Geothermal Resources Council TRANSACTIONS, Vol. 18, October 1994

IGNEOUS ACTIVITY AT RELEASING BENDS AND TRANSFER ZONES IN EXTENSIONAL SYSTEMS: IMPLICATIONS FOR SITE AND MODE OF GEOTHERMAL ACTIVITY

Allen F. Glazner(1), J Douglas Walker(2), John M. Bartley(3), Drew S. Coleman(4) and Wanda J. Taylor(5)

(1) Department of Geology, CB 3315, Mitchell Hall, University of North Carolina, Chapel Hill, Chapel Hill, NC 27599
(2) Department of Geology, 2291 Irving Hill Drive, University of Kansas, Lawrence, KS 66045
(3) 717 Browning Building, Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112
(4) Department of Earth, Atmospheric, and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA 02139
(5) Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV 89154

INTRODUCTION

A key question in geothermal studies concerns the focusing agent responsible for producing an economic deposit. A prime location for such deposits is within extensional orogens where heat is transferred through a variety of advection mechanisms. An important mechanism of heat transfer through the crust is the emplacement of plutonic rocks. Here we present evidence from two localities in the western United States Cordillera for how strike-slip/extensional fault systems may serve to focus plutonism and geothermal activity. The first example is from the Miocene record of an extensional system in the Mojave Desert. We present an interpretation for the localization and development of plutonism and hydrothermal alteration (and hence probably an ancient geothermal system) at a releasing bend/pull apart structural position. The second example is for Miocene to recent plutonism and hydrothermal and geothermal activity in the Basin and Range Province of southwestern Utah. This system is located near transfer fault steps in the locus of extensional faulting. Both of these examples are from areas where extensional deformation was accommodated by low angle normal faulting and the development of extensional core complexes.

CENTRAL MOJAVE METAMORPHIC CORE COMPLEX

Many highly extended areas of the southern Basin and Range province are characterized by intense, widespread hydrothermal alteration of rocks, indicating that extension was accompanied by large-scale fluid flow. Low-angle normal faults commonly juxtapose potassic, oxidized upper-plate rocks with chloritized lower-plate rocks (Chapin and Glazner, 1983; Bartley and Glazner, 1985; Brooks, 1986; Roddy et al., 1988; Glazner et al., 1989). A key question is whether these regimes developed independently or represent complementary parts of an integrated large-scale fluid circulation system. Geochemical and structural data from the Mojave Desert support the latter interpretation.

In the southern Basin and Range there is nearly a perfect correlation between pervasive K-metasomatism and intense normal faulting in upper-crustal rocks. K-metasomatized rocks are strongly enriched in K (>12 wt% K_2O) and Rb, and depleted in Ca, Mg, and Sr; complementary lower-plate alteration in footwall granodiorite of the Waterman Hills detachment fault, near Barstow, California, involves depletion in K, Rb, and Si and enrichment in a large suite of elements, including Ti, P, Mg, Zr, Hf, and Eu (Glazner, 1988; Glazner and Bartley, 1991). In accord with other studies of phyllonites (O'Hara, 1988), we interpret enrichments in low-mobility elements (Ti, P, etc.) to reflect volume loss caused by leaching of Si, Al, K, and Na. Volume loss exceeded 50% and may have been as great as 75% or more. Calculations using solubility data for Si, Al, etc. in metamorphic fluids indicate that water/rock ratios exceeded 500 (Glazner and Bartley, 1991).

Near-universal association of chloritic lower-plate alteration with potassic upper-plate alteration, and the complementary chemical changes in the two systems, support their being coupled in a high-volume, crustal-scale hydrothermal system. However, other authors (Chapin and Lindley, 1986; Roddy et al., 1988) have proposed that (1) lower-plate alteration records infiltration of low-volume igneous or metamorphic fluids, (2) upper-plate alteration is accomplished by downward-percolating lake brines, and (3) the upper- and lower-plate systems are decoupled and

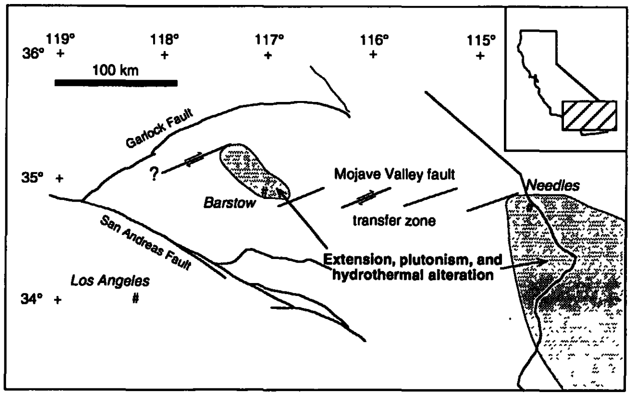

Figure 1. Schematic map of the Mojave Desert showing the position of the central Mojave metamorphic core complex. Also shown are the areas of extension, plutonism and hydrothermal alteration. We interpret the central Mojave metamorphic core complex, with associated hydrothermal activity and alteration, to have formed in a releasing position in a strike-slip fault system. The areal extent of the core complex is coincident with the area around and north of Barstow.

independent. Our data contradict these conclusions, because (1) they require large water-rock ratios in lower-plate alteration; (2) there were no saline lakes in areas of K-metasomatism; and (3) the K-bearing fluids were derived from below. K-depleted cataclastic zones along steep reverse faults in the lower plate of the central Mojave system may serve as deeply penetrating recharge zones for the hydrothermal system, and may permit multiple-pass convection to explain the large water-rock ratios in the lower plate.

Evidence from the Mojave Desert therefore is inconsistent with the decoupled-regimes model but is closely consistent with lower- and upper-plate alteration in extensional terranes being a record of integrated large-scale fluid circulation during extension.

Structural relations indicate that the central Mojave metamorphic core complex developed at a releasing bend in a dextral strike-slip system. Many paleogeographic elements (e.g., Independence dike swarm) east of Barstow are truncated near Interstate 15 and reappear to the southwest, indicating dextral displacement (Bartley and Glazner, 1991; Martin et al., 1993; Glazner et al., 1994). The location of this truncation zone is aligned with the southern extent of large-scale early Miocene extension and hydrothermal alteration (Figure 1). Although structural relations to the north are obscured by alluvium, mapping at Fremont Peak and sedimentologic relations in the Gravel Hills indicate that extension dies out there (Miller et al., 1992; Fillmore, 1994). South of Fremont Peak we have mapped a northeast-striking dextral shear zone with shallow lineation that cuts an early Miocene dike and may have served as a transfer zone north of the central Mojave metamorphic core complex (Miller et al., 1992; Figure 1). If this interpretation is correct, then the overall tectonic setting was similar to present-day Death Valley rotated counterclockwise 90° (Burchfiel and Stewart, 1966). Thus, we infer that Miocene plutonism and related hydrothermal activity were focused in the Barstow area by strike-slip tectonics. Similar relations between strike-slip faults and plutonism have been noted in many localities around the world (Hutton and Reavy, 1992).

SOUTHWESTERN UTAH EXAMPLE

Another example of the position of plutons and geothermal systems within an extensional setting is the Mineral Mountains and adjacent ranges of southwestern Utah (Figure 2). The area has been the site of igneous activity since the Oligocene (Aleinikoff et al., 1987; Coleman and Walker, 1992; Nielson et al., 1986; Nielson et al., 1978) and is presently the location of the Roosevelt Hot Springs KGRA. In addition, it is located in an area of active Basin and Range extension. Extension at this locality is apparently accommodated by low-angle normal faulting (Coleman and Walker, 1992; Nielson et al., 1986; Coleman and Walker, 1994).

The Mineral Mountains are part of a train of plutons of Oligocene to Miocene age along the transition between the Basin and Range and Colorado Plateau (Figure 2). These plutons are typically located near the intersection segments of the extensional system with different orientations or new steps in the extensional system related to transfer faults. This leads us to interpret there to be a connection between the

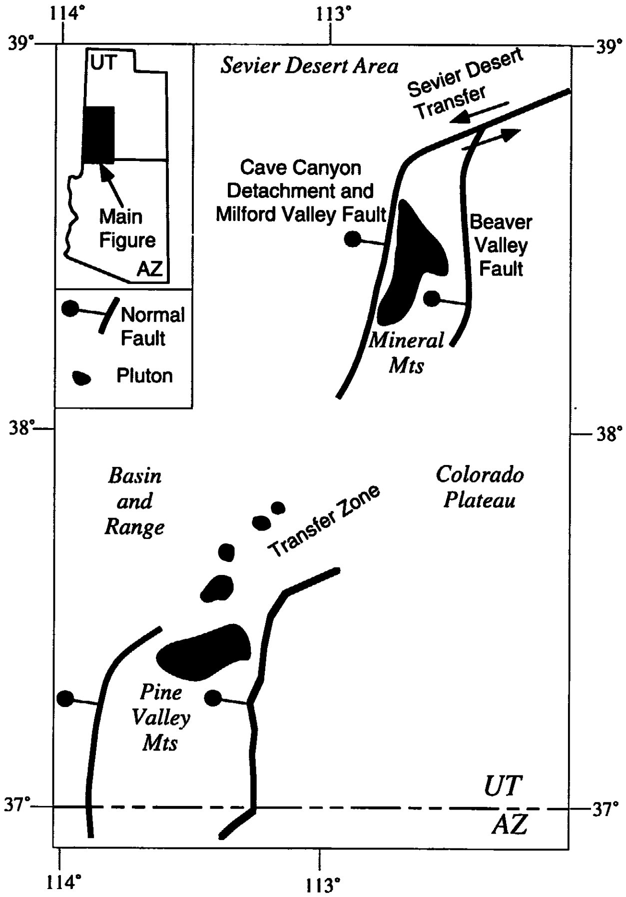

Figure 2. Map showing the position of plutons and major normal and transfer fault zones in southwestern Utah. The silicic plutonic centers are mostly associated with the position of transfer zones.

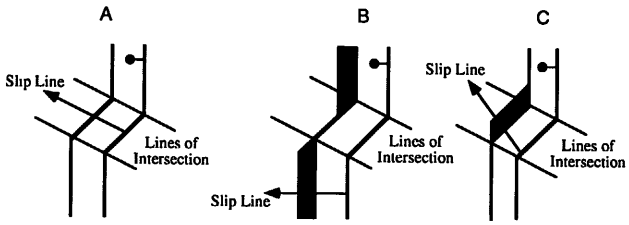

Figure 3. Diagram showing how bends and steps in normal fault systems can lead to the creation of space to be filled by plutons. The space created does not correspond to actual holes, but areas of material deficiency that could be occupied and filled by plutonic rocks. The "lines of intersection" are the line formed by the intersection of two different segments of the normal fault system. A. No space is created if the slip on the faults is parallel to the lines of intersection. B. Here gaps are opened (black regions) because of the mismatch of slip and fault orientation. This case may correspond to the southwestern Utah example. C. Gaps opened by mismatch in slip and lines of intersection.

steps in the extensional system and the locus of plutonism. Figure 3 shows that space is created in areas where extension along two adjacent segments of an extensional fault system is not parallel to the line of intersection of the fault segments. Because the size of these intersection zones and the amount of slip on the fault systems is of the order of several to tens of kilometers, space is opened that can easily accommodate sizable igneous centers. The igneous activity provides the heat to drive geothermal/hydrothermal systems in the extensional setting (see Mojave discussion above). The extensional faulting gives rise to a ready plumbing system (Nielson et al., 1986; Nielson et al., 1978).

The Mineral Mountains are presently located at a major offset in the locus of extensional faulting in southwestern Utah: they are south of a fault that transfers faulting related to the Sevier Desert detachment fault west of the Pavant Range into Milford Valley west of the Mineral Mountains (Figure 2). A mechanism directly analogous to those discussed above is not easy to envision for this setting. This location may be the site of enhanced crustal dilation related to the interaction of the extensional faults with the transfer system.

CONCLUSIONS

Two examples were presented for the structural settings of areas where there is evidence for either an ancient geothermal resource (Mojave) or a present one (Utah). These structural settings, releasing bends in strike-slip systems and transfer zones in normal fault systems, should be considered as exploration targets for geothermal resources. Many possible examples exist for areas that reside in such structural settings yet have no obvious surface manifestation of a geothermal resource. The southern Canyon Range of Utah resides at a major transfer zone in the Sevier Desert detachment system. Owens Valley in east-central California is a basin formed at a releasing bend in a strike-slip system. Although neither of these areas is presently volcanically or apparently geothermally active, both could contain blind geothermal resources because of their structural settings.

ACKNOWLEDGMENTS

Financial support for this project was provided by National Science Foundation grants EAR-8816944 and EAR-8916838 to Bartley, EAR-8817076 and EAR-8917291 to Glazner, and EAR-8816628 and EAR-8916802 to Walker.

REFERENCES CITED

Aleinikoff, J. N., Nielson, D. L., Hedge, C. E., and Evans, S. H., 1987, Geochronology of Precambrian and Oligocene rocks in the Mineral Mountains, south-central Utah: United States Geological Survey Bulletin, v. p. 1-12.

Bartley, J. M., and Glazner, A. F., 1985, Hydrothermal systems and Tertiary low-angle normal faulting in the southwestern United States: Geology, v. 13, p. 562-564.

Bartley, J. M., and Glazner, A. F., 1991, En echelon Miocene rifting in the southwestern United States and model for vertical-axis rotation in continental extension: Geology, v. 19, p. 1165-1168.

Brooks, W. E., 1986, Distribution of anomalously high K_2O volcanic rocks in Arizona: Metasomatism at the Picacho Peak detachment fault: Geology, v. 14, p. 339-342.

Chapin, C. E., and Glazner, A. F., 1983, Widespread K_2O metasomatism of Cenozoic volcanic and sedimentary rocks in the southwestern United States: Geological Society of America Abstracts with Programs, v. 15, p. 282.

Chapin, C. E., and Lindley, J. I., 1986, Potassium metasomatism of igneous and sedimentary rocks in detachment terranes and other sedimentary basins: economic implications: Arizona Geological Society Digest, v. 16, p. 118-126.

Coleman, D. S., and Walker, J. D., 1992, Evidence for the generation of juvenile granitic crust during continental extension, Mineral Mountains batholith, Utah: v. 97, p. 11,011-11,024.

Coleman, D.S., and Walker, J.D., 1994, Modes of tilting during extensional core complex development: Science, vol. 263, p. 215-218.

Fillmore, R.P., 1994, Sedimentary and tectonic evolution of Miocene extensional basins, central Mojave Desert, California: Ph.D. dissertation, University of Kansas, Lawrence, 181 pp.

Fillmore, R.P., and Walker, J.D., 1994, Evolution of a supradetachment extensional basin: The Early Miocene Pickhandle Basin, central Mojave Desert, California: Geological Society of America Special Paper, in press.

Glazner, A. F., 1988, Stratigraphy, structure, and potassic alteration of Miocene volcanic rocks in the Sleeping Beauty area, central Mojave Desert, California: Geological Society of America Bulletin, v. 100, p. 424-435.

Glazner, A. F., and Bartley, J. M., 1991, Volume loss, fluid flow and state of strain in extensional mylonites from the central Mojave Desert, California: Journal of Structural Geology, v. 13, p. 587-594.

Glazner, A. F., Bartley, J. M., and Walker, J. D., 1989, Magnitude and significance of Miocene crustal extension in the central Mojave Desert, California: Geology, v. 17, p. 50-53.

Glazner, A.F., Walker, J.D., Bartley, J.M., Fletcher, J.M., Martin, M.W., Schermer, E.R., Boettcher, S.S., Miller, J.S., Fillmore, R.P., and Linn, J.K., 1994, Reconstruction of the Mojave Block, in McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America Cordilleran Section Guidebook, Redlands, California, San Bernardino County Museum Association, p. 3-30.

Hutton, D. H. W., and Reavy, R. J., 1992, Strike-Slip tectonics and granite petrogenesis: Tectonics, v. 11, p. 960-967.

Martin, M. W., Glazner, A. F., Walker, J. D., and Schermer, E. R., 1993, Evidence for right-lateral transfer faulting accommodating en echelon Miocene extension, Mojave Desert, California: Geology, v. 21, p.

Miller, J. S., Fletcher, J. M., Boettcher, S. S., Martin, M. W., and Glazner, A. F., 1992, Late Cretaceous deformation, plutonism, and cooling around Fremont Peak, central Mojave Desert, California: EOS, v. 73, p. 574.

Nielson, D. L., Evans, S. H., and Sibbett, B. S., 1986, Magmatic, structural, and hydrothermal evolution of the Mineral Mountains intrusive complex, Utah: Geol. Soc. Am. Bull., v. 97, p. 765-777.

Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S., M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah: Salt Lake City, Earth Science Laboratory, University of Utah Research Institute, p. 120.

O'Hara, K., 1988, Fluid flow and volume loss during mylonitization: An origin for phyllonite in an overthrust setting, North Carolina, U.S.A.: Tectonophysics, v. 156, p. 21-36.

Roddy, M. S., Reynolds, S. J., Smith, B. M., and Ruiz, J., 1988, K-metasomatism and detachment-related mineralization, Harcuvar Mountains, Arizona: Geological Society of America Bulletin, v. 100, p. 1627-1639.