOLOGY

The West Flank FORGE area is dominated by diorite to quartz-diorite of Jurassic age distinguishable in hand sample by a mineral assemblage of hornblende, plagioclase ± quartz. These rocks occupy the intermediate endmember of the Jurassic “mixed complex”, Jmci (Fig. 7) (Whitmarsh, 1998 and 1998b). An analysis of cuttings and core from 6 wells drilled over the last 4 decades, 3 within the West Flank and 3 in the Coso geothermal field to the east, indicates that Jmci comprises ~67% of the interpreted rock volume of the West Flank. Locally Jmci is intruded by and intermingled with Jurassic granite consisting of plagioclase, alkali feldspar and quartz, with ≤ 10% mafic minerals (primarily muscovite ±biotite) (Whitmarsh, 1998b). These rocks represent the felsic endmember of the Jurassic mixed plutonic complex, Jmcf (Fig. 7). Contact relationships between Jmci and Jmcf are highly diffuse, typically consisting of several meters to tens of meters of mixed and intermingled dikes and/or sills of Jmci, Jmcf, and of compositions intermediate between the two endmembers. Magmatic deformation and magmatic stoping textures are abundant, confirming that Jmci and Jmcf are age equivalent. Jmcf constitutes ~18% of the interpreted rock volume in the West Flank and occurs almost exclusively at levels shallower than ~1350 m below ground surface.

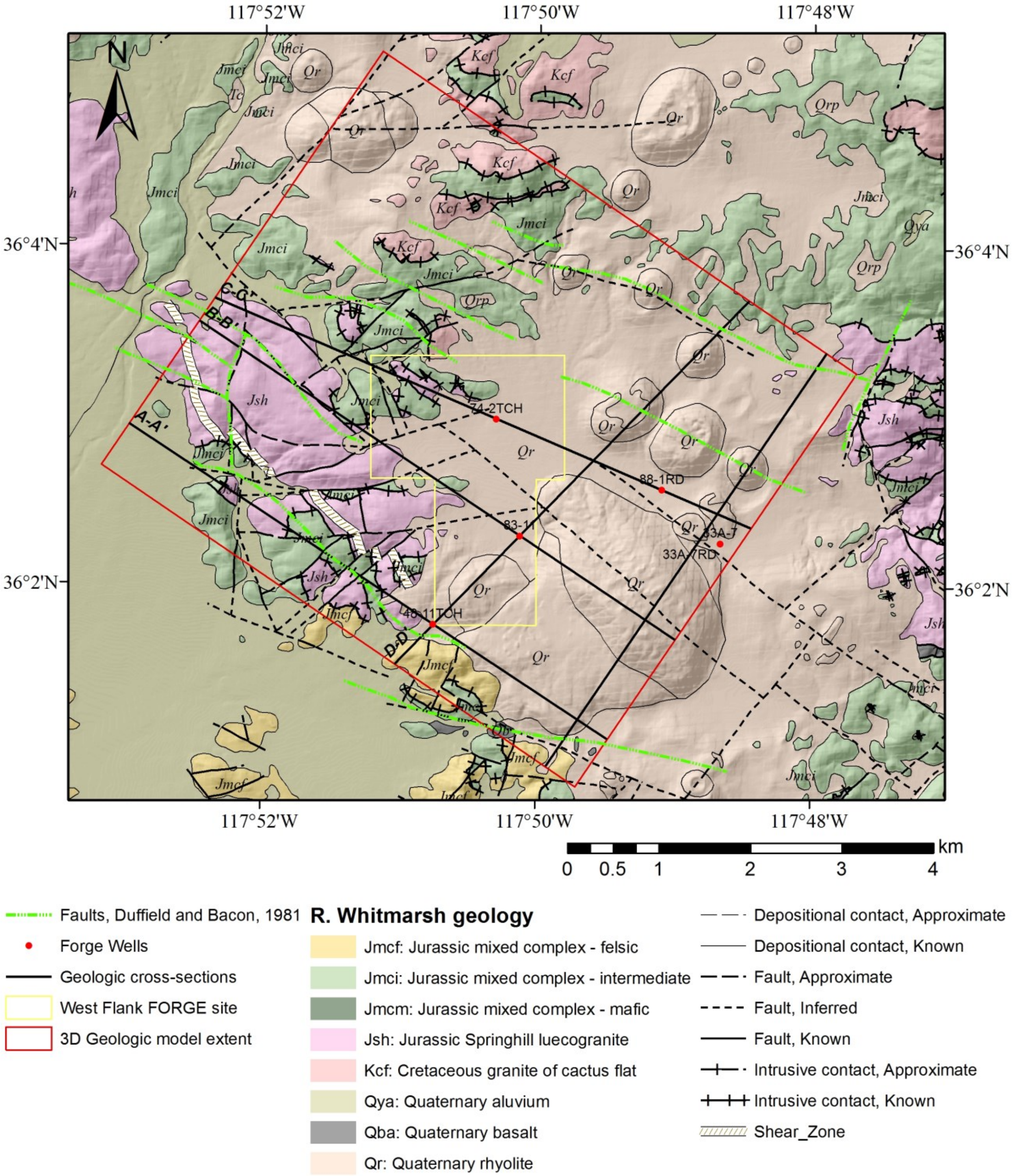

Figure 7. Geologic map of West Flank FORGE area (after Whitmarsh, 1998). Yellow T shaped polygon is 1,100 acre, main FORGE site. Red polygon is portion of Coso volcanic field included in the FORGE conceptual model. Red numbered dots are Coso geothermal wells (all are non-commercial). Heavy black diagonal lines are geologic cross sections that have been drawn. Line CC' is the cross-section presented in Figure 8.

Other volumetrically important lithologies in the six wells analyzed are garnet-bearing, quartz and feldspar leucogranite, which we equate to the Jurassic Springhill leucogranite, Jsh, and rhyolite dikes that are likely the intrusive equivalent of the Quaternary rhyolite domes (Qr) mapped at the surface (Fig. 7) (Duffield and Bacon, 1981; Whitmarsh, 1998). These rocks constitute ~3% and ~4% of the rock volume within the six wells analyzed. Jsh occurs predominately in wells CGEH-1 and 74-2, which are adjacent to mapped exposures of Jsh (Whitmarsh, 1998). Qr occurs predominantly below ~1000 m and in the highest density below ~2000 m. Mafic intrusions are volumetrically insignificant and their affinity is poorly constrained as several different Mesozoic and Cenozoic mafic units are mapped throughout the area (Duffield and Bacon, 1981; Whitmarsh, 1998).

Well data along with geologic map data (Whitmarsh, 1998) constrain the geometries of geologic cross-sections drawn through the FORGE area (Fig. 8). The cross-sections are characterized by primarily Jmci with discontinuous Jmcf bodies between ~500 and ~1000 m bgs (Fig. 8). Two separate Jsh intrusions occur along the northwestern and northeastern edges of the West Flank FORGE area, although lithologic data are largely insufficient to constrain their subsurface geometries.

The FORGE temperature window of > 175°C occurs at ~1500 m bgs in well 83-11. Temperature data from coreholes previously drilled within the FORGE area, 74-2 and 48-11, were also utilized to update the thermal model for this area. Within the West Flank FORGE area and extending to ~3750 m bgs, this corresponds to ~40 km^3 of rock volume with temperatures expected to meet or exceed 175°C. Jmci is the dominant formation in this area although Qr may constitute as much as ~15% rock volume, locally.

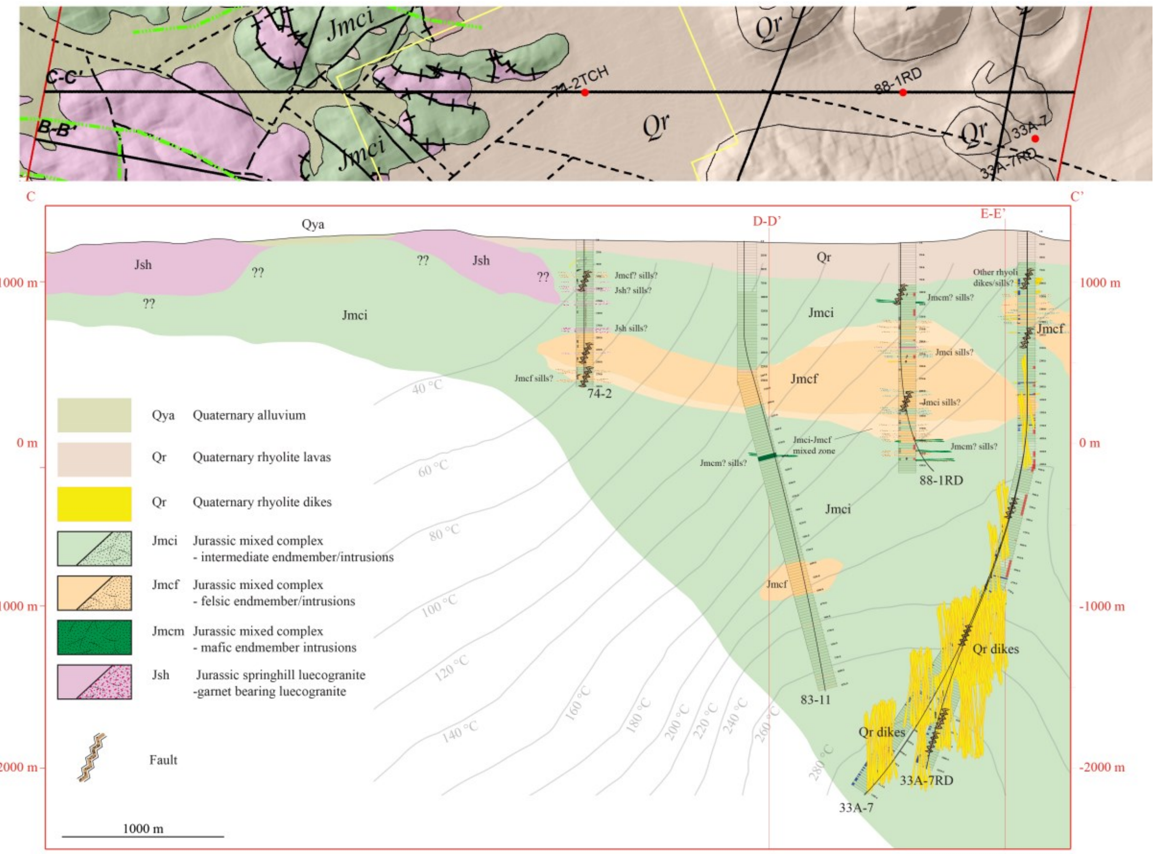

Figure 8. Preliminary CC' (west to east) cross-section through West Flank. Unit labels are based on logging of core and cuttings with Whitmarsh (1998) map unit nomenclature applied. Qr dikes near eastern margin form what appears to be a structural and permeability break between the West Flank and the Coso geothermal field. DD' and EE' are cross-sections not represented in this report. Temperature contours are constrained by data from wells 74-2, 83-11, 33A-7, and 48-11 (not shown) as well as other data from the Coso geothermal field.

6. SEISMICITY

Seismicity within the Coso geothermal field occurs both tectonically and as a consequence of injection and production within the field (Monastero et al., 2005; Kaven et al., 2011; Kaven et al., 2014; Schoenball et al., 2015). After several decades of geothermal production and seismic monitoring, there have been no adverse effects experienced in geothermal operations or locally due to seismicity.

The seismicity is recorded by the Navy Geothermal Program Office (GPO) using a combination of down-hole and surface seismometers (Fig. 9). Seismicity is recorded reliably from magnitudes down to Ml=-0.5 and the largest events recorded near the Coso West Flank area are up to Ml 5.2 (Kaven et al., 2011). The Navy GPO network records several hundred seismic events in the West Flank area per month, thus providing an extensive catalog that informs the structural setting in the West Flank (Fig. 10).

Seismic event locations reveal diffuse clouds of seismicity that occur near Sugarloaf Mountain and further west at the boundary of the West Flank site (Fig. 9). These "clouds" do not clearly coincide with the mapped fault traces at the surface. Subsurface imaging of fault structure from reflection seismic (Monastero et al., 2005) or magnetotelluric imaging (Newman et al., 2008) lacks sufficient resolution to precisely image faults; thus, the relationship of these earthquake locations to reservoir-scale fault structure at depth remains poorly constrained. We are currently using high precision relocated seismicity to inform the fault structure at the West Flank. These preliminary findings suggest that large, through-going faults have traces oriented north-northwest to south-southeast. This orientation is consistent with faults observed within the Main Field of the Coso Geothermal field.

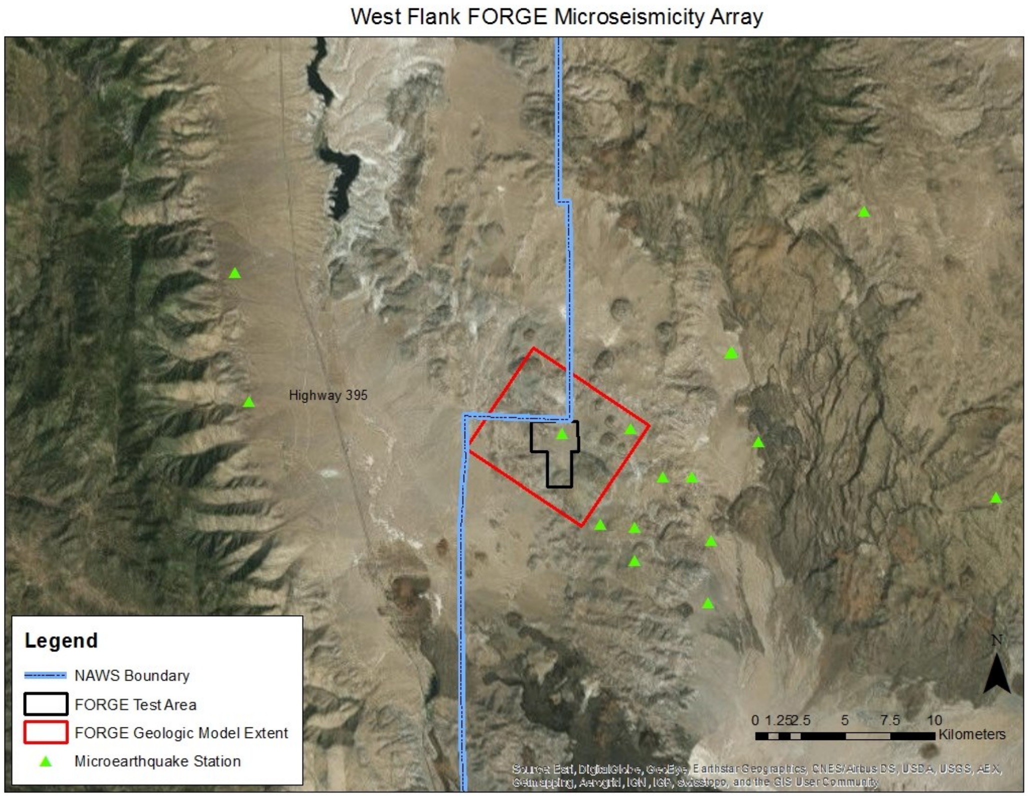

Figure 9. Navy GPO seismic monitoring network consisting of borehole and surface station locations.

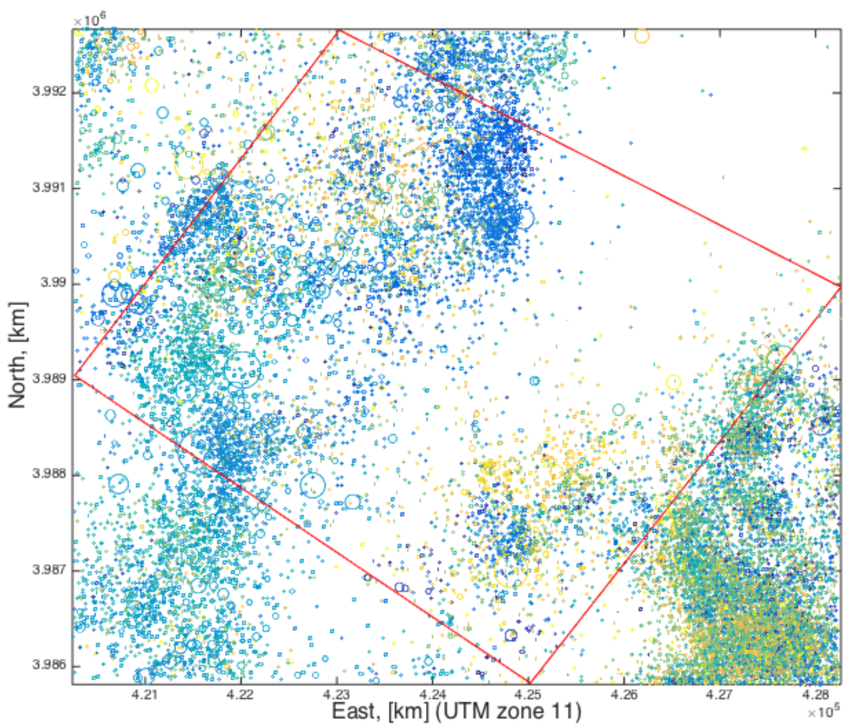

Figure 10. Seismicity recorded on the Navy GPO seismic network from 1996 through 2012 (blue indicates early catalog, yellow indicates 2012). Circle sizes indicate relative magnitudes of seismic event (i.e., smaller circles are smaller magnitudes). The red polygon is the same polygon is illustrated in Figs. 7 and 9. It approximates the West Flank geological model boundary, presented in cross-section in Fig. 8 and in 3d in Fig. 11.

7. SUMMARY

The West Flank covers 1,100 acres and is within a secure and remote portion of NAWS China Lake. Analysis of existing well data suggest that ~40 km^3 crystalline basement rock exceeding temperatures of >175˚C (347˚F) is available for EGS testing for FORGE. Basement rock is comprised largely of Jurassic age "mixed complex" diorite and granite (Fig. 11). Testing of the only production-size well drilled in the West Flank demonstrates that it is very hot but has non-commercial permeability. Pressure tests as well as principal stress analyses from image logs in well 83-11 indicate that this well is distinct from the productive Coso geothermal field to the east. Three decades of seismic monitoring has been performed in the area. Preliminary findings from interpretations of these data suggest that through-going faults may exist in the West Flank.

8. ACKNOWLEDGEMENTS

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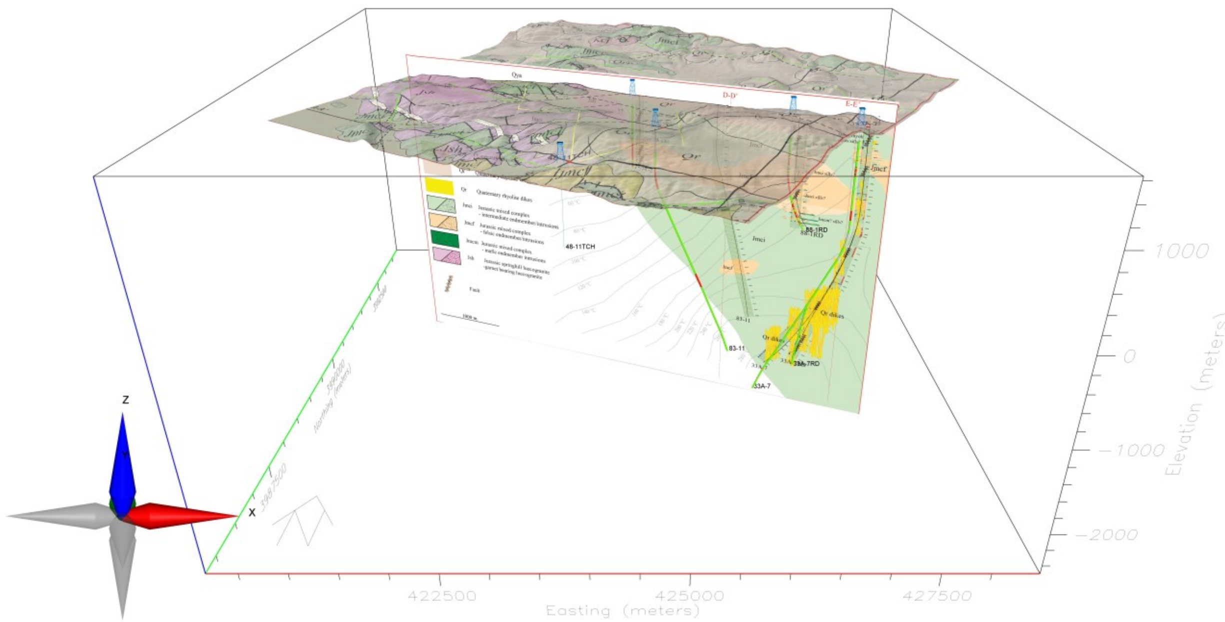

Figure 11. Oblique 3d view of West Flank. Unit labels are from Whitmarsh (1998). Qr dikes form what appears to a structural and/or permeability break between the West Flank and the Coso geothermal field. Temperature contours are constrained by data from wells 74-2, 83-11 and 48-11 (not shown) as well as other data from the Coso geothermal field.

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