Geothermal Potential of Transtensional Plate Boundaries

Scott Bennett

University of California, Davis, Geology Department

Keywords

Geothermal potential, transtension, strain localization, lithospheric thinning, extension, strike-slip faults, pull-apart basin, fault step-over, Walker Lane, Salton Trough

ABSTRACT

Active transtensional orogens within continental lithosphere likely host elevated geothermal potential. Many existing electrical-grade geothermal resources (e.g. Walker Lane, Salton Trough) are found in regions influenced by both shear and tensile stresses (i.e. transtension). The tectonic controls related to the geothermal potential of transtensional areas are fundamentally different than that of pure continental extension. In extensional regions driven solely by gravitational buoyancy forces, factors such as flexural forces, crustal thickness variations, and lower crustal flow of ductile material into the extending region limit total strain and strain rate on normal faults. Where strain rate is low, each of these processes produces a negative feedback on the ability for non-vertical normal faults to develop high strain rates or accommodate large amounts of strain. As a result, regions of pure continental extension commonly form an area of distributed, rather than localized, dilational deformation. In contrast, transtensional regions inherently contain strike-slip faults with higher strain rates that absorb some fraction of the driving plate boundary forces. Because the negative feedbacks from buoyancy forces do not affect sub-vertical strike-slip faults, their presence can allow for elevated strain and strain rates in a more focused zone. Where these strike-slip structures are kinematically linked and adjacent to extensional structures (e.g. releasing bend or step-over), an elevated extensional strain rate and focused lithospheric thinning can occur in the intervening region of extension. This rapid and localized extension can more efficiently thin the lithospheric column, exhume hot lower crustal material, and promote extrusive and/or shallow intrusive volcanic activity. These processes can elevate the brittle-ductile transition and steepen the geothermal gradient, providing the necessary heat to a high-enthalpy geothermal system (e.g. Cerro Prieto, Coso). Transtensional structures, such as fault intersections and terminations, may also intimately control and help to focus the pathways of fluids in the upper crust. In summary, the oblique forces across a transtensional plate boundary may be more efficient at rapidly thinning the lithosphere than regions of continental extension, and thus have a higher potential for development of electrical-grade geothermal resources.

Introduction

Geothermal resources are commonly found in regions of active extension (e.g. western North America; Figure 1).

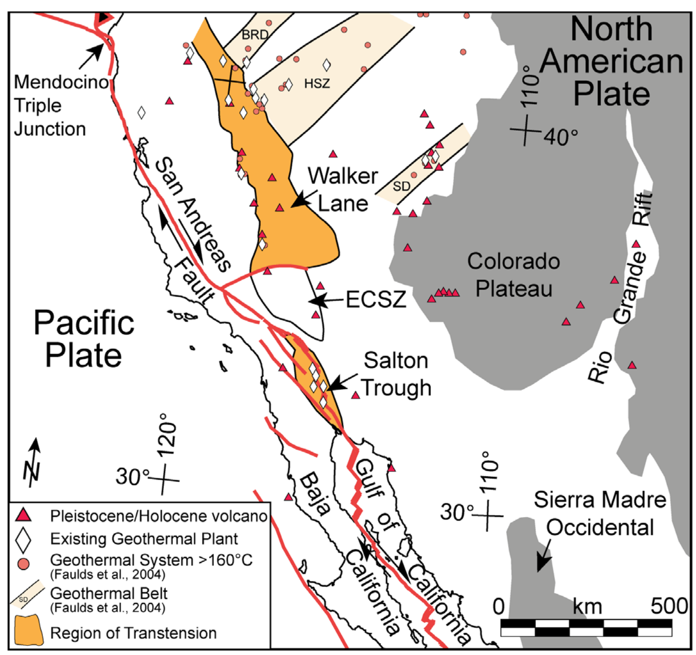

Figure 1. Simplified tectonic map of the Pacific-North America plate boundary. Geothermal systems and volcanoes from Blackwell & Richards (2004). Tectonic provinces adapted from Oldow (2003), Faulds et al. (2004), Oskin & Stock (2003). Stable North American plate are gray. ECSZ - Eastern California Shear Zone; SD - Sevier Desert; HSZ - Humboldt structural zone; BRD - Black Rock Desert.

Lithospheric thinning associated with extension can lead to elevation of geotherms to a shallower depth. This steepened geothermal gradient can create the potential for a geothermal resource. Although areas of continental extension are prospective for geothermal resources, many existing geothermal resources are found in regions influenced by active transtension. Here, I propose a rationale for why the geothermal potential may be enhanced along transtensional plate boundaries.

The Efficiency of Lithospheric Thinning

The ability to efficiently thin the lithospheric column can vary across extensional tectonic settings, and may affect the development of a high-enthalpy geothermal resource. Where gravitational buoyancy forces drive orthogonal extension, low deformation rates on inclined normal faults leads to distributed rather than localized deformation (Buck et al., 1999). Where external, plate boundary forces drive extension, potentially high deformation rates can overcome these hindrances and localize strain. Additionally, in transtensional settings, deformation along non-vertical faults may not be subject to these hindrances. Thus, the balance between buoyancy and boundary forces can control the distribution of strain and the efficiency of lithospheric thinning.

During orthogonal extension multiple factors inhibit the concentration of strain and the ability to localize thinning that could generate an electrical-grade geothermal resource. Lateral variations in lithospheric thickness can develop during extension, leading to differential vertical body forces (Buck, 1991). These greater vertical stresses in thicker areas produce horizontal stress gradients towards thinner areas, constricting regions of active extension, and distributing extensional strain elsewhere. These differential stresses also cause lateral pressure variations whose gradients may drive lower crustal flow of weaker or warmer crust (Buck, 1991). Lower crust will typically flow from thicker to thinner areas, preventing further localized extension (Bialas et al., 2007). Additionally, these crustal thickness variations can lead to differential buoyancy forces and cause isostatic rebound in thinner areas. This isostatic uplift flexes the crust and creates normal stress on dipping faults (Forsyth, 1992). Each of these factors limits fault displacement and reduces the strain rate on non-vertical normal faults and leads to formation of distributed, rather than localized, lithospheric thinning.

In contrast, the efficiency to thin the lithosphere in transtensional settings may be enhanced relative to orthogonal extension, and can increase the potential for geothermal resource development. These oblique orogens are controlled in the brittle crust by strike-slip, oblique-slip, and dip-slip structures that together accommodate oblique-divergent relative plate motions (Sanderson and Marchini, 1984). Common features associated with transtensional regions include en-echelon strike-slip faults that are connected by pull-apart basins that form above kinematically-linked normal or oblique-normal faults (Figure 2 A-D). In particular, fault stepovers are the locus of crustal thinning and potential geothermal resources in a transtensional regime. Formation of these pull-apart or stepover basins and the magnitude of extension are controlled by displacement along adjacent strike-slip faults. Slip on these vertical strike-slip faults does not by itself lead to crustal thinning or shallowing of fault dip. Thus, buoyancy and flexural forces do not limit fault displacement or reduce strain rate on strike-slip faults. Because many transtensional regions are directly accommodating relative plate motions, these strike-slip faults may accommodate large displacements and be able to maintain higher strain rates. As a result, the intervening pull-apart region of kinematically-linked extension could experience higher strain rates than areas of orthogonal extension. Higher strain rates may locally weaken the lithosphere by outpacing conductive cooling. This strain softening may allow for localized strain and formation of a narrow zone of deformation. Focused strain in turn fosters a positive feedback of a further increased extensional strain rate (England, 1983). This may allow for development of focused shear zones and large amounts of localized thinning on large-offset normal faults (Kusznir and Park, 1987; Huismans and Beaumont, 2003). Thus, transtensional regions are expected to have areas of more localized and rapid lithospheric thinning.

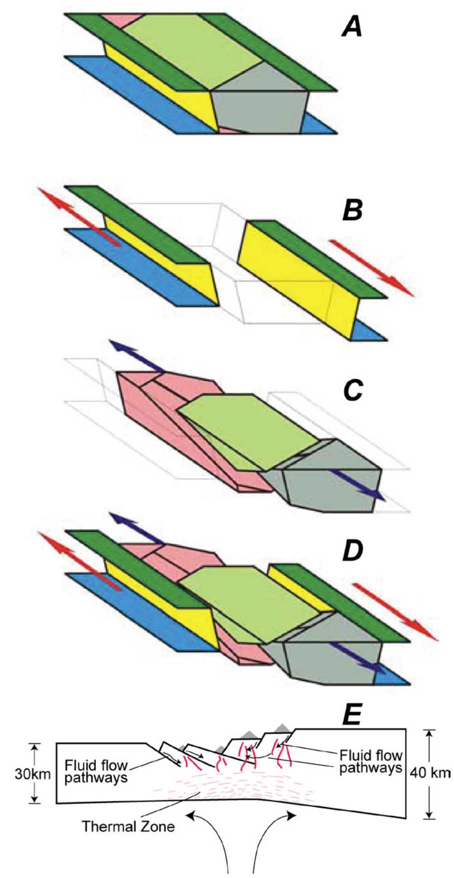

Figure 2. Common structural components of transtensional deformation. (A) Prior to deformation. (B) Sub-vertical strike-slip faults. (C) Large-offset normal faults. (D) Net effect is crustal thinning across pull-apart basin (from Aragón-Arreola and Martín-Barajas, 2007) (E) Schematic cross section across extensional pull-apart zone (adapted from Glassley (2010) and McCarthy & Parsons (1994)).

Transtensional Controls on Geothermal Potential

Rapid and efficient lithospheric thinning during transtension should enhance a regions geothermal potential. Common consequences of rapid and localized extension include tectonic exhumation of lower crustal material (Figure 2E).

With sufficient dip-slip displacement, warm ductile crust is advected upwards in the footwall of large-offset normal faults (e.g. Coleman and Walker, 1994). In a transtensional setting, high extension rates on normal faults kinematically linked and adjacent to strike-slip faults can tectonically exhume hot ductile crust (e.g. metamorphic core complex). Rapid thinning also promotes extrusive and/or shallow intrusive volcanic activity. At the base of the lithosphere, thermal or mechanical thinning of the mantle lithosphere can advect hot asthenosphere towards the base of the crust. Emplacement of shallow intrusions and the vertical advection of hot material can both elevate the brittle-ductile transition to shallow depths. A shallow brittle-ductile transition can steepen the local geothermal gradient, enhance heat flow, and provide the necessary heat to a geothermal system.

Transtensional structures, such as fault intersections and terminations, may also intimately control and help to focus the pathways of mobile fluids (e.g. magma, hot water) in the upper crust. Intersections of faults create linear conduits for hot, buoyant fluids to be mobilized upwards (Figure 3). Fault terminations can control where these fluids may ascend (e.g. Cerro Prieto, Baja California; Elders et al., 1984). Fluids could also be captured and focused by other complexities in oblique fault geometries, such as fault corrugations or fault bends (e.g. Hawthorne, NV; Hinz et al., 2010). Additionally, block rotations and wrench-faulting associated with oblique tectonics (e.g. Walker Lane; Oldow, 2003) will form a dense network of variably oriented fractures. Such a fracture network will increase fracture permeability and improve the potential for fluid mobility in a geothermal system.

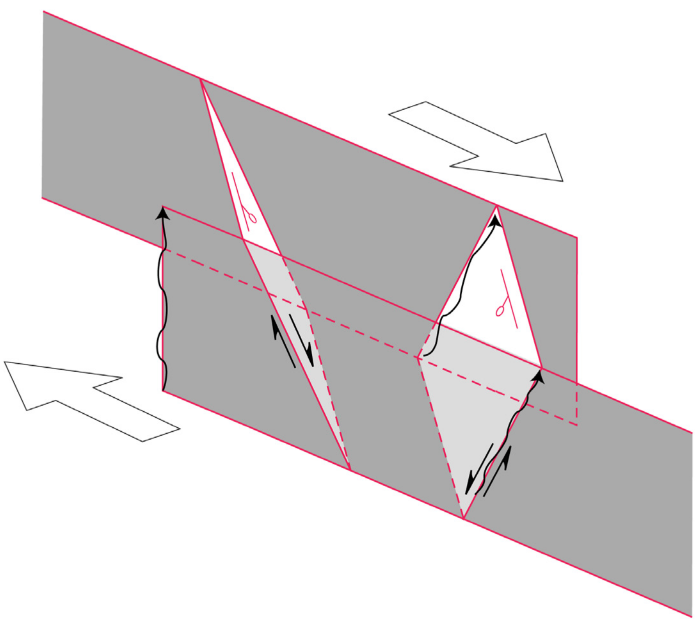

Figure 3. Fluid flow pathways (black wiggly arrows) are caused by fault intersection and fault terminations.

A Geothermal Case Study: The Pacific-North American Plate Boundary

In western North America (Fig. 1), the Pacific-North America (PAC-NAM) plate boundary accommodates ~52 mm/yr of dextral relative plate motion (Atwater and Stock, 1998). North of the Salton Trough, strain is partitioned across a wide plate boundary, with the Walker Lane transtensional belt accommodating up to 25% of plate motion. In contrast, beginning at the Salton Trough and south into the Gulf of California, the plate boundary is largely a focused transtensional system of strike-slip faults connecting short extensional regions that accommodates >90% of plate motion. This well-studied plate boundary contains multiple existing geothermal resources, allowing for an examination of the role that transtensional deformation may play in concentrating geothermal resources.

In the north, the majority (~75-80%) of PAC-NAM relative plate motion is currently accommodated by dextral displacement on the San Andreas fault system. The remaining ~20-25% of relative plate motion (~1cm/yr) is partitioned into belts of active transtensional and extensional fault systems east of the Sierra Nevada (Fig. 1; Argus and Gordon, 1991). From the Sierra Nevada to the Colorado Plateau, Basin and Range deformation is progressively influenced less by PAC-NAM boundary forces and more from gravitational buoyancy forces (Jones et al., 1996; Flesch et al., 2000). The dextral component of this deformation is concentrated in the western portion of the province, along strike-slip faults of the Walker Lane transtensional belt and northeast-striking normal faults in the northern and northwestern Great Basin (Unruh, 2003; Oldow, 2003). These normal faults are concentrated into seismic belts associated with Quaternary-active faults (USGS, 2006).

Existing geothermal resources north of the Eastern California Shear Zone (Figure 4) correspond with areas of either transtensional strain (e.g. Coso, Long Valley, Hawthorne) or relatively high rates of extension (e.g. Dixie Valley). A more comprehensive examination of geothermal potential along this portion of the plate boundary (Blackwell and Richards, 1994) reveals that elevated heat flow (>90mW/m^2) is associated with active tectonic areas that are both extensional and transtensional. In the Great Basin, previous workers have documented the empirical relationships between high strain rate and electrical-grade geothermal resources (e.g. Faulds et al., 2005; Coolbaugh et al., 2005). Geothermal plants east of the Walker Lane (e.g. Dixie Valley) are thought to be located where a portion of PAC-NAM NW-directed dextral strain is being transferred into the Walker

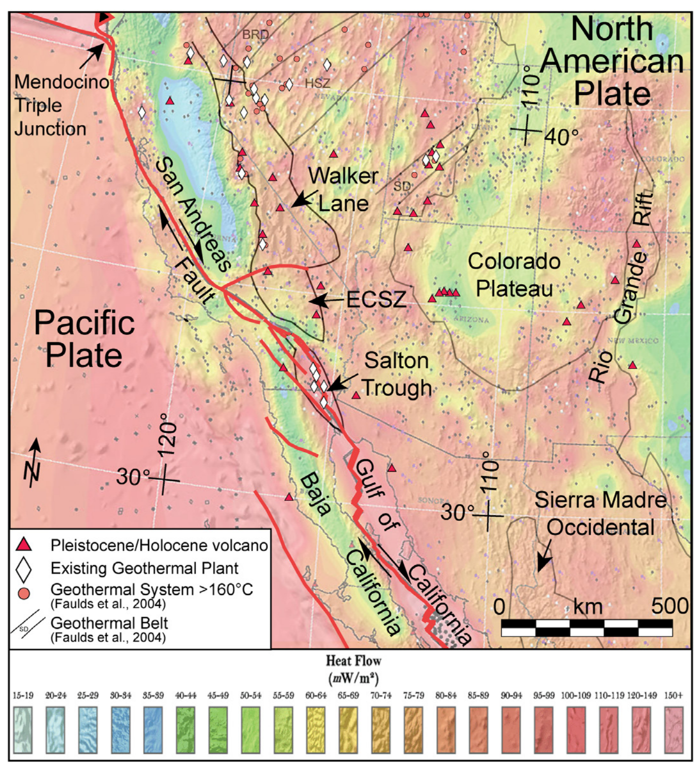

Figure 4. Geothermal (heat flow) map by Blackwell & Richards (2004). Provinces and abbreviations as Figure 1.

Lane along NE-SW-oriented belts of NW-directed extension with high strain rates (Faulds et al., 2005); however, magmatic geothermal systems (e.g. Coso, Long Valley) are concentrated within fault stepovers or along transfer zones only in the transtensional Walker Lane (Figure 4).

In the south, the majority (>90%) of relative plate motion is accommodated on the primary plate boundary, with the remaining dextral motion absorbed on offshore faults west of the Baja California peninsula (Plattner et al., 2007). The plate boundary consists of en-echelon dextral strike-slip faults connecting short extensional regions. Along the 200 km-long trace of the PAC-NAM plate boundary between the Salton Trough and waters of the northern Gulf of California, existing geothermal resources are presently being exploited (e.g. Salton Sea, Cerro Prieto), and additional areas are currently being explored (e.g. Superstition Mountain). Each of these geothermal systems is intimately associated with a transtension-related fault stepover, pull-apart basin, or fault terminations (e.g. Elders et al., 1984), corroborating early postulations that pull-apart basins may hold potential geothermal energy resources (Elders et al., 1972).

Guiding Future Geothermal Exploration

The assertion that transtensional settings may inherently have an enhanced geothermal potential can guide exploration of future geothermal resources. Active transtensional tectonic settings within continental lithosphere are somewhat common features related to plate boundaries and are found across the globe (Mann, 2007). Oblique tectonic settings such as the Dead Sea (Shamir, 2006), the Malawi Rift (Ebinger et al., 1987), or other less studied transtensional regions may yield undeveloped geothermal resources.

Conclusions

Tectonic regions undergoing active transtensional plate deformation may hold higher potential for geothermal resources. In transtensional settings, high strain rates from plate boundary forces on en-echelon strike-slip faults can drive rapid extension on kinematically-linked normal faults while efficiently thinning the lithosphere in a localized zone. In contrast, in areas of orthogonal continental extension, slip on normal faults is limited by buoyancy forces, leading to delocalized extension and less efficient lithospheric thinning. Efficient lithospheric thinning can advect warm crust upwards and promote volcanism, both of which can locally steepen the geothermal gradient, enhance heat flow, and provide the necessary heat to a geothermal system. In conclusion, where extension is hosted within a strike-slip-dominated setting (i.e. transtension), the overall higher strain rates that may result could ultimately enhance the potential of rapid lithospheric thinning and the potential for the presence of unexplored geothermal resources.

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