PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Three-Dimensional Structural Model Building, Induced Seismicity Analysis, Drilling Analysis and Reservoir Management at The Geysers Geothermal Field, Northern California

Craig S. Hartline[1], Mark A. Walters[1], Melinda C. Wright[1], Corina K. Forson[2] and Andrew J. Sadowski[3]

1 Calpine Corporation, 10350 Socrates Mine Road, Middletown, CA 95461

2 Washington State Department of Natural Resources, 1111 Washington St. SE, Olympia, WA 98504

3 Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV

Craig.Hartline@calpine.com, Mark.Walters@calpine.com, Melinda.Wright@calpine.com, corinaforson@gmail.com, andrew.j.sadowski@gmail.com

Keywords: Three-dimensional, Visualization, Structural Model, Induced Seismicity, Reservoir Management, The Geysers

ABSTRACT

A three-dimensional structural model of The Geysers geothermal field is being developed by Calpine Corporation using Paradigm Geophysical SKUA GOCAD software originally designed for the oil and gas industry. Structural model building constraints include lithology logs, surface geologic maps and seismicity hypocenters available from the Northern California Earthquake Data Center (NCEDC) and Lawrence Berkeley National Laboratory (LBNL), as well as temperature logs, pressure logs, tracer analysis patterns, heat flow patterns, and reservoir history matching. A field-wide ArcGIS digital surface map compiled in 2014 from existing hard copy surface geology maps and refined in 2015 now provides improved constraint on the surface-to-subsurface structural relationships. Recent advances to the SKUA GOCAD 3D seismicity analysis software include the ability to perform synchronized time animation of water injection volumes and induced seismicity hypocenters at any time interval. This provide an additional and substantial constraint on structural model building through enhanced visualization of the spatiotemporal relationships between water injection, induced seismicity and fracture orientations at The Geysers. The result is a refined understanding of structural relationships, fluid flow paths, fluid boundaries, reservoir heterogeneity and compartmentalization at The Geysers. We can now demonstrate that The Geysers reservoir is subdivided by intersecting zones of faulting and fracturing, the majority of which are oriented NNW-SSE and ENE-WSW and sometimes expressed in the surface geology. The 3D structural model development is part of a program to honor a vast collection of field data and more closely link geoscience, reservoir engineering and drilling. This is anticipated to contribute to reservoir management and induced seismicity mitigation efforts at The Geysers.

1. INTRODUCTION

The Geysers, located in Northern California and approximately 75 miles north of San Francisco, is the largest producing geothermal field in the world. Calpine Corporation operations at The Geysers include 14 geothermal plants, approximately 330 active steam production wells, and 60 active water injection wells producing about 720 million watts of electricity (and approximately 18% of California's renewable power).

1.1 Regional Geology

This geothermal resource exists within a complex assemblage of Franciscan rocks (200 to 80 Ma in age) representing the ancient Farallon plate subduction complex. Approximately 30 Ma ago a transition from eastward-directed subduction to right-lateral strike-slip faulting occurred as the spreading center between the Pacific Plate and the Farallon Plate descended beneath the western edge of the North American Plate. Since this transition, the relative motion between the Pacific Plate and North American Plate has been accommodated by right-lateral strike-slip motion along the San Andreas Fault Zone (DeCourten, 2008). This zone of subparallel right-lateral strike-slip faults move at progressively slower slip rates eastward and initiated a transtensional tectonic environment between the active Maacama fault and the active Bartlett Springs Fault Zone (Figure 1).

The modern-day Geysers geothermal field is bounded to the southwest by the inactive Mercuryville and Big Sulphur Creek fault zones and to the northeast by the inactive Collayomi fault zone (see inset within Figure 1). There are no faults in or adjacent to The Geysers which are known to be active within the last 15,000 years. Beginning about 1.1 Ma ago, a 1400 °F (760 °C) multiphase granitic pluton locally known as "Felsite" began intruding the brittle Franciscan graywacke found throughout the subsurface of The Geysers region. Extensive fracture enhancement by the mechanical and hydraulic forces associated with intrusion as well as the thermal metamorphism of the graywacke to a biotite hornfels occurred above the granitic pluton. Heating of the formation water within this fracture system created a liquid-dominated hydrothermal reservoir in the Franciscan graywacke and the upper portion of the granitic pluton.

Containment of The Geysers initial hydrothermal reservoir was primarily dependent on the transition from abundant open fractures to very limited open fractures with decreasing depth. This is well illustrated in the present-day northwest Geysers, where an open fracture network in the silicified graywacke reservoir rock transitions to very limited open fractures within the overlying graywacke caprock. Caprock development throughout The Geysers was aided by the acid alteration of rock to clay minerals and the shallow precipitation of dissolved silica derived from deeply circulating ground water (that reacted with magmatic and hydrothermal gases). The present maximum enthalpy 465 °F (240 °C) vapor-dominated Geysers geothermal reservoir exists due to a phreatic eruption approximately 0.25

Ma, the subsequent boil down, and reservoir flushing (or dilution) from southeast to northwest, lowering non-condensible gas and chloride concentrations (Hulen et al., 1997a, 1997b; Hulen, 2000; Moore et al., 2000, Beall, J et al., 2010). Finally, renewed heating by additional magmatic intrusions as recently as 0.25 - 0.01 Ma have resulted in a "high temperature reservoir" in the NW Geysers (Walters et al, 1991).

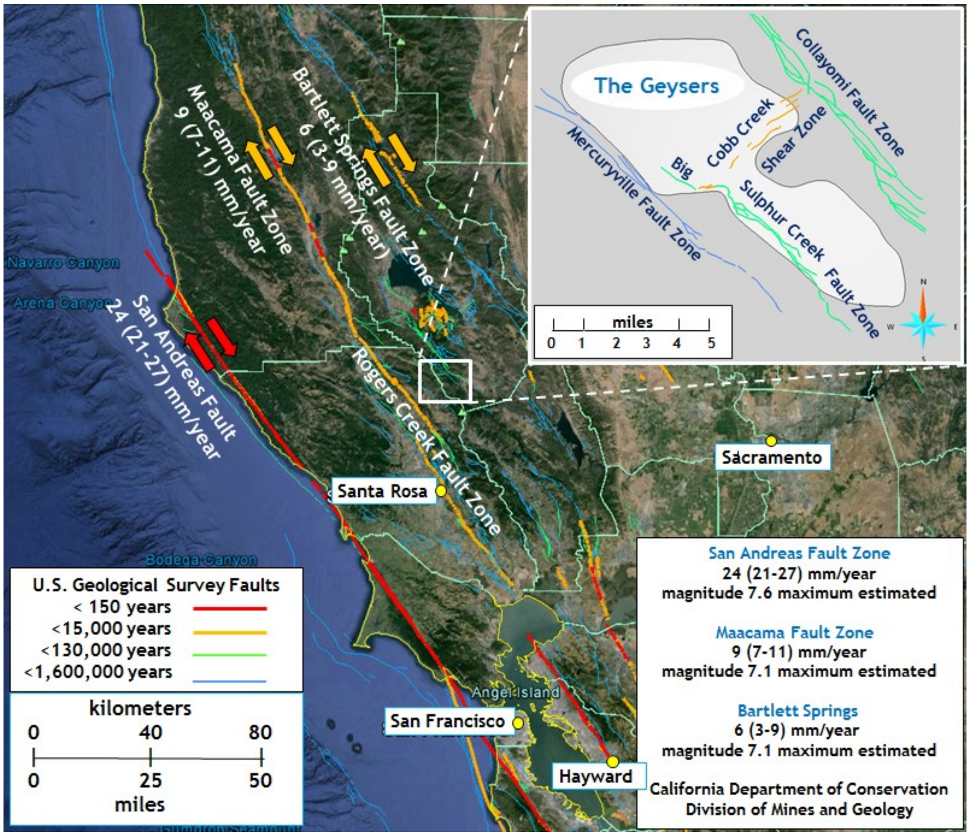

Figure 1: The San Andreas Fault System, including the Maacama / Rodgers Creek Fault Zone and Bartlett Spring Fault Zone. United States Geological Survey Faults with activity in the past 1.6 million years are displayed. Primary bounding fault zones are shown in the inset at upper right. This Google Earth image includes fault parameters from the California Division of Mines and Geology, 1996.

2. WATER INJECTION AND INDUCED SEISMICITY ANALYSIS

On a yearly basis, about 75% of the dry steam mass produced to The Geysers' power plants is lost to the atmosphere through cooling towers. So, sustainable electrical power production at The Geysers relies on recharge from two large-scale treated wastewater injection projects based in (1) Lake County and (2) the City of Santa Rosa (Sonoma County) which supply a nominal flow rate of 18 million gallons per day, in addition to recovered steam condensate from the power plants and creek water injection during peak precipitation run-off.

2.1 Recent Investigations

The ambient temperature "injection" water falls freely into the injection wells (with wellhead gauge pressure at near-vacuum due to reservoir steam condensation and the resulting volume reduction) and is responsible for induced seismicity at The Geysers. This occurs primarily in the near-borehole environment due to thermal contraction as relatively cool water encounters hot rock and reactivates existing fractures. Modest pressure perturbations associated with a static water column at the base of the injection wells are a secondary source of fracture reactivation (Majer et al., 2007; Rutqvist et al., 2013; Martínez-Garzón et al, 2014).

The Geysers' seismicity is measured as three components of motion on 36 stations of the Lawrence Berkeley National Laboratory (LBNL) seismic monitoring network distributed throughout the resource. Seismic waveforms are accumulated by a LBNL radio telemetry network and imported to the United States Geological Survey (USGS) "Waveserver" located within Calpine's Geysers Administration Center. The three-component seismic waveforms and calculated P-wave arrival times are forwarded by a radio link to the USGS facility at Menlo Park and integrated with P-wave arrival times from other monitoring networks operated by the USGS, the University of California Berkeley, the California Geological Survey, and the California Department of Water Resources. The USGS then provides an automated determination of seismic event magnitude, seismic event positioning (3D hypocenter), first-motion mechanisms, and moment tensor solutions and shake maps for seismic events with magnitude > 3.5.

Boyle and Zoback (2014) concluded that a predominance of normal and strike-slip faulting (maximum horizontal stress ≈ vertical stress > minimum horizontal stress, or SHmax ≈ Sv > SHmin), consistent with the local strike-slip and extensional tectonics, exists within and below The Geysers vapor-dominated reservoir, and determined an average SHmax orientation of N23°E within the analyzed crustal volume. This determined SHmax orientation is consistent with Oppenheimer (1996), and seems to indicate that The Geysers injection and production activities have not significantly affected the local stress field (Boyle and Zoback, 2014). Multiple investigations have indicated that The Geysers' reservoir rocks are stressed to near the failure point, and small perturbations of the stress field associated with geothermal development are responsible for the increased frequency of low magnitude seismicity (Oppenheimer, 1996; Rutqvist et al, 2013). Importantly, the USGS and California Geological Survey have identified no mapped active faults within The Geysers (Field et al., 2015). The highly-fractured steam reservoir (as defined by extensive drilling activities and recent induced seismicity pattern analysis) provides confidence that there is not sufficient fault area to support a large earthquake at The Geysers (Majer et al, 2007; Major, 2014, Personal Communication).

Calpine sees encouraging trends field-wide concerning the water injection volume vs. induced seismicity:
- Magnitude ≥ 3.0 seismic events since 01 January 1987 show a downward linear regression trend of approximately -0.5 events per year, from a peak of 32 events per year in 1988 to recent values of 15 to 18 events per year, with only 7 magnitude ≥ 3.0 seismic events in 2014 and 2015. This is at least partially in response to an extended drought-related water injection volume reduction (Figure 2).
- Magnitude ≥ 4.0 seismic events at The Geysers (4.7 maximum) have declined from 2.5 events per year during the four-year period from 01 January 2003 through 31 December 2006 to about 1.0 event per year since 01 January 2007 (Figure 3).

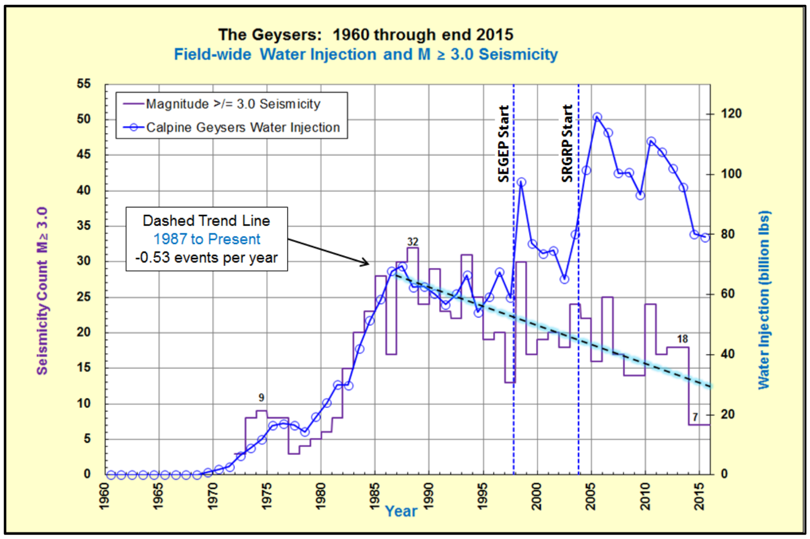

Figure 2: The Geysers' field-wide water injection (scale at right) and yearly seismicity count for magnitude ≥ 3.0 induced seismicity (scale at left). Database: Northern California Earthquake Data Center (NCEDC); University of California Berkeley Seismological Laboratory

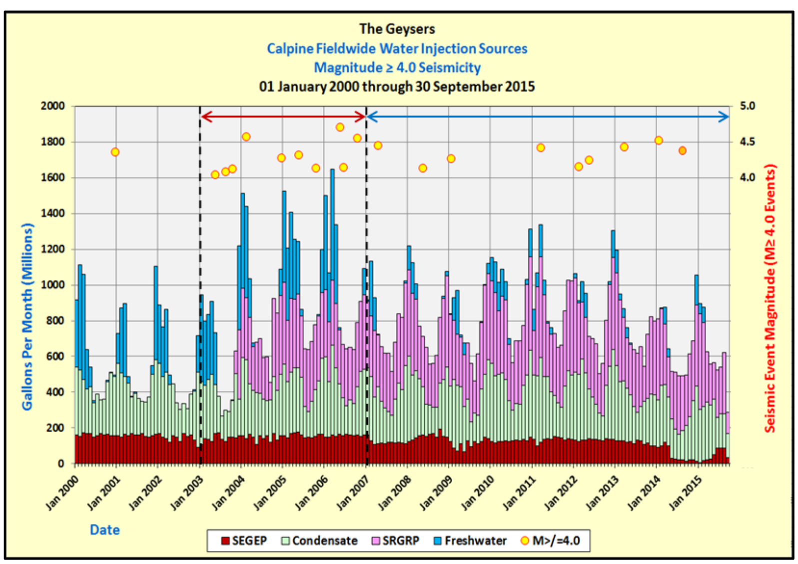

Figure 3: Calpine Geysers field-wide water injection volume by source from 01 January 2000 to 30 September 2015 (scale at left) and magnitude ≥ 4.0 (maximum 4.7) induced seismicity (scale at right). SEGEP = Southeast Geysers Effluent Pipeline, SRGRP = Santa Rosa Geysers Recharge Project. Seismicity Database: Northern California Earthquake Data Center (NCEDC); University of California Berkeley Seismological Laboratory

Building on the work of Beall et al. (2010), Calpine is currently directing significant internal effort toward a better understanding of the physical mechanisms responsible for The Geysers' induced seismicity.

2.2 New Methods of Analysis

Since 1983, AutoCAD design software was available for engineering and 2D geological investigations at The Geysers. Calpine completed a detailed assessment of the available software for 3D model building and visualization in 2011, and selected Paradigm Geophysical GOCAD software, now SKUA GOCAD (Subsurface Knowledge Unified Approach / Geologic Objects Computer Aided Design) software. This software was initially utilized for 3D induced seismicity analysis and communication of the analysis conclusions. Concurrently, significant effort was directed toward 3D database preparation and 3D structural model development to improve the understanding of The Geysers subsurface geology, provide more effective drilling target analyses, and assist with real-time drilling and reservoir management decisions.

The primary goals for the Calpine Geysers 3D visualization and structural model building program are:

- Develop an extensive and properly formatted SKUA GOCAD 3D project database.
- Develop a 3D structural model representing the complex geology of The Geysers using all available data constraints.
- Utilize 3D visualization and 3D seismicity analysis software to better understand the spatial and spatiotemporal relationships between water injection and induced seismicity.
- Refine the understanding of fluid flow paths, fluid boundaries, reservoir heterogeneity and reservoir compartmentalization at The Geysers, with goals of improved reservoir management and induced seismicity mitigation.
- Refine the understanding of fracture systems and fault zones at The Geysers. This relates directly to seismicity analysis, as the seismic moment of an earthquake or induced seismic event is dependent upon the elastic shear modulus (rigidity), the average slip and the fault slip area (Hanks and Kanamori, 1979; Aki and Richards, 1980; Segall, 1998).
- Development of a refined 3D Vp/Vs velocity model allowing refined 3D seismicity hypocenter positioning, utilizing lithology determinations and rock properties as a proxy for velocity, and performing tomographic updates based on this Vp/Vs velocity model.
- Well planning and real-time drilling analysis within a continually refined 3D structural model.
- Transfer of the refined 3D structural model elements into The Geysers reservoir engineering model, providing an improved basis for upscaling and simulations.
- A more integrated approach to field development and reservoir management by "completing the loop" between geoscience, drilling and reservoir engineering. Knowledge gained from reservoir modeling, history matching and drilling activities will provide feedback for continuing refinement of the 3D structural model.
- Utilization of an improved communication tool for public outreach and technical discussions.

3. 3D VISUALIZATION

Calpine's initial Paradigm Geophysical SKUA GOCAD 3D software utilization was directed toward induced seismicity analysis and has improved our understanding of the spatiotemporal relationships between The Geysers' water injection and induced seismicity. 3D visualization has evolved into an improved communication tool to discuss water injection and induced seismicity analysis with the public, industry and academia at forums such the Geysers semi-annual Seismic Monitoring Advisory Committee (SMAC) meeting, and Geothermal Resource Council and Stanford Geothermal Workshop annual meetings. Calpine now utilizes 3D visualization as an effective tool for conveying technical subsurface information during drilling target analyses and real-time well drilling analyses involving geoscientists, reservoir engineers and drilling specialists.

4. 3D STRUCTURAL MODEL DEVELOPMENT

Extreme subsurface conditions (high temperature, corrosive fluids, complex metamorphic rocks and a fracture-dominated reservoir) have significantly limited the use of typical oil and gas geophysical logging methods at The Geysers. Extreme topography and prohibitive costs have also restricted the potential for active 2D/3D seismic data acquisition and imaging. Consequently, the constraints for The Geysers' 3D structural model development are provided by approximately 870 lithology logs (compiled by various well-site geologists over several decades and painstakingly converted to digital form since 2011), surface geology maps (including a recent ArcGIS digital map compilation), reservoir temperature and pressure, tracer analysis patterns, heat flow patterns, reservoir history matching, non-condensible gas concentrations and seismicity hypocenter databases provided by the Northern California Earthquake Data Center (NCEDC) and LBNL. The most recent Geysers seismicity analyses utilize the NCEDC refined relative hypocenter location tomographic "double-difference" seismic data available within the 1984-2011 "base catalog" (Waldhauser, 2008) and more recently available within a 01 January 2012 to present "real-time" seismic data catalog (Waldhauser, 2009).

The Geysers geology has been likened to a tipped bookshelf with the contents spilling out and the individual books still maintaining some degree of order (Conant, 2014 personal communication). This degree of order is sometimes seen in the lithology logs for adjacent wells, particularly on the northeast flank of the granitic Felsite intrusion. Figure 4 illustrates the well-to-well lithological correlation of northeast-dipping units on this northeast flank using two isolated and properly oriented well "corridors" assigned within the Paradigm Geophysical SKUA GOCAD 3D project.

Several surfaces or "horizons" have been developed and refined within the SKUA GOCAD software. Smaller localized surfaces have been developed primarily from the picked lithological markers and interpreted fracture zones. However, some of the more extensive horizons with extreme surface variability and clustered data control points (such as the Top Felsite and Top Steam) were developed using an iterative technique. Here, the numerous markers picked within SKUA GOCAD (574 Top Steam markers, for example) were exported to AutoCAD for the development of mapping contour files, which allowed for some degree of geologic insight to be provided when these horizons encounter sparse data zones. Next, the combination of SKUA GOCAD picked markers, AutoCAD mapped contour lines, SKUA GOCAD interpreted fault zones and additional inserted control points were utilized within the 3D software to constrain or guide the surface development. Lithological logs and other subsurface constraints acquired since the late 1960's by many technical experts were observed to have varying degrees of reliability. Several iterations of surface generation and well data quality control were performed to ensure the correlation with all reliable well data, the removal of unreliable data outliers and the production of refined surfaces or horizons. The Geysers Top Steam has been re-interpreted as (1) a shallower, ~350°F two-phase reservoir and (2) a deeper , ~465°F single phase maximum enthalpy (now superheated) steam reservoir.

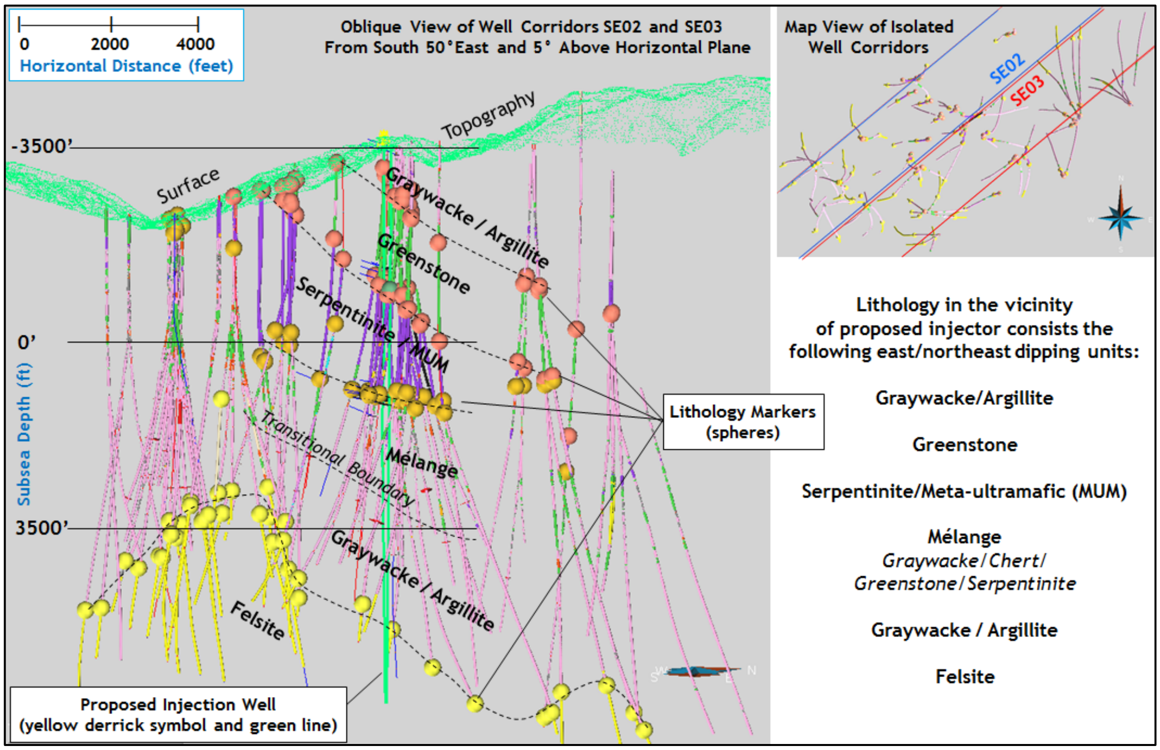

Figure 4: Upper Right: Map view of two southwest-to-northeast oriented well corridors in the central Geysers. The corridors SE02 and SE03 each include the wells within a 2500' wide polygon. Left: Oblique SKUA GOCAD view of the relatively uncomplicated 3D structural interpretation for the northeast flank of The Geysers granitic "Felsite" pluton. Lithological "markers" (spheres) are interpreted on well tracks overlain with lithological logs. Lower Right: Generalized geology for this 3D structural interpretation.

Recent and detailed 3D analyses of induced seismicity associated with existing Calpine injection wells, pre-drilling studies for proposed injection and production wells, and analysis associated with the multi-discipline Department of Energy co-funded Northwest Geysers Enhanced Geothermal System Demonstration Project have provided strong evidence that induced seismicity hypocenter patterns can be correlated with other reservoir parameters and are indicative of fluid flow paths and boundaries (Garcia et al., 2012; Garcia et al., 2015; Jeanne et al., 2014). Boundaries or hydraulic discontinuities can in turn be indicative of structural or lithological variations present within the complex geology of The Geysers geothermal field.

The Geysers induced seismicity patterns appear to be strongly influenced by the regional stress field of the San Andreas Fault System (SAFS). This extensive (800 mile long) system of right-lateral strike-slip faults accommodates the relative motion between the Pacific Plate and North American Plate over a 60 to 180 mile wide zone, with successively smaller slip rates for active faults toward the east (Figure 1). These seismicity patterns seen in depth slices (see Figure 5) and cross-sectional slices are believe to represent (1) relict shear zones responsive to the local maximum principal horizontal stress (SHmax) orientation of ~N23°E (Boyle and Zoback, 2014) and oriented subparallel (~N140°-N160°) to the SAFS and North Coast Range regional strike (Hulen and Norton, 2000) and (2) intersecting (~N050°-N070°) transtensional fault/fracture zones, including Reidel system shearing (Jeanne, 2014). The transtensional fault/fracture zones are a response to different slip rates within the active right-lateral strike-slip fault systems to the east (Bartlett Springs Fault Zone; 3-9 mm per year) and to the west (Maacama Fault Zone; 7-11 mm per year) of The Geysers geothermal system, resulting in NW-SE directed extension (Walters, 1996; Stanley et al., 1997). The existence of approximately SW-NE oriented transtensional fault/fracture zones is strongly supported by decades of tracer studies conducted at The Geysers indicating preferential SW-NE fluid flow (Wright and Beall, 2007).

Calpine has benefitted greatly from recent Paradigm Geophysical SKUA GOCAD 3D seismicity analysis software advances developed primarily to assess the stimulated rock volume associated with oil and gas hydraulic fracturing. Utilizing various time-ranges of LBNL and NCEDC tomographic "double-difference" seismic data, the ability to rapidly set up and progress through induced seismicity time-animations can be very instructive, particularly when induced seismicity depth slices and cross-sectional slices are isolated from background clutter for analysis and interpretation. Saving successive captured SKUA GOCAD seismicity slice images, typically in the range of 500 to 1000 feet (152 to 304 meters) thick, and animating through the image series using conventional software has also assisted in defining consistent patterns which progress azimuthally or sub-vertically through the data. Analysis of these induced seismicity patterns provide a better understanding of the complex (inactive) fault zones and fracture systems existing throughout The Geysers.

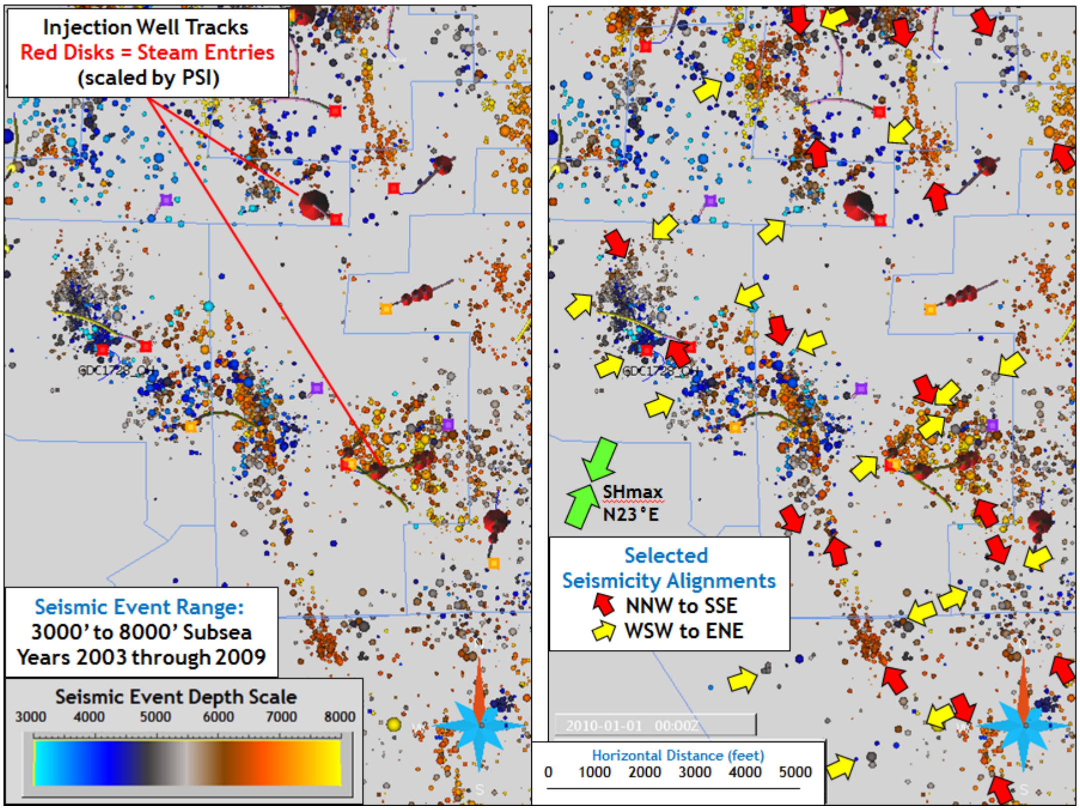

Figure 5: NCEDC tomographic double difference seismic event hypocenters for the time range 01 January 2003 to 31 December 2009 and depth range 3000 to 8000 feet (915 to 2440 meters). The orthogonal, linear seismicity alignments are believed to represent (1) relict shear zones responsive to SHmax and oriented at ~ N140°-N160° and (2) intersecting ~N050°-N070° transtensional fault zones. The depth and cross-sectional slices used in 3D interpretation are generally 500 to 1000 feet (152 to 304 meters) thick. This 5000 foot (1525 meter) thick depth slice allows the display of multiple seismicity alignments within a single image.

Interpretation of the Magnitude 4 Divide Shear Zone and the Cobb Creek Shear Zone

A map view of The Geysers historical seismicity greater than magnitude 4.0 (up to a maximum of 4.7) clearly shows that these events occur almost entirely to the *northwest* of a west-southwest to east-northeast (WSW-ENE) trending line often referred to as the "Magnitude 4 Divide" shear zone (M4D) (Figure 6, Figure 10). Seismic events also extend to a much greater depth *northwest* of the M4D, which is considered to be a major structural transition within The Geysers (Beall and Wright, 2010). A 2015 3D evaluation in this area was originally focused on a proposed water injection well in the central Geysers. The evaluation expanded into a 3D analysis of this major structural transition zone, including refined surficial geology constraint from summer 2014 and summer 2015 surface mapping (see the companion paper *Surface Geology for Use in Three-Dimensional Structural Model Building at the Geysers Geothermal Field, Northern California*). Time animation of seismicity hypocenters within 500 foot wide north-to-south oriented seismicity slices from January 2001 to December 2015 clearly shows the downward progression of induced seismicity (indicative of fluid flow) through a network of permeable fractures. Interpretation of this shear zone as a series of "fault curves" was then completed while progressing through the series of 500' wide north-to-south, and northwest-to-southeast, oriented seismicity slices intersecting this structural transition. Confirmation of the resulting shear zone interpretation was completed by performing an un-biased interpretation of 500 foot wide east-west oriented seismicity slices. The results appear to indicate that an extensive WSW-ENE oriented shear zone consisting of anastomosing fractures (and not a single, well-defined fault) defines this major structural transition within The Geysers.

A recent 3D investigation was designed with the goals of (1) providing supporting 3D information for a proposed steam production well in the west-central Geysers, and (2) providing additional insight into the subsurface structure associated with the west-southwest to east-northeast oriented Cobb Creek Shear Zone (Figure 1), identified during several decades of surface mapping and refined during the summers of 2014 and 2015 (Neilson and Nash, 1996, Hulen and Nielson, 1996). The proposed well is designed to target deep steam reservoir potential near a southeastward transition toward relatively limited seismic event density and limited shallow steam reservoir potential. This transition toward lower seismic event density is easily apparent when viewing 500' wide east-to-west, north-to-south and northwest-to-southeast oriented seismicity slices, and has been interpreted as a structural transition (or boundary) with a series of fault curves at this 500' interval. Figure 7 shows fault curve interpretations for 14 east-west oriented seismicity slices (at 500' intervals). When properly 3D-oriented, the curves align or "stack" more favorably and indicate the fracture plane orientation and extent. This technique has been used to guide the generation of multiple anastomosing fracture planes representing the Cobb Creek Shear Zone. The interpreted planes also indicate that the proposed steam production well should encounter more permeable zones (and potentially lost circulation zones) centered at measured depths of approximately 2100 feet and 5200 feet.

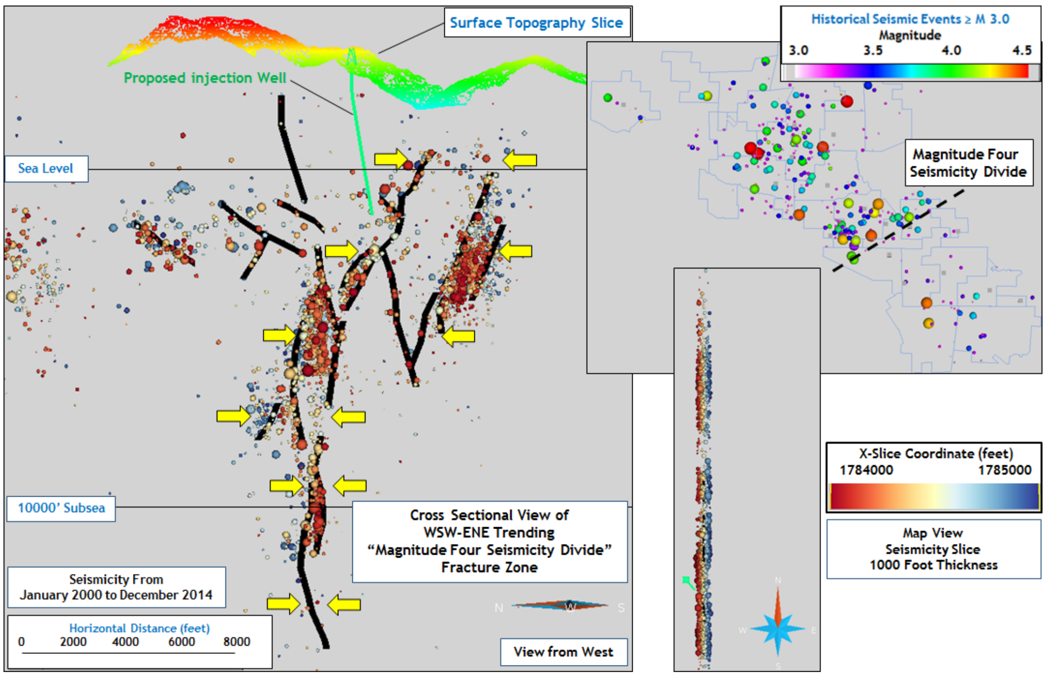

Figure 6: Magnitude 4 Divide (M4D) Shear Zone Interpretation. Upper right: Map view of The Geysers with historical seismic events of magnitude ≥ 3.0 scaled by color and symbol size. The M4D is the WSW-ENE oriented black dashed line. Lower right: Map view of the 1000 foot thick north-south oriented cross-sectional seismicity slice. Left: View from west. Shear zone interpretation of the 1000 foot wide north-south oriented seismicity slice shown at lower right.

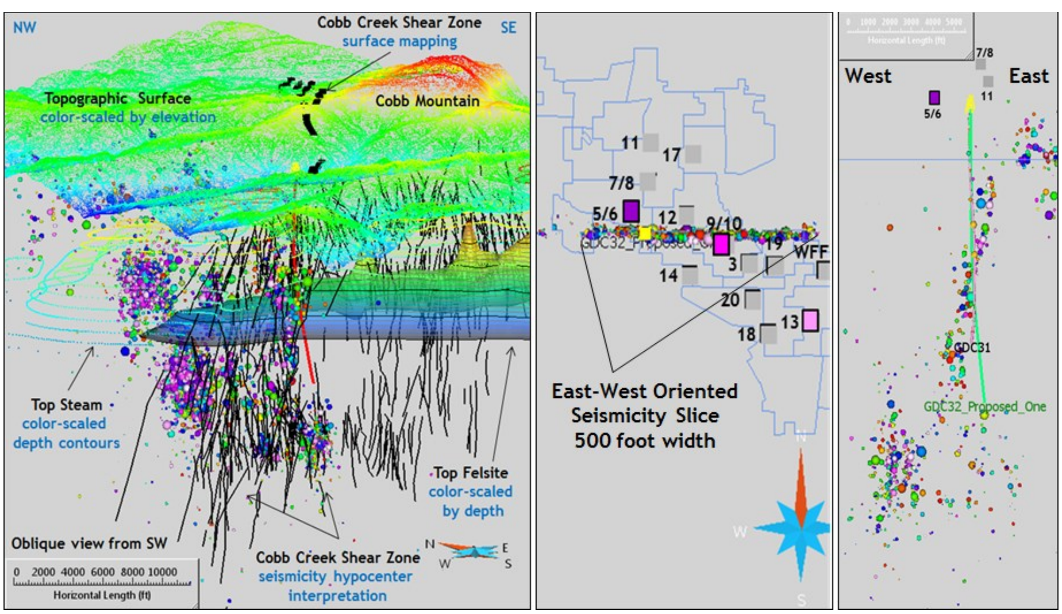

Figure 7: Cobb Creek Shear Zone Interpretation. Left: Interpreted shear zone oriented to emphasize "stacking" of fault curve interpretations. Vertical exaggeration = 1.35. Center: Location of east-west seismicity slice seen at right. Numbered squares are Calpine geothermal power plants. Right: Proposed steam production well (green) should encounter more permeable zones (and potentially lost circulation zones) centered at measured depths of approximately 2100 feet and 5200 feet.

Synchronized 3D Animation of Water Injection Volumes and Induced Seismicity Hypocenters

A recent addition to Calpine's induced seismicity analysis and structural model building capabilities is the time-synchronized 3D animation of well-by-well water injection volumes and the resulting induced seismicity. Water injection (and steam production) volumes have been accurately measured and verified throughout The Geysers geothermal field's operational history, and are available within Calpine databases at a monthly interval. The Paradigm Geophysical SKUA GOCAD 3D project database currently includes monthly injection well volumes and refined induced seismicity hypocenters for the period from January 1995 through December 2015. The water injection volumes are displayed three-dimensionally utilizing disks positioned at the wellbore's center-of-injection, or "perforation", with the disk radii for all wells scaled to a reference monthly injection volume. These time-synchronized animations are very instructive when assessing the progression of seismicity hypocenters, which are in turn indicative of fluid flow patterns. This is especially instructive in areas where injection well "interference" is limited and does not greatly complicate the induced seismicity pattern analysis. Relatively isolated injection wells (with limited interference) currently exist on the field perimeter and in the NW Geysers, and are seen *historically throughout The Geysers* during the *early phases* of the large scale injection programs. The images in Figure 8 show the progression of seismic events northward and downward from a particular water injection well along a permeable fracture zone during the time period from March 2000 through March 2015, following a November 1997 injection start.

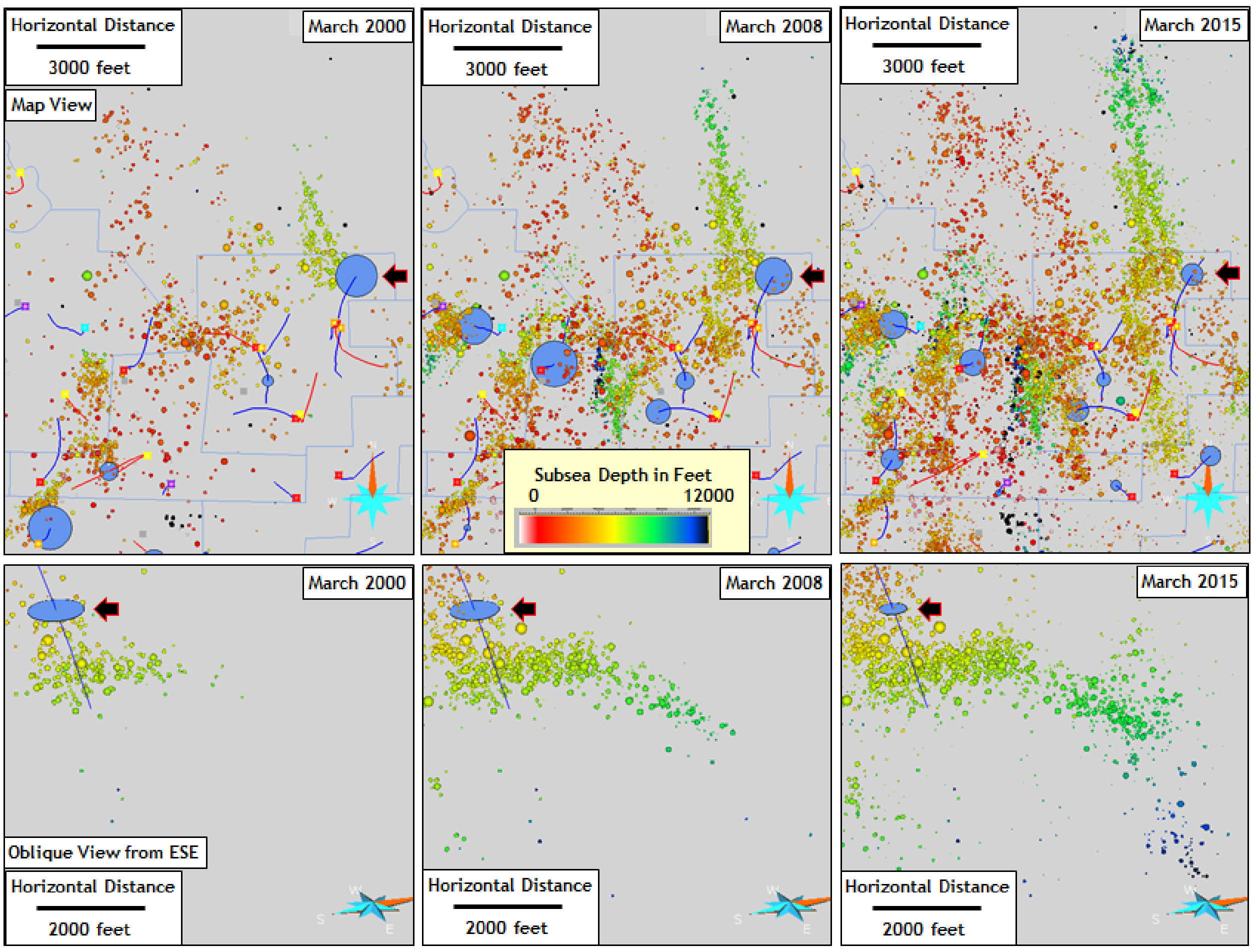

Figure 8: Time-synchronized 3D animation of water injection volumes and induced seismicity hypocenters for the east-central Geysers in map view (top row) and an oblique view from the east-southeast (bottom row). The northward and downward progression of induced seismicity associated with the water injection well identified by the black arrow(s) is captured following the November 1997 injection start for (1) March 2009 (left), (2) March 2008 (center) and (3) March 2015 (right). The blue disc radii are equivalently scaled to represent the water injection volume and the seismicity hypocenters are color-scaled by depth and sized by magnitude from 0.5 to 4.5.

The Geysers 3D Structural Model

Several recent 3D pre-drilling analyses and detailed 3D fracture zone interpretations indicate that there is potential to utilize induced seismic event patterns and progressions, including those seen on synchronized water injection and induced seismicity animations, as a *significant* constraint on Geysers 3D structural model development. Induced seismicity patterns and seismic event density variations appear to be indicative of permeability variations and resulting fluid flow, allowing the interpretation of fracture zones and lithological changes. For example, the transition from hornfelsic graywacke to Felsite generally correlates with a decrease in seismic event density decrease in the west-central and southeast Geysers. Of course, seismic event hypocenter determinations are highly dependent upon (1) the accuracy of the ray-tracing velocity model and (2) the first-arrival event pick accuracy. With the potential for significant lateral and/or depth errors, this approach must be used with caution. However, the fact that the Top Felsite markers (based on drilling information or “hard data”) and the seismic event density transition are spatially consistent increases Calpine’s confidence in the utilization of seismic event hypocenters as an additional constraint on Top Felsite surface development (and 3D structural model development in general). In addition to the fracture zone interpretations discussed previously, induced seismicity patterns were utilized to interpret the Big Sulphur Creek Fault Zone and Mercuryville Fault Zone as series of anastomosing faults that essentially form the productive boundary of the Geysers’ geothermal reservoir to the southwest.

5. DRILLING ANALYSIS AND RESERVOIR MODEL BUILDING

The 3D structural model under development for The Geysers will continue to be refined through detailed investigations, including localized pre-drilling analyses and real-time drilling analyses (which provides additional “hard data” as the drill bit descends). 3D visualization is proving to be an effective communication tool for drilling analysis, particularly when discussions include a broad range of specialists.

The pre-drilling analysis 3D cross section for a northwest-to-southeast oriented well corridor in the southeast Geysers is shown in Figure 9. In this example, particular lithological units were enhanced (scaled by 3x) to assist with the 3D structural interpretation. Although The Geysers is structurally very complex, continuity can often be seen over limited distances within properly oriented well corridors. In areas of sufficient well control, it has been possible to provide reliable lithological unit depth predictions. Based on predictions of this type, several lithological units for the LF-22 water injection well (drilled in 2014) were encountered within 50-80 feet of prognosis, and the final Graywacke interval was within 15 feet of pre-drilling estimates. Additionally, real-time drilling analysis of the well deviation surveys and lithology logs identified a close encounter with an adjacent wellbore, providing increased confidence when expensive drilling decisions are required at The Geysers.

The developing Geysers 3D structural model (Figure 10) has been converted for limited test volumes to a cell-based 3D model constrained by interpreted lithological boundaries and faults/fracture zones, and populated with geological and geophysical properties (hard data provided by well control). The next step is further refinement of these structural elements throughout The Geysers resulting in a *field-wide* cell-based 3D structural model for use in well planning and reservoir management. Upscaling of this cell-based model will produce a refined reservoir model that is anticipated to allow improved reservoir simulation and history matching, with simulation-derived reservoir model refinements transferred back into the 3D structural model, thereby “completing the loop”.

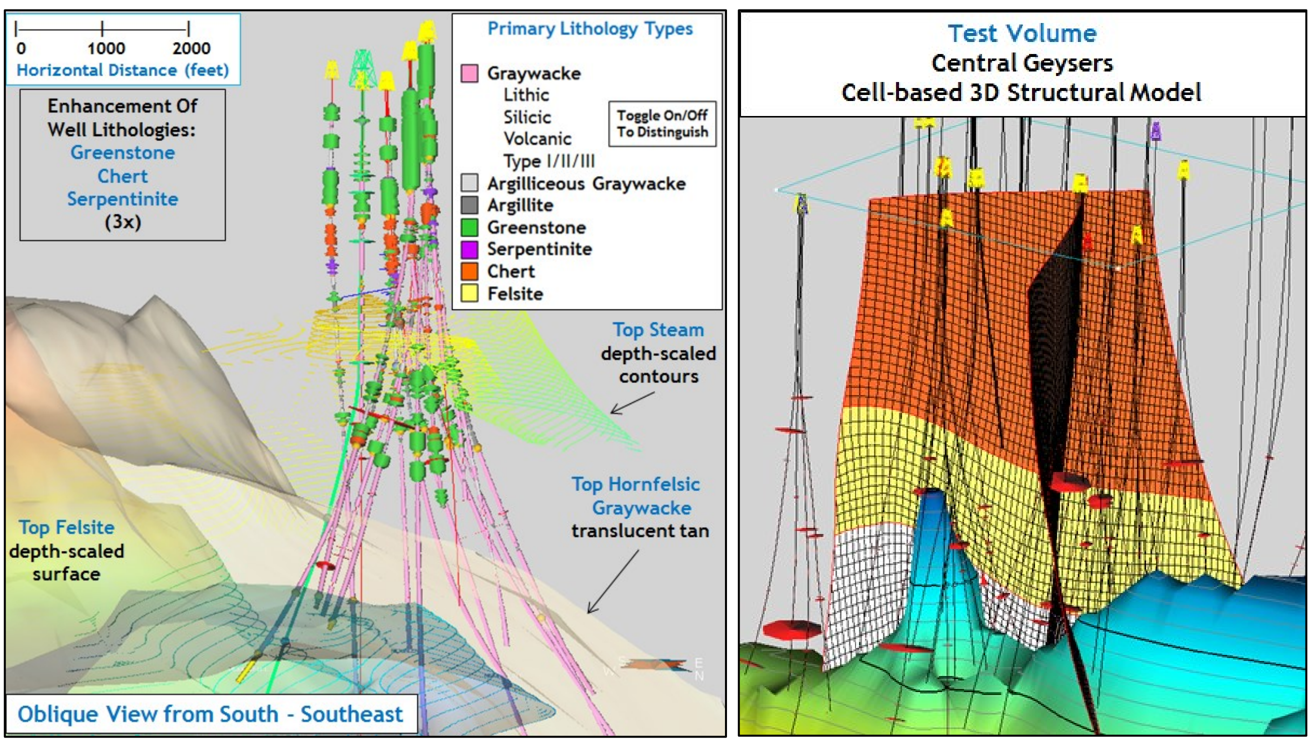

Figure 9: Left: Pre-drilling target analysis of a proposed southeast Geysers injection well. Although The Geysers is geologically complex, structural continuity can be observed locally along selected azimuths. Here a selected 3D corridor of wells trending from NNW to SSE show similar lithology. Enhancement of particular lithological units often assists with structural interpretation. Blue lines projecting from the wells are lost circulation zones, and red disks are steam entries (scaled by steam pressure increase).Vertical exaggeration = 1.5. Right: Limited-volume cell-based structural model test (~920,000 cells) created for determination of reservoir model upscaling workflow steps and parameters.

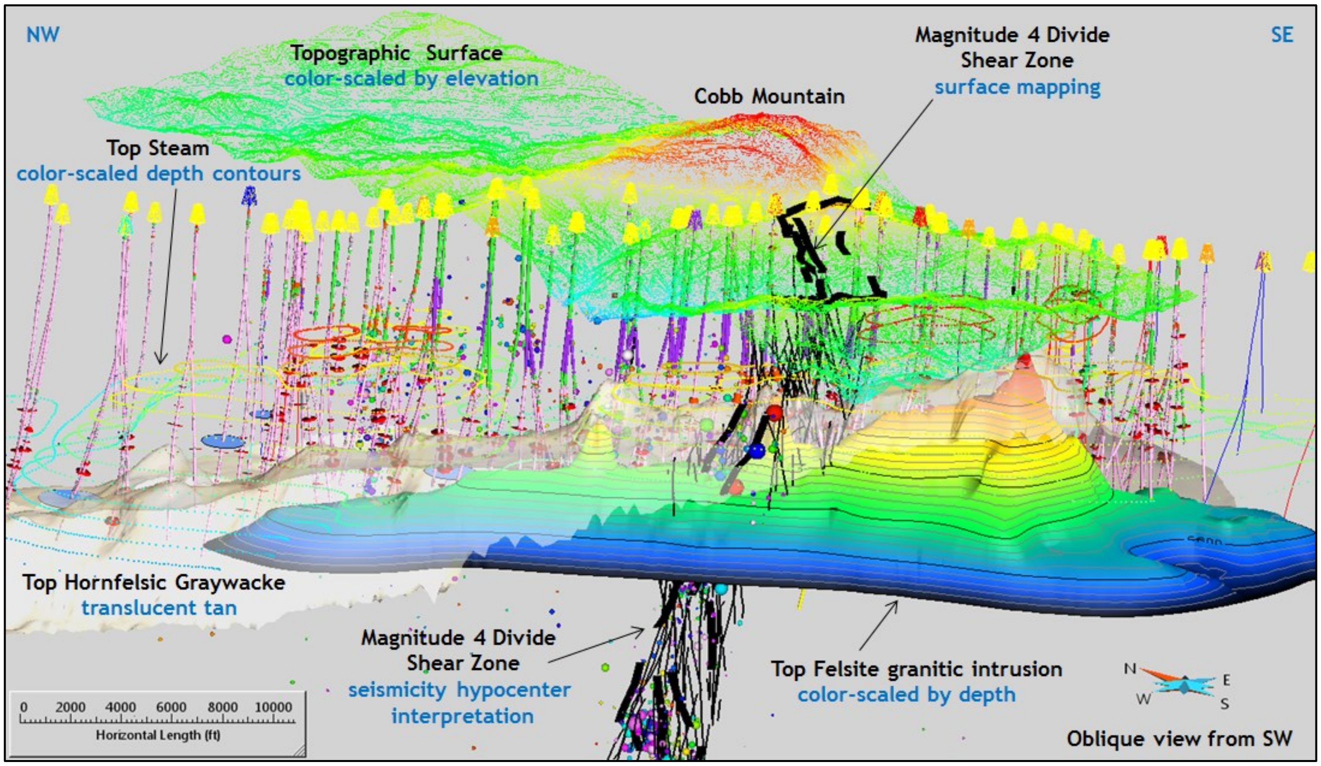

Figure 10: Oblique view from the southwest of (from base to top) the Top Felsite granitic pluton (color-scaled by depth), the Top Hornfels surface (translucent tan), and the Top Steam surface(s) as color-scaled depth contours, the east-central topographic surface (as points; color-scaled by elevation), and selected northwest-to-southeast well track "corridor" with assigned lithologies; steam entries are displayed as red disks (scaled by stream pressure increase). Seismicity is displayed for a single 500 foot (152 meter) wide north-to-south oriented corridor. The anastomosing Magnitude 4 Divide shear zone is shown (1) on the topographic surface as thick black lines, (2) in the subsurface for a selected seismicity slice as thick black lines and (3) for 21 adjacent seismicity slices at a 500 foot interval as thin black lines. Vertical exaggeration = 1.35.

6. SUMMARY AND CONCLUSIONS

Three-dimensional visualization, data analysis and structural model building are assisting the ongoing effort to better understand the complex geology and steam reservoir of The Geysers. This has long-term benefits for effective reservoir management, including well planning for optimal reservoir utilization, real-time drilling decisions and the potential for induced seismicity mitigation. The available 3D structural model building constraints include lithology logs, temperature logs, pressure logs, tracer analysis patterns, heat flow patterns, reservoir history matching, and seismicity hypocenters, all acquired over an extended period with a range of data reliability. In addition, a field-wide ArcGIS digital surface map compiled in 2014 from existing hard copy surface geology maps and refined in 2015 now provides improved constraint on the surface-to-subsurface structural relationships. Future 3D structural model development and induced seismicity analysis depends on (1) maximizing the utilization of The Geysers existing data; (2) acquiring additional data to further constrain model development, and (3) continuing advances in data utilization software tools and techniques. Calpine intends to continue the development of productive research collaborations and the utilization of developing technology to achieve these goals.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the guidance of Dr. Ernie Majer of Lawrence Berkeley National Laboratory, Dr. David Oppenheimer of the United States Geological Survey and Dr. Roland Gritto of Array Information Technology concerning The Geysers induced seismicity analysis, along with Dr. Joe Beall for his significant contributions to the understanding of The Geysers geology. Summer Geophysics Interns Rob Klenner (2011), Ramsey Kweik (2012) and Patrick Pierce (2013) assisted greatly with the painstaking conversion of hard copy lithology logs and steam entry data to digital form for entry into the 3D database. Summer Geoscience Intern Corina Forson (2014) merged the existing hard copy surface geology maps and completed some additional field mapping, resulting in a field-wide ArcGIS (digital) surface map compilation. Summer Geoscience Intern Andrew Sadowski (2015) completed several refinements to the field-wide ArcGIS (digital) surface map compilation, including a detailed assessment of the surface geology in the vicinity of the Magnitude 4.0 Seismic Divide. These mapping projects have provided some insight on the surface-to-subsurface structural relationships. The education, attention to detail, and dedication of these Calpine summers interns assisted greatly with database preparation for the SKUA GOCAD 3D model building. Seismic waveform data, metadata, or data products for this study were accessed through the Northern California Earthquake Data Center (NCEDC), doi:10.7932/NCEDC and the LBNL seismicity database. Installation and maintenance of a reliable LBNL seismic monitoring network has been provided primarily by LBNL contractor Ramsey Haught. Paradigm Geophysical provided excellent guidance concerning software requirements and hardware specifications.

Calpine appreciates the collaboration with worldwide seismicity research institutions and seismic technology developers (listed below with primary contributions) to better understand the induced seismicity associated with geothermal power production. This includes the testing of "next-generation" seismic sensor systems designed to more faithfully recover the true seismic wavefield and tolerate the extreme borehole temperatures associated with geothermal systems.

Lawrence Berkeley National Laboratory
- 32 station three-component permanent seismic monitoring network
- Collaboration on successful Department of Energy co-funded Enhanced Geothermal System Demonstration Project, including the installation and management two temporary seismic monitoring networks with a total of 20 three-component stations
- Collaboration on high-temperature tolerant fiber optical seismic sensor testing
- Borehole sensor installation and testing in southeast Geysers

United States Geological Survey
- Geysers' seismicity processing and real-time availability, detailed analysis of magnitude ≥ 3.5 events
- Collaboration on full-waveform six-component (3 translational/3 rotational) seismic sensor testing
- Collaboration on Silicon Audio high-sensitivity optical accelerometer testing

Massachusetts Institute of Technology
- Collaboration on installation and operation of three continuous monitoring GPS instruments

Array Information Technology
- Research Collaboration with European GEISER Project
- Installed 33 continuous broadband seismic recording instruments from GFZ Potsdam / GEISER Instrument Pool

GFZ Potsdam
- Collaboration on studies of spatiotemporal induced seismicity changes associated with variable water injection in the northwest Geysers (Prati 9 water injection well)

United States Seismic Systems Incorporated
- High-temperature tolerant borehole fiber optical seismic sensor array testing

Seismic Warning Systems
- Calpine is providing a testing and calibration site for earthquake early warning systems.
- Small, limited duration seismic events typical of The Geysers should not trigger automated warnings and shutdowns

REFERENCES

Aki, K. and P.G. Richards, 1980, *Quantitative Seismology: Theory and Methods*, 932 pp, Freeman, San Francisco, CA.

Beall, J.J. and M.C. Wright, 2010, Southern Extent of The Geysers High Temperature Reservoir Based on Seismic and Geochemical Evidence. *Geothermal Resources Council Transactions* 34, The Geysers Geothermal Field, Special Report No. 20, 1199-1202.

Beall, J.J. M.C. Wright, A.S. Pingol and P. Atkinson, 2010. Effect of high rate injection on induced seismicity in The Geysers. *Geothermal Resources Council Transactions* 34, The Geysers Geothermal Field, Special Report No. 20, 47-52.

Boyle, K. and M. Zoback, 2014, The stress state of the northwest Geysers, CA geothermal field and implications for fault-controlled fluid flow, *Bulletin of the Seismological Society of America*, Vol. 104, No. 5, pp. 1-10, October 2014, doi: 10.1785/0120130284.

California Department of Conservation, Division of Mines and Geology, Open File Report 96-08, U.S. Department of the Interior, *U.S. Geological Survey Open-file Report* 96-706, Appendix A, California Fault Parameters.

Conant, T., 2014, *Personal Communication*

DeCourten, F., 2008, Geology of Northern California, 48 pages, Available online at: http://www.cengage.com/custom/regional_geology.bak/data/DeCourten_0495763829_LowRes_New.pdf

Field, E.H., and 2014 Working Group on California Earthquake Probabilities, 2015, UCERF3: A new earthquake forecast for California's complex fault system: *U.S. Geological Survey* 2015–3009, 6 p., http://dx.doi.org/10.3133/fs20153009.

Garcia, J., M. Walters, J. Beall, C. Hartline, A. Pingol, S. Pistone and M. Wright, 2012, Overview of the Northwest Geysers EGS demonstration project, *Proceedings*, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, Jan. 30-Feb. 1, 2012.

Garcia, J., C. Hartline, M. Walters and M. Wright., 2015, The northwest Geysers EGS Demonstration Project, California – Part 1: Characterization and response to injection, *Geothermics*, http//dx.doi.org/10.1016.j.geothermics.2015.08.003.

Hanks, T. and H. Kanamori, 1979, A moment magnitude scale, *Journal of Geophysical Research*, 84, 2348-2350.

Hulen, J. B., J. C. Quick, and J. N. Moore, (1997a), Converging evidence for fluid overpressures at peak temperatures in the pre-vapor dominated Geysers Hydrothermal system, in *Geothermal Resources Council Transactions,* vol. 21, pp. 623–628.

Hulen, J. B., M.T. Heizler, J.A. Stimac, J.N. Moore, and J.C. Quick, (1997b), New constraints on the timing and magmatism, volcanism and the onset of the vapor dominated conditions at The Geysers steam field, Workshop on Geothermal Reservoir Engineering Proceedings, vol. 22, pp. 75-82, Stanford Geothermal Program, California, Stanford University, Stanford, California, USA.

Hulen, J.B. and D.L. Nielson, 1996, The Geysers Felsite, *Geothermal Resources Council Transactions*, v 20, pp. 295-306.

Hulen, J.B. and D.L. Norton, 2000, Wrench-Fault Tectonics and Emplacement of The Geysers Felsite, *Geothermal Resources Council Transactions v* 24, 289-298.

Jeanne, P., J. Rutqvist, C. Hartline, J. Garcia, P.F. Dobson and M. Walters, 2014, Reservoir structure and properties from geomechanical modeling and microseismicity analysis associated with an enhanced geothermal system at The Geysers, California, *Geothermics*, 51, 460-469.

Majer, E. L., R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith and H. Asanuma., 2007, Induced seismicity associated with Enhanced Geothermal Systems, *Geothermics*, 36(3), 185–222, doi:10.1016/j.geothermics.2007.03.003.

Majer, E.L., 2014, *Personal Communication*

Martínez-Garzón, P., G. Kwiatek, H. Sone, M. Bohnhoff, G. Dresen and C. Hartline, 2014, Spatiotemporal changes, faulting regimes, and source parameters of induced seismicity: A case study from The Geysers geothermal field, *Journal of Geophysical Research*, 119, 11, p. 8378-8396, doi:10.1002/2014JB011385.

Moore, J. N., M. C. Adams, and A. J. Anderson (2000), The fluid inclusion and mineralogical record of the transition from liquid to vapor-dominated conditions in The Geysers geothermal system, *Econ Geol*, 95.

Neilson, D. and Nash, G.: unpublished ESRI–enhanced thematic mapping imagery with interpreted fault structure presented at DOE Annual Review, Berkeley Marriot Hotel, CA, April 9-11, 1996.

NCEDC, 2014, Northern California Earthquake Data Center. *UC Berkeley Seismological Laboratory.* Dataset. doi:10.7932/NCEDC.

Oppenheimer, D., 1986, Extensional tectonics at The Geysers geothermal area, California, *Journal of Geophysical Research*, 91, 11463-11476.

Rutqvist, J., P. F. Dobson, J. Garcia, C. Hartline, P. Jeanne, C. M. Oldenburg, D. W. Vasco, and M. Walters, 2013, The Northwest Geysers EGS Demonstration Project, California: Pre-stimulation Modeling and Interpretation of the Stimulation, *Math. Geosci*., 1–27, doi:10.1007/s11004-013-9493-y.

Segall, P. and S.D. Fitzgerald, 1998, A note on induced stress changes in hydrothermal and geothermal reservoirs, *Tectonophysics*, 289(1-3) 117-128, doi:10.1016/S0040-1951(97)00311-9.

Stanley, W.D., H.M. Benz, M.A. Walters and B.D. Rodriguez, 1997, Tectonic controls on magmatism and geothermal resources in The Geysers-Clear Lake Region, CA: Integration of new geologic, earthquake, tomography, seismicity gravity, and magnetotelluric data. *USGS Open File Report* 97-95, 48 pp.

Stark, M.A., 1992, Microearthquakes – a tool to track injected water in The Geysers geothermal reservoir, *Geothermal Resource Council,* Monograph on The Geysers Geothermal Field, Special Report No. 17, 111-117.

Waldhauser, F., Near-real-time double-difference event location using long-term seismic archives, with application to Northern California, *Bull. Seism. Soc. Am*., 99, 2736-2848, doi:10.1785/0120080294, 2009.

Waldhauser, F. and D.P. Schaff, Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res*.,113, B08311, doi:10.1029/2007JB005479, 2008.

Walters, M.A., 1996, Field data and references for a northeast-trending extensional zone, The Geysers – Clear Lake region, California, *Lockheed Martin Technologies Company,* Modification No. 1 to Purchase Order C96-176014.

Walters, M.A., J.R. Haizlip, J.N. Sternfeld, A.F. Drenick and J. Combs, 1991, A vapor-dominated high-temperature reservoir at The Geysers, California, *Geothermal Resource Council,* Monograph on The Geysers Geothermal Field, Special Report No. 17, 77-87.

Wright, M.C. and Beall, J.J. 2007, Deep cooling response to injection in the southeast Geysers. *Geothermal Resources Council Transactions* 31, 457-461.