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Three-Dimensional Structural Model Building Constrained By Induced Seismicity Alignments at The Geysers Geothermal Field, Northern California

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ABSTRACT

A three-dimensional structural model of The Geysers geothermal field has been developed and is continually being refined by Calpine Corporation. The primary structural model building constraints for this complex assemblage of late Mesozoic Franciscan rocks include lithology logs and topologic surfaces, surface geologic maps, steam entries and refined tomographic double-difference seismicity hypocenters available from the Northern California Earthquake Data Center (NCEDC) and Lawrence Berkeley National Laboratory (LBNL). The secondary constraints include temperature logs, pressure logs, tracer analysis patterns, isotopic patterns and heat flow patterns. Paradigm Geophysical SKUA GOCAD software originally designed for the oil and gas industry allows synchronized time animation of water injection interval volumes and induced seismicity hypocenters at any selected time step and time interval. For additional clarity and detail, these synchronized animations can be spatially limited, generally in the form of variously oriented seismicity hypocenter slices. The resulting analysis technique is analogous to the progression through a series of magnetic resonance imaging (MRI) slices by medical experts during the assessment of injuries.

Utilizing primarily the NCEDC catalog of refined tomographic double-difference seismicity hypocenters available from January 1984 to the present, patterns and alignments seen during spatiotemporal analyses of The Geysers' induced seismicity and tracer patterns seem indicative of (1) fluid flow progressing away from an injection well via fluid flow pathways which are generally near-vertical fault/fracture networks, and/or (2) fluid flow progressing from injection wells as a fairly uniform spherical front until encountering relatively linear fluid flow barriers (hydrological and/or geological discontinuities). A refined understanding of The Geysers' fracture surfaces, fluid flow paths, fluid boundaries, reservoir heterogeneity and reservoir compartmentalization assists with well planning/targeting, real-time drilling analysis, reservoir management and provides the potential for improved seismicity mitigation at The Geysers.

1. Introduction

The Geysers, located in Northern California and approximately 75 miles north of San Francisco (Figure 1), is the largest producing geothermal field in the world. Calpine Corporation operations at The Geysers span 29,000 acres (45 square miles) and include 13 geothermal plants, 80 miles of steam production pipelines, 69 miles of water injection pipelines, and 167 miles of project roads. Calpine produces approximately 700 million watts of electrical power output from 315 steam production wells with an average wellhead temperature of 359°F and an average steam production of 35,470 pounds/hour/well.

1.1 Regional Geology

This geothermal resource exists within a complex assemblage of late Mesozoic 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). The slip rates within this zone of subparallel, right-lateral strike-slip faults progressively decrease to the east and create a transtensional tectonic environment between the active Maacama Fault Zone and the active Bartlett Springs Fault Zone (Figure 1).

The present-day Geysers geothermal field is bordered to the southwest by the inactive Mercuryville Fault Zone and Big Sulphur Creek Fault Zone, and to the northeast by the inactive Collayomi Fault Zone (see Figure 1 inset). There are no mapped faults in or adjacent to The Geysers 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 “the Felsite” began intruding the brittle Franciscan graywacke found throughout the subsurface of The Geysers region. Extensive fracture enhancement above the granitic pluton occurred due to mechanical and hydraulic forces associated with intrusion, along with contact thermal metamorphism of the overlying graywacke to a biotite hornfels. 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.

The containment of the initial hydrothermal reservoir was primarily dependent on the transition from abundant open fractures to very limited open fractures with decreasing depth. This is well-represented in the present-day northwest Geysers, where an open fracture network in the 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 and Norton, 2000; Moore et al., 2000, Beall and Wright, 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).

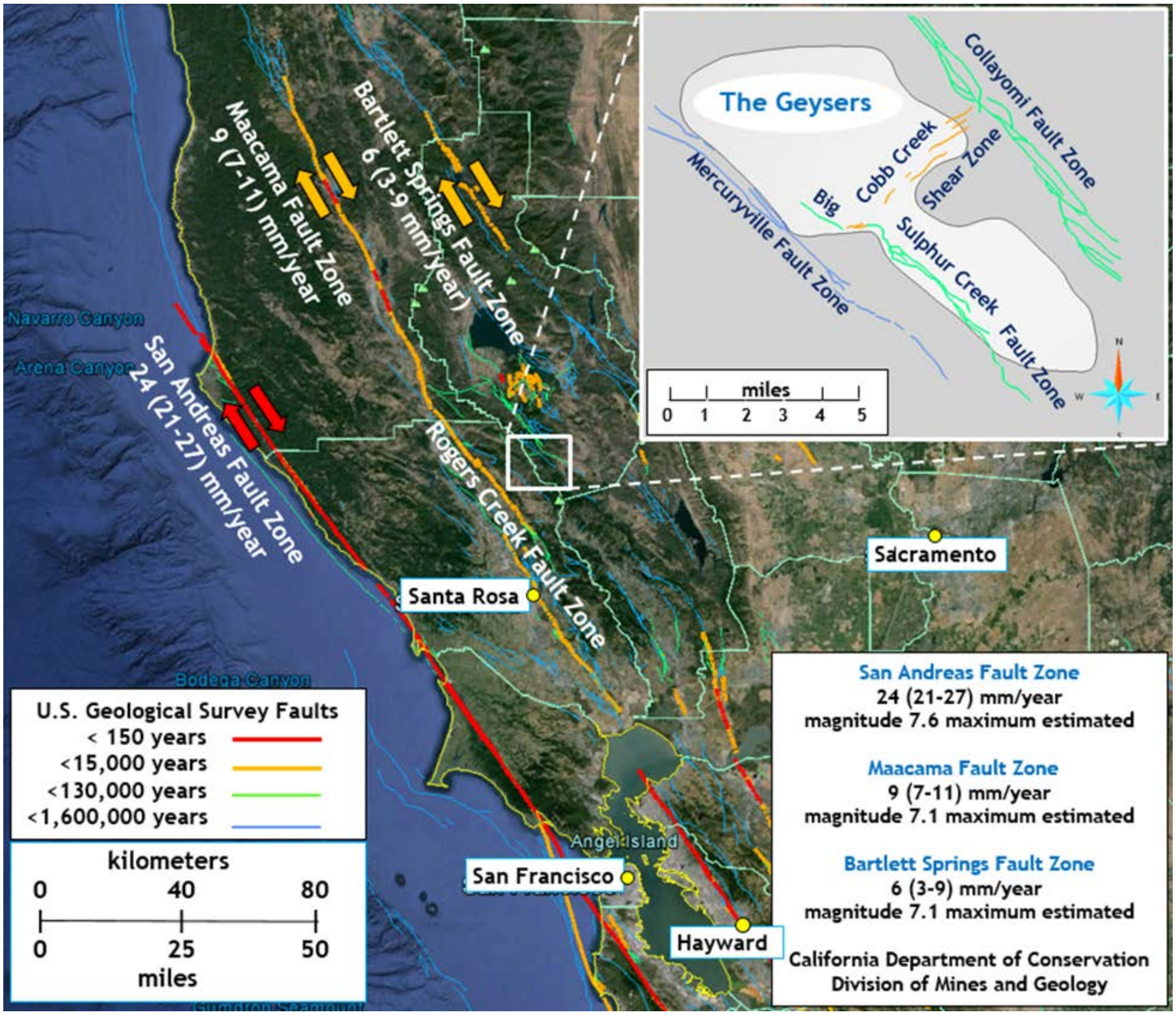

Figure 1: The San Andreas Fault System, including the Maacama / Rodgers Creek Fault Zone and Bartlett Spring Fault Zone. United States Geological Survey Faults with activity in the past 1.6 million years overlain on Google Earth image. Primary Geysers bounding fault zones shown in the upper right inset,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

1.2 Water Injection

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. 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 combined nominal flow rate of 18.7 million gallons per day, in addition to recovered steam condensate from the power plants and creek water injection during peak precipitation periods.

1.3 Induced Seismicity

The ambient temperature "injection" water falls freely into approximately 58 injection wells (with a near vacuum wellhead gauge pressure of -13 psig 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).

Seismicity at The Geysers is recorded as three components of motion on 36 stations of the Lawrence Berkeley National Laboratory (LBNL) seismic monitoring network distributed throughout and slightly beyond The Geysers steamfield. Six stations of the United States Geological Survey (USGS) regional seismic monitoring network also contribute data to The Geysers' seismicity determinations.

Seismic waveforms are accumulated at each station by the LBNL radio telemetry network and imported to the USGS "Waveserver" located within Calpine's Geysers Administration Center. The three-component seismic waveforms and calculated P-wave arrival times are forwarded by 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, along with 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 (1986), 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, 1986; Rutqvist et al, 2013).

The USGS and California Geological Survey have identified no surface-mapped active faults within The Geysers (Field et al., 2015), and the highly-fractured steam reservoir (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; Hartline et al, 2016).

Importantly for Calpine and the nearby communities, there are very encouraging field-wide trends concerning The Geysers water injection volume vs. induced seismicity. Most significant is a downward linear regression trend of approximately -0.5 events per year for magnitude ≥ 3.0 seismic events beginning in 1988 (from a peak of 32 events per year in 1988 to recent ranges of 7 to 14 events per year) (Figure 2).

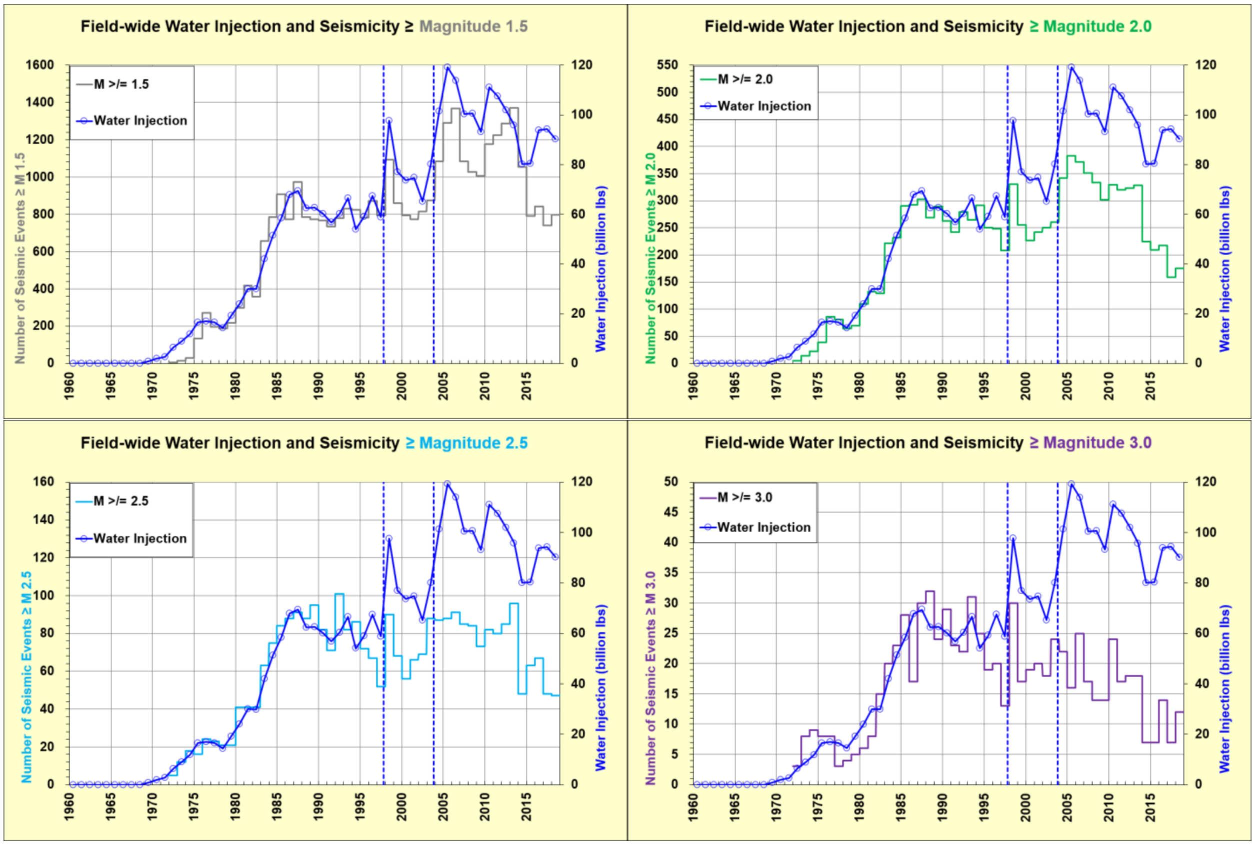

Figure 2: The Geysers yearly fieldwide water injection in billions of pounds (scale at right) vs. the number of seismic events per year (scale at left) greater than or equal to the specified threshold for the years 1960 through 2018 (scale at bottom). Proper scaling of water injection and seismicity profiles highlight the direct correlation between water injection and induced seismicity through approximately 1995 for magnitude thresholds 1.5 (upper left), 2.0 (upper right), 2.5 (lower left) and 3.0 (lower right). After that time, seismicity counts descend below anticipated levels (based on previous correlation) with the degree of de-coupling more pronounced for increasingly higher magnitude thresholds. The vertical blue dashed lines on each graph indicate (1) the late 1997 start of Southeast Geysers Effluent Pipeline injection and (2) the late 2003 start of Santa Rosa Geysers Recharge Project injection. Database: Northern California Earthquake Data Center (NCEDC); University of California Berkeley Seismological Laboratory

It is difficult to fully understand the causes of these encouraging trends due to the complex interactions of fracture reactivation mechanisms, primarily resulting from thermal contraction and secondarily from modest pressure variations. However, a steam reservoir approaching steady-state conditions would clearly be desirable with respect to induced seismicity, and Calpine is attempting to approach this condition through (to the degree possible) a broad and uniform distribution of injected water that is mass-balanced with steam production. Support for this approach is derived from an extensive National Research Council study concerning induced seismicity potential in energy technologies, which concluded that geothermal induced seismicity appears related to (1) the existing stress field in the rocks, (2) the stress introduced by temperature variability, and (3) the net fluid balance considerations (National Research Council. 2013).

2. 3D Visualization and 3D Induced Seismicity Analysis

Paradigm Geophysical SKUA GOCAD (Subsurface Knowledge Unified Approach / Geologic Objects Computer Aided Design) software was purchased in 2011 by Calpine Corporation with the following goals:

- 3D visualization and 3D seismicity analysis for a refined understanding of the spatial and spatiotemporal relationships between water injection and induced seismicity.
- 3D visualization as an improved communication tool for public outreach and technical discussions concerning induced seismicity.

During software utilization for the above-stated goals, it became apparent that the development of a Geysers' 3D structural model could benefit steam production and water injection well planning, real-time drilling analysis, induced seismicity analysis and mitigation, and assist with reservoir management.

3. 3D Structural Model Development

The extreme surface topography of The Geysers causes (1) access limitations, (2) prohibitive cost for active 2D/3D seismic data acquisition and (3) severe datum concerns for active 2D/3D seismic data imaging. Additionally, extreme subsurface conditions (high temperature and corrosive fluids) significantly limit the use of typical oil and gas geophysical logging methods to investigate the properties of The Geysers' complex metamorphic rocks and fractured steam reservoir.

Consequently, the constraints for The Geysers' 3D structural model development are provided by approximately 900 lithological log segments (compiled by various well-site geologists over nearly five decades and painstakingly converted to digital form since 2011), surface geology maps (including an ArcGIS digital map compilation completed in 2017), isotopic patterns, reservoir temperature and pressure, reservoir tracer test patterns, heat flow patterns, non-condensible gas concentrations and seismicity hypocenter databases provided by the Northern California Earthquake Data Center (NCEDC) and LBNL. The Geysers' seismicity alignment/pattern analyses primarily utilize the NCEDC refined relative hypocenter location tomographic "double-difference" seismic data available within the 1984-2011 "base catalog" (Waldhauser, 2008) and the more recently available "real-time" seismic data catalog (Waldhauser, 2009) for the period from 01 January 2012 to the present.

A three-dimensional structural model of The Geysers geothermal field was initially developed and is continually being refined by Calpine Corporation using Paradigm Geophysical SKUA

GOCAD software (Figure 3). Refinements to the 3D structural model often occur during detailed 3D pre-drilling analyses in the vicinity of proposed steam production and water injection wells, along with other localized scientific studies. An example is the microseismic stimulated reservoir analysis volume identified within Figure 3, where several iterations of detailed 3D fault/fracture interpretation were completed in relation to the Department of Energy co-funded Northwest Geysers Enhanced Geothermal System Demonstration Project (Hartline et al. 2019).

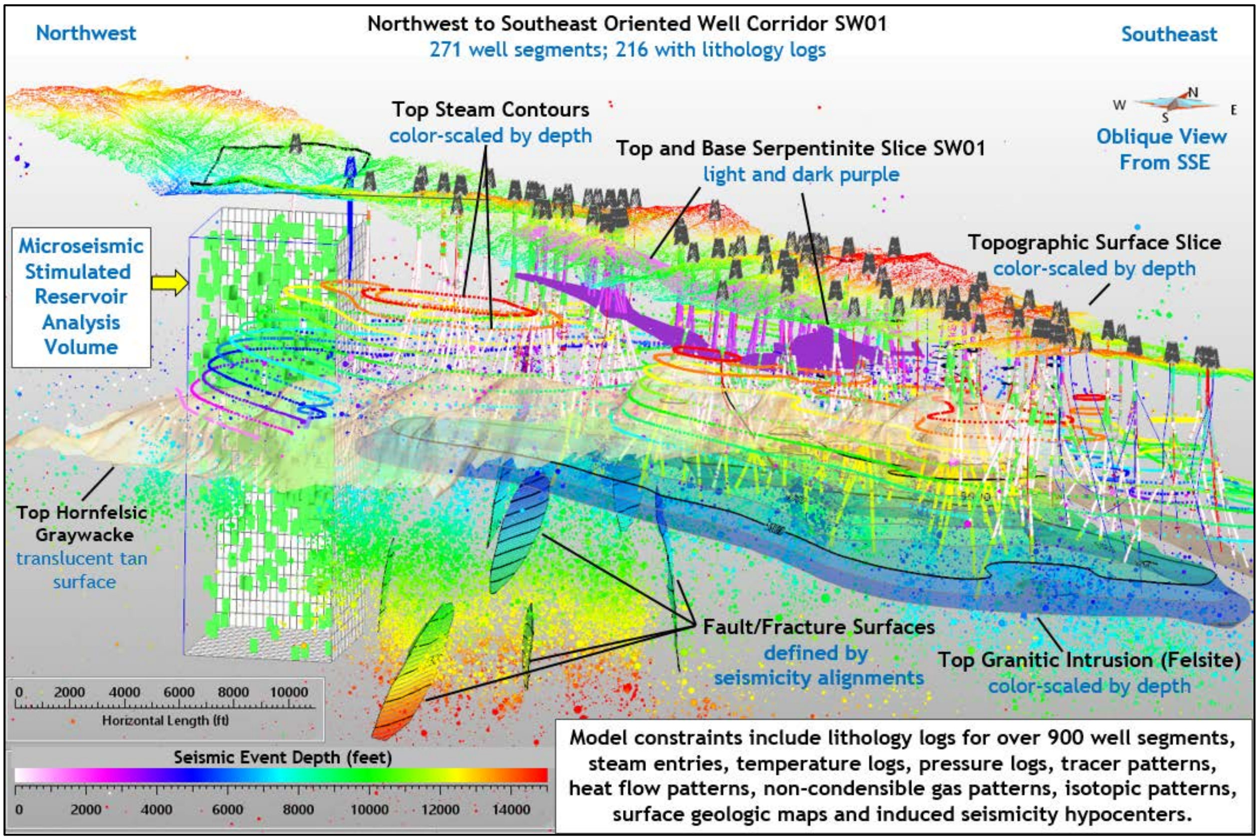

Figure 3: Oblique view from the south-southeast of The Geysers 3D structural model including several identified horizons, a well corridor including 216 wells with lithology logs, preliminary fracture surfaces and a microseismic stimulated reservoir analysis volume in the northwest portion of the field associated with the Department of Energy co-funded Northwest Geysers Enhanced Geothermal System Demonstration Project. Modified from Hartline et al. 2019.

3.1 Structural and Stratigraphic Model Workflow

The primary steps for the development of the 3D structural model representing The Geysers' complex geology are:

- 3D data development
- Import to 3D database
- Preliminary fracture/fault surface interpretation (well-log based)
- Preliminary structural horizon interpretation
- Refined fracture/fault surface interpretation (seismicity pattern/alignment based)

- Refined structural horizon interpretation
- Integration of refined structural horizons and refined fault/fracture surfaces
- 3D structural/stratigraphic model building workflow

- **Phase one** of the workflow is the construction of a coherent **3D structural model** representing the geometric relationships and geologic boundaries within the subsurface, including appropriate horizon displacement at fracture/fault intersections based on the available constraints. This is an iterative process with model inconsistencies identified and corrected.

- **Phase two** of the workflow is the construction of a **3D cell-based geological model** at a grid resolution suitable to represent reservoir properties, and available as an improved basis for upscaling to a reservoir flow simulation grid.

The complexity and scale of the Geysers' geothermal field presents significant challenges for 3D structural modeling and particularly cell-based 3D geological modeling. Utilizing the desired grid cell resolution for a model representing the entire geothermal resource strains software capabilities. For comparison: [1] the North Sea Ekofisk oil field with 6.7 billion barrels of oil in place has an area of approximately 19 square miles (49 km^2), a vertical closure of 800 feet (244 m) and a hydrocarbon column of 1000 feet (305 m), while [2] The Geysers geothermal field has an area of approximately 45 square miles (117 km^2) and a steam reservoir vertical extent believed to exceed 15,000 feet (4,570 m) at field center.

3.2 Structural and Stratigraphic Model Goals

The primary Geysers 3D structural and stratigraphic model building goals include:

- Refine the understanding of fluid flow paths, fluid boundaries, reservoir heterogeneity and reservoir compartmentalization at The Geysers, *contributing* to improved reservoir management at The Geysers.
- Improved seismicity mitigation with a refined understanding of fracture systems and fault zones at The Geysers. Seismic event magnitude relates directly to induced 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/fracture slip area (Hanks and Kanamori, 1979; Aki and Richards, 1980; Segall, 1998).
- Provide a 3D perspective for well planning/targeting and real-time drilling analysis within a continually refined 3D structural model.
- Develop a refined 3D Vp/Vs velocity model allowing improved 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.

4.0 Fault/Fracture Interpretation

Calpine's Paradigm Geophysical SKUA GOCAD 3D software allows the synchronized time animation of water injection and induced seismicity hypocenters at any appropriate time step and time interval. Interval water volume or cumulative water volume is represented by the radius of a disk assigned at the well's center of injection. For additional clarity, these synchronized animations are often completed with spatially and/or temporally limited seismicity hypocenters, and within variously oriented seismicity hypocenter slices. The resulting evolution of induced seismicity patterns often provide quite dramatic results, such as that evident for the "Magnitude 4 Seismicity Divide" (Beall and Wright, 2010) (Figure 4). Synchronized animations completed for a series of adjacent 1000' wide north-to-south oriented seismicity slices and the time interval January 2000 to December 2014 allow visualization of fluid flow progression within a high permeability fracture network in the central Geysers. Seismicity descends and progresses laterally throughout this fracture zone in a series of steps or pulses that are consistent with periods of increased fluid flow from several nearby injection wells. This fracture zone defines a significant structural discontinuity between relatively shallow, lower magnitude seismicity to the southeast and deeper, potentially higher magnitude seismicity to the northwest, with 34 of the 36 magnitude $\geq$ 4.0 seismic events within or northwest of this extensive, anastomosing fracture zone. This fracture zone obviously represents a significant structural boundary within The Geysers geothermal field.

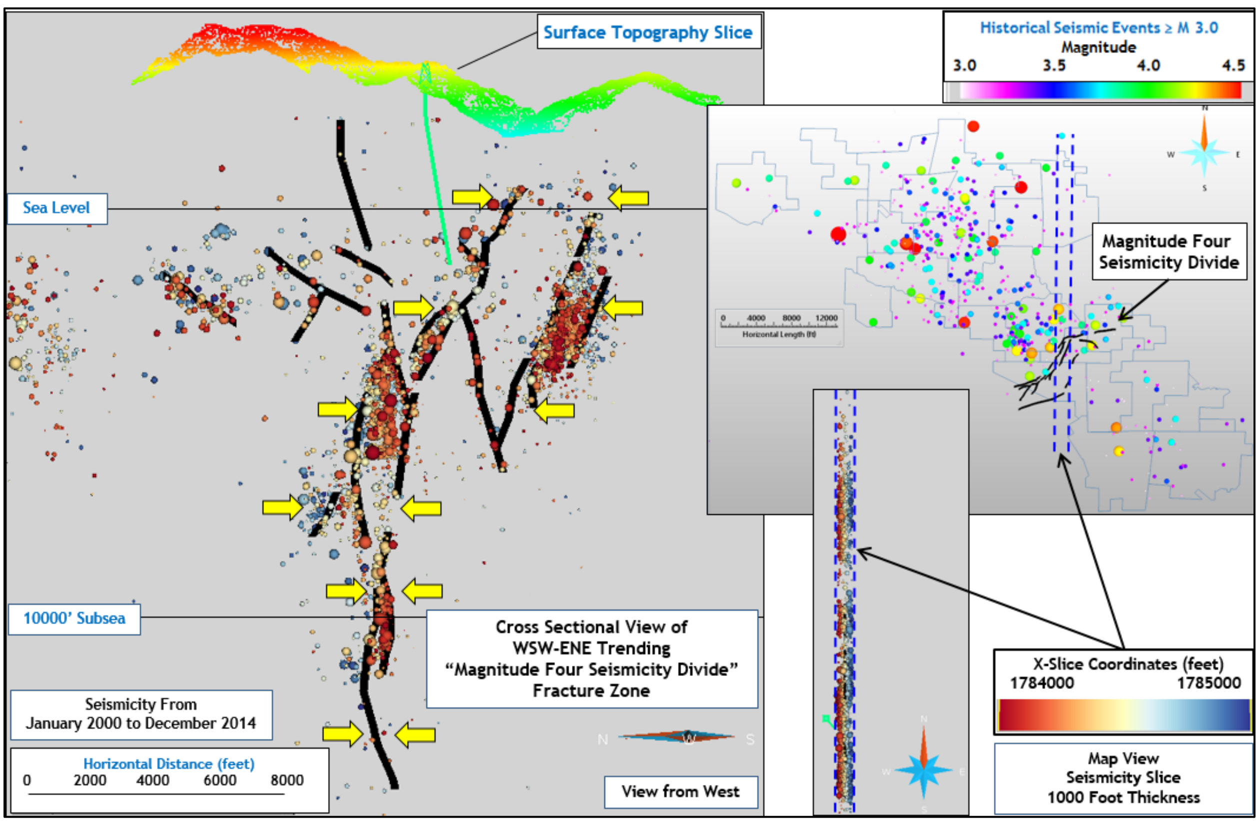

Figure 4: Left: View from west of the Magnitude 4 Seismic Divide as imaged by NCEDC tomographic double difference seismicity hypocenters for time range 01 January 2000 to 31 December 2014 and California II 402 State Plane Easting range 1784000 to 1785000. Yellow arrows define the approximate width of the fracture zone. The north-to-south oriented cross sectional seismicity slice (seen in map view at lower right) intersects the SW-NE trending "Magnitude 4 Seismicity Divide" fracture zone as shown at upper right (Modified from Hartline et al., 2016).

While completing induced seismicity analyses and visualization associated with required semi-annual technical presentations, and 3D pre-drilling analysis projects, it became increasingly clear that seismicity patterns/alignments indicative of fluid flow and subsurface structure and present on a series of seismicity slices and could be analyzed with techniques analogous to medical experts progressing through a series of magnetic resonance imaging (MRI) slices during injury assessment ("I'm sorry, your reservoir appears to be fractured").

Utilizing 3D visualization software and the Northern California Earthquake Data Center catalog of refined tomographic double-difference seismicity hypocenters available from January 1984 to the present (Waldhauser and Schaff, 2008), induced seismicity alignments at The Geysers seem to primarily represent contributions from (1) fluid flow migration from an injection well via fluid flow pathways which are generally near-vertical fault/fracture networks, and/or (2) fluid flow progressing from injection wells as a fairly uniform spherical front until encountering relatively linear fluid flow barriers (hydrological and/or geological discontinuities).

Additionally, vertical lithological transitions identified on lithology logs sometimes correlate with a vertical transition in induced seismic event density. The transition from overlying hornfelsic graywacke with a high seismic event density to the granitic intrusion (felsite) with a low seismic event density is especially apparent for (1) the eastern flank of the felsite in the southeast Geysers and (2) the western flank of the felsite in the west central Geysers. The seismic event density decrease below this lithological transition is thought to represent a transition from metamorphosed and embrittled hornfelsic graywacke into a lower permeability granitic intrusion.

Seismicity patterns or alignments evident in static displays or evolving during time-animations of variously oriented seismicity slices contribute to the interpretation of fracture/fault surfaces, structural discontinuities, and lithology contrasts, providing an additional and significant constraint on the 3D structural model building process (Figure 5).

Certain depth levels and field locations provide optimal starting points for the identification of significant seismicity patterns/alignments and allow the initiation of fault/fracture interpretation. After identification of a potential alignment, expansion of the seismicity slice thickness and/or progression through a series of properly oriented adjacent slices is completed to see if the seismicity alignment is sustained spatially (and worthy of interpretation). The actual interpretation, or point picking, is completed *directly* on individual aligned seismicity hypocenters believed to be indicative of injection fluid flow paths and fluid flow barriers/discontinuities. Fault/fracture surfaces are then developed by picking aligned seismic hypocenters on a series of seismicity depth slices, north-south slices, east-west slices, reservoir long-axis "strike" slices, or reservoir short-axis "dip" slices with a 500' to 1000' width or thickness. During the interpretation phase, display parameters are re-optimized frequently, as the proper color scales, symbol types, and symbol sizes can significantly emphasize (or de-emphasize) seismicity alignment patterns. *Note that it is generally not possible to display all seismicity alignments optimally within a single seismicity slice or time step during seismicity animations.*

The initial progression of induced seismicity hypocenter patterns or alignments from a particular injection well is often especially instructive, prior to interference or "masking" by subsequent induced seismicity resulting from (1) additional injection into the same well, or (2) injection into a nearby well. In areas of masking/interference between water injection wells, or simply areas with an extended period of water injection, it is instructive to limit animations both spatially and temporally, often receiving insight from the early phases of water injection and seismicity.

For example, central Geysers' seismicity animations restricted to various time intervals within the 1980's and 1990's often clearly illuminate fluid flow paths and boundaries for particular wells prior to the onset of seismicity interference from adjacent wells . Patterns often lose clarity with additional injection as seismicity, indicative of fluid flow from a particular well, appears to break through partial flow barriers and eventually merges with seismicity progressing from another injection well.

There are excellent opportunities to visualize apparently well-defined fluid flow paths, fluid flow boundaries and reservoir compartmentalization from relatively isolated injection wells using seismicity hypocenters through the present in the northwest Geysers - with careful data isolation and display parameter selection (Figures 5 and 9).

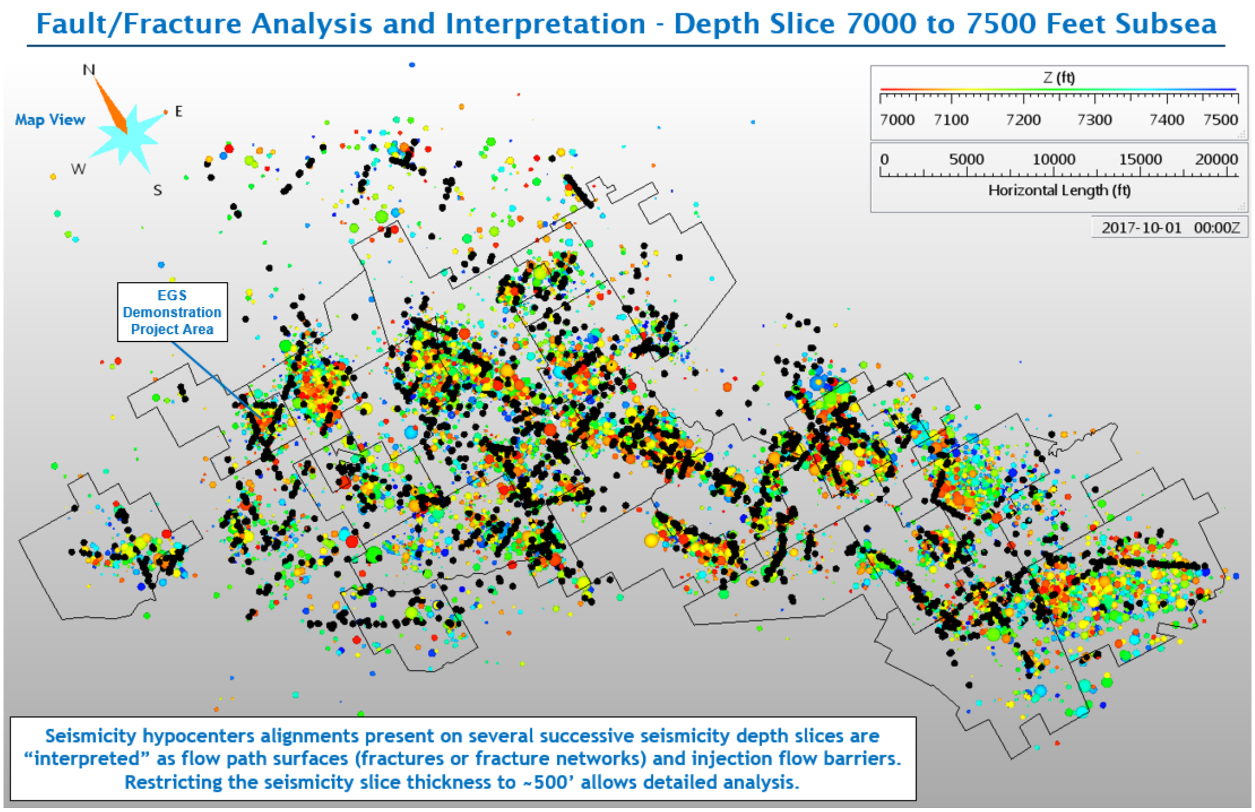

Figure 5: Map view with north at upper left. Fault/fracture interpretation example for a seismicity depth slice from 7000 to 7500 feet below sea level. Picks (black circular symbols) are made directly on aligned seismicity hypocenters for a series of depth slices. The resulting picks provide control points for the construction of a triangulated mesh surface representing the interpreted fault/fracture surface.

Seismicity may progress from one injection well at a particular depth interval and progress from an adjacent injection well at a different depth interval. This can result in a seismicity alignment seen as a high-to-low seismic event density transition at one depth level and as a low-to-high seismic event density transition at a different depth step. This is believed to be indicative of fault displacement and the resulting juxtaposition of lower permeability rock and higher permeability rock across a fault/fracture system.

A complication for structural interpretation is incomplete "illumination" of the subsurface by water injection. The seismicity patterns, indicative of subsurface fluid flow, often have inter-well seismicity gaps that introduce uncertainty in the interpretation the fault/fracture systems. The challenge is to push the seismicity hypocenter interpretation sufficiently into the data gap (but not too far). The available spatial resolution of seismicity hypocenters and well lithology logs are often not sufficient to provide confidence in the lithologic horizon displacement across faults.

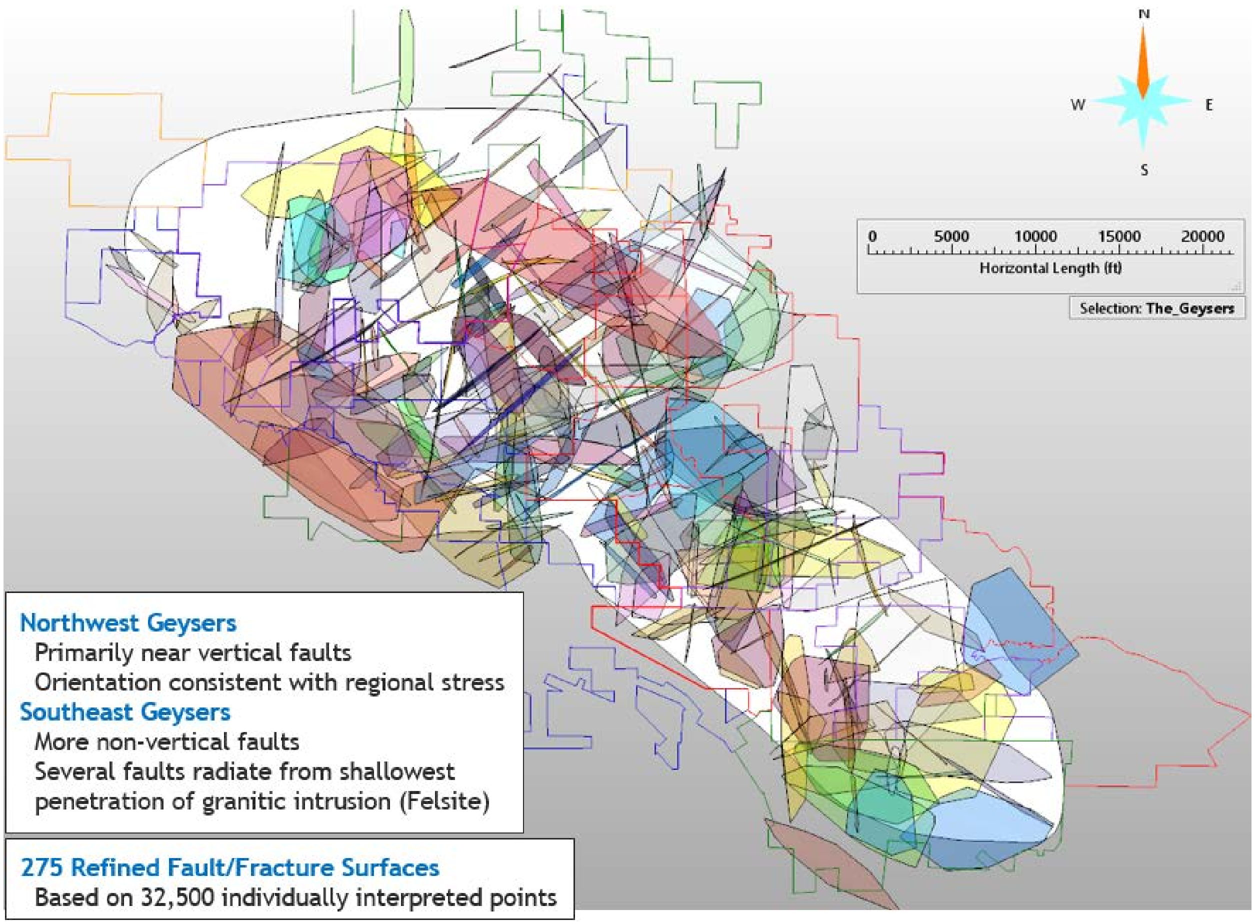

Figure 6: Fracture surfaces interpreted based on seismicity patterns/alignments seen within variously oriented seismicity slices. The picks made directly on aligned seismicity hypocenters are used to construct triangulated surfaces. These surfaces are refined during pre-drilling project analysis for specific wells and contribute to the developing Geysers 3D structural model.

Interpretation of over 275 individual fault/fracture surfaces has been completed field-wide based on sustained seismicity alignments that range from discrete, isolated surfaces to extensive anastomosing fracture zones (Figures 4 and 6). In the northwest Geysers, the interpreted fault/fracture zones are primarily near vertical with orientations aligned predominately to the regional stress field. In the southeast Geysers, the interpreted fractures/fracture zones become more complicated, often non-vertical, apparently responding to a more complicated stress field, with multiple fracture zones radiating outward from the shallowest penetration of the granitic intrusion (felsite).

The Geysers induced seismicity patterns and resulting interpreted fault/fracture patterns appear to be strongly influenced by the regional stress field associated with the San Andreas Fault System. This extensive (800-mile-long) system of northwest to southeast oriented 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. At The Geysers, the resultant stress field is responsible for northwest-to-southeast oriented fractures consistent with the San Andreas Fault System and southwest-to-northeast oriented faults/fractures due to transtensional forces (Walters, 1996). 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).

4.1 Fracture/Fault Surface Verification

Fault/fracture surface interpretation techniques utilized in the 3D structural model building process must be subject to verification. The validity of Geysers' interpreted fault/fracture surfaces, structural/hydrological discontinuities and lithologic boundaries is supported by several lines of evidence including:

- Several major fault/fracture surface interpretations can be extended to the topographic surface, where they align very well with mapped surface faults determined by government agencies and/or geothermal operators. Excellent examples are the north Geysers Ridgeline Fault Zone and southeast Geysers Magnitude 4 Divide Fault Zone (Figure 7).
- Well-based lithology log correlations provide strong evidence of fault-related rock unit displacement that are consistent with interpreted fault/fracture surfaces.
- Static reservoir pressure variation patterns, non-condensible gas variation patterns, and ammonia variation patterns are consistent with interpreted fault/fracture surface orientations.
- Tracer studies indicate fluid flow directions consistent with interpreted fault/fracture surface orientations.
- The Department of Energy co-funded Northwest Geysers Enhanced Geothermal System Demonstration Project, provides strong evidence that induced seismicity hypocenter patterns correlate with other reservoir parameters and are indicative of fluid flow paths and boundaries (Garcia et al., 2012; Garcia et al., 2015; Hartline et al., 2019; Jeanne et al., 2014).
- Steam entries for water injection wells often correlate directly with interpreted fault/fracture surfaces. Initial attempts to correlate interpreted fault/fracture surfaces with all steam entries documented during drilling campaigns were disappointing (and concerning). Subsequently, it was realized that water injection wells "illuminate" fluid flow pathways associated with steam entries and allow fault/fracture surface interpretation. However, production well steam entries and associated fluid pathways are simply not well illuminated, as steam production apparently produces limited seismicity (Figure 8).

- Drilling records that provide direct evidence of an extended fault zone:
    - Possibly the most direct (and most satisfying) confirmation of fault/fracture surface interpretation resulted from the early 2019 northwest Geysers Prati 15 steam production well pre-drilling analysis program (discussed in Section 5.1).

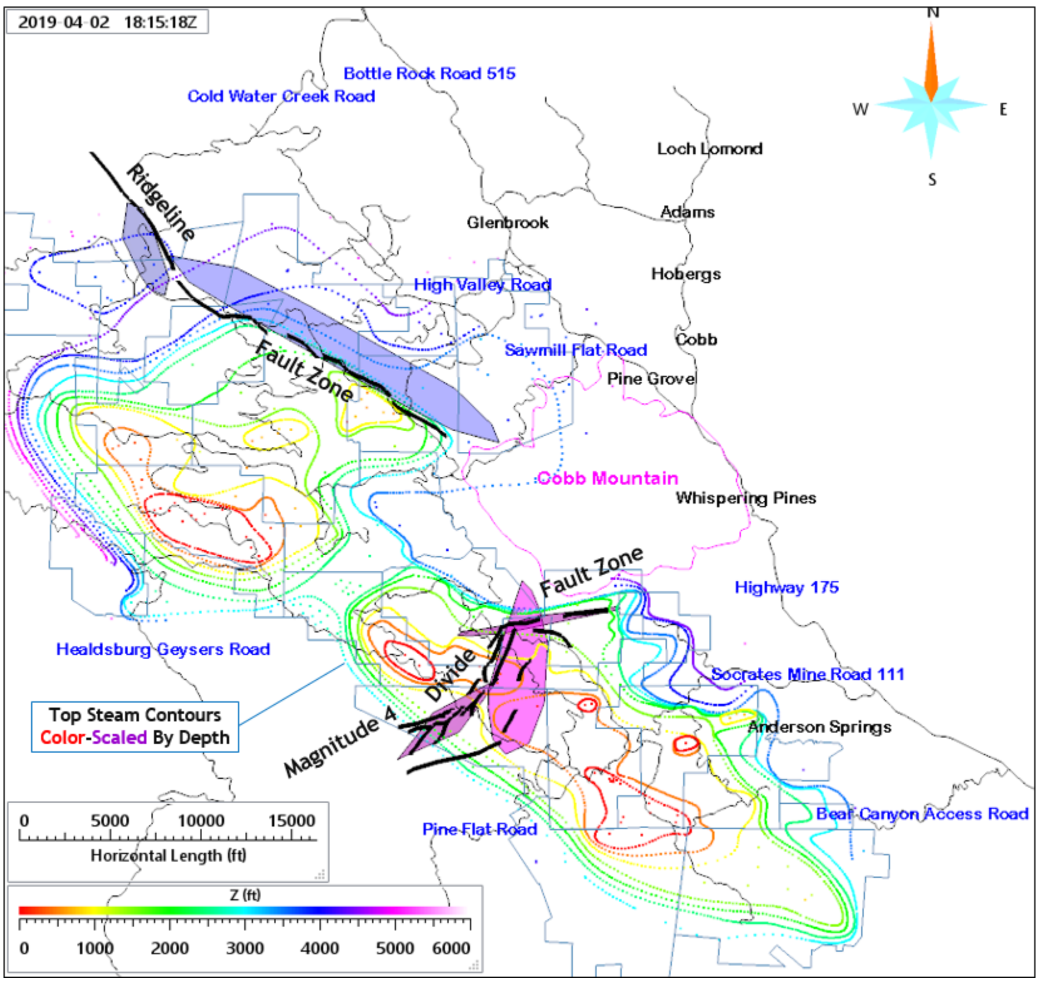

Figure 7: Overhead view rotated about east-west axis (north 12° downward) to best align surface mapped fault/fracture systems (thick black lines) with subsurface fault/fracture zones interpreted using seismicity alignments for (1) the Ridgeline Fault Zone (two blue surfaces) and (2) the Magnitude 4 Divide Fault Zone (three magenta surfaces). The upper extent of all fault/fracture surfaces intersect the surface mapped fault/fracture systems. Color scaled top steam reservoir depth contours define the geothermal resource. Particularly for the southern portion of the Ridgeline Fault Zone, the interpreted fault/fracture surface defines part of the steam reservoir boundary.

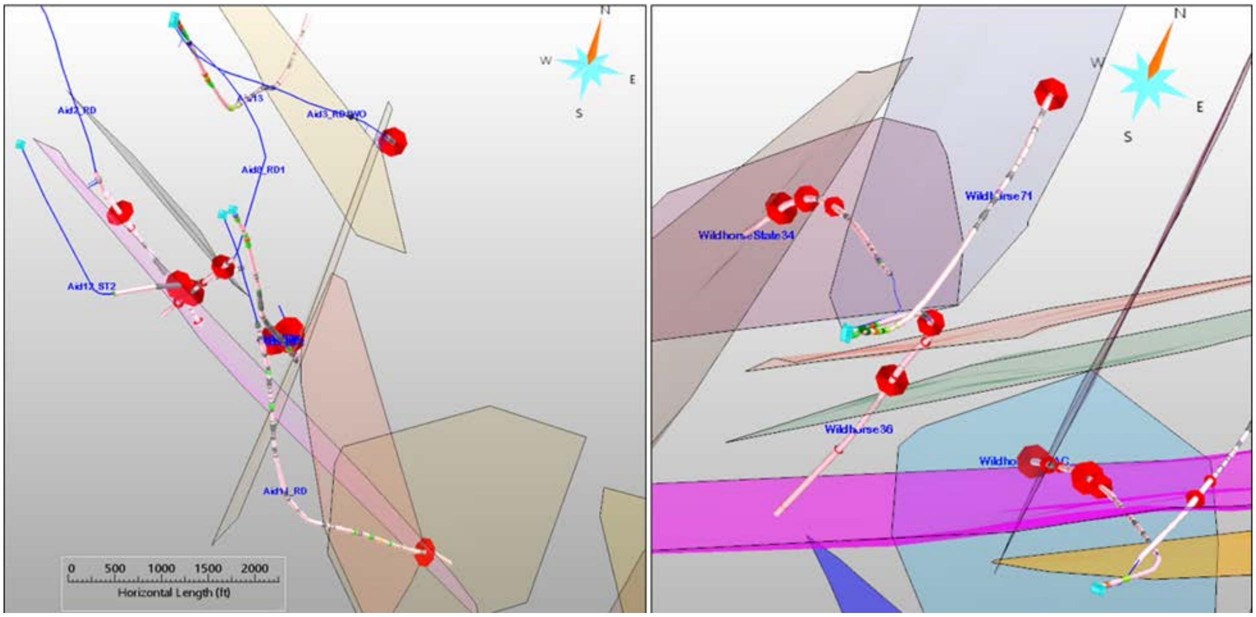

Figure 8: Map views of the northwest Geysers Aidlin area (left) and Wildhorse area (right). The majority of significant water injection well steam entries (red disks with radius scaled to steam pressure increase) occur approximately at the intersection with interpreted fault/fracture surfaces. Fluid flow from water injection wells appears to be illuminating these fault/fracture systems as injection progresses. Fault/fracture surfaces associated primarily with steam production wells are not significantly illuminated by induced seismicity.

5.0 Well Planning and Real-Time Drilling Analysis

The 3D structural model has proven very useful for well planning, allowing target refinements and improving the prediction of lithology transition depths, important for expensive drilling and casing programs. Real-time 3D drilling analysis has highlighted departures from the planned well trajectory and concerns with proximity to existing wells that have influenced drilling programs.

5.1 Prati 15 Pre-drilling Analysis Program

The northwest Geysers Prati 15 steam production well planning included a 3D pre-drilling analysis program. Induced seismicity patterns in the northwest Geysers Prati area strongly suggest significant reservoir heterogeneity and reservoir compartmentalization (Figure 9). This is seen particularly well within the depth range of approximately 7000 to 9000 feet below sea level. Seismicity animations for this depth interval strongly suggest seismicity progression (indicative of fluid flow) northward from injection wells OS-16 (active 1997; 2003-2016), OS-12 (active 1998-2008) and OS15-RD1 (active 2017-2019) that merges with Prati State 54 (active 2007-2019) injection-related seismicity, with the northward progression eventually inhibited by a series of NNE-SSW, SW-NE and NW-SE trending structural/hydrological discontinuities. Note that certain seismicity alignments are more/less evident at one of the two depth levels displayed. The interpreted fault/fracture surfaces believed primarily responsible for reservoir compartmentalization related to (1) Prati 32, (2) Prati 9 and (3) the OS 12, OS 15, OS 16 and Prati State 54 group are displayed within Figure 9.

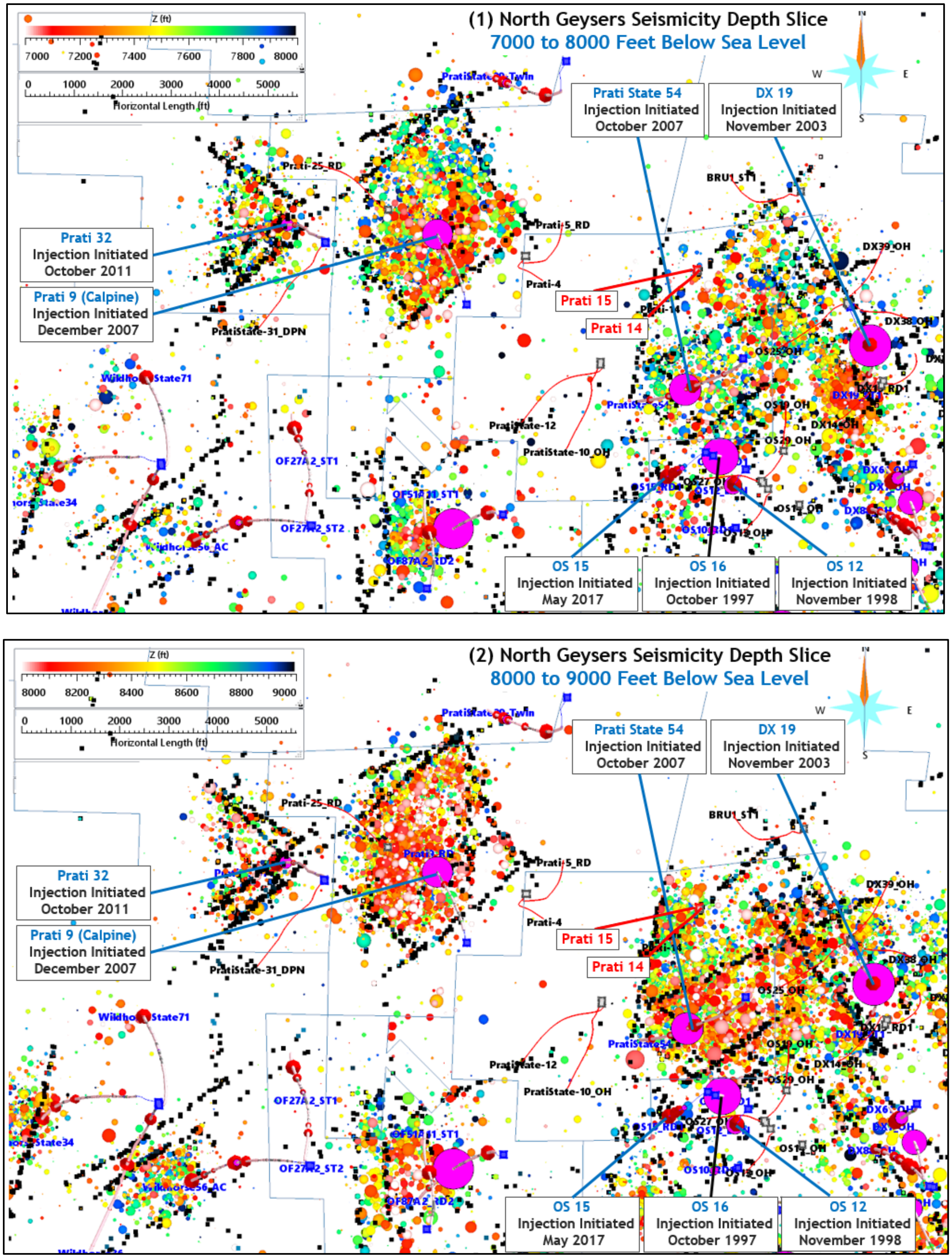

Figure 9: North Geysers seismicity depth slices from (1) 7000 to 8000 feet subsea (above) and (2) 8000 to 9000 feet subsea (below) for the time interval 2000 through 2018. SKUA GOCAD picks (black square symbols) completed directly on aligned seismicity hypocenters are shown for a depth interval from 6500 to 8000 feet subsea in each image, allowing picks to be displayed that are above and not obscured by the actual seismic events. The resulting aligned picks are believed to be indicative of fault/fracture surfaces, hydrological discontinuities and reservoir compartmentalization.

Detailed investigation associated with the Prati 15 pre-drilling analysis program determined that:

- A SW-NE linear transition from very low seismic event density (southeast) to very high seismic event density (northwest), and interpreted as a fault/fracture surface, intersected (and was nearly parallel to) the Prati 14 steam production well borehole (Figure 10).
- The 1987 Prati 14 drilling program encountered an extensive high permeability zone coincident with the interpreted fault/fracture surface distinguished by (Figure 11):
    - Lost circulation zones, and water entries between ~4880' and 5850'
    - Shallow steam entries from ~5500' to 5850'
    - Significantly increased drilling rate of penetration between ~5320' and 8830'
    - Fault gouge with calcite veining identified by mud loggers beginning at ~ 4700'
    - Large euhedral quartz crystals indicating the presence of open fractures at 5550'

This is direct drilling evidence of an extended fault zone that correlates exceptionally well with the seismically interpreted fault/fracture zone noted in Section 4.1 (Fracture/Fault Surface Verification).

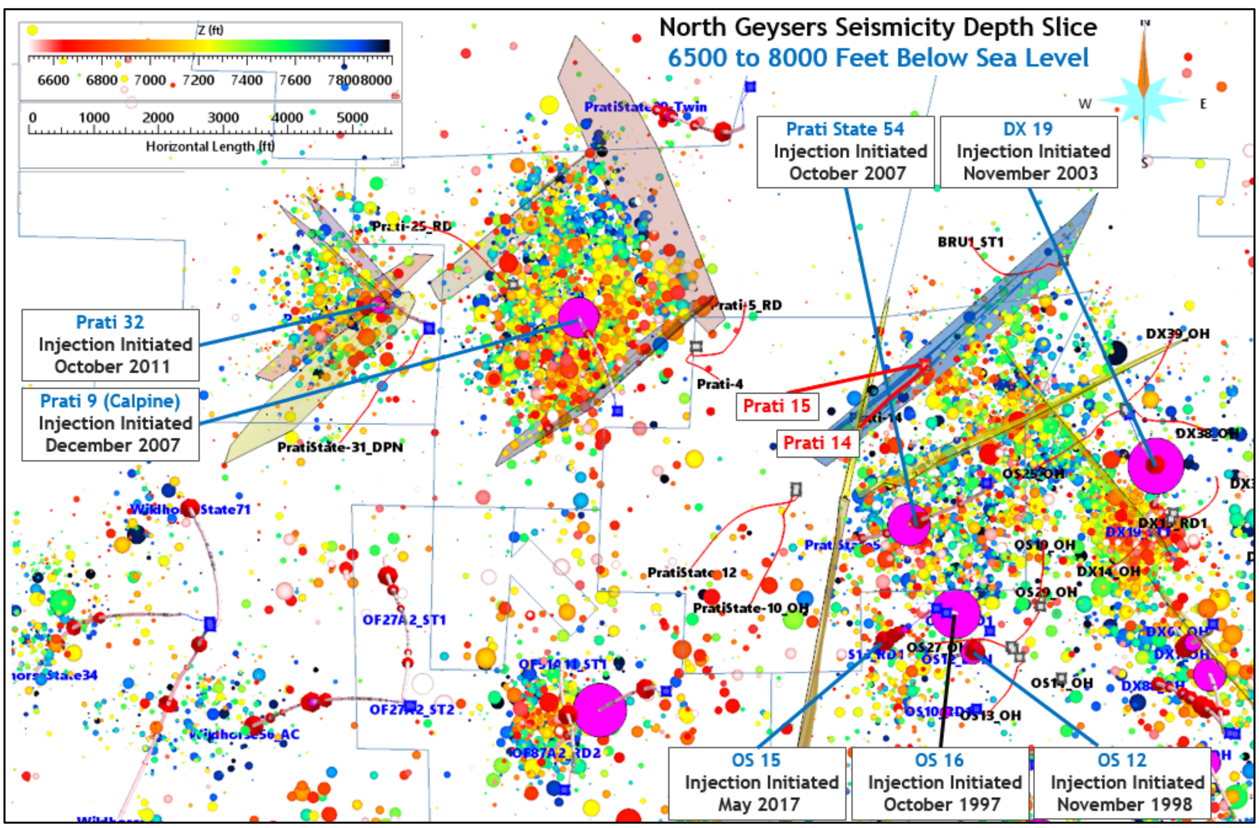

Figure 10: North Geysers seismicity depth slice from 6500 to 8000 feet subsea for the time interval 2000 through 2018. The interpreted fault/fracture surfaces primarily responsible for reservoir compartmentalization related to (1) Prati 32, (2) Prati 9 and (3) the OS 12, OS 15, OS 16 and Prati State 54 group are displayed. Note the location of steam production well Prati 14 and the intersecting (blue) SW-NE trending fault surface discussed concerning fault/fracture verification. Purple disc radii represent the cumulative water injection at each well.

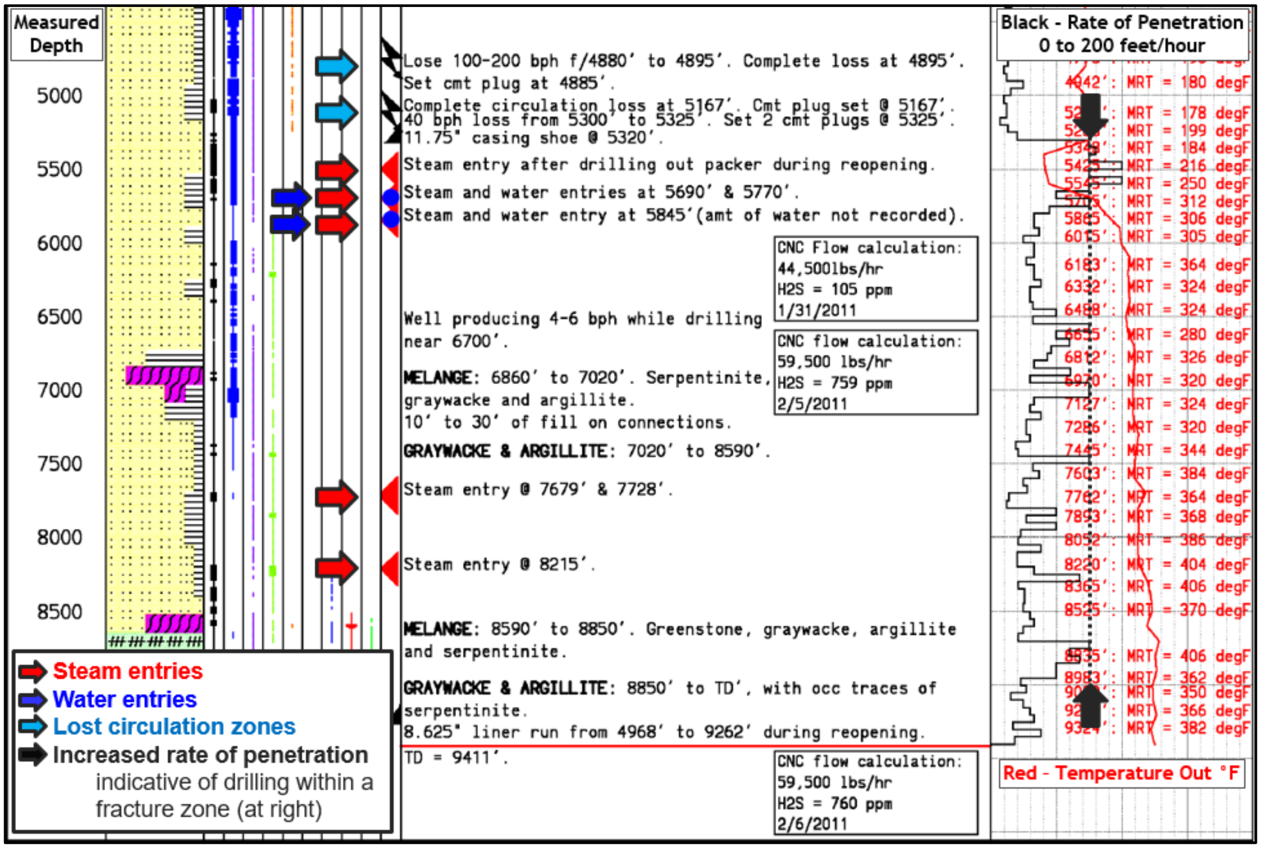

Figure 11: High permeability zone defined within Tecton Geologic Summary Log for the 1987 Prati 14 steam production well drilling program correlates exceptionally well with the fault/fracture zone defined independently from induced seismicity patterns/alignments.

6.0 Northwest Geysers Enhanced Geothermal System Demonstration Project

The ability to determine fracture orientations from induced seismicity hypocenters was highlighted by studies associated with the Department of Energy co-funded Northwest Geysers Enhanced Geothermal System (EGS) Demonstration Project under the guidance of Principal Investigator Mark Walters. During map-based analysis of the induced seismicity progression associated with water injection beginning on 06 October 2011, Jeanne et al. (2014) identified (1) several near vertical northwest-striking shear zones consistent with the San Andreas Fault Zone and the regional structural strike in the North Coast Ranges (e.g., Hulen and Norton, 2000), complemented by (2) northeast-striking transtensional shear zones and (3) NNE-SSW Reidel R´-shears at approximately 75° clockwise from the northwest-striking shear zones (Davis et al., 2000). This near vertical shear-zone network is associated with the Riedel system formed within the regional strike-slip fault zone system of the North Coast Ranges (Nielson and Nash, 1996). The shear-zone network was determined to be consistent with local surface geological mapping around the EGS area, in particular a northeast-striking low permeability shear zone (and pressure boundary), which appears to bound the EGS to the southeast, clearly coinciding with a feature previously mapped on the ground surface (Jeanne et al., 2014).

Seismicity time animations within limited slices and volumes are a primary tool for Calpine interpretation of the EGS Demonstration Project area fluid flow pathways, fluid flow barriers, reservoir heterogeneity and reservoir compartmentalization. The seismicity depth range of 7000 to 9000 feet subsea is especially diagnostic in/near the EGS area. The progression of induced seismicity away from the Prati 32 EGS water injection well during animations provides strong evidence of initial fluid flow along NW-SE and SW-NE fracture networks and eventual compartmentalization by similarly oriented fracture surfaces at slightly greater distances. Certain fault/fracture surfaces appear to isolate rock volumes and create hydrological discontinuities, likely due to:

- Limited fluid transfer across low permeability fault/fracture zones (fault gouge/sealing faults),
  and/or:
- Water injection initially into higher permeability rock, with lower permeability rock beyond fault/fracture zones that create hydrological discontinuities.

The interpreted 3D fracture surfaces appear to act as conduits for fluid flow or to inhibit fluid flow in the northwest Geysers EGS Demonstration Project. Their variable orientations and dip angles create difficulties for simultaneous display. However, it is possible to display certain fracture surfaces and illustrate their relationships with seismicity/fluid behavior. Seismicity appears to have progressed initially along a pair of intersecting westward and eastward dipping fault/fracture surfaces, with fluid flow containment to the west of the intersecting surfaces through the end of 2012 (Figure 12).

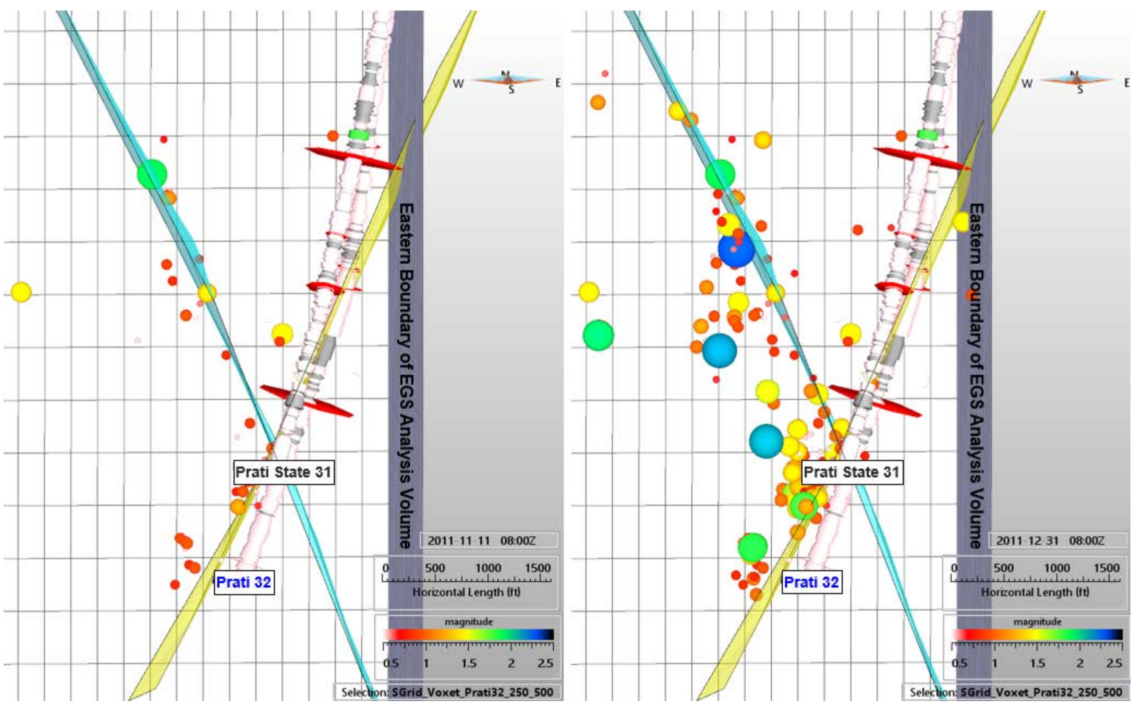

Figure 12: Oblique views from south-southwest. Left: The seismicity animation snapshot for 11 October 2011 shows the initial progression of seismicity primarily along east-dipping (blue) and west-dipping (yellow) interpreted fault/fracture surfaces. Right: The seismicity animation snapshot for 31 December 2011 appears to indicate containment of fluid flow to the west (left) of the intersecting surfaces.

Continued injection highlighted twelve (interacting) fluid conduits and discontinuities, the majority oriented NW-SE and SW-NE with varying dip angles complicating simultaneous display (Figure 13).

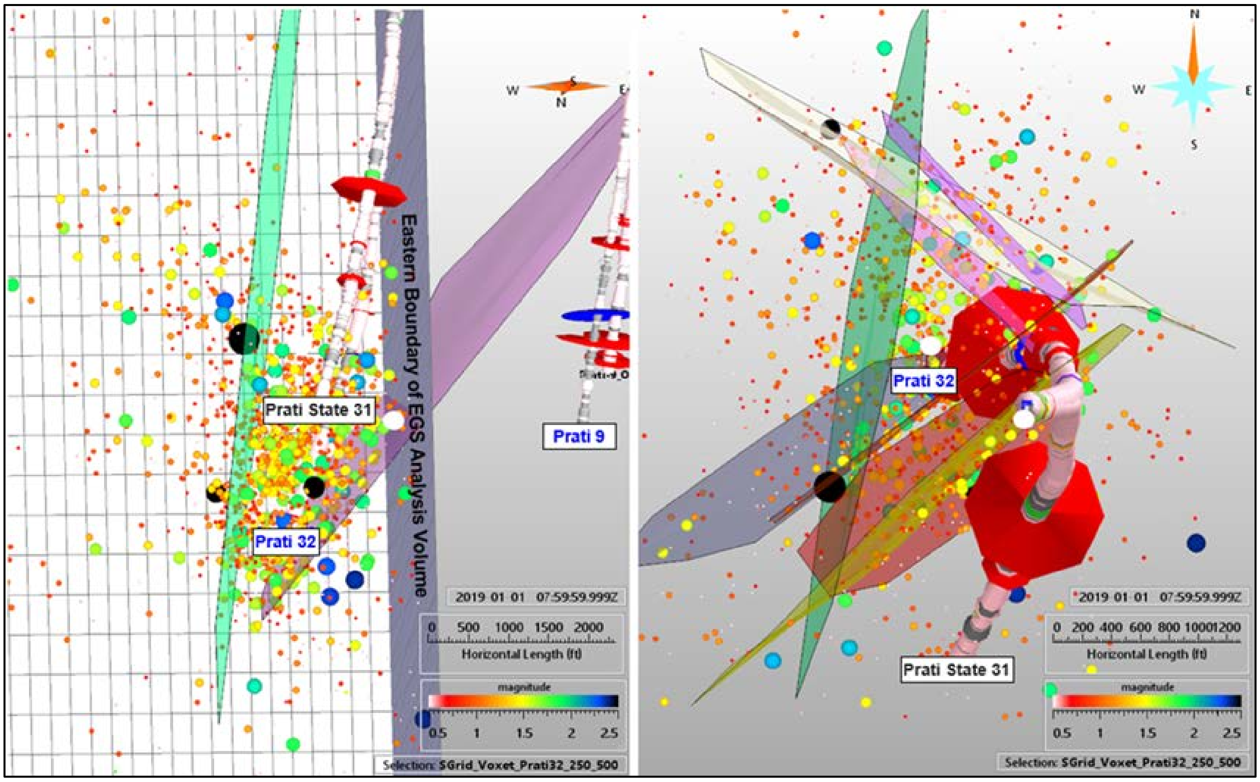

Figure 13: Left: Oblique view from south-southwest of two interpreted fault/fracture surfaces that appear to inhibit or confine fluid flow through 01 January 2019. Several of the larger magnitude seismic events in the EGS Demonstration Area occur along these interpreted fault/fracture zones. Right: Map view of the primary NW-SE and SW-NE near vertical interpreted fault/fracture surfaces that appear to guide and inhibit the lateral progression of seismicity to the northeast and southeast. The green NNE-SSW Reidel R´-shear fault/fracture surface shown in both figures provides a locational reference.

The SKUA GOCAD software includes modules developed to assess the stimulated rock volume associated with hydraulic fracturing in petroleum reservoirs that have proven useful for induced seismicity analysis at The Geysers. Since injection began in October 2011, the stimulated volume of the northwest Geysers EGS reservoir as determined by the lateral and downward progression of seismicity hypocenters has increased from approximately 7.4 to 38.7 billion feet^3 (0.21 to 1.09 kilometers^3), an increase of approximately 5.2x (Figure 14).

6.0 Current Research

Calpine is currently collaborating with Lawrence Berkeley National Laboratory and Array Information Technology in a California Energy Commission co-funded program entitled “High-

Resolution Micro-Earthquake Imaging of Flow Paths Using a Dense Seismic Network and Fast-Turnaround, Automated Processing". The program goals include the development of advanced, low-cost, microseismic imaging producing high-resolution spatial and temporal images of subsurface fluid flow, flow barriers and heterogeneity in producing geothermal fields. The program, including the 2018 installation of 93 temporary autonomous three-component seismic stations within a 5x5 kilometer area in the northwest Geysers, is anticipated to provide additional insight into induced seismicity imaging challenges unique to geothermal reservoirs, and assist with seismicity mitigation efforts at The Geysers.

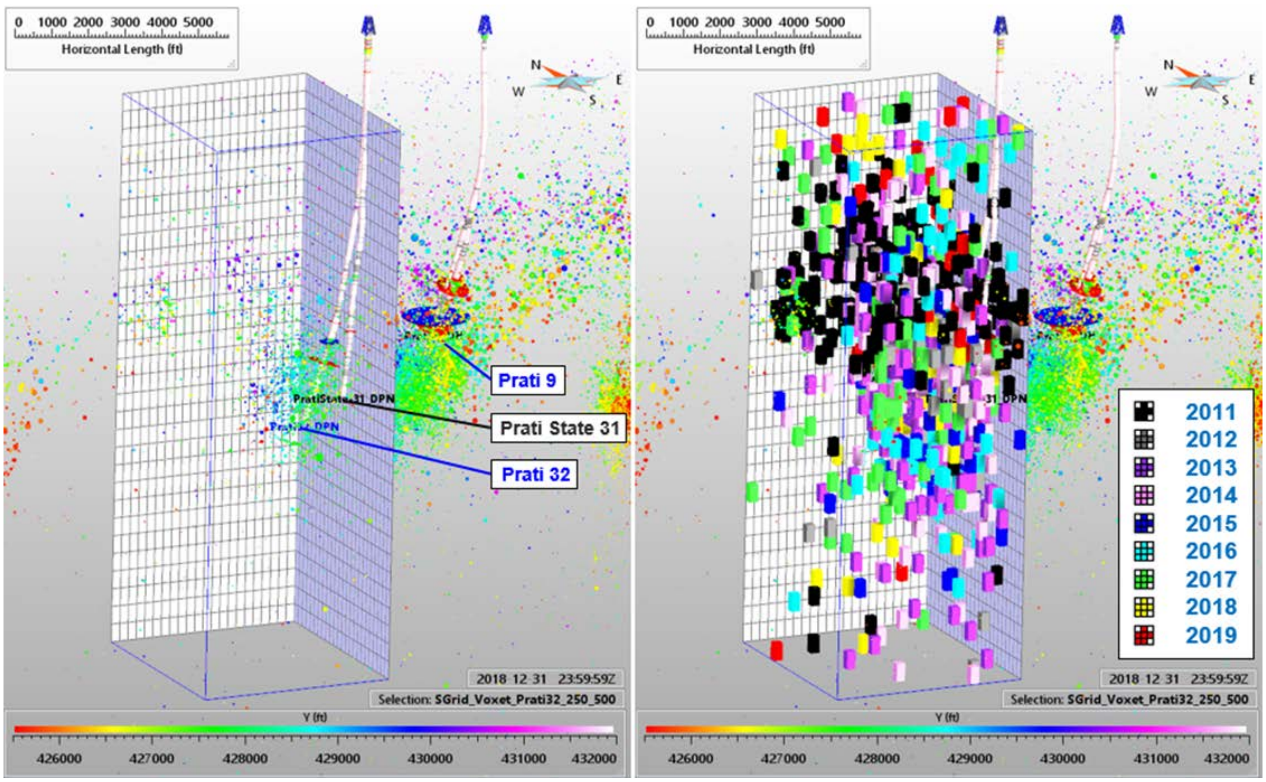

Figure 14: Left: Oblique view from southwest of the EGS Demonstration Project analysis volume with "Sgrid" cell dimensions seen on bounding walls. Also shown are wells Prati 32, Prati State 31, Prati 9 and induced seismicity hypocenters color-scaled based on their California II 402 State Plane Northing value (Y value from 425500 to 432000 feet). The seismicity analysis volume includes seismicity progressing laterally and downward from the Prati 32 injection well to a depth of 16,000 feet below sea level, and avoids contributions from the nearby Prati 9 water injection well. Right: The microseismic stimulated reservoir volume associated with each year is color-coded and the progression can be animated within the 3D project.

Conclusions

Calpine is progressing toward a refined understanding of 3D structural relationships, fluid flow paths, fluid boundaries, reservoir heterogeneity and compartmentalization at The Geysers. Fault/fracture surface interpretations based on seismicity patterns/alignments seen in variously oriented seismicity slices further constrain 3D structural model development and contribute to refinements in well planning, reservoir management and induced seismicity mitigation efforts at The Geysers geothermal field.

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