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

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Keywords

3D Visualization, 3D model building, induced seismicity, reservoir management, The Geysers

ABSTRACT

Calpine has adopted the use of Paradigm Geophysical SKUA GOCAD software originally developed for the oil and gas industry in its 3D visualization and model building of The Geysers geothermal reservoir. Structural model building constraints include lithology logs, temperature logs, pressure logs, tracer analysis patterns, heat flow patterns, reservoir history matching, surface geologic maps and seismicity hypocenters available from the Northern California Earthquake Data Center (NCEDC) and Lawrence Berkeley National Laboratory (LBNL). Recent upgrades to the Paradigm Geophysical SKUA GOCAD 3D seismicity analysis and time animation software have allowed an improved understanding of the spatiotemporal relationships between water injection, induced seismicity, and fracture orientations at The Geysers. This in turn provides a refined understanding of fluid flow paths, fluid boundaries, reservoir heterogeneity and compartmentalization at The Geysers. We can now demonstrate The Geysers reservoir is subdivided by intersecting zones of faulting and fracturing the majority of which are oriented NNW-SSE and ENE-WSW. The 3D structural model development is part of a program to more closely link geoscience, drilling and reservoir engineering, and is anticipated to contribute to reservoir management and induced seismicity mitigation efforts at The Geysers.

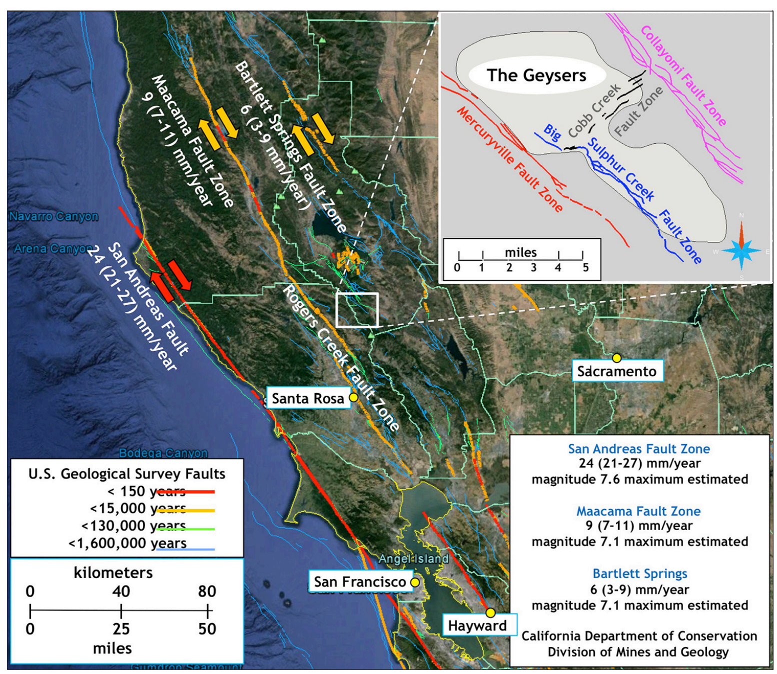


Figure 1. The San Andreas Fault System, including the Maacama / Rodgers Creek Fault Zone and Bartlett Spring Fault Zone. United States Geological Survey Faults with activity in the past 1.6 million years are displayed. Primary bounding fault zones are shown in the inset at upper right. This Google Earth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

Background

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).

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 (Figure 1) (DeCourten, 2008). This zone of subparallel right-lateral strike-slip faults moves at progressively slower slip rates eastward and initiated a transtensional tectonic environment between the active Maacama fault and the active Bartlett Springs Fault Zone.

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-condesible 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).

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 two large-scale treated wastewater injection projects based in (1) Lake County and (2) the City of Santa Rosa (Sonoma County), in addition to recovered steam condensate from the power plants and creek water injection during peak precipitation run-off.

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, 2014).

The Geysers' seismicity is measured as three components of motion on 32 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 seem 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 large mapped active faults within The Geysers (Field et al., 2015), and the highly-fractured steam reservoir (as defined by extensive drilling activities) 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 water injection volume vs. induced seismicity, particularly when seismic events of magnitude ≥ 3.0 are isolated for analysis:

- A linear regression of yearly magnitude ≥ 3.0 seismic event totals since 01 January 1987 seen in Figure 2 shows a downward 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 (at least partially in response to a 2014 drought-related water injection volume reduction).

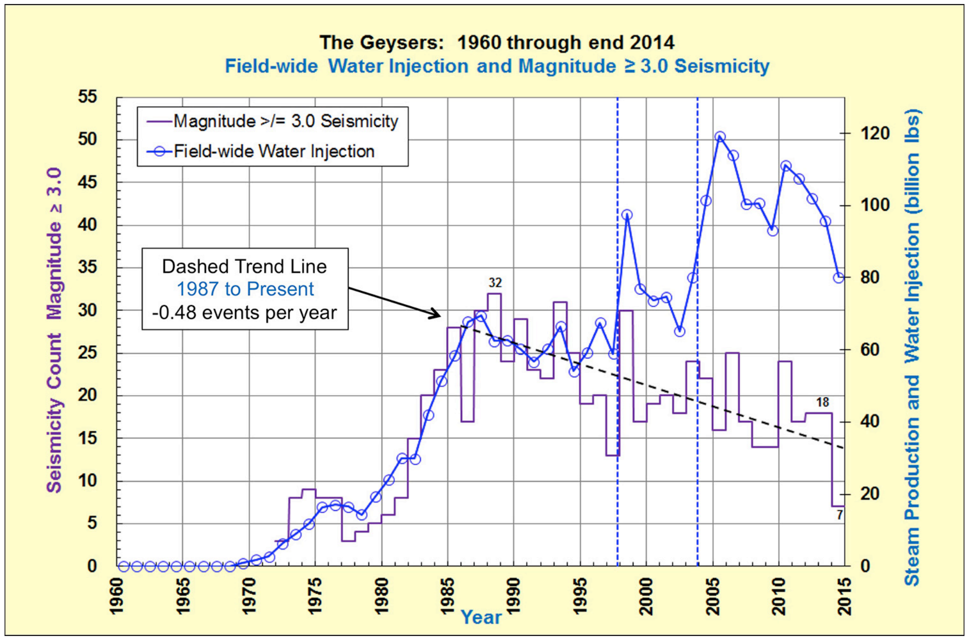


Figure 2. The Geysers' field-wide water injection (scale at right) and magnitude ≥ 3.0 induced seismicity (scale at left). Database: Northern California Earthquake Data Center (NCEDC); University of California Berkeley Seismological Laboratory.

Time Period	M ≥ 4.0 Seismic Events	
January 2003 through December 2006	2.50 events per year	10.0 / 4.0
January 2007 through September 2014	1.09 events per year	9.0 / 8.25

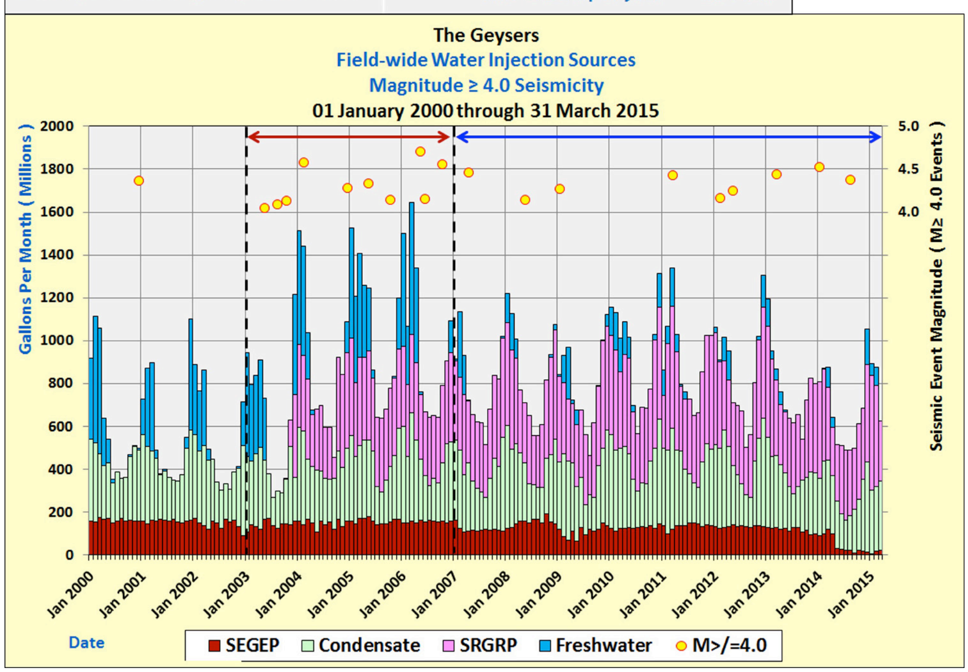


Figure 3. The Geysers field-wide water injection by source from 01 January 2000 to 31 March 2015 (scale at left) and magnitude ≥ 4.0 induced seismicity (scale at right). SEGEP = Southeast Geysers Effluent Pipeline, SRGRP = Santa Rosa Geysers Recharge Project. Seismicity Database: Northern California Earthquake Data Center (NCEDC); University of California Berkeley Seismological Laboratory.

- Magnitude ≥ 4.0 seismic events at The Geysers have declined from 2.5 events per year during the four-year period from 01 January 2003 through 31 December 2007 to about 1.1 events per year since 01 January 2008.

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 encouraging induced seismicity trends and The Geysers' induced seismicity in general.

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 Calpine 3D visualization and structural model building program are:

- Extensive 3D database preparation and development of 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 for 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.

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 also 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. Calpine also believes 3D visualization is 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.

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, to date, 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 recently and painstakingly converted to digital form), 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 "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.

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 Pate 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).

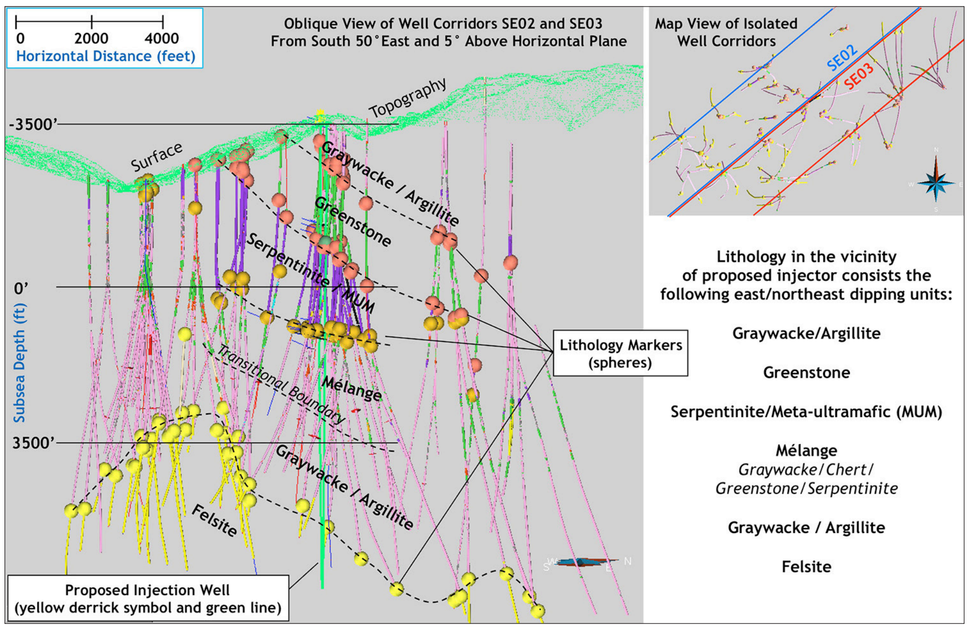


Figure 4. Upper Right: Map view of two southwest-to-northeast oriented well corridors in the central Geysers. The corridors SE02 and SE03 each include the wells within a 2500′ wide polygon. Left: Oblique SKUA GOCAD view of the relatively uncomplicated 3D structural interpretation for the northeast flank 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.

The Geysers' seismicity patterns seen in limited depth or 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 zones (including Reidel system shearing) (Jeanne, 2014). The transtensional faults are a response to different slip rates within the active right-lateral strike-slip faults 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 faults 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 "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).

A particularly instructive pre-drilling analysis project completed in early 2015 utilized 3D time animations of seismicity to assess the proposed conversion of two adjacent and shut-in production wells (GGC4 ST1 and GGC5 OH) to water injection wells, including possible deepening of the existing production wells. A map view from the west-central Geysers shows characteristic low magnitude induced seismicity clusters in the vicinity of injection wells, including limited indications of flow paths and flow barriers. What is also evident is an unanticipated and well–contained seismicity cluster in the vicinity of shut-in production wells GGC4-ST1 and GGC5-OH (Figure 6).

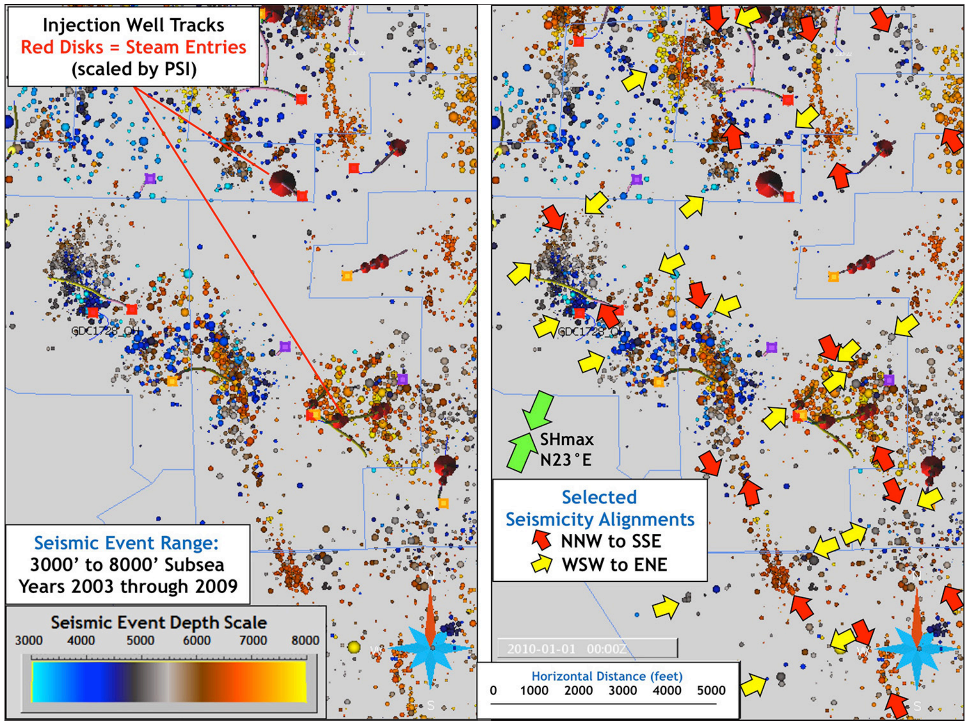


Figure 5. NCEDC tomographic double difference seismic event hypocenters for the time range 01 January 2003 to 31 December 2009 and depth range 3000 to 8000 feet (915 to 2440 meters). The orthogonal, linear seismicity alignments are believed to represent (1) relict shear zones responsive to SHmax and 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.

To better understand this unanticipated seismicity cluster, time animations of January 2002 through April 2009 refined induced seismicity hypocenter data were completed utilizing various depth slices and cross-sectional slices. The time animation of a 2000 foot (610 meter) thick north-south oriented cross-sectional slice provided strong evidence that water injection well OF87A2-RD2 generated a typical low magnitude seismicity cluster at a depth of about 5000 feet subsea shortly after the November 2003 start of injection. However, by December 2005 seismicity began to "descend" southward from the main cluster along an apparent permeability conduit. A secondary and somewhat contained seismicity cluster then developed approximately 2500 feet (762 meters) to the south at a depth of about 7000 feet (2133 meters) subsea and slightly below shut-in production wells GGC4-ST1 and GGC5-OH. The seismicity patterns suggest fluid movement within a heterogeneous rock volume (Figure 7).

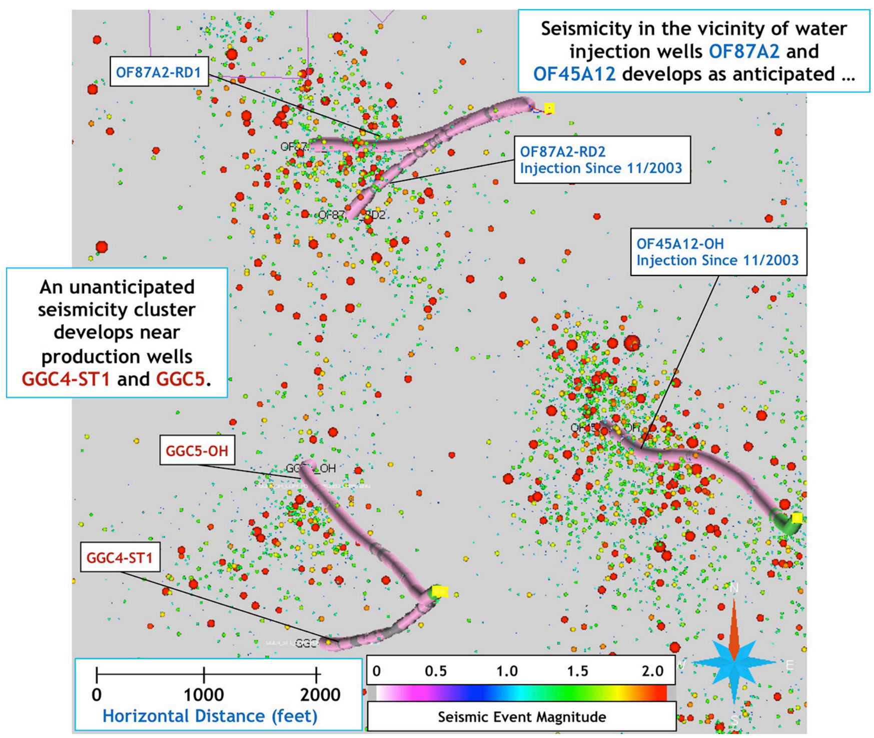


Figure 6. Map view showing January 2002 through April 2009 NCEDC tomographic double-difference induced seismicity hypocenters, injection wells OF87A2 (RD1/RD2) and OF45A-12, and production wells GGC4-ST1 and GGC5-OH. The seismic event hypocenter magnitudes are scaled by size and color.

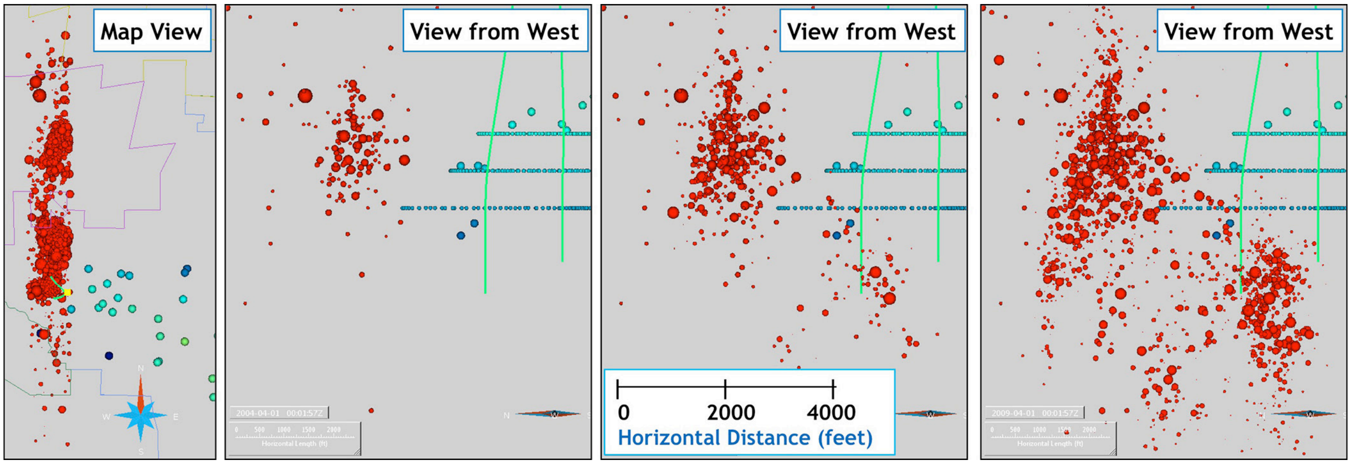


Figure 7. Left: Map view of 2000 foot (610 meter) wide north-south seismicity cross-section for time period January 2002 through April 2009. Left Center through Right: The same north-south seismicity cross-section viewed *from the west* at time steps of April 2004, July 2005 and April 2009. Vertical Exaggeration = 1.5.

Another interesting relationship discovered during the GGC4-ST1 and GGC5-OH pre-drilling analysis project was a significant decrease in the seismic event density, apparently due to a significant decrease in permeability (fluid flow), when transitioning from the overlying fractured and metamorphosed hornfelsic greywacke into the granitic pluton (Felsite). A reasonable analogy is a leaky umbrella, which sheds the majority of fluid downward along its surface, but does allow some degree of fluid penetration. This relationship has been observed elsewhere in The Geysers, particularly along the eastern flank of the Top Felsite in the southern Geysers. This seismic event density transition appears to offer a useful constraint on 3D structural model development, allowing interpolation between, and extrapolation beyond, the existing Top Felsite well control "markers". The map view in Figure 8 (left) shows a 1500 foot (457 meter) wide seismicity cross section or slice that has been isolated for analysis, along with the Top Felsite control points or "markers" picked directly from well lithology logs. Note that we are approaching the northwest limit of available well control points for the Top Felsite, due to increasing depth to the granitic pluton. The cross-sectional view in Figure 8 (right) shows a continuation of the Top Felsite as a dashed line with yellow highlighting from the right (where well control exists) to the left (where well control is absent). In this particular case, the Top Felsite has been extrapolated to the north along the transition from higher seismic event density to lower seismic event density.

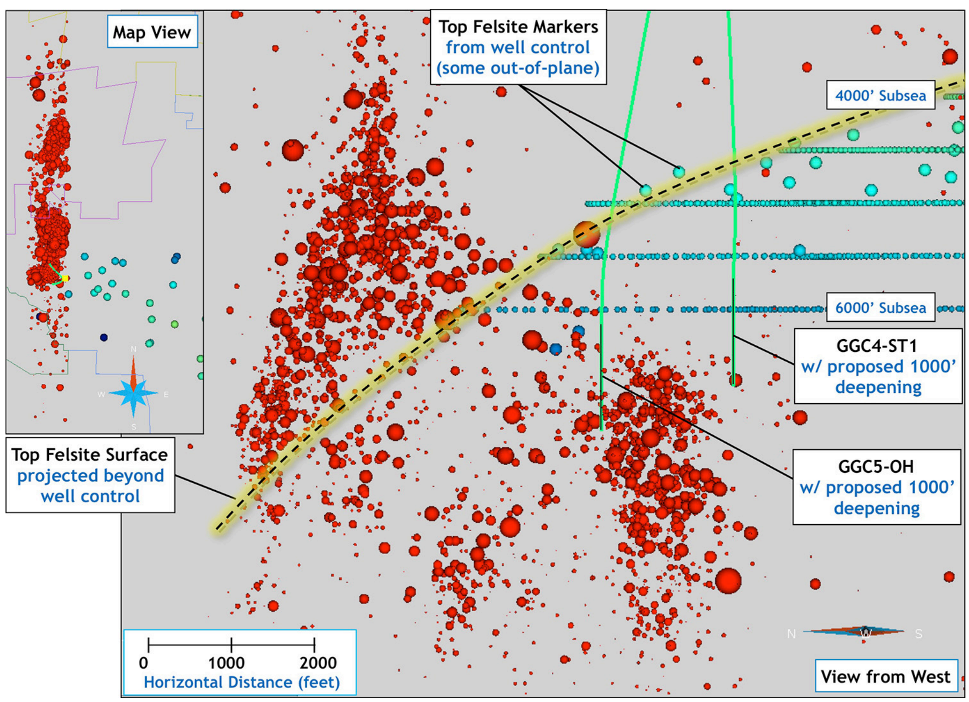


Figure 8. Upper Left: Map view of a 1500′ wide north-south seismicity cross-section with data from January 2000 through October 2009. Right: View from west of this seismicity slice with Top Felsite markers (depth-scaled spheres), Top Felsite contours (depth-scaled small and horizontally-aligned spheres) and lower portions of well tracks GGC4-ST1 and GGC5-OH (including proposed extensions). The dashed black line with yellow highlighting is a continuation of the Top Felsite interpretation from an area of well control (to right) into the seismic event density transition (to left). Vertical exaggeration = 1.5.

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,

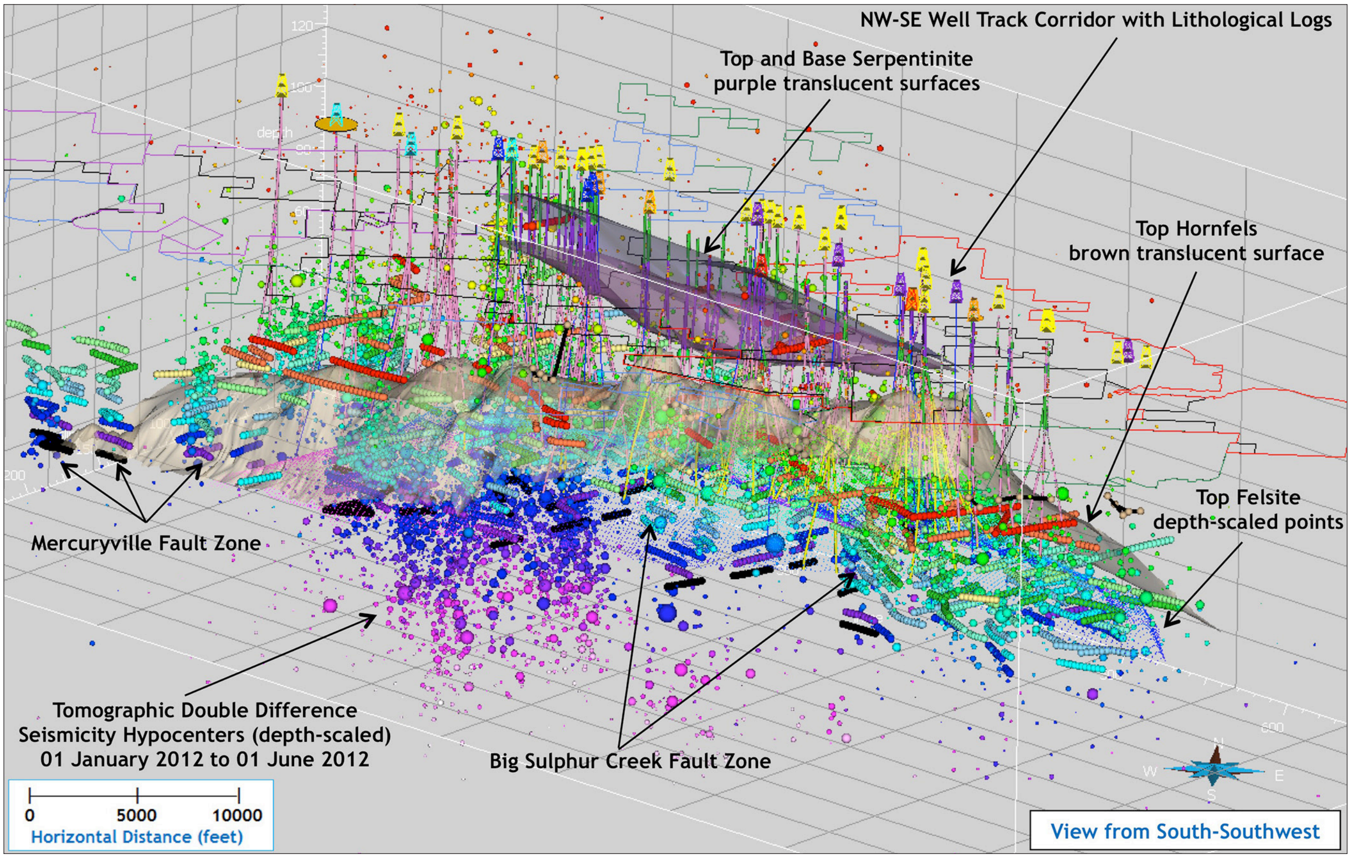


Figure 9. Oblique view from the south-southwest of the developing Geysers 3D structural model. Fault curves or segments derived from seismicity depth slices are color-scaled by depth, and include the anastomosing faults representing the Mercuryville Fault Zone and Big Sulphur Creek Fault Zone.

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).

Fault zone interpretation is generally completed in SKUA GOCAD by creating fault "sticks" or "curves". For The Geysers 3D structural model, curves were assigned while progressing through 500' thick seismicity depth slices. This was followed by a confirmation procedure with interpretation of orthogonal 1000' wide seismicity cross-sections (oriented east-west; north-south and along structural strike/dip). Iterating through this interpretation process allows refinement of fault zone determinations, and indicates that The Geysers subsurface is subdivided by intersecting zones of faulting, the majority of which are oriented NNW-SSE and WSW-ENE (Figure 5; Figure 9). Induced seismicity hypocenters 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 (Figure 9).

Several surfaces or "horizons" have been developed and refined within the SKUA GOCAD software. Smaller localized surfaces were developed primarily from the picked lithological markers and interpreted fault 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 required to ensure correlation with all reliable well data, removal of unreliable data outliers and the production of refined surfaces or horizons (Figure 10). The Geysers Top Steam has been interpreted as (1) a shallower, ~350°F two-phase reservoir and (2) a deeper , ~465°F single phase maximum enthalpy (now superheated) steam reservoir.

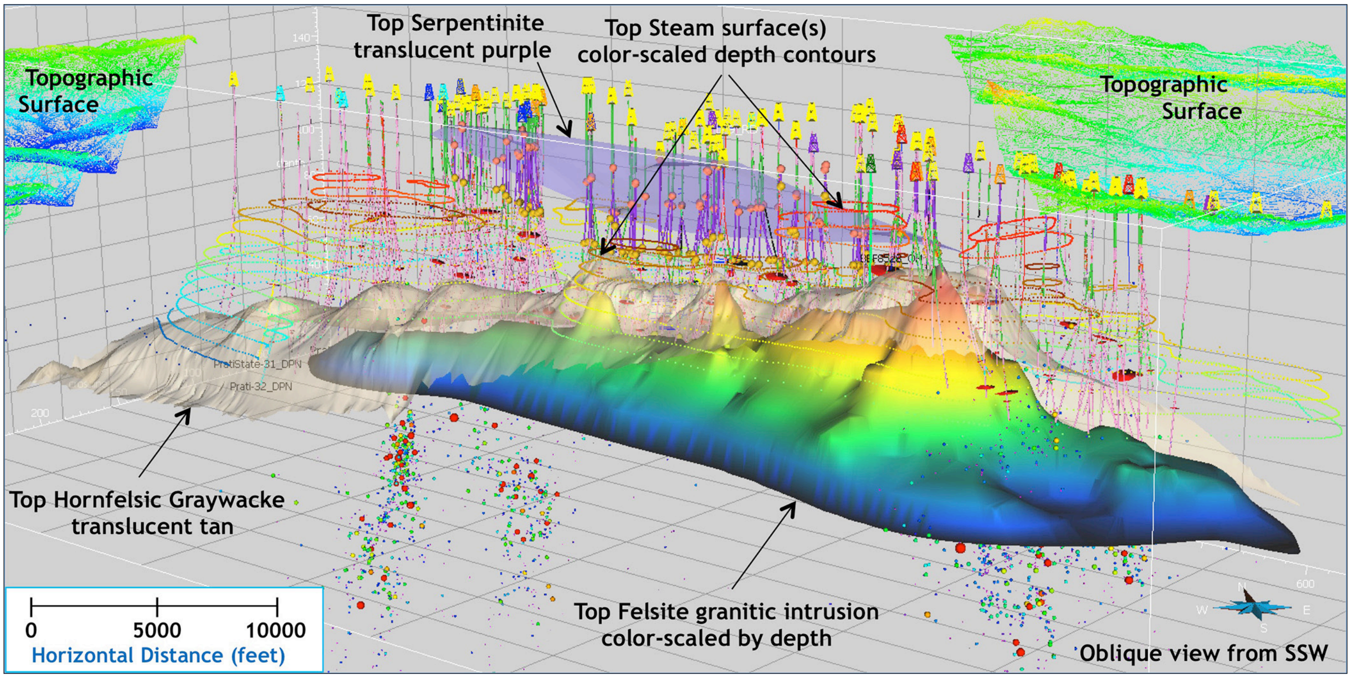
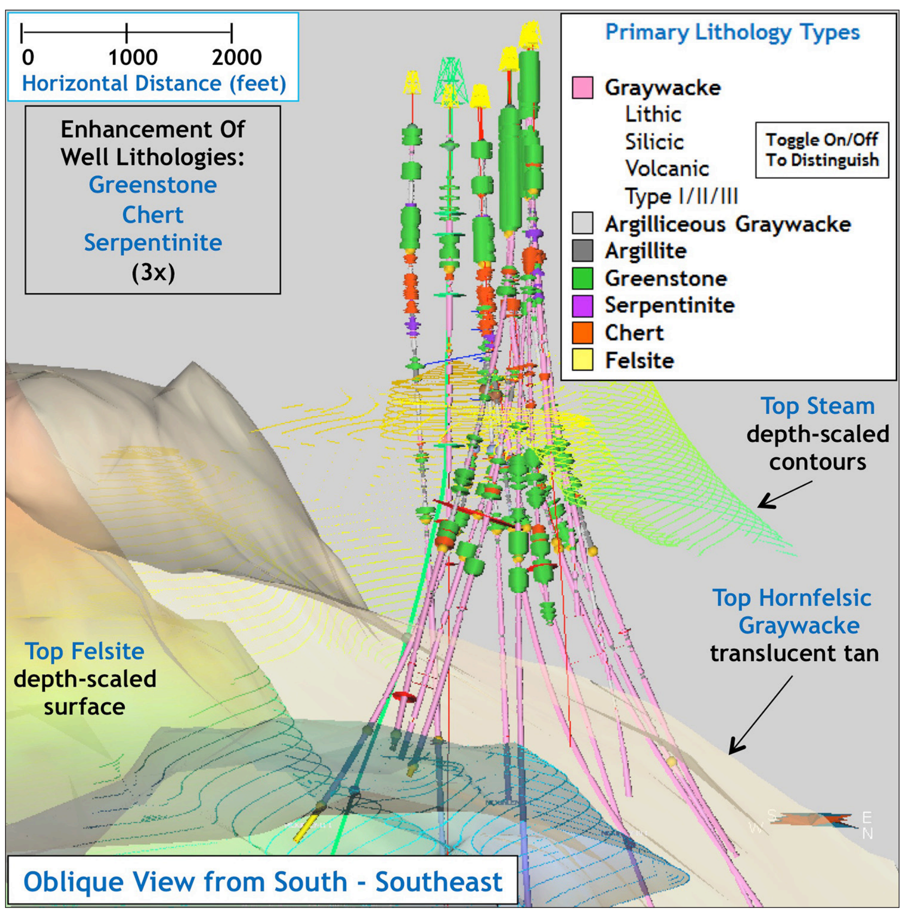


Figure 10. Oblique view from the SSW of (from base to top) the Top Felsite granitic pluton (color-scaled by depth), the Top Hornfels surface (translucent tan), and the Top Steam surface(s) as color-scaled depth contours, the Top Serpentinite (translucent purple) on the northeast flank of the Felsite, northwest and southeast topographic surfaces (as points; color-scaled by elevation), two selected northwest-to-southeast well track "corridors" with assigned lithology, steam entries displayed as red disks (scaled by stream pressure increase). Seismicity is displayed for two 2500 foot (762 meter) wide southwest-to-northeast oriented corridors in (1) the NW Geysers -NW04, and (2) the SE Geysers - SE09. Vertical exaggeration = 1.25.

Figure 11. Left: Pre-drilling 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.



Pre-Drilling Analysis and Real-Time Drilling Analysis

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 well control or "hard data" as the drill bit descends). 3D visualization is proving to be an effective communication tool for these purposes, 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 11. 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. A pair of optimally oriented wells in the southeast Geysers (Thorne 3 and McKinley 11), separated by approximately 3000 feet, are believed to be within a single northwest to southeast oriented structure and show excellent lithological correlation (Figure 12). In areas of sufficient well control, it has been possible to provide reliable lithological unit depth predictions.

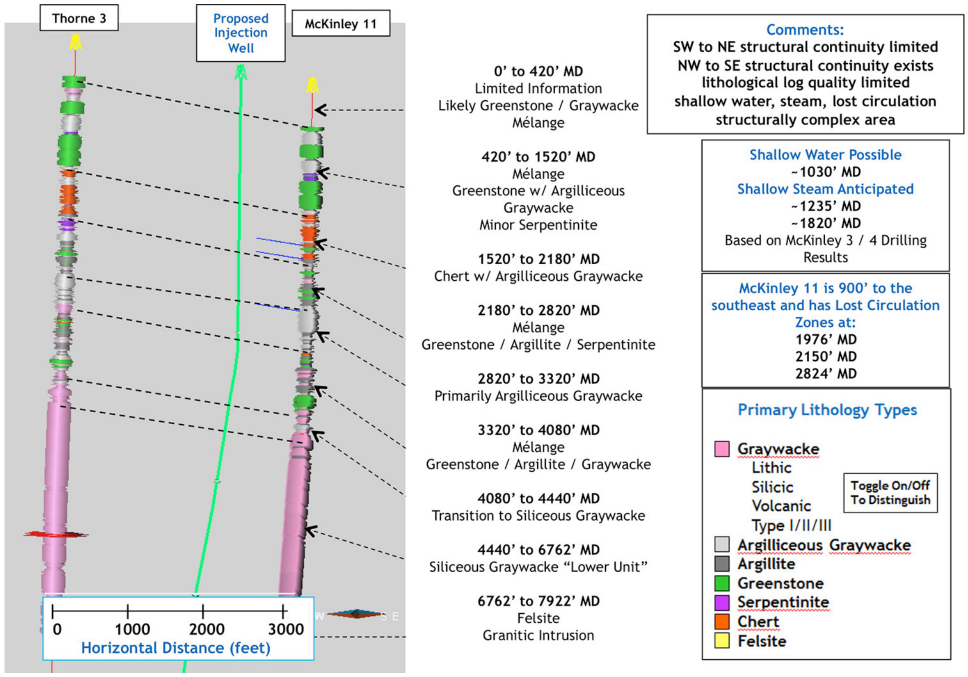


Figure 12. Pre-drilling analysis of a proposed southeast Geysers injection well. A pair of optimally oriented wells in the southeast Geysers (Thorne 3 and McKinley 11) show excellent lithological correlation. Blue lines projecting from the wells are lost circulation zones, and the red disks is a steam entry (scaled by steam pressure increase). Vertical exaggeration = 1.5.

Based on predictions of this type, several lithological units of the LF-22 injection well (drilled in 2014) were encountered within 50-80 feet of prognosis, and the final Graywacke interval was within 20 feet of pre-drilling estimates. Additionally, Real-time analysis of the well deviation surveys and lithology logs identified a close encounter with an adjacent wellbore. Real-time 3D drilling analysis provides increased confidence when (expensive) drilling decisions are required at The Geysers.

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, surface geologic maps and seismicity hypocenters, all acquired over an extended period with a range of data reliability. 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 utilize developing technology to achieve these goals.

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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

- High-temperature tolerant borehole fiber optical seismic sensor array testing

Paulsson Incorporated

- High-temperature tolerant borehole fiber optical seismic sensor array testing
- Active surface source vertical seismic profiling (subsurface imaging)

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

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