Stepovers and Beyond: Structural Controls of The Geysers Geothermal System and the Broader Clear Lake Region

Benjamin L. Melosh

U.S. Geological Survey
350 N. Akron Rd.
Moffett Field, CA, 94035, USA
bmelosh@usgs.gov

Abstract

Fault geometry exerts a first-order control on geothermal systems by governing stress localization, fracture development, and permeability, yet in complex fault networks or broader shear zones, the relative influence of individual geometric features is often difficult to resolve. In the northern California Coast Ranges, The Geysers geothermal field is commonly interpreted to occur within a releasing stepover, although no single, clearly defined stepover is identified in published studies. To investigate the structural controls on The Geysers and the broader Clear Lake region, a two-dimensional elastic boundary element model is developed to evaluate spatial patterns of dilational strain associated with progressively more complete fault geometries. Model results show that dilation in the region is not controlled by a single structure but instead reflects the combined effects of multiple interacting fault elements. Three primary controls are identified: (1) opposing bends in the regional strike-slip fault system, including a releasing bend along the Maacama fault; (2) the southern fault tip of the Collayomi fault, which generates a prominent dilational lobe beneath the southern Geysers; and (3) a releasing stepover between the Collayomi fault and the Geyser Peak–Mercuryville–Big Sulphur Creek fault system, inferred to collectively behave as a right-lateral shear zone bounding the western margin of The Geysers. Predicted dilational strain magnitudes are sufficient to localize permeability between faults. These results highlight that incorporating complete fault networks and bedrock geological mapping can enhance geothermal assessments and provide a transferable framework for evaluating structurally controlled permeability in tectonically active regions.

1. INTRODUCTION

Dilational deformation is an important control on modern hydrothermal systems because it promotes the formation and persistence of open fluid pathways (e.g., Curewitz and Karson, 1997; Faulds et al., 2011; Siler et al., 2018; Siler, 2023). Open fracture networks and fluid pathways commonly develop at fault irregularities, including stepovers, bends, and fault terminations (e.g., Faulds and Hinz, 2015). Therefore, mapping fault geometry and off-fault deformation and fractures can enhance the evaluation of structural controls on modern geothermal systems. Using boundary element modeling, Siler (2023) mapped spatial variations in dilational strain at commonly observed fault irregularities in the Great Basin.

In this study, I focus on the Clear Lake region and The Geysers geothermal field in the northern California Coast Ranges (Figure 1), an area well known for its geothermal resources, active volcanoes, and active faulting (e.g., McLaughlin, 1981; Hearn et al., 1995; Ball, 2022; Langenheim et al., 2024). The northern California Coast Ranges have experienced continuous deformation during a long history of subduction and the transition to a transform plate boundary (e.g., McLaughlin, 1981; McLaughlin et al., 1988). The Clear Lake region is bound and bisected by large strike-slip faults of the greater San Andreas fault system, which provide the primary active structural controls on modern geothermal systems.

Oppenheimer (1986) postulated that a northeast-oriented zone of extension occurs in The Geysers – Clear Lake region between the Maacama fault and the Bartlett Springs fault ~30 km to the east (Fig. 1). This extensional zone contains volcanic vents and eruptive products of the Clear Lake volcanic field (Hearn et al., 1995), the northern part of The Geysers geothermal field (e.g. Stanley et al., 1997), and is subparallel to the maximum horizontal stress orientation (Bufe et al., 1981). Although this zone of extension was supported by later geophysical and tectonic studies (e.g., Stanley et al., 1997, 1998), the mechanism generating this extension remains ambiguous (Oppenheimer, 1986).

In the absence of a right-stepping geometry between major strike-slip faults (Oppenheimer, 1986; Eberhart-Phillips, 1988), alternative structural mechanisms must be invoked to account for extensional deformation. One such mechanism is block rotation driven by differential slip rates on subparallel strike-slip faults (Stanley and Rodriguez, 1995). However, the large strike-slip faults extend well beyond the Clear Lake region into areas where extension has not been documented, implying that locally distinctive fault geometry and connectivity, or interactions with elevated heat flow and magmatism, play a key role within the Clear Lake region.

Although faults are a single variable in a complex system, a robust understanding of how fault geometry influences modern extensional deformation supports geothermal resource exploration and interpretation of magmatism and neotectonics. Early seismic lineament mapping (e.g., Stanley and Blakely, 1995) does not incorporate bedrock or Quaternary geologic fault mapping and provides an incomplete representation of fault network geometry. Recent advances in geologic mapping and geophysical studies of the region's major strike-slip

faults (Lienkaemper, 2010, 2012; McLaughlin et al., 2018; Melosh et al., 2024a,b; Langenheim et al., 2024) (Figure 1) motivate a reexamination of the structural controls on deformation in the Clear Lake region.

The position of The Geysers is commonly attributed to a releasing fault stepover (e.g., Sadowski et al., 2016), or two parallel faults with different slip rates (Martínez-Garzón et al., 2014; Garcia, 2016). However, there is no clear right step between the Collayomi and Mercuryville or Big Sulphur Creek faults, which bound The Geysers (Figure 1) (McLaughlin, 1978; Sadowski et al., 2016). The southern part of the Geyser Peak fault may form a releasing stepover with the Collayomi fault, but this is complicated by its change in orientation and by the presence of other faults. Also, two parallel, straight strike-slip faults will not generate dilation unless fault geometry, along strike slip gradients, or material properties vary along the fault (Okada, 1992).

The observations and assumptions of previous work leave many questions, such as: What is the geometry and kinematics of the stepover at The Geysers and which faults are involved? If multiple fault strands are included, how is slip partitioned between them? How well does the current mapped extent of faults contribute to these interpretations? Are there other important structural controls on the position of The Geysers?

In this paper, I discuss a boundary element model of The Geysers – Clear Lake region, between the Maacama fault in the west, and the Bartlett Springs – Hunting Creek – Berryessa faults in the east (Fig. 1). Structural controls on dilation are tested through a series of models that progressively incorporate increasingly complete fault geometries, enabling isolation of the effects of fault bends, fault tips, and multi-fault stepovers. Results suggest that dilation arises from the interaction of these three structural elements operating simultaneously. Model assumptions and simplifications are discussed, along with the broader implications for Clear Lake tectonics and geothermal resources at The Geysers.

2.   BACKGROUND

2.1 Structural Setting of The Geysers - Clear Lake region

The Geysers–Clear Lake region of the northern California Coast Ranges lies within the broader right-lateral San Andreas transform fault system (Figure 1). The Maacama and Bartlett Springs faults, including the Hunting Creek and Berryessa strands, accommodate significant right-lateral plate motion and can generate large earthquakes (Lozos et al., 2015). These faults obliquely cut and offset the Mesozoic to Neogene Franciscan subduction complex and the Great Valley sequence, along with serpentinite mélanges of the Coast Range ophiolite, which occur as tectonically and diapirically emplaced slivers throughout the northern Coast Ranges (e.g., McLaughlin et al., 1988, 2018).

In general, strike-slip faults are oriented northwest-southeast with the structural grain of the northern Coast Ranges (e.g., McLaughlin et al., 2018) and are poorly oriented for slip relative to the maximum horizontal stress, forming an angle of ~55° (Provost and Houston, 2003). Despite this unfavorable orientation, these faults continue to accommodate slip, possibly due to weak fault surfaces developed within argillite-rich or serpentinite-matrix mélanges (e.g., Murray et al., 2014; Melosh et al., 2024b).

The Bartlett Springs - Hunting Creek - Berryessa faults together form a broad, concave west geometry; and a releasing bend in the Maacama fault, ~18 km to the northwest of The Geysers, produces a concave east geometry (Figure 1). Other shorter faults include the Collayomi fault, which is hosted in a steeply east-dipping layer of serpentinite mélange along, and in contact with, the east side of The Geysers plutonic complex (McLaughlin, 1978). The Big Sulphur Creek, Mercuryville, and Geyser Peak faults are located to the east of the Maacama fault and the west of The Geysers (Figure 1).

Extensional deformation at The Geysers is primarily identified in focal mechanism data as the rugged, mountainous terrain obfuscates geomorphic signatures (Oppenheimer, 1986). The distribution of volcanic rocks in Clear Lake has been postulated to be caused by the modern stress orientations (Hearn et al., 1981), which is supported by dike alignments in the slightly older (late Miocene to Pliocene) Sonoma Volcanics near Middletown (Figure 1). Dike populations there have average orientations of N14°E (Fox, 1983), and the modern maximum horizontal stress orientation is N26°E (Provost and Houston, 2003; Boyle and Zoback, 2014). This suggests that fracture opening within critically stressed crust is a fundamental control on both volcanism and fluid flow, and that static strain analysis provides an appropriate framework for identifying regions prone to open-mode failure.

3.   NUMERICAL METHODS

I constructed a numerical boundary element model using CutAndDisplace (Davis, 2017), following an approach similar to that of Siler (2023). A two-dimensional, linear elastic fault-interaction model was used that assumes a homogeneous, isotropic elastic medium with a Young's modulus of 30 GPa and a Poisson's ratio of 0.25. Fault slip is computed using a stress-controlled, shear-only elastic formulation in which faults accommodate shear displacement in response to the imposed remote stress field, without enforcing a Coulomb friction criterion or permitting fault-normal opening. These assumptions provide a physically reasonable first-order representation of upper-crustal crystalline rocks and minimize model complexity.

The area of interest is The Geysers - Clear Lake region within 38.48812, -123.22933 and 39.29671, -122.21141 (lower left, upper right) (see the black box in Figure 1), a total area of approximately 7,921 km². I extended faults past this region by 150 km to avoid edge effects caused by artificial fault tips. To assure a square cell geometry, I divided the model into 100 cells in the X direction and 159 cells in the Y direction, resulting in a cell length of 2369 meters and a cell area of ~5.6 km². This coarse resolution prevented long processing times.
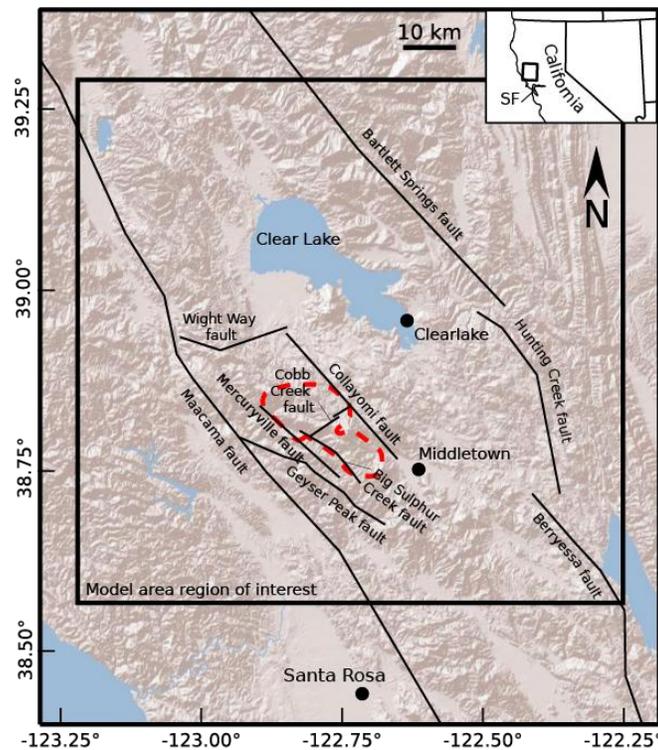
Figure 1: Location of the study area and the faults used in the numerical model, the red dashed polygon is the approximate location of The Geysers geothermal field, and the black box is the model area region of interest. The inset figure shows the location of the study area in northern California, SF: San Francisco. Basemap is from Esri world Hillshade (sources: Esri, USGS, NGA, NASA, and others).

Using GIS software, I simplified fault traces from the Quaternary Fault and Fold Database (U.S. Geological Survey (USGS) and California Geological Survey, 2019) and detailed geologic mapping at The Geysers (McLaughlin, 1978; Sadowski et al., 2016). This simplification preserved first-order fault geometry and avoided uncertainties in fault location and orientation on a detailed scale more suitable to site-specific studies.

I prescribed far-field stresses on the model using a principal stress tensor with maximum and minimum principal stresses of $\sigma_1 = 50 MPa$ and $\sigma_3 = 5 MPa$, and a maximum horizontal stress orientation of N26°E. I used stress magnitude values from a stress drop study on San Francisco Bay region faults (Lozos et al., 2015), and stress orientation from microseismicity inversion studies (Provost and Houston, 2003; Boyle and Zoback, 2014).

I assume purely elastic deformation in the model and do not include damage evolution, or time-dependent rheology, nor do I incorporate the effects of magmatism or elevated heat flow on crustal strength. I also exclude gravitational loading and topographic effects. As a result, stress interactions arise solely from elastic coupling among fault elements embedded within a homogeneous elastic medium.

3.1 Model Iterations

I conducted model simulations iteratively, with individual faults progressively added in separate runs to isolate and quantify the influence of specific fault geometries on dilation patterns. A) The first model iteration used a highly simplified fault network that included only the Maacama and Bartlett Springs faults, capturing their major bends by combining the Hunting Creek and Berryessa fault segments and their associated stepovers. B) The second iteration added the Hunting Creek and Berryessa faults, including the stepover geometries between segments (Lienkaemper, 2010; Melosh et al., 2024a). C) The third iteration incorporated the Collayomi fault system, which bounds the eastern side of The Geysers geothermal field (Sadowski et al., 2016). D) The fourth iteration added the Geyser Peak fault; E) the fifth added the Mercuryville and Big Sulphur Creek faults; and F) the sixth added the Wight Way and Cobb Creek faults (Figure 1).

I present dilation results in cross section view along two profiles through the model. Section A-A' spans a southwest to northeast orientation across the Clear Lake region and section B-B' spans a southeast-northwest orientation through The Geysers geothermal field (Figure 2A).

4.   RESULTS

Elevated dilational strain occurs across The Geysers – Clear Lake region and is focused around, and amplified by, fault tips, bends and stepovers. These structures generate interconnected lobes and zones of dilation that span a roughly southwest to northeast orientation.

Early model iterations reveal an interconnected zone of dilation that spans roughly west to east across The Geysers – Clear Lake region between the Maacama and Bartlett Springs faults (Figure 2A). Isostrain contours are oriented ~east to west across the region but are relatively low at < 0.02%. The west side of this dilation originates at the releasing bend in the Maacama fault northwest of The Geysers and connects to the broad concave-west geometry of the Bartlett Springs fault zone. Dilation is slightly amplified in model iteration B with the introduction of the Hunting Creek and Berryessa fault segments and associated stepovers in the east (Figure 2B). However, this difference does not increase dilation at The Geysers (Section B-B' in Figure 3), which remains low at ~ 0.01%.

The introduction of the Collayomi fault, in model iteration C, produces dilation and contraction signatures associated with the fault tips, including a lobe of dilation located in the southern part of The Geysers geothermal field that exceeds 0.068 % (Figure 2C). The inclusion of the Geyser Peak fault in model iteration D expands the area with dilation >0.03% further to the west, to where it connects with the releasing bend in the Maacama fault. This also increases maximum dilation in the southern Geysers geothermal area to 0.086 % (Figure 2D). Inclusion of the Mercuryville and Big Sulphur Creek faults in model iteration E increases the magnitude of dilation over a similar area as iteration D. Dilation magnitudes are notably increased between the Geyser Peak and Mercuryville faults west of The Geysers. The area of high dilation >0.04% expands to the northwest along the Mercuryville fault, and a contractional anomaly appears near the northern termination of the Big Sulphur Creek fault (Figure 2E). Interestingly, this contractional anomaly is removed in the final model iteration by the inclusion of the Cobb Creek fault (Figure 2F), which also decreases dilation in the northern part of The Geysers. The Wight Way fault reduces the contractional anomaly at the northwest tip of the Collayomi fault and increases dilation near its termination next to the Maacama fault where it forms a wedge-shaped geometry with opposing kinematics (Figure 2F). Dilation at The Geysers in model iteration F is reduced to a maximum of 0.069 %, below previous iterations D and E.

Dilation results in section A-A' display distinct peaks and troughs related to the location of fault tips, bends, and stepovers (Section A-A' in Figure 3). There is contraction west of the Maacama fault and east of the Bartlett Springs fault and a broad zone of dilation between these faults across The Geysers–Clear Lake region. Each progressive model iteration changes the distribution and generally increases the magnitude of dilation and contraction anomalies. However, the final iteration, which includes ~east-west structures, reduces strain anomaly magnitudes in places.

Dilation is higher in the southern part of The Geysers and tails off to the northwest where it approaches 0% (Section B-B' in Figure 3). This strain gradient is introduced in model iteration C, with the addition of the Collayomi fault, and strain magnitudes are only changed by ~0.01 to 0.015% in subsequent runs.

5.   DISCUSSION

Dilation in The Geysers – Clear Lake region does not arise from a single geometric feature but instead reflects the cumulative influence of multiple structural elements acting together. A combination of large-scale bends in regional strike-slip faults and localized strain concentrations associated with fault tips and stepovers on shorter fault segments, such as the Collayomi fault, produce the observed distribution of dilational strain patterns.

Early model iterations indicate the presence of background levels of dilational strain are controlled by the regional fault-bend geometries of the Maacama and Bartlett Springs fault systems. Although this dilation signature is relatively minor, it may play an important role in facilitating larger-scale magma migration within the region and establishes conditions for localized zones of fluid flow.

In the absence of strain localization associated with stepovers, fault-tip effects of the Collayomi fault appear to dominate the spatial distribution of dilation. This fault generates a dilational strain gradient at The Geysers that decreases to the northwest, coinciding with the least permeable part of the geothermal reservoir (Garcia et al., 2016), and mirroring the northwest plunging geometry of The Geysers plutonic complex (Hartline et al., 2015). However, a direct relationship between strain gradient and pluton geometry remains speculative and cannot be resolved with the present elastic framework. The model indicates that the Collayomi fault tips play a fundamental, first-order role in localizing dilation and may represent the most critical upper-crustal deformation control on the location of The Geysers geothermal system.

The stepover between the Collayomi fault and the Geyser Peak – Mercuryville – Big Sulphur Creek faults, plays a meaningful, but perhaps secondary role, increasing dilation by 26% and expanding and intensifying the dilation anomaly to the west. This western lobe of dilation coincides with areas of extensive hydrothermal alteration outside of the footprint of the modern geothermal field, suggesting that dilational strain in this region may have promoted enhanced fluid circulation over recent geologic time (McLaughlin, 1978).

The interpretation of a multi-fault stepover implies that slip is partitioned among the Geyser Peak, Mercuryville, and Big Sulphur Creek faults rather than concentrated on a single structure. Of these, the Geyser Peak fault is the only one extending far enough south to create a true geometric stepover with the Collayomi fault. However, despite its geometric significance, the Geyser Peak fault is the most poorly oriented for slip as it bends toward the west, which may limit its capacity to accommodate substantial displacement. For this reason, I infer that slip along the southern part of the Geyser Peak fault is partitioned farther north onto the Mercuryville and Big Sulphur Creek faults.

East–west–oriented faults such as the Wight Way and Cobb Creek faults act as strain-accommodating structures that redistribute localized strain concentrations, consistent with observations that secondary faults and splays accommodate strain around fault tips in distributed strike-slip systems (e.g., Bürgmann and Pollard, 1994; Kirkpatrick et al., 2008). The intersection of the Wight Way and Maacama faults increases dilation and may be analogous to wedge-shaped, strike-slip structures in southern California that form transtensional sedimentary basins (Crowell, 1974). Similar strike-slip stepover basins are mapped along the Maacama fault west of The Geysers (McLaughlin and Nilsen, 1982; Nilsen and Mclaughlin, 1985).
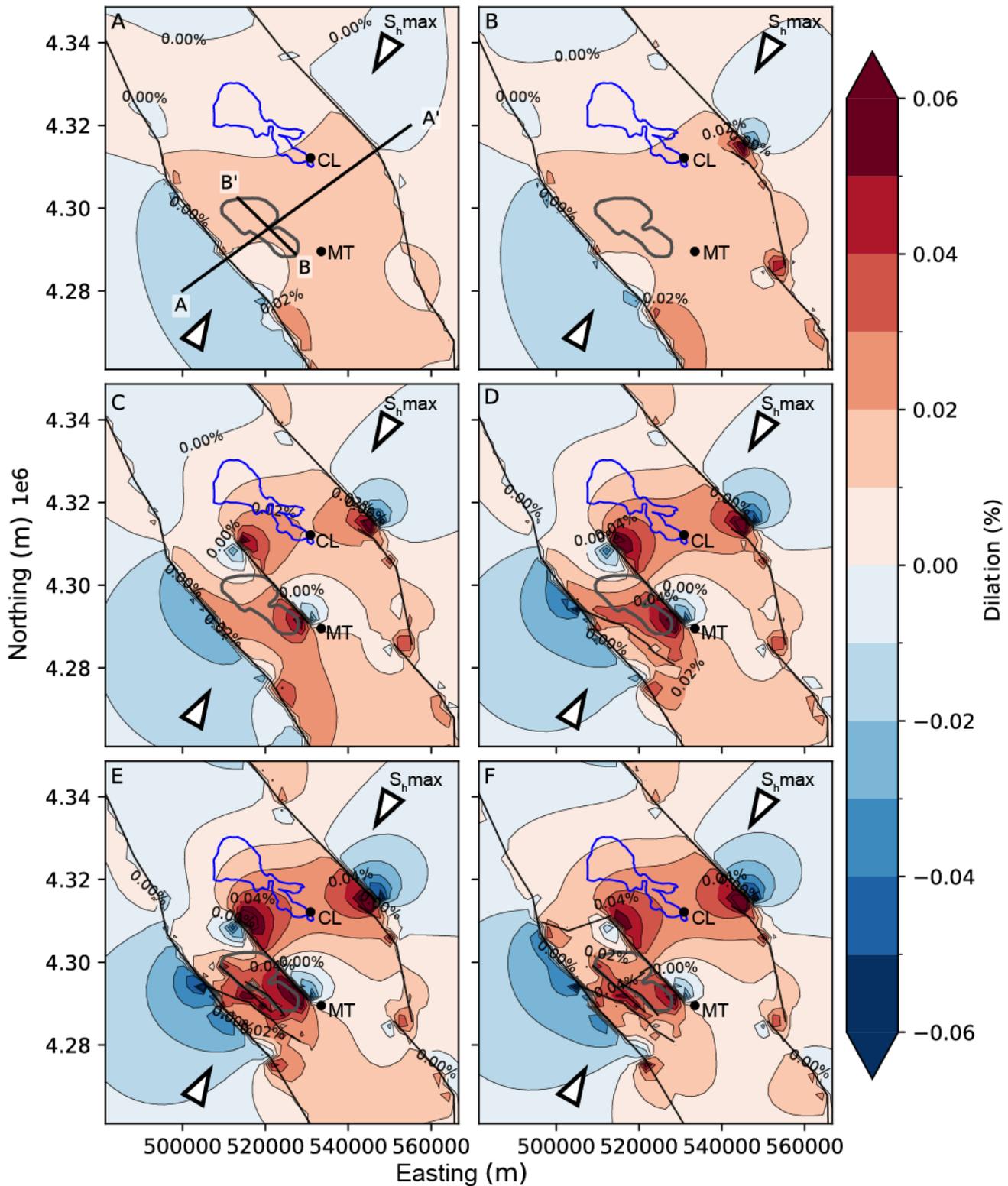
Figure 2: Modeled elastic dilational strain in the The Geysers–Clear Lake region. The gray polygon outlines the approximate extent of The Geysers geothermal field, and the blue polygon shows the outline of Clear Lake. CL denotes the city of Clearlake and MT denotes the city of Middletown. The white arrows outlined in black denote the orientation of the maximum horizontal stress ($S_h$max). Panels show results from a sequence of progressively more complete fault-geometry model iterations: (A) a simplified model including only the bounding regional strike-slip faults, represented by the Maacama fault and a combined Bartlett Springs–Hunting Creek–Berryessa fault system; (B) addition of the Hunting Creek and Berryessa faults and their associated stepovers; (C) addition of the Collayomi fault; (D) addition of the Geyser Peak fault; (E) addition of the Mercuryville and Big Sulphur Creek faults; and (F) addition of the Wight Way and Cobb Creek faults. Cross-section profiles A–A' and B–B' are shown only in panel A for visual clarity but were calculated for all model iterations.
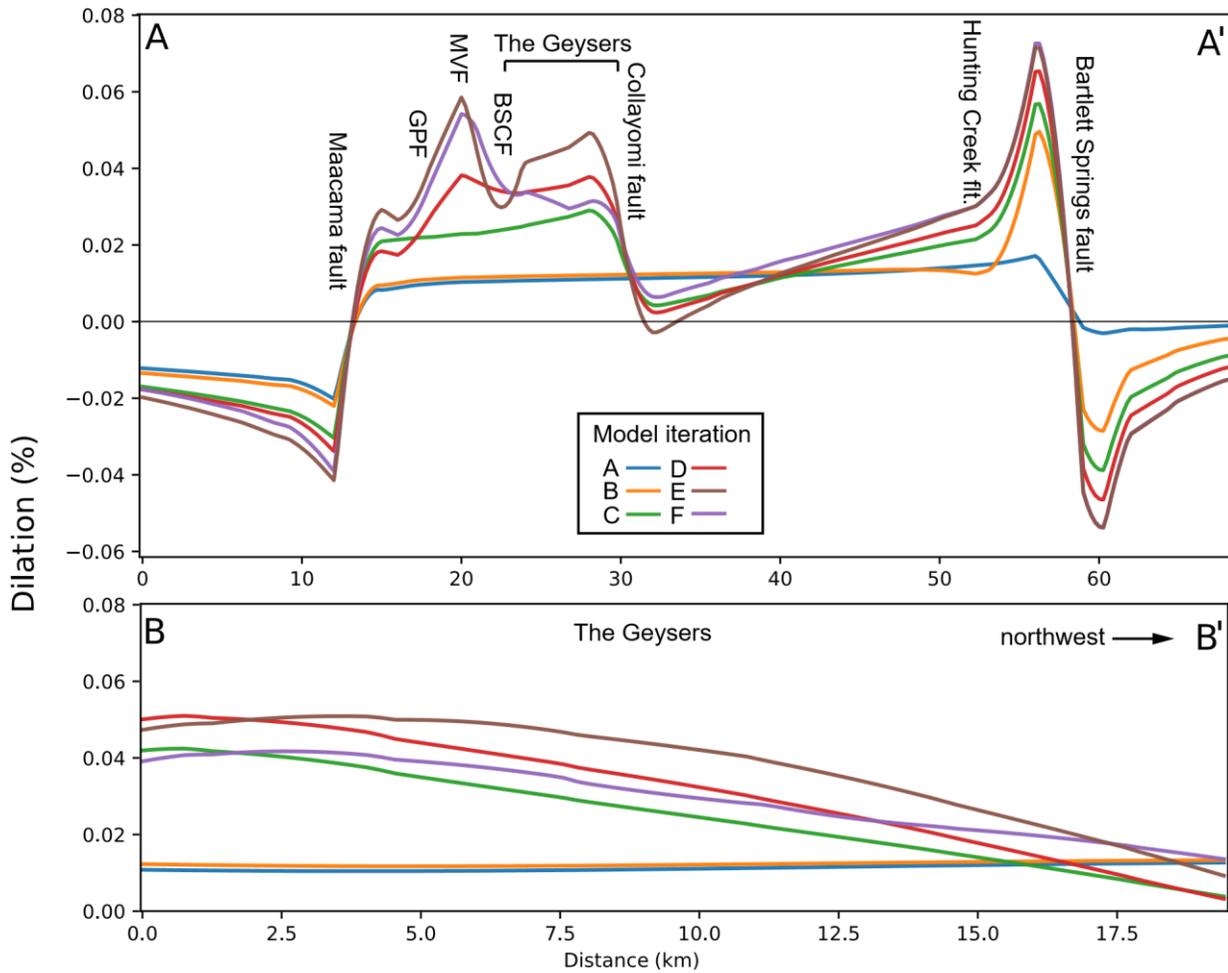
Figure 3: Dilation profiles along sections A-A' and B-B' shown on Figure 2A but calculated for all model iterations. Fault names depict the approximate location of faults, GPF: Geyser Peak fault, MVF: Mercuryville fault, BSCF: Big Sulphur Creek fault. The approximate location of The Geysers geothermal field is annotated.

5.1 Assumptions and simplifications

This modeling approach involves several assumptions that warrant careful consideration. First, the model adopts a top-down perspective, focusing only on elastic strain. This framework is appropriate for evaluating fault-controlled strain patterns at shallow to mid-crustal levels, but it does not explicitly account for magmatic influences. In the Clear Lake region, magmatism extends through much of the crust and into the upper mantle, indicating that magmatic processes operating at depth may influence the stress field and fault behavior in ways not captured by this elastic model (e.g., Hartline et al., 2015; Mitchell et al., 2023).

The position and viability of geothermal systems in the region ultimately depend on the interplay between shallow intrusions that provide heat and fault geometries that generate and maintain permeability for fluid circulation (e.g., Faulds and Hinz, 2015). However, tectonomagmatic systems are inherently complex, with faults influencing magma ascent and emplacement by modifying the local stress field, and magmatic intrusions modifying fault behavior through changes in stress, temperature, and host-rock strength (e.g., Magee et al., 2014; Acocella, 2021). Incorporating these complexities would require thermo-mechanical or viscoelastic modeling frameworks and detailed constraints on subsurface material properties, rheology contrasts, temperature gradients, and fluid flow and hydrothermal alteration histories. Although such approaches enhance full characterization of natural resources and fault behavior, they are beyond the scope of this study.

An important limitation of the model is the omission of rheological and strength contrasts that can strongly influence fault localization and associated strain patterns. In the varied bedrock of the northern Coast Ranges it is important to consider interactions between faulting, large subsurface serpentinite bodies, and intrusions (e.g., Mitchell et al., 2023; Langenheim et al., 2024). For example, the Collayomi fault bounds the eastern margin of The Geysers plutonic complex and is hosted within a mechanically weak serpentinite body that is near vertically dipping (McLaughlin, 1978). Such rheological contrasts are therefore likely to exert a control on fault geometry and strain distribution and may feed back into the spatial distribution of permeability and geothermal resources in ways not captured by the present homogeneous elastic model.

This model considers only two-dimensional, strike-slip deformation under a plane-strain assumption. In reality, many faults and folds in the region likely accommodate significant components of dip-slip and vertical motion that are not captured by this approach. For example, the distribution of the Coast Range ophiolite suggests the presence of a large antiformal structure underlying The Geysers geothermal field, potentially cored by rocks of the central belt part of the Franciscan Complex (McLaughlin, 1978; McLaughlin retired U.S. Geological Survey employee personal oral communication). The long history of oblique strike-slip faulting, together with vertical pluton emplacement, has likely contributed to the complex three-dimensional geometry of the region and may influence present-day deformation patterns.

Additional assumptions concern the mechanical properties of the crust. The model treats the crust as a homogeneous, isotropic elastic medium with a Young's modulus of 30 GPa. In reality, elastic moduli in the region likely vary substantially, potentially ranging from ~15 to 30 GPa, reflecting the complex lithologic heterogeneity of the Coast Ranges. The model further assumes a Poisson's ratio of 0.25, which represents a reasonable average value but does not capture possible spatial variations associated with differing lithologies, fracture densities, or degrees of alteration.

Representing inherently inelastic fault-zone processes with a purely elastic model is a limitation of this approach. Although inelastic deformation and fluid–rock interactions ultimately govern permeability evolution in mature fault zones (e.g., Sibson, 1996), the elastic strain patterns identified here provide a robust first-order proxy for structurally controlled permeability in geothermal systems.

Modeled dilational strains of ~0.02–0.08% (2×10^{-4}–8×10^{-4}) are mechanically significant. For a representative Young's modulus of 30 GPa, these strains correspond to stress perturbations of ~6–24 MPa, comparable, but slightly lower than strengths of hydrothermally altered rocks (Callahan et al., 2019). Such stress changes are sufficient to promote fracture opening and reactivation within fault damage zones (Sibson, 1996).

The faults in the model represent our current and best understanding of faults in the region, however, this mapping can still be improved upon. For example, we use the Big Sulphur Creek fault geometry compiled and mapped by Sadowski et al. (2016), however mapping by McLaughlin (1978) shows various fault traces continue to the southeast. It is possible that the Mercuryville or Big Sulphur Creek faults continue farther to the southeast, which if verified in future mapping, could form a more clearly defined releasing stepover with the Collayomi fault.

The simplified fault geometries in the model are appropriate because the goal is to examine first-order controls on dilation rather than site-specific complexities. Many aspects of fault geometry at scales of kilometers to hundreds of meters remain highly uncertain due to limited exposure and the resolution of bedrock and Quaternary fault mapping. Additionally, several faults from the model were omitted from the model, particularly on the east side of the Clear Lake region, including the Cross Springs fault, the Sulfur Banks fault, the Konocti Bay fault zone, and the Clover Valley fault. The faults were omitted in order to focus on The Geysers in the west, and because of uncertainty in defining a broad, multi-strand fault zones, such as the Konocti Bay fault zone, with a single line.

I used stress magnitudes from studies on the Hayward fault (Lozos et al., 2015) because there are no equivalent studies on the Maacama or Bartlett Springs faults. The Hayward fault is a similar-sized, near-by, right lateral, strike-slip fault, and stress magnitudes are likely similar. The maximum horizontal stress orientation used in this study is based on independent stress inversions from two separate studies (Provost and Houston, 2003; Boyle and Zoback, 2014). Although stress inversion methods have inherent uncertainties, the close agreement between these independently derived values provides confidence in its use for the present analysis. There are local variations in stress orientation that are not incorporated in this model.

6. CONCLUSION

The Geysers–Clear Lake region is characterized by active volcanism, seismicity, and one of the world's largest geothermal systems, yet the structural controls linking fault geometry, magmatism, and geothermal permeability have remained incompletely resolved. This study addresses that gap by applying a two-dimensional elastic boundary element model to evaluate the first-order influence of fault geometry on dilational strain in the upper crust.

Model results demonstrate that The Geysers geothermal field is situated within a persistent dilational strain field produced by the combined effects of (1) the southern tip of the Collayomi fault, (2) a releasing bend along the Maacama fault zone, and (3) a releasing stepover involving multiple faults along the western margin of the geothermal field. Large-scale bends in regional strike-slip faults generate a background field of dilation that is locally amplified by fault tips and stepovers, producing spatially focused strain anomalies. Predicted dilational strain magnitudes are sufficient to reduce effective normal stress, increase fracture aperture, and promote sustained fluid circulation.

These results represent a robust quantitative assessment of the elastic deformation state of The Geysers–Clear Lake region and provide a structural framework for interpreting the distribution of geothermal and volcanic activity. Although long-term permeability evolution and magma–fault interactions involve additional thermo-mechanical and chemical processes beyond the scope of this elastic model, the results demonstrate that fault geometry alone can generate strain conditions capable of localizing geothermal systems. More broadly, this study highlights that elastic strain modeling as a tool can facilitate identification of structurally controlled permeability in tectonically and magmatically active regions.

REFERENCES

Acocella, V.: Volcano-tectonic processes, *Switzerland: Springer*, 567, (2021).

Ball, J. L.: Stratigraphy and eruption history of maars in the Clear Lake Volcanic Field, California, *Frontiers in Earth Science*, 10, (2022), https://doi.org/10.3389/feart.2022.911129.

Boyle, K. and Zoback, M.: The Stress State of the Northwest Geysers, California Geothermal Field, and Implications for Fault-Controlled Fluid Flow. *Bulletin of the Seismological Society of America*, 104, (2014), 2303–2312, https://doi.org/10.1785/0120130284.

Bufe, C., Marks, S., Lester, F., Ludwin, R., and Stickney, M.: Seismicity of The Geysers-Clear Lake region, *U.S. Geol. Surv. Prof. Pap, 1141*, (1981), 129–133.

Bürgmann, R. and Pollard, D.D.: Strain accommodation about strike-slip fault discontinuities in granitic rock under brittle-to-ductile conditions, Journal of Structural Geology, 16, (1994), 1655–1674, https://doi.org/10.1016/0191-8141(94)90133-3.

Callahan, O.A., Eichhubl, P., Olson, J.E., and Davatzes, N.C.: Fracture mechanical properties of damaged and hydrothermally altered rocks, Dixie Valley-Stillwater Fault Zone, Nevada, USA, Journal of Geophysical Research: Solid Earth, 124, (2019), 4069–4090, https://doi.org/10.1029/2018JB016708.

Crowell, J.C.: Origin of late Cenozoic basins in southern California, in Ed. Dickenson, W.R., Tectonics and Sedimentation, Society for Sedimentary Geology Special Publication, 22, (1974), https://doi.org/10.2110/pec.74.22

Curewitz, D. and Karson, J.A.: Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction, Journal of Volcanology and Geothermal Research, 79(3-4), (1997), 149–168, https://doi.org/10.1016/S0377-0273(97)00027-9.

Davis, T.: A new open-source boundary element code and its application to geological deformation: Exploring stress concentrations around voids and the effects of 3D frictional distributions on fault surfaces (M.Sc thesis. Aberdeen University), (2017), Code available at https://github.com/Timmmdavis/CutAndDisplace.

Eberhart-Phillips, D.: Seismicity in the clear lake area, California, 1975–1983, *in* Sims, J.D., editor, Late Quaternary Climate, Tectonism, and Sedimentation in Clear Lake, Northern California Coast Ranges, number 214 in *Geological Society of America Special Paper*s, *Geological Society of America*, (1988), https://doi.org/10.1130/SPE214-p195.

Esri, *World Hillshade* [basemap]. Sources: Esri, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS User Community. ArcGIS Online, item ID 1b243539f4514b6ba35e7d995890db1d. (Accessed 12/5/2025).

Faulds, J.E. and Hinz, N.H.: Favorability of structural settings of geothermal systems in the great basin: Characterization of the most productive fault-controlled geothermal systems, In Proceedings of the *40th Workshop on Geothermal Reservoir Engineering*, Stanford, California. Stanford University, (2015), https://doi.org/10.2172/1724080.

Faulds, J. E., Hinz, N. H., Coolbaugh, M. F., Cashman, P. H., Kratt, C., Dering, G., Edwards, J., Mayhew, B., and McLachlan, H.: Assessment of favorable structural settings of geothermal systems in the Great Basin, western USA, *Geothermal Resources Council Transactions*, 35, (2011), 777–783.

Fox, K.F.: Tectonic setting of late Miocene, Pliocene, and Pleistocene rocks in part of the Coast Ranges north of San Francisco, California, *U.S. Government Printing Office*, volume 1239 (1983).

Garcia, J., Hartline, C., Walters, M., Wright, M., Rutqvist, J., Dobson, P.F., and Jeanne, P.: The Northwest Geysers EGS demonstration project, California: Part 1: characterization and reservoir response to injection, *Geothermics*, *63*, (2016), 97-119, https://doi.org/10.1016/j.geothermics.2015.08.003.

Hartline, C.S., Walters, M.A., Wright, M.C., Forson, C.K., and Sadowski, A.J.: Three-dimensional structural model building, induced seismicity analysis, drilling analysis, and reservoir management at The Geysers Geothermal Field, Northern California. *Geotherm. Resour. Counc. Trans*, 39, (2015), 603–614.

Hearn, B.C., Donnelly-Nolan, J.M., and Goff, F.E.: The Clear Lake volcanics: Tectonic setting and magma sources, *U.S. Geological Survey Professional Paper*, 1141, (1981), 25–45.

Hearn, B.C., J., Donnelly-Nolan, J., and Goff, F.: Geologic map and structure sections of the clear lake volcanics, northern California, U.S. Geological Survey, IMAP 2362, 3 sheets, scale 1:24,000, (1995), https://doi.org/10.3133/i2362

Kirkpatrick, J., Shipton, Z., Evans, J. P., Micklethwaite, S., Lim, S., and McKillop, P.: Strike-slip fault terminations at seismogenic depths: The structure and kinematics of the Glacier Lakes fault, Sierra Nevada United States, *Journal of Geophysical Research: Solid Earth*, 113(B4), (2008), https://doi.org/10.1029/2007JB005311.

Langenheim, V. E., McLaughlin, R. J., and Melosh, B. L.: Integrated geologic and geophysical modeling across the bartlett springs fault zone, northern California (USA): Implications for fault creep and regional structure. *Geosphere*, 20(1), (2024), 129–151, https://doi.org/10.1130/GES02684.1.

Lienkaemper, J.J.: Recently active traces of the Bartlett Springs fault, California: A digital database, U.S. Geological Survey, Data Series 541, (2010), https://doi.org/10.3133/ds541.

Lienkaemper, J.J.: Recently active traces of the Berryessa fault, California: A digital database, U.S. Geological Survey, Data Series 710, version 1.0, (2012), https://pubs.usgs.gov/ds/710/.

Lozos, J.C., Harris, R.A., Murray, J.R., and Lienkaemper, J.J.: Dynamic rupture models of earthquakes on the Bartlett Springs Fault, Northern California. *Geophysical Research Letters*, 42(11), (2015), 4343–4349, https://doi.org/10.1002/2015GL063802.

Magee, C., McDermott, K. G., Stevenson, C. T., and Jackson, C. A.-L.: Influence of crystallised igneous intrusions on fault nucleation and reactivation during continental extension, *Journal of Structural Geology*, 62, (2014), 183– 193, https://doi.org/10.1016/j.jsg.2014.02.003.

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

McLaughlin, R.J., Blake Jr, M., Griscom, A., Blome, C., and Murchey, B.: Tectonics of formation, translation, and dispersal of the Coast Range ophiolite of California, *Tectonics*, 7(5), (1988), 1033–1056, https://doi.org/10.1029/TC007i005p01033.

McLaughlin, R.J., Moring, B., Hitchcock, C., and Valin, Z.: Framework geologic map and structure sections along the Bartlett Springs fault zone and adjacent area from Round Valley to Wilbur Springs, northern Coast Ranges, California, U.S. Geological Survey, Scientific Investigations Map 3395, 2 sheets, (2018), 60 p., https://doi.org/10.3133/sim3395.

McLaughlin, R.J.: Preliminary geologic map and structural sections of the central Mayacmas Mountains and The Geysers steam field, Sonoma, Lake, and Mendocino Counties, California. *U.S. Geological Survey*, *Open-file report 78-389,* (1978), 128 pages, https://doi.org/10.3133/ofr78389.

McLaughlin, R.J.: Tectonic setting of pre-Tertiary rocks and its relation to geothermal resources in The Geysers-Clear Lake area, *U.S. Geological Survey Professional Paper 1141*, 3, (1981).

McLaughlin, R.J. and Nilsen, T.H.: Neogene non-marine sedimentation and tectonics in small pull-apart basins of the San Andreas fault system, Sonoma County, California, *Sedimentology*, 29(6), (1982), 865–876, https://doi.org/10.1111/j.1365-3091.1982.tb00089.x.

Melosh, B.L., Bodtker, J., and Valin, Z.: Geologic map and structure sections along the southern part of the Bartlett Springs fault zone and adjacent areas from Cache Creek to Lake Berryessa, Northern Coast Ranges, California, *U.S. Geological Survey, Scientific Investigations Map 3514*, 2 sheets, scale 1:24,000, (2024a), 20 p. pamphlet, https://doi.org/10.3133/sim3514.

Melosh, B.L., McLaughlin, R.J., and Ohlin, H.N.: The geometry of fault reactivation and uplift along the central part of the Maacama Fault Zone, Northern California Coast Ranges (USA), *Geosphere*, 20(6), (2024b), 1511–1532, https://doi.org/10.1130/GES02750.1.

Mitchell, M.A., Peacock, J.R., and Burgess, S.D.: Imaging the magmatic plumbing of the clear lake volcanic field using 3-d gravity inversions. *Journal of Volcanology and Geothermal Research*, (2023), https://doi.org/10.1016/j.jvolgeores.2023.107758.

Murray, J.R., Minson, S.E., and Svarc, J.L.: Slip rates and spatially variable creep on faults of the northern San Andreas system inferred through Bayesian inversion of Global Positioning System data, *Journal of Geophysical Research: Solid Earth*, 119(7), (2014), 6023–6047, https://doi.org/10.1002/2014JB010966.

Nilsen, T.H. and Mclaughlin, R.J.: Comparison of tectonic framework and depositional patterns of the Hornelen strike-slip basin of Norway and the Ridge and Little Sulphur Creek strike-slip basins of California, 37, (1985), https://doi.org/10.2110/pec.85.37.0051.

Okada, Y.: Internal deformation due to shear and tensile faults in a half-space, *Bulletin of the seismological society of America*, 82(2), (1992), 1018–1040, https://doi.org/10.1785/BSSA0820021018.

Oppenheimer, D.H.: Extensional tectonics at The Geysers geothermal area, California, *Journal of Geophysical Research: Solid Earth*, 91(B11), (1986), 11463–11476, https://doi.org/10.1029/JB091iB11p11463.

Provost, A. and Houston, H.: Stress orientations in northern and central California: Evidence for the evolution of frictional strength along the San Andreas plate boundary system, *Journal of Geophysical Research: Solid Earth*, 108(B3), (2003), 2175, https://doi.org/10.1029/2001JB001123.

Sadowski, A. J., Forson, C. K., Walters, M. A., and Hartline, C.S.: Compilation surface geologic map for use in three-dimensional structural model building at The Geysers geothermal field, Northern California, In *Proceedings: 41st Workshop on Geothermal Reservoir Engineering, Stanford University*, (2016).

Sibson, R.H.: Structural permeability of fluid-driven fault-fracture meshes, *Journal of Structural geology*, 18(8), (1996), 1031–1042, https://doi.org/10.1016/0191-8141(96)00032-6.

Siler, D.L.: Structural discontinuities and their control on hydrothermal systems in the Great Basin, USA, *Geoenergy,* (2023), https://doi.org/10.1144/geoenergy2023-009.

Siler, D.L., Hinz, N.H., and Faulds, J.E.: Stress concentrations at structural discontinuities in active fault zones in the western united states: Implications for permeability and fluid flow in geothermal fields, *Geological Society of America Bulletin*, 130(7-8), (2018), 1273–1288, https://doi.org/10.1130/B31729.1.

Stanley, W.D., Benz, H. M., Walters, M.A., and Rodriguez, B.D.: Tectonic controls on magmatism and geothermal resources in the Geysers-Clear Lake region, California: Integration of new geologic, earthquake tomography, seismicity, gravity, and magnetotelluric data, *U.S. Geological Survey, Open-File Report 97-95*, (1997), https://doi.org/10.3133/ofr9795.

Stanley, W.D., Benz, H.M., Walters, M.A., Villaseñor, A., and Rodriguez, B.D.: Tectonic controls on magmatism in The Geysers–Clear Lake region: Evidence from new geophysical models. *Geological Society of America Bulletin*, 110(9), (1998), 1193–1207, https://doi.org/10.1130/0016-7606(1998)110<1193:TCOMIT>2.3.CO;2.

Stanley, W. D. and Blakely, R.J.: The Geysers-Clear Lake geothermal area, California—An updated geophysical perspective of heat sources, *Geothermics*, 24(2), (1995), 187–221, https://doi.org/10.1016/0375-6505(94)00048-H.

Stanley, W.D. and Rodriguez, B.D.: A revised tectonic model for The Geysers-Clear Lake geothermal region, California. In *Proceedings of the World Geothermal Congress, Florence, Italy*, (1995), pages 18–31.

U.S. Geological Survey and California Geological Survey: Quaternary Fault and Fold Database of the United States: California. https://www.usgs.gov/programs/earthquake-hazards/faults, Accessed August 1, 2019, (2019).

ACKNOWLEDGMENTS