Advancements in 3D Structural Analysis of Geothermal Systems*

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General Comments

Robust geothermal activity in the Great Basin, USA, is a product of both anomalously high regional heat flow and active fault-controlled extension. Elevated permeability associated with some fault systems provides pathways for circulation of geothermal fluids. Constraining the local-scale 3D geometry of these structures and their roles as fluid-flow conduits is crucial in order to mitigate both the costs and risks of geothermal exploration and to identify blind (no surface expression) geothermal resources. Ongoing studies have indicated that much of the robust geothermal activity in the Great Basin is associated with high-density faulting at structurally complex fault intersection/interaction areas, such as accommodation/transfer zones between discrete fault systems, step-overs or relay ramps in fault systems, intersection zones between faults with different strikes or different senses of slip, and horse-tailing fault terminations. These conceptualized models are crucial for locating and characterizing geothermal systems in a regional context. At the local scale, however, pinpointing drilling targets and characterizing resource potential within known or probable geothermal areas requires precise 3D characterization of the system.

Employing a variety of surface and subsurface data sets, we have conducted detailed 3D geologic analyses of two Great Basin geothermal systems. Using EarthVision (Dynamic Graphics Inc., Alameda, CA), we constructed 3D geologic models of both the actively producing Brady's geothermal system and a 'greenfield' geothermal prospect at Astor Pass, NV. These 3D models allow spatial comparison of disparate data sets in 3D and are the basis for quantitative structural analyses that can aid geothermal resource assessment and be used to pinpoint discrete drilling targets.

3D Geologic Models

Brady's

The relatively abundant data set at Brady's, ~80 km NE of Reno, NV, includes 24 wells with lithologies interpreted from careful analysis of cuttings and core, a 1:24,000 scale detailed geologic map and cross-sections, 2D seismic reflection profiles and other geophysical data, and downhole temperature data. The 3D geologic model based on these data consists of 61 fault planes, 25 distinct stratigraphic units, and 2 intrusive bodies. Geothermal fluids are produced from a left step-over/relay ramp within the Brady's Fault Zone (BFZ) (**Figure 1**). Under local stress conditions, fault segments that strike NNE-to-NE are most likely to slip and/or dilate, and therefore transmit geothermal fluids. The 3D model defines the locations of discrete fault intersections within the BFZ and indicates that the densest zones of structurally controlled fracture permeability are ~10-to-10s of meters in diameter and plunge ~55° NW-NNW beneath the heart of the BFZ step-over. The locations of high-intersection density, high-fault slip and dilation tendency, high subsurface temperature, and lithologies known to support high fracture permeability are combined to produce 3D 'fairway' maps useful in both assessments of geothermal resource potential and for defining drilling targets.

Astor Pass

Astor Pass is located on the Pyramid Lake Paiute Reservation, ~80 km north of Reno, NV. It is a prospective 'greenfield' geothermal area, and thus subsurface data are relatively sparse. Available data include: two relatively deep wells (~1400 m) and one shallower well (~500 m) with lithologies interpreted from drill cuttings, several 2D seismic reflection profiles, a 1:24,000 scale geologic map and cross-section, a shallow temperature survey, and downhole temperature data. 3D modeling based on these data has defined 19 distinct fault planes and 16 stratigraphic units (**Figure 2**). Based on the stress field calculated from borehole breakouts, drilling induced tensile cracks and petal-centerline cracks in the two relatively deep wells; 3D-slip and dilation-tendency analysis indicates that northerly striking fault segments are most likely to slip and/or dilate and, therefore, transmit geothermal fluids. Analysis of fault-intersection density indicates that the highest density of structurally controlled permeability within the field lies in a narrow (10-to-10s of m) zone plunging moderately (~35°) to the NNW beneath Pleistocene tufa deposits. This zone of increased fracture density, which we interpret as the primary upflow zone, is controlled by the intersection of N-to-NNW-striking normal faults and a WNW-striking dextral fault zone and represents the most promising target for future drilling.

Conclusion

Construction of a 3D geologic model involves integration of a variety of data into an internally consistent framework. A robust model allows for spatial comparison between the various types of data (structural, stratigraphic, geophysical, temperature, etc.) that are commonly used independently to site geothermal wells. Furthermore, highly detailed 3D geologic models provide the basis for additional quantitative analysis, including 3D-fault-slip and dilation-tendency analysis and the precise location of structurally controlled permeability pathways. These analyses provide detailed information relating to the internal dynamics of geothermal systems and can mitigate the costs and risks of geothermal exploration and development by contributing to better well targeting and more accurate evaluations of resource potential.

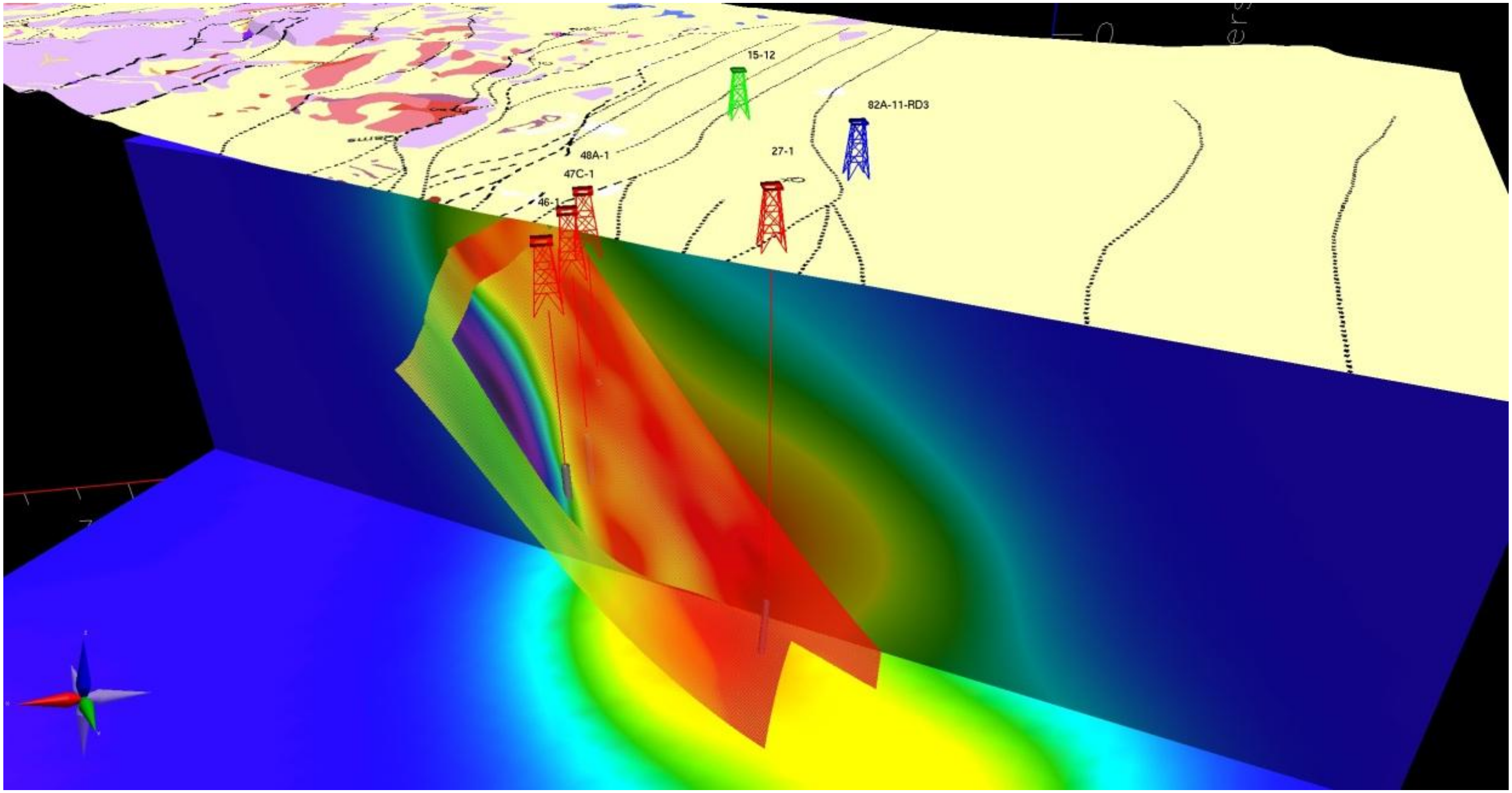

Figure 1. Perspective view looking SE at the BFZ step-over. Two of the discrete fault planes within the step-over are colored by slip tendency; warm colors for high-slip tendency and cool colors for low-slip tendency. In the background, fault-intersection density is shown; warm colors for high-intersection density and cool colors for low-intersection density. Production wells are colored red, injection wells blue. Grey tubes around the well paths show where the wells are open to inflow of geothermal fluids.

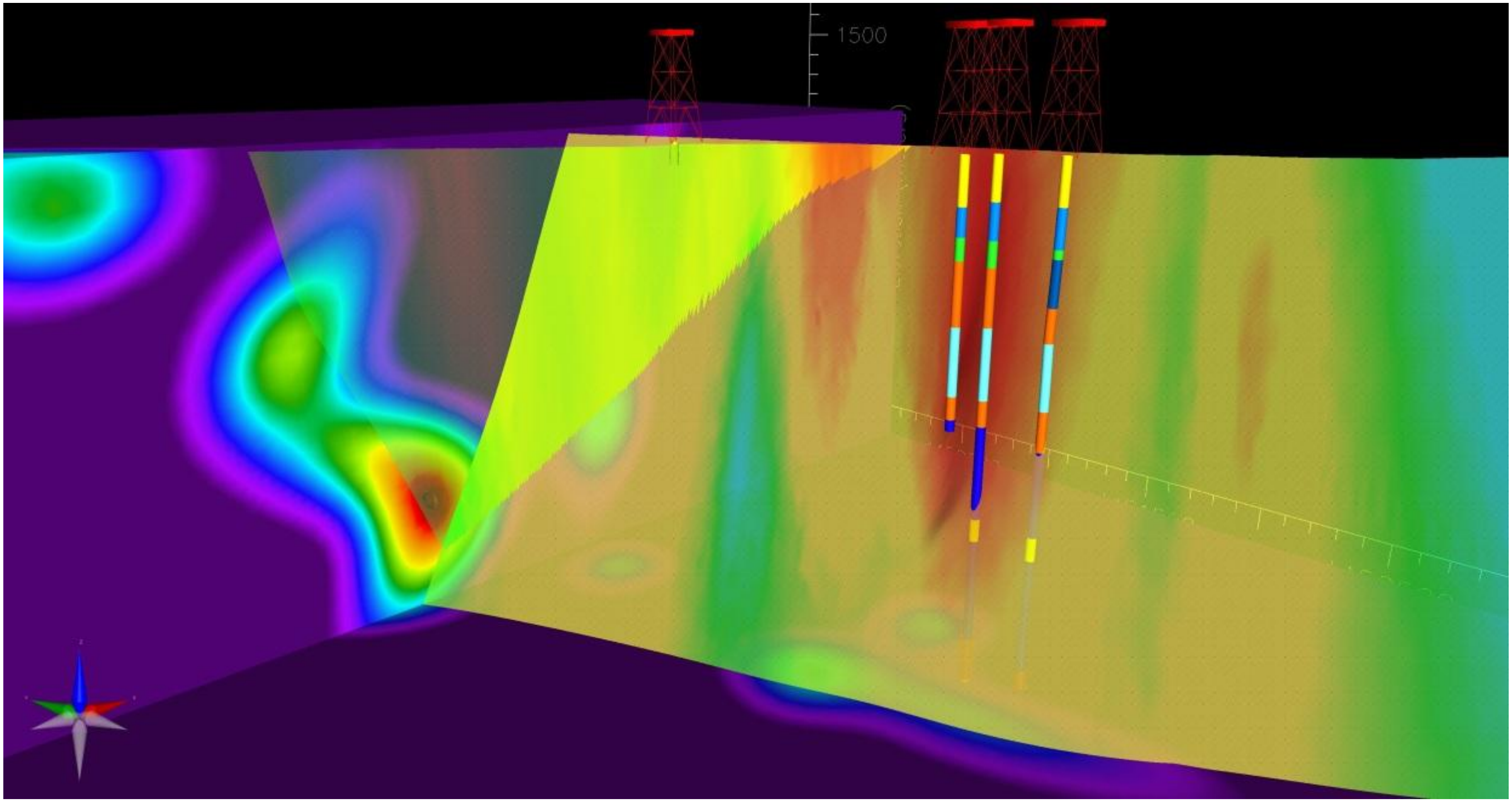

Figure 2. Perspective view looking ~NNE at the fault intersection that we interpret to control geothermal upflow at Astor Pass. The dextral fault, to the left, and the normal fault, to the right, are colored for dilation tendency; cool colors for low-dilation tendency and warm colors for high-dilation tendency. In the background, fault-intersection density is shown; warm colors for high-intersection density and cool colors for low-intersection density. Wells are colored by lithology; blues are Tertiary mafic-to-intermediate lava flows; orange is Tertiary rhyolites; green is Tertiary volcaniclasitic and sedimentary rocks; yellow is Quaternary, and red is pre-Tertiary basement.