PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

THE ROLE OF STRESS MODELING IN STIMULATION PLANNING AT THE NEWBERRY VOLCANO EGS DEMONSTRATION PROJECT

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ABSTRACT

Field work and planning has begun on the Enhanced Geothermal Systems (EGS) Demonstration Project at Newberry Volcano in central Oregon. The tectonic and volcanic setting of the site suggests that the stress state and fracture patterns may be complex. Because the stress state is a primary control on the growth of an EGS reservoir, the technical team has begun building a preliminary 3-D stress model for Newberry by collecting new field and laboratory data, including borehole imaging using an ultrasonic borehole televiewer, micro-seismic monitoring through a local network, mineralogical characterization and mechanical testing of existing core, and regional fault and fracture mapping using LiDAR. Analysis of the data sets has just begun, but preliminary results indicate that the stress and fracture patterns may be more straightforward than indicated by the complex geologic setting.

INTRODUCTION

The *in situ* stress tensor is a primary control on the design and creation of an Enhanced (or Engineered) Geothermal System (EGS; see MIT, 2006). Stress orientations and relative magnitudes control which fractures are most likely to slip and, consequently, the orientation and overall shape of the resulting EGS reservoir (e.g., Hickman and Davatzes, 2010). Stress magnitudes determine the fluid pressure required to initiate hydroshearing, the effectiveness of that shearing in enhancing permeability (depending also on rock mechanical properties; see Lutz et al., 2010), and the volume of the EGS reservoir. At the outset of any EGS project, tectonic studies, well tests and geophysical logs must be used to constrain the stress state. However, it remains a challenge to model the stress tensor in the EGS volume due to the potential effect of local stress variations caused by weak fault zones, recent fault slip, density variations, natural fluid pressures, volcanic activity, and variability in the mechanical properties of the rock mass.

NEWBERRY EGS DEMONSTRATION

A DOE-funded EGS demonstration project is now underway at Newberry Volcano in central Oregon. Preliminary investigations suggest that this is one of the most promising EGS sites in the United States, with a large conductive thermal anomaly yielding high-temperature wells, but with permeability orders of magnitude less than conventional hydrothermal wells. Northwest Geothermal (NWG) 55-29, drilled in 2008 to a total measured depth of 10,060, is very hot but with very low permeability, making it an ideal EGS target.

The project has brought together a multi-disciplinary team led by AltaRock Energy (ARE) with participants from Newberry Geothermal, Davenport Power, Temple University, the U.S. Geological Survey (USGS), Lawrence Berkeley National Lab, Texas A&M University, and the University of Utah. The goals of the project include (Osborn et al., 2010):

- Stimulate multiple zones in well NWG 55-29 using ARE's proprietary diverter technologies,
- Create an EGS reservoir,
- Test single well tracers,
- Confirm EGS reservoir viability through flow back of >30 L/s to the stimulated well,
- Drill two production wells to intersect the EGS reservoir, and
- Using well NWG 55-29 as the injector, demonstrate EGS viability through a three month production test.

Newberry Volcano is located at the intersection of three distinct structural zones: the Basin and Range, the Cascades Graben, and the Brother's Fault Zone (Figure 1), each with a different tectonic history, deformation style and fault orientation. The Basin and Range here and further south in Nevada is characterized by NNE-trending normal faults that

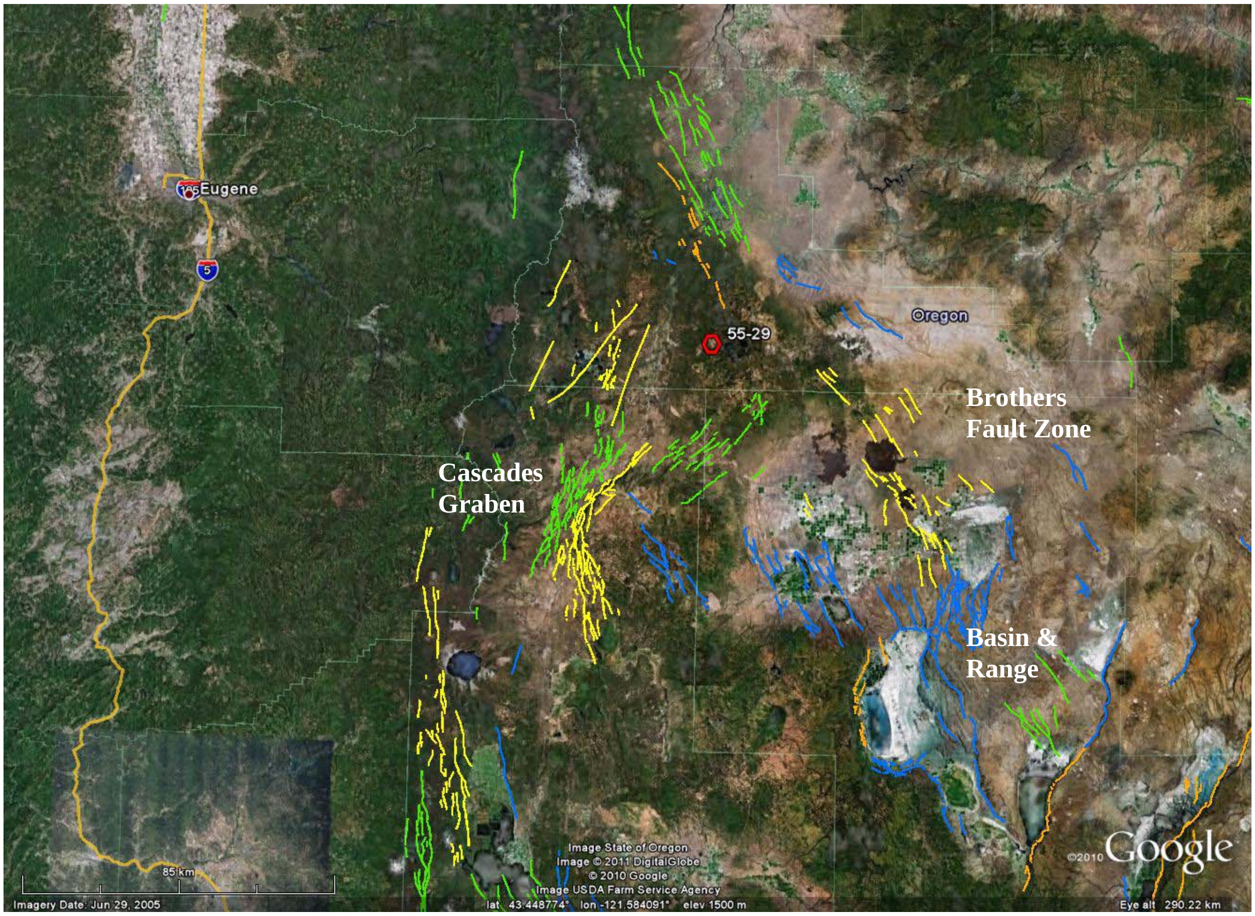

Figure 1: Regional Map showing location of the Newberry EGS demonstration site (well NWG 55-29) at the intersection of three structural trends in central Oregon. Colored lines are faults from the USGS Quaternary fold and fault database. The fault ages are coded by color, from oldest to youngest: blue, green, yellow, orange.

divide the terrain into the characteristic basins and ranges. The northern boundary of the Basin and Range is the Brothers Fault Zone, a major WNW-trending zone of faults. The Cascades Graben, defined by various sets of N-trending normal faults, is an important structural feature of the Cascades Volcanic Arc of central Oregon. These three sets of fault orientations, all classified as Quaternary in the USGS database (Personius, 2002a), are mapped in the region surrounding Newberry Volcano (Figure 1). In addition, the local stress state at the EGS injection well 55-29 may be complicated by its proximity to ring fractures associated with caldera collapse.

EGS IN CALDERA SETTINGS

The injection well, NWG 55-29, is on the west flank of Newberry Volcano, ~3 km from the caldera rim. The caldera itself, a ~6 km-wide depression, is the site of the Big Obsidian flow, the youngest (1400 ybp) volcanic activity at Newberry Volcano. Activity as young at 7000 ybp has also occurred in cinder cones as far as 20 km to the north. The Newberry Volcanic Monument encompasses much of this young volcanic activity.

Two important Hot Dry Rock (HDR) projects, Fenton Hill, New Mexico, and Hijiori, Japan, were also located at calderas and employed stimulation techniques similar to those used in EGS. Below we briefly review the findings related to stress from those projects to provide background on what might also be expected at Newberry.

The geologic setting of the Fenton Hill HDR project is similar to that of Newberry. Fenton Hill is on the western flank of Valles Caldera, just outside the ring fractures which define this large (20-km-diameter) caldera. Valles Caldera is within the Rio Grande Rift, which is characterized by N-S striking normal faults and E-W crustal extension.

In the first phase of HDR development (1974-1979) at Fenton Hill, the injector and producer wells were eventually connected by a single, near-vertical fracture zone after three stimulations and two redrills of the production well, resulting in the world's first HDR reservoir (Duchane and Brown, 2002). Flow tests in 1980 on the Phase 1 reservoir achieved a near constant flow rate of 90 gpm, but the temperature declined from 156°C to 149° C. Thus, the reservoir was deemed too small to be commercial.

In the second phase of HDR development at Fenton Hill (1982-1984) two wells were drilled in advance of stimulation that were intended to comprise a production well and injection well doublet, each with a 35° sloped section near the bottom. The sloped section of the production well was drilled vertically above the sloped section of the deeper injector. The stimulation plan was based on the assumption that the reservoir would grow in the same way as it did in Phase 1, upward as vertical fractures, thus connecting the two sloped wellbores. However, the Phase 2 reservoir grew as an ellipsoid with a long axis along the trajectory of the injection wellbore and extensive subsequent hydraulic fracturing could not connect the wells. Redrills were then necessary to connect the wells to the stimulated reservoir, resulting in large portions of the ellipsoidal reservoir being not accessible to flow (Duchane and Brown, 2002).

The assumption that the fractures stimulated at Fenton Hill were primarily tensile failures, oriented perpendicular to the minimum principle stress, resulted in an interpretation that the two phases of reservoir creation at Fenton Hill were performed in regions with different stress regimes. The alternative interpretation, now widely accepted, is that the fluid connections in an EGS reservoir are created when preexisting fractures and faults are reactivated through shearing in response to the changes in the effective stress due to increased pore fluid pressure. In this interpretation, the principle difference between the Phase 1 and Phase 2 reservoirs at Fenton Hill is not the stress direction but a change in the orientation of the pre-existing, natural fractures (Duchane and Brown, 2002).

Further support for the interpretation that elevated fluid pressure could cause shear slip along pre-existing fractures at Fenton Hill is provided in Fehler (1987). First, a large data set of injection-induced microseismic events from Phase 2 was analyzed to determine the planes along which seismic slip had occurred. Second, the *in situ* stress field determined from wellbore breakouts was determined to be horizontal and oriented N104°E, consistent with the project's tectonic setting within the Rio Grande Rift. Third, it was shown that the fault planes that slipped during injection were ideally oriented for slip in the measured stress field; i.e., the ratio of shear stress to effective normal stress on these faults was at a maximum.

The Hijiori, Japan HDR site is located on the southern rim of a small (~2 km-diameter) Quaternary caldera on the northern part of Honshu. Four boreholes were drilled through ~1.5 km of basalts, andesites, tuffs, and pyroclastic flows to reach the EGS target formation and depth: the granodiorite basement at a depth of 1.5 to 2.2 km (Kitani and Tezuka, 1999).

Two HDR reservoirs were created at Hijiori: a shallow (1550-1800-m-deep) reservoir by injecting into well SKG-2 in 1988-1989 and a deep (2200-m-deep) reservoir by injecting into HDR-1 in 1991-1996. Microseismic data from the creation of the deeper reservoir has been more extensively analyzed. Tezuka and Niitsuma (2000) identified seven major clusters of microseismic activity defined by multiplets, i.e., seismic events with similar waveforms. Stress inversions using the focal mechanisms from each cluster indicated that six of the clusters were consistent with the same *in-situ* stress directions and failure planes. The maximum principal stress was shown to be nearly vertical, and the minimum stress sub-horizontal and oriented north–south. These stress direction are roughly consistent with estimates derived from interpretation of drilling-induced fractures observed on borehole televiewer images (Okabe et al., 1995). Tezuka and Niitsuma (2000) also conclude that the growth direction of the EGS reservoir was strongly controlled by the distribution of favorably oriented pre-existing fractures and their interaction with the stress field.

Thus the available data and interpretations at Fenton Hill and Hijiori point to consistent stress orientations at the well-scale, but variable pre-existing fracture orientations which control the directions of EGS reservoir growth at different depths and clusters. One of the best documented cases of a change in the stress direction in a single well can be found at the geothermal field in Dixie Valley, Nevada (This producing geothermal field is adjacent to a major Basin and Range normal fault, not near a caldera). Hickman et al. (2000) analyzed data from well 82-5, which penetrated the Stillwater Fault Zone (SFZ) but failed to encounter significant permeability. Borehole breakouts and cooling cracks indicated a ~90° rotation in the azimuth of the least horizontal principal stress at a depth of about 2.7 km, 20-50 m above the top of the SFZ. This stress rotation is most readily explained through the occurrence of one or more recent normal faulting earthquakes in the hanging wall of the SFZ in the northern part of the reservoir.

In the examples above, the full complexity of the interaction between the stress, natural fractures, and hydraulic stimulation was not revealed until the EGS experiments were performed. That will likely be true in future EGS demonstration projects as well. However, as the knowledge base on EGS continues to grow, there should be fewer surprises. The Newberry EGS team has begun building a preliminary 3-D stress model for Newberry by collecting a variety of new data. Below we review the various data sets that we have recently collected and are currently analyzing.

BHTV IMAGES

In October 2010, NWG 55-29 was logged using a high-temperature Borehole Televiewer (BHTV) manufactured by Advanced Logic Technology (ALT). In order to cool the well and extend the maximum depth to which the well could be logged, cold water was injected into the well at the highest flow rate that the formation would take at moderate surface pressures (<1000 psi). After more than a week of injection, temperature logs indicated that the injected water exited the well near a depth of 9600 ft, significantly cooling the well above the exit point and allowing a longer interval of the open hole to be logged. The well was successfully logged down to a depth of 8860 ft.

The processed BHTV data became available in January 2011, and are currently being analyzed. As shown in Figure 2, the data quality of the BHTV images is high. As expected, the fracture density in the well appears to be low. Contacts between numerous volcanic units were also observed in the images, including basalt flows, dikes, and granodiorite intrusives.

Stress-induced borehole breakouts were observed over many depth intervals in NWG 55-29. Breakouts, caused by compressive failure of the borehole wall, are revealed as irregular patches exhibiting low reflectivity and slow, two-way travel time on diametrically opposed sides of the borehole in the BHTV images (Figure 2). These breakouts will be analyzed to determine the orientation of the minimum horizontal stress and provide constraints on the relative magnitudes of the horizontal principal stresses, using image-log analysis techniques applied in other deep geothermal wells (e.g., Davatzes and Hickman, 2006). Any changes in stress orientations with depth in the more than 2000 feet of open hole that were logged should be readily apparent in the breakout data.

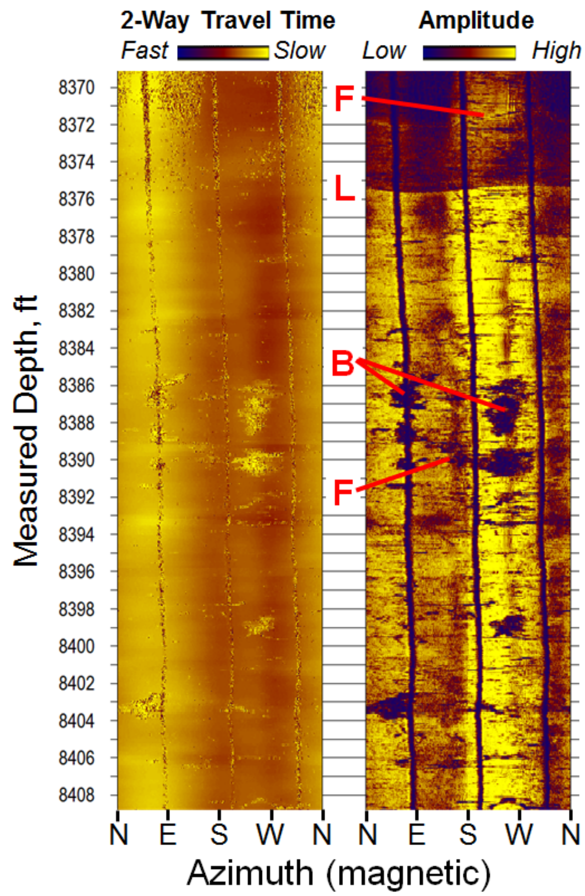

Figure 2: BHTV image from October 2010 logging of well NWG 55-29, processed to display two-way travel time (left) and amplitude (right) of the reflected ultrasonic pulse. Characteristic features are labeled as L=lithological contact, F=natural fracture, and B=borehole breakout. The three dark, vertical bands are not natural features in the borehole, but rather are shadows produced by structural rods attached to the BHTV.

MICROSEISMIC NETWORK

Newberry Volcano is essentially aseismic. A search of the earthquake archives shows just one M=2.2 seismic event detected within 20 km of the caldera (ANSS, 2010). Because this may in part be due to a lack of seismic sensors in the area, ARE is adding two new regional, short period seismic stations to the Pacific Northwest Seismic Network (PNSN): one in La Pine and another in Three Rivers (see Figure 4 for locations).

A temporary surface array of 7 stations (Figure 3) was deployed by ARE in 2010 in order to gather information about the background seismicity below

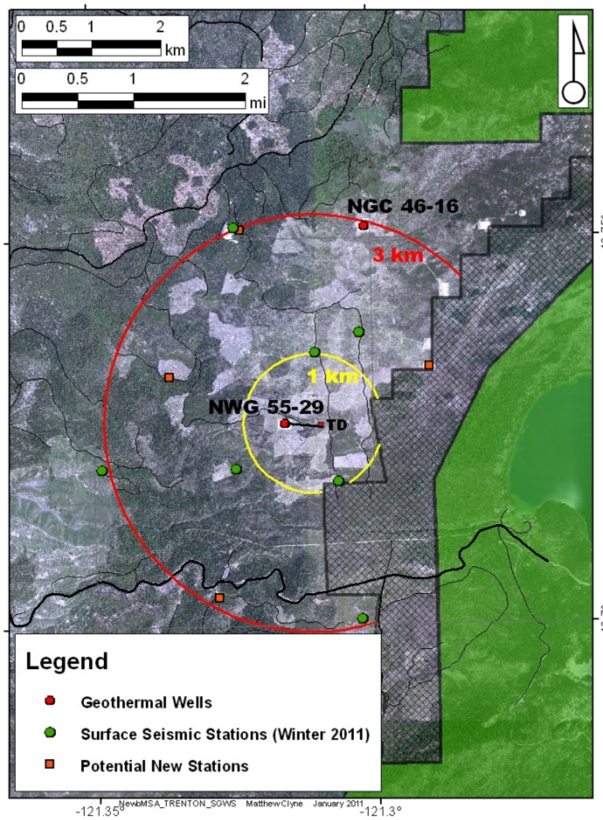

Figure 3: EGS Project's Microseismic Array (MSA), centered on the EGS injection well NWG 55-29. TD marks the bottom of the well which is deviated to the east.

the array and help design an improved array that will be operating during stimulation in 2011. In cooperation with the USGS, a calibration survey of the surface stations was performed in August 2010. For the experiment, an additional 25 seismometers, borrowed from PASSCAL, were deployed by the USGS. The main calibration shots were 20-24 pounds of explosive set off at 12 shot points in ~15 m deep shot holes

In order to develop a velocity model as close as possible to the stimulation zone, original plans called for a seismometer to be deployed as deep as possible in NWG 55-29. However, problems prevented this seismometer from being deployed. Analysis of 36 arrival time measurements on seven ARE seismometers and 182 arrivals on 25 USGS seismometers, all at the surface, yielded a robust 5-layer velocity model down to a depth of 900 m (Foulger, 2010). Analysis of the calibration survey indicated that deploying an array of surface instruments would likely result in unreliable detection and location of injection-induced microseismic events below a magnitude of about 0.5.

The surface array of seven stations (Figure 3) is currently running in order to collect background seismicity data in the EGS project area. The data will be downloaded from the sites in February and analyzed to determine whether any seismic events with magnitudes between 0.5 and 2.0 are occurring below the array and are being missed by the regional network.

The final microseismic array is currently being designed and will include at least seven sensors installed in 700-1000 foot deep boreholes to push the detection threshold lower than a magnitude of 0. If possible, fault-plane solutions or moment tensors will be calculated for the larger events anticipated during EGS stimulation, providing an important constraint on the stress tensor within the EGS reservoir.

CUTTINGS AND CORE ANALYSIS

Cuttings from NWG 55-29 were sub-sampled at regular intervals and in zones targeted by indication of alteration in mud logs and geophysical logs. These cuttings are being analyzed by XRD and XRF at Temple University. Preliminary chemical and mineralogical results have not shown evidence of significant hydrothermal alteration. However, cuttings from the zone that took fluid during injection prior to the BHTV log have yet to be analyzed; it is possible that this flow horizon may correlate with an alteration zone.

Although there is no core from 55-29, core was collected from several shallower (<3500 ft) holes nearby. These cores had been stored at the Energy & Geoscience Institute core library in Salt Lake City, and are currently being tested for failure strength at Texas A&M University.

LIDAR

ARE joined the Oregon LiDAR consortium in order to add La Pine, the community nearest the project, to the 2010 survey. In particular, we were interested in better characterizing the La Pine Graben faults previously mapped at the western edge of the valley (Personius, 2002a). Our preliminary analysis of the 880 km^2 area made available to ARE in December 2010 is shown in Figures 4 and 5. On the west side of the image in Figure 4 are a swarm of short (<6 km), discontinuous normal faults that occur in nested grabens and are often related to volcanic flows and cones. The USGS fault and fold database includes many of these faults, but in less detail. The USGS database also includes two long (30 and 35 km), NNE-trending faults in the La Pine Graben fault set (see long yellow lines on Figure 1 west of 55-29). However, no evidence of these longer faults can be

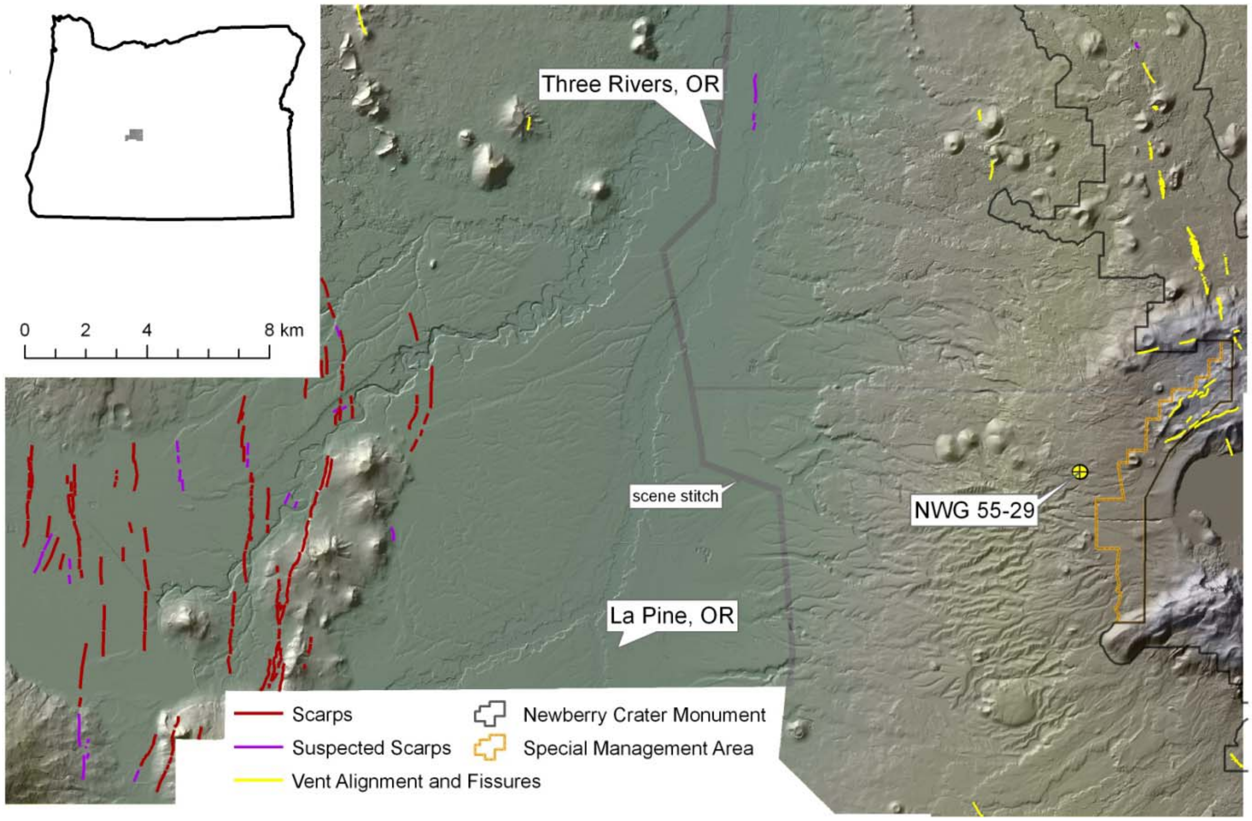

Figure 4: Oregon LiDAR Consortium image from the west flank of Newberry Caldera. Fault interpretations shown are by ARE.

found in the LiDAR. On the east side of the image on the north flank of the Newberry Volcano, we have mapped fissures and vent alignments consistent with previous observations in the area (Sherrod et al., 2004). In detail, the fissure zones consist of individual fissures with N-S orientations while the fissure zones themselves trend NNW. On the LiDAR image (Figure 4) the ring fractures mapped in the USGS database (class B) and by Sherrod et al. (2004) are not prominent. This is not surprising, as Personius (2002b) notes that "these faults are everywhere concealed, and have been mapped on the basis of the topographic expression of these escarpments." Dip-slip offset is not observed in the LiDAR surfaces; rather the curved fractures seem to be defined by fissures and an alignment of vents. Field work will be necessary to further characterize the faults and fissures mapped here.

Figure 5 summarizes the orientations of the features mapped. The average fault orientation on the west side of the LiDAR image and the average fissure orientation on the east side of the image differ by ~10°. As a first approximation, we can assume that the minimum principle stress is perpendicular to the traces of both normal faults and fissures, indicating a roughly East-West extension regime across the area shown in Figure 4. This inferred regional stress orientation is simpler than might be expected for the Newberry region based upon the juxtaposition of three different structural trends discussed above (see Figure 1). However, the stress orientations may show variability in the remaining LiDAR scenes and with depth. Further analysis of the adjacent LiDAR scenes and the BHTV images will provide the data needed to more fully address the variation of stress orientations in the region and with depth at the Newberry EGS site.

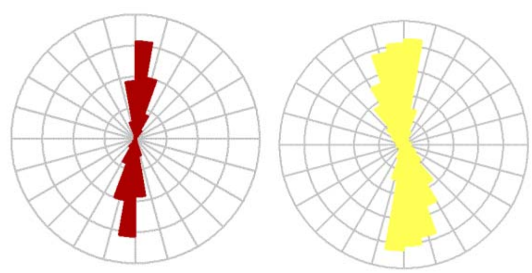

Figure 5: Rose diagram of LiDAR scarps (left) and fissures (right) mapped in Figure 4.

DICUSSION

The tectonic setting of the Newberry EGS project and the experience of HDR projects already carried out at other calderas indicate that the orientations of the principle stresses and natural fractures could vary considerably in the planned Newberry EGS reservoir. Based on preliminary analysis of the LiDAR and a consistent N-S orientation of mapped features, there is not yet evidence to support this level of complexity in the local fracture population and stress field. However, the BHTV interpretation will be available soon and will provide valuable data on fracture populations and stress directions at the depth of interest.

Once we have characterized the natural fracture populations and developed a preliminary stress model for the NWG 55-29 site, we will use a stochastic fracture/flow model developed by ARE (AltaStim) to model and visualize EGS stimulation scenarios. The inputs to this model will include: 1) the three principal stress orientations and relative magnitudes, 2) natural fracture statistics (orientation, distribution, apparent aperture, and assumed radius), 3) geomechanical parameters of the fractures and reservoir rock, and 4) injection depth and pressure in the well bore. This model will allow us to estimate the geometry, spatial distribution, and hydrologic properties of stimulated fractures, to provide guidance for final planning of the Newberry EGS stimulation.

ACKNOWLEDGEMENTS

The Newberry EGS Demonstration Project is 50% funded by the Department of Energy via the Recovery Act (DE-EE0002777/004). The authors also thank our partner and well owner Davenport Newberry.

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