Developing Systematic Workflow From Field Work to Quantitative 3D Modeling for Successful Exploration of Structurally Controlled Geothermal Systems

Nicholas H. Hinz, James E. Faulds, and Drew L. Siler

Nevada Bureau of Mines and Geology, University of Nevada, Reno, USA

Keywords

3D geologic mapping, 3D modeling, exploration workflow, Great Basin, Basin and Range, structural analysis, drill targeting, structural controls, fault zone permeability

ABSTRACT

Ongoing research has shown that structurally controlled geothermal systems are associated with specific structural settings, such as terminations of major normal faults, accommodation zones, pull-aparts in strike-slip faults, displacement transfer zones, or step-overs in range-front faults. The structural framework of each of these principal structural settings is innately complex, and the permeable and productive areas are commonly spatially discrete, limited in some cases to a single part of an individual fault zone. Successful development of these systems relies on accurately defining these permeable up-flow zones in 3D space for precise well targeting and resource estimation. However, there is no single tool that can both define the detailed structural framework of a geothermal area and also define the individual parts of which faults currently host the geothermal fluids. Through recent and ongoing detailed studies of over 20 systems in the Great Basin region, we have been developing a systematic workflow that integrates multiple geologic and geophysical data sets. The workflow is centered on constructing an accurate and detailed 3D geologic map while using the same conventional geologic reasoning as is used in constructing 2D geologic cross-sections and maps of the ground surface. The 3D geologic map is then used to run quantitative 3D models, consider discrete geothermal indicator data sets relative to the entire 3D map, define a conceptual fluid-flow model, and select well targets.

Introduction

There is a growing body of evidence that shows that the structurally controlled geothermal systems are commonly associated with specific structural settings. A global survey found that hot springs are generally concentrated near the ends of faults or at fault intersections (Curewitz and Karson; 1997). In the Taupo volcanic zone of New Zealand, Rowland and Sibson (2004) noted that most of the geothermal systems were structurally controlled and that nearly two thirds were associated with accommodation zones. Research in the Great Basin region has shown that most of the geothermal systems in the Great Basin region are associated with specific structural settings, such as terminations of major normal faults, accommodation zones, pull-aparts in strike-slip faults, displacement transfer zones, or step-overs in range-front faults in contrast to central segments of major normal faults with maximum displacement (Faulds et al., 2006, 2011, this volume).

The structural framework of each of these principal structural settings is innately complex. Examination of developed systems shows that only one productive fault per system may exist at economic depths of <2 km within a locally abundant region of faults and fractures (e.g. Dering and Faulds, 2012; Edwards and Faulds, 2012). Because each geothermal system is hosted within a local stratigraphic and structural framework and has discrete geometric permeable pathways that the geothermal fluids follow, we need a systematic exploration strategy that can identify the permeable faults in 3D space in varied geologic terranes.

To help develop a successful exploration strategy for structurally controlled systems, we are currently in the process of assessing the structural setting of the ~450 known geothermal systems in the Great Basin region (Faulds et al., 2011, this volume). We have completed or are in the process of conducting detailed structural studies of over 20 systems (Faulds et al., 2006, 2010; Faulds and Melosh, 2008; Vice et al., 2007; Hinz et al., 2008, 2010, 2011; Rhodes et al., 2010; McLachlan et al., 2011; Edwards and Faulds, 2012; Dering and Faulds, 2012; Anderson and Faulds, this volume), and several of these geothermal systems have been selected for systematic three-dimensional mapping and modeling (e.g., Moeck et al., 2010; Jolie et al., 2012; Siler et al., 2012; Siler and Faulds, this volume). These projects have been built around a methodical workflow, which we present in this paper, for deciphering the details of each system to identify the location of the discrete conduits of geothermal fluid flow in three-dimensional space.

Exploration Workflow

Many tools are available for geothermal exploration, each with their inherent strengths and weaknesses in defining the inner workings of a given geothermal system. In targeting structurally controlled systems, the most effective exploration strategy is systematic integration of multiple tools, synergistically adding each data set in a workflow that facilitates logical geologic interpretation of the results. The workflow presented here is built around constructing 3D geologic maps using a set of geologic and geophysical tools customized according to applicability for each individual study area (Figure 1).

Geologic Mapping

Geologic mapping is one of the most important components to this exploration workflow by providing key data on structure, stratigraphy, alteration, and surface manifestations. Along with drill-hole data, data collected through boots-on-the ground field mapping provides first order constraints on stratigraphy and structure for constructing geologic cross-sections, interpreting geophysics, and building 3D geological maps. The optimal aerial extent and level of detail of mapping needed for each geothermal system varies according to the size of the system and the quality and quantity of exposures, as controlled by vegetation cover and/or terrain.

In areas of good exposure, defining the structural and stratigraphic framework typically requires mapping beyond the extent of surface manifestations (when present) at 1:24,000 scale (Figure 2A). Delineating the extent and precise locations of surface manifestations at ≤1:12,000 scale is particularly important for both defining discrete structures (Figure 2B) and also for using in developing a conceptual model once 2D and 3D geological maps have been completed.

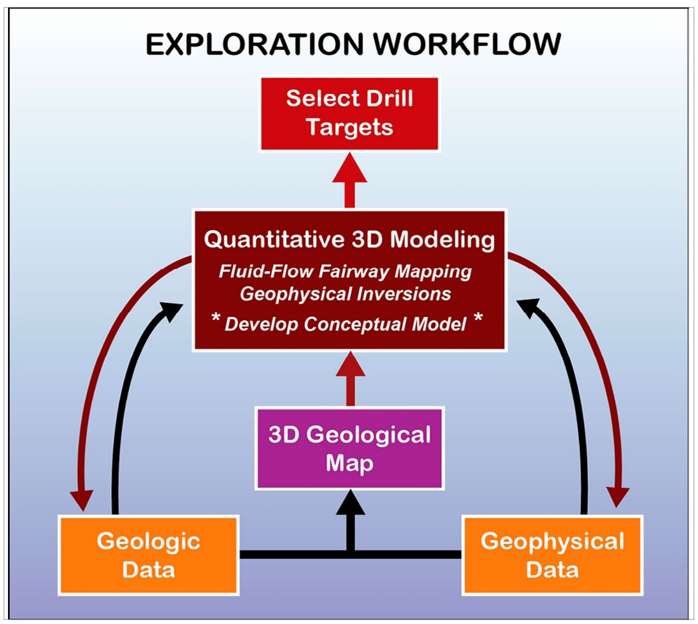

Figure 1. Geothermal exploration workflow diagram for structurally controlled systems.

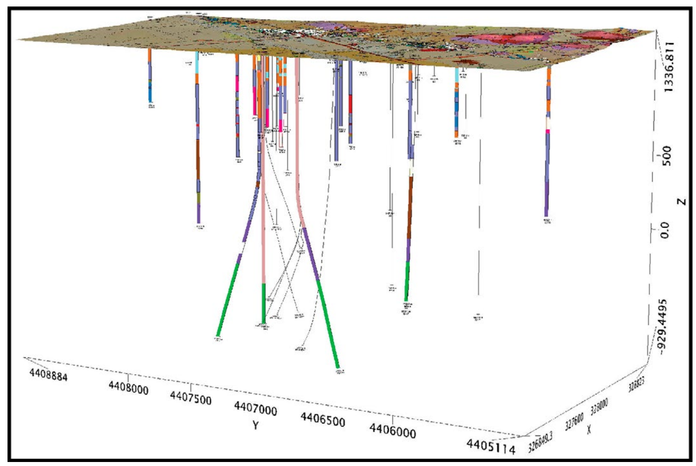

Figure 3. Three-D view of well paths color coded by lithology at the Bradys geothermal area.

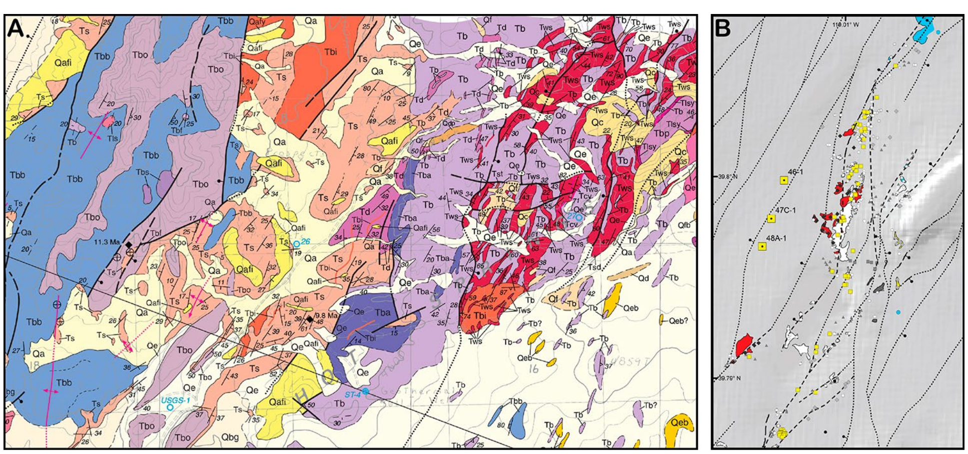

Figure 2. A) Example of detailed geologic mapping of bedrock in the Hot Springs Mountains near the Desert Peak geothermal area of western Nevada (Faulds and Garside, 2003). B) Example of detailed mapping of faults and surface manifestations at the Bradys geothermal area (from Faulds et al., 2012 and unpublished data).

Drill-Hole Data

Similar to geologic mapping, drill-hole data provide first order constraints on stratigraphy and structure for constructing geologic cross-sections and 3D geological maps (Figure 3). Key features from well data for building a 3D geologic map include lithologic data and drilling conditions such as loss of circulation zones. Lost circulation zones, which can correspond to faults, are important for correlation with the map data and seismic profiles in constructing geologic cross-sections.

Stress Field Determination

Since critically stressed fault segments within zones are most likely to act as fluid flow conduits (Barton et al., 1995; Sibson, 1994; Townend and Zoback, 2000), the tendency of a fault segment to slip (Morris et al., 1996) or to dilate (Ferrill et al., 1999) provides an indication of which sections of which fault zones within a geothermal system are most likely to transmit geothermal fluids. Slip and dilatation tendency analyses can be carried out on 2D (plan view) or 3D faults (e.g. Moeck et al., 2009, 2010) and requires local stress field magnitude and orientation as input data. Stress field orientations can be determined from GPS geodesy, bore-hole breakout data, kinematic analysis of fault surfaces, and resolved earthquake focal mechanisms. Vertical stress magnitudes can be estimated using average densities above a given depth, whereas maximum and minimum horizontal stresses are calculated from drilling-induced tensile fractures and the upper frictional limit to stress (e.g., Reynolds et al., 2006). Availability of each of these data sets varies according to given project areas.

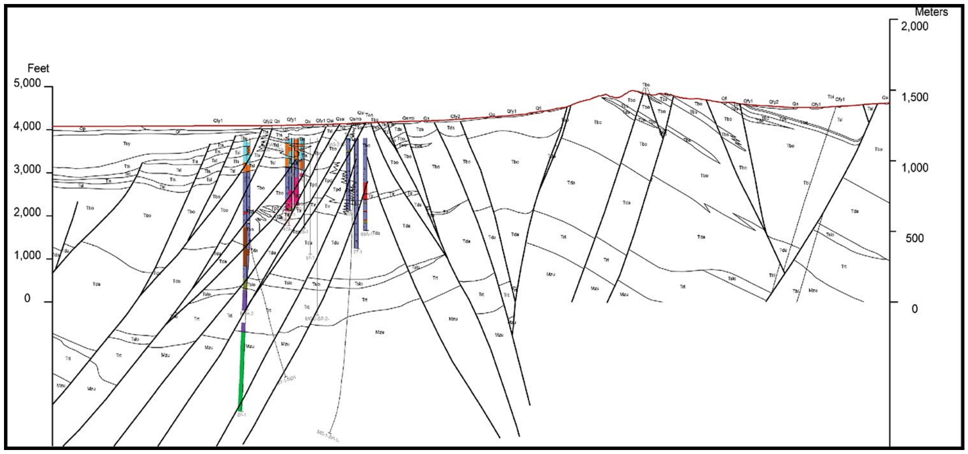

Figure 4. Geologic cross-section through the Bradys geothermal area with drill-hole lithologies projected perpendicular to the plane of cross section from within a 500 m later buffer along either side of the plane of cross-section.

Geophysics

Geophysical studies complement geothermal exploration workflow in two crucial areas: 1) defining structure and stratigraphy, and 2) inferring alteration, mineralization, and up- and out-flow parts of the geothermal system. Methods such as seismic reflection, gravity, and magnetic studies can help define the stratigraphic and structural framework necessary for building a 3D geologic map. These methods are especially critical for exploration in areas where bedrock is completely or largely concealed beneath basin fill sediments or vegetation. The results of electric and electromagnetic studies can be integrated and constrained with the 3D map (e.g. Witter and Phillips, 2012) to derive a conceptual model up-flow and outflow areas within the geothermal system.

Fluid Geochemistry and Alteration

Geochemical analyses yield data valuable for developing the conceptual model by delineating fluid chemistry and characterizing alteration relative to the structural framework of the 3D geologic map. Geothermometry is important for two reasons: 1) estimating the potential reservoir temperature during green-field exploration, and 2) comparing against measured down-hole temperatures in building a conceptual model. Down-hole temperatures that are significantly lower than geothermometry data suggest that wells do not tap the heart of the up-flow zone and that the 3D geologic map and conceptual model should be consulted to estimate where and if the higher temperature fluids are economically accessible. Mapping alteration type, extent, and interpreting how this fits with the modern geothermal system is helpful for confirming up-flow and out-flow areas relative to the 3D geologic map and developing working conceptual models. Alteration data are gathered by field mapping, logging of core and cuttings, wireline logs, hyperspectral data, and chemical analyses of field and drill-hole samples.

2D Geologic Cross-Sections

Construction of 2D geologic cross-sections as an intermediate step toward eventual 3D maps and models enables the geologist to subjectively interpret the available map, drill-hole, and geophysical data in a single plane, whereby the patterns of data points delineating stratigraphy and structure can be most easily interpreted. We have been accomplishing this by overlaying respective data sets in separate 2D digital layers, so that different sets can be turned off and on individually and/or viewed semi-transparent relative to other data sets (Figure 3). This allows the geologist to infer the most reasonable stratigraphic and geometric solutions while considering the multiple data sets at once. One critical step in this process is integrating drill-hole data into a single planar cross-section. Typically, we project drill-hole data perpendicular to the plane within a selected lateral distance, say 250-500 m, and adjust points vertically as needed to accommodate relative dip. The width of the buffer depends on the density of data and complexity of the geology.

3D Geologic Map

The specific XYZ input data for building 3D geologic maps comes from the 2D geologic cross-sections, the geologic map of the ground surface, and drill-hole data. Fault geometries are constructed first, followed by stratigraphic horizons (Figure 5) using methods similar to those used in other recent 3D geologic mapping and modeling studies (e.g., Dhont et al., 2005; Moeck et al., 2010; Jolie et al., 2012). Each fault is built from a grid of XYZ data points. Two-D cross-sections provide initial constraints on 3D fault geometries, but in many cases, initial correlation of faults between cross-sections and/or drill-holes needs to be iteratively re-evaluated during construction of the 3D geologic model. As the fault surfaces are built, a fault hierarchy is established in accord with cross-cutting relationships constrained by geologic mapping and during cross-section construction (Figures 5B, C). Stratigraphy is constrained by geologic map data, down-hole lithologic data, and cross-sections. Both faults and stratigraphy require intermediate control points such that the software gridding formulas extrapolate geologically reasonable solutions where hard data are limited or absent. This process builds a 3D geologic map around inferring reasonable geologic solutions from known constraints gathered from geologic mapping, drill-holes, and geophysics.

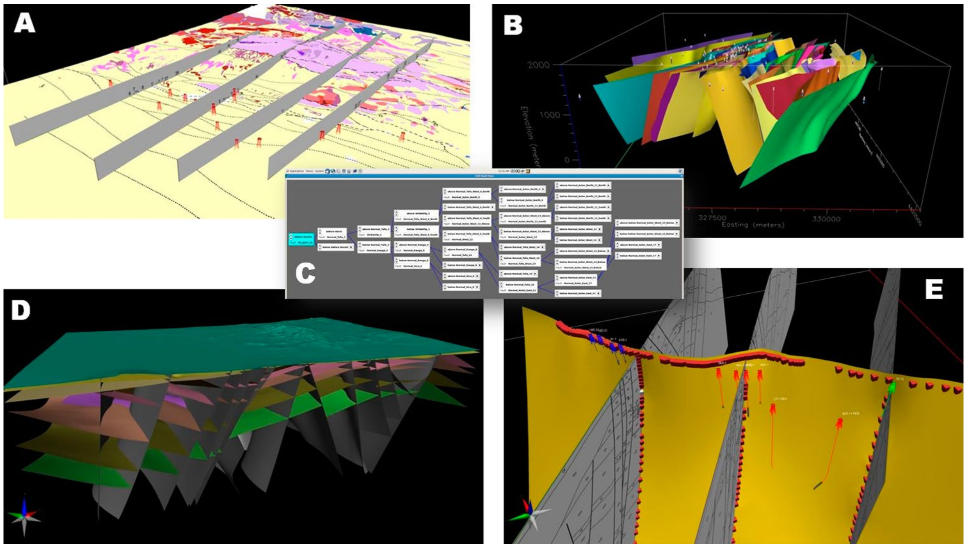

Figure 5. Constructing the 3D geologic map. A) 2D geologic cross-sections and surface geologic map for the Bradys geothermal area. B) Fault surfaces of the 3D geologic map for the Bradys geothermal area. C) Example of EarthVision software driven fault hierarchy guiding which faults terminate against which other faults. D) 3D geologic map of Bradys with lithologic volumes turned off, fault planes in gray, stratigraphic contacts in colors, ground surface. E) A single fault surface from the Bradys 3D geologic map showing XYZ input data points from the surface map, cross sections and drill hole intersections. All images are from EarthVision software.

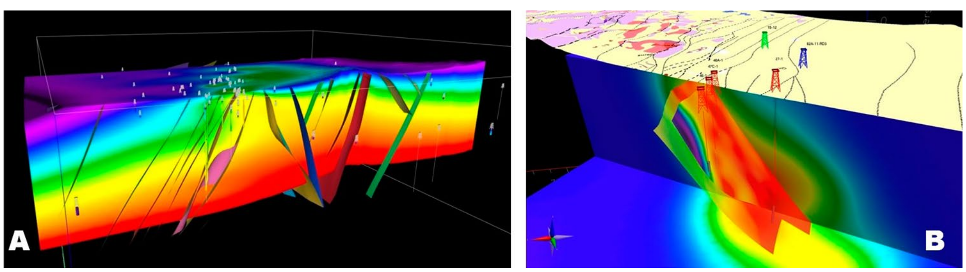

Figure 6. Examples of 3D modeling using the Bradys geothermal area 3D geologic map. A) Thermal model consisting of a 3D grid of down-hole temperature logs, warm colors represent highest temperatures. B) Results of slip tendency on 3D fault surfaces from the Bradys 3D geologic map. Warmer colors indicate greater tendency for slip. All images are from EarthVision software.

Quantitative 3D Analyses and Developing Conceptual Models

The 3D geologic map can be used as a foundation for quantitative 3D analyses, such as slip and dilation tendency analyses, fluid-flow fairway mapping, constrained geophysical inversions, thermal modeling, and reservoir modeling (Figure 6). Fluid-flow fairway modeling can be used to cross-correlate data relevant to permeability in 3D space, such as slip and dilation tendency analyses, density of fault intersections, and lithology for quantitative probability modeling of pathways conducive to the flow of geothermal fluids (Siler and Faulds, this volume). The quantitative 3D geologic and fluid-flow fairway models can then be spatially compared with alteration patterns defined through mapping and geochemical analyses, with geophysical data sets such as MT, and thermal data. In essence, the co-location and co-interpretation of quantitative and qualitative 3D data constrain working conceptual models of discrete geothermal systems and can be used to select additional exploration tools as necessary and ultimately site exploration, production, and injection wells.

Conclusions

Though much work remains in understanding the complexities associated with structurally controlled geothermal systems, as well as how best to specifically integrate the interpretations of each exploration tool, three-dimensional mapping and modeling provide an efficient, cost-effective methodology to systematically integrate the data for each respective geothermal area. From these 3D maps and models, we can plan additional exploration, development, and provide an eventual platform for detailed reservoir modeling and management. And finally, the "magic bullet" of geothermal exploration may not be a single instrument, rather it is a strategically conducted orchestra of instruments hand selected, tuned, and managed for each area.

Acknowledgments

We are grateful for the assistance and advice of Robert McFaul at Dynamic Graphics Inc. and to our industry partners, including Ormat Technologies, U.S. Geothermal, Gradient Resources, Nevada Geothermal Power Company, Alterra Power Corporation, Enel, Ram Power Corporation, and the U.S. Navy Geothermal Program Office. This work was principally supported by an American Recovery and Reinvestment Act grant from the Department of Energy (EE0002748) awarded to Faulds with additional funding through the Great Basin Center for Geothermal Research at the University of Nevada, Reno and Department of Energy (DE-FG36-02ID14311). This manuscript benefited from a thoughtful review by Patrick Walsh and from numerous discussions with Jeff Witter.

References

Anderson, R.B., and Faulds, J.E., 2013, Structural controls of the Emerson Pass geothermal system, Washoe County, Nevada: Geothermal Resources Council Transactions, *this volume*.

Barton, C. A., M. D. Zoback, and D. Moos, 1995, Fluid flow along potentially active faults in crystalline rock: Geology, v. 23, p. 683-686.

Curewitz, D. and Karson, J.A., 1997, Structural settings of hydrothermal outflow: fracture permeability maintained by fault propagation and interaction: Journal of Volcanology and Geothermal Research, v. 79, p. 149-168.

Dering, G., and Faulds, J., 2012, Structural Controls of the Tuscarora Geothermal Field, Elko County, Nevada: Geothermal Resources Council Transactions, v. 36, p. 41-46.

Dhont, D., Luxey, P., Chorowicz, J., 2005, 3-D modeling of geologic maps from surface data: American Association of Petroleum Geologists Bulletin, v. 89, no. 11, p. 1465-1474.

Edwards, J.H., and Faulds J.E., 2012, Preliminary assessment of the structural controls of Neal Hot Springs Geothermal Field, Malhuer County, Oregon: Geothermal Resources Council Transactions, v. 36, p. 891-896.

Faulds, J.E., and Garside, L.J., 2003, Preliminary geologic map of the Desert Peak – Brady geothermal fields, Churchill County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 03-27.

Faulds, J.E., and Melosh, G., 2008, Preliminary structural model for the Blue Mountain geothermal field, Humboldt County, Nevada: Geothermal Resources Council Transactions, v. 32, p. 273-278.

Faulds, J.E., Coolbaugh, M.F., Benoit, D., Oppliger, G., Perkins, M., Moeck, I., and Drakos, P., 2010, Structural controls of geothermal activity in the northern Hot Springs Mountains, western Nevada: The tale of three geothermal systems (Brady's, Desert Perk, Desert Queen): GRC Transactions, v. 34, p. 675-683.

Faulds, J.E., Coolbaugh, M.F., Vice, G.S. and Edwards, M.L., 2006, Characterizing structural controls of geothermal fields in the northwestern Great Basin: A Progress Report. GRC Transactions, v. 30, p. 69-76.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Cashman, P.H., Kratt, C., Dering, G., Edwards, J., Mayhew, B., and McLachlan, H., 2011, Assessment of favorable structural settings of geothermal systems in the Great Basin, Western USA: Geothermal Resources Council Transactions, v. 35, p. 777-784.

Faulds, J.E., Hinz, N.H., Dering, G.M., and Siler, D.L., 2013, The Hybrid Model – The most accommodating structural setting for geothermal power generation in the Great Basin, Western USA: Geothermal Resources Council Transactions, *this volume*.

Faulds, J.E., Ramelli, A.R., Garside, L.J., Coolbaugh, M.F., and Green, H.L., 2012, Preliminary geologic map of the Desert Peak Quadrangle, Churchill County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 12-5, scale 1:24,000.

Ferrill, D.A., Winterle, J., Wittmeyer, G., Sims, D., Colton, S. and Armstrong, A., 1999, Stressed rock strains groundwater at Yucca Mountain, Nevada: GSA Today, v. 9, no. 5, p. 1-8.

Hinz, N.H., Faulds, J.E. and Oppliger, G.L., 2008, Structural controls of Lee-Allen Hot Springs, southern Churchill County, western Nevada: A small pull-apart in the dextral shear zone of the Walker Lane: Geothermal Resources Council Transactions, v. 32, p. 285-290.

Hinz, N.H., Faulds, J.E. and Stroup, C., 2011, Stratigraphic and structural framework of the Reese River geothermal area, Lander County, Nevada: A new conceptual structural model: Geothermal Resources Transactions, v. 35, p. 827-832.

Hinz, N.H., Faulds, J.E., Moeck, I., Bell, J.W. and Oldow, J.S., 2010, Structural controls of three blind geothermal resources at the Hawthorne Ammunition Depot, west-central Nevada: Geothermal Resources Transactions, v. 34, p. 785-790.

Jolie, E., Faulds, J. and Moeck, I., 2012, The Development of a 3D Structural-Geological Model as part of the Geothermal Exploration Strategy -- A Case Study from the Brady's Geothermal System, Nevada, USA, Thirty-Seventh Workshop on Geothermal Reservoir Engineering., Stanford University, p. 421-425.

McLachlan, H.S., Benoit, W.R., Faulds, J.E., 2011, Structural framework of the Soda Lake geothermal area, Churchill County, Nevada: Geothermal Resources Council Transactions, v. 35, p. 925–930.

Moeck, I., Hinz, N., Faulds, J., Bell, J., Kell-Hills, A., and Louie, J., 2010, 3D geological mapping as a new method in geothermal exploration: A case study from central Nevada: Geothermal Resources Council Transactions, v. 34, p. 807–812.

Moeck, I., Kwiatek, G., Zimmermann, G., 2009, Slip tendency, fault reactivation potential and induced seismicity in a deep geothermal reservoir, Journal of Structural Geology, v. 31, p. 1174-1182.

Morris, A., Ferrill, D.A. and Henderson, D.B., 1996, Slip-tendency analysis and fault reactivation: Geology, v. 24, no. 3, p. 275-278.

Reynolds, S.R., Mildren, S.D., Hillis, R.R., and Meyer, J.J., 2006, Constraining stress magnitudes using petroleum exploration data in the Cooper-Eromanga Basins, Australia: Tectonophysics, v. 415, p. 123-140.

Rhodes, G.T., Faulds, J.E., and Teplow, W., 2010, Structural Controls of the San Emidio Desert Geothermal Field, Northwestern Nevada: Geothermal Resources Council Transactions, v. 34, p. 819-822.

Rowland, J.V., and Sibson, R.H., 2004, Structural controls on hydrothermal flow in a segmented rift system, Taupo volcanic zone, New Zealand: Geofluids, v. 4, no. v, p. 259-283.

Sibson, R.H., 1994, Crustal stress, faulting and fluid flow: Geological Society, London Special Publication, v. 78, p. 69-84.

Siler, D.L., and Faulds, J.E., 2013, Three-dimensional geothermal fairway mapping: Geothermal Resources Council Transactions, *this volume*.

Siler, D.L., B. Mayhew, and J.E. Faulds, 2012, Three-Dimensional Geologic Characterization of Geothermal Systems: Astor Pass, Nevada, USA: Geothermal Resources Council Transactions, v. 36, p. 783-786.

Townend, J., and Zoback, M.D., 2000, How faulting keeps the crust strong: Geology, v. 28, no. 5, p. 399-402.

Vice, G.S., Faulds, J.E., Ehni, W.J. and Coolbaugh, M.F., 2007. Structural controls of a blind geothermal system in the northern Pyramid Lake area, northwestern Nevada: Geothermal Resources Council Transactions, v. 31, p. 133-137.

Witter, J.B. and Phillips, N., 2012, Integrated 3D geophysical and geological modeling for improved geothermal exploration and drillhole targeting: Geothermal Resources Council Transactions, v. 36, p. 831-834.