Using Geodesy to Explore Correlations between Crustal Deformation Characteristics and Geothermal Resources

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ABSTRACT

The Great Basin is characterized by non-magmatic geothermal fields, which we hypothesize are created, sustained, and controlled by active tectonics. We present geodetic velocities from the MAGNET (Mobile Array of GPS for NEvada Transtension) network that we use to infer relationships between the spatial variation in the style of geodetically inferred crustal deformation and the locations of existing geothermal systems. The velocity results from the MAGNET network are consistent and close to expectations based on analysis of prior networks, although MAGNET time-series at present are relatively short (0.8–2.2 yr), and any interpretation should be considered preliminary. We use the new velocities, supplemented with those from the BARGEN and USGS networks, to model the deformation field with two complementary approaches. In the first we determine the strain rate tensor field everywhere in our study area, and in the second we solve for rotations of pre-defined crustal blocks and the slip on the blocks' fault boundaries. We conclude from the preliminary results that there is a positive correlation between existing geothermal systems and areas that are either under transtension or that are in areas of transition between different deformation styles, such as in the Carson Sink area. The only exception to these inferred correlations is the geothermal activity in Dixie Valley. This discrepancy may be attributable to imperfections in the postseismic relaxation model that is used to correct the observed velocities for upper mantle viscoelastic relaxation following large historic earthquakes, which are themselves based on preliminary data. Our results suggest high favorability in some yet unexplored regions such as the Carson City Valley and the northeastern Carson Sink.

Introduction

We present preliminary results of a geodetic network in the Great Basin, which has been developed to target potential geothermal resources. Blewitt, *et al.* [2002] originally noted that, on a regional scale, the locations of existing economic and sub-economic geothermal fields together with the spatial pattern of geothermal well temperatures are strongly correlated with GPS-measured rates of tectonic strain. Blewitt, *et al.* [2005a] proposed a conceptual model in which non-magmatic geothermal systems are controlled by transtensional strain, where shear (strike-slip faulting) and extension (normal faulting) both play key roles. Such a model of combined shear and dilatation is consistent with the notion that geothermal plumbing systems might in some regions be controlled by fault systems acting as conduits that are continuously being stressed and fractured by tectonic activity [Blewitt, *et al.*, 2003]. With the creation of the MAGNET (Mobile Array for Nevada Transtension) geodetic network in 2004, our objective has been to further seek and explore relationships between geologic structures and GPS-geodetic observations of regional tectonic strain. Here we present initial results from the MAGNET network and discuss preliminary model results aimed at quantifying and understanding the relationship between geodetic deformation and geothermal potential.

MAGNET: Mobile Array of GPS for Nevada Transtension

In 2004 we began installing a new GPS network "MAGNET" with the objective to map crustal strain rates with basin-scale (~20 km) spatial resolution, and 1 mm/yr precision. To date (May 2006), 60 stations have been installed and are measured using 34 GPS receivers that we move from site to site around the network. This network roughly spans a rectangular area across the northern Walker Lane and Central Nevada Seismic Belt from the Sierra Nevada in the west, out to Battle Mountain and Austin, NV in the east (Figure 1a).

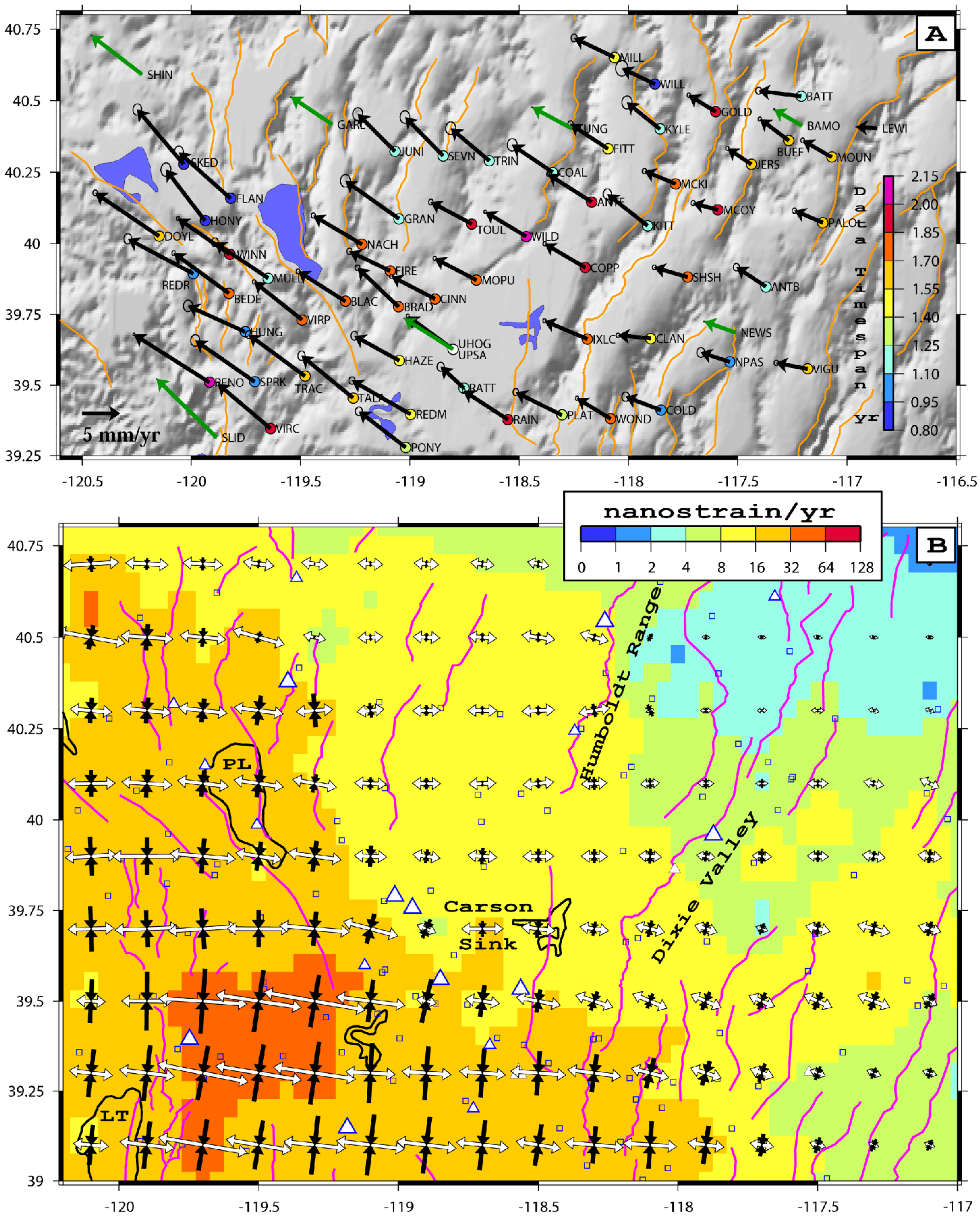

Figure 1. A) Geodetic velocities in a North American reference frame estimated for BARGEN and MAGNET sites (green and black vectors, respectively). Colored dots for MAGNET sites relate to the data time span, as indicated by bar on the right. Orange lines are major Quaternary faults. B) Contour plot of second invariant of the model strain rate field superimposed with the principal axes of the average strain tensor for each 0.2° by 0.2° grid cell (white and black vectors represent principal extension and contraction, respectively). Large triangles are locations of geothermal power plants (existing and under construction). Small triangles are all other geothermal systems (≥150°C).

The network spans a broad region that has relatively high geothermal well temperatures, and is well poised to investigate crustal strain rates around the economic geothermal fields at Brady's/Desert Peak, and Dixie Valley. The network also covers the tectonically important transition from extension dominated Basin-and-Range-style deformation in the east to shear and transtension dominated deformation in the Walker Lane belt to the west.

The strategy used to obtain position employed precise point positioning [Zumberge, *et al*., 1997] using dual frequency carrier phase and pseudorange data and precise orbit, clock, and reference frame transformation products publicly available from the Jet Propulsion Laboratory (JPL). The analysis includes automatic data editing for cycle slips and outliers [Blewitt, 1990] and carrier phase ambiguity resolution [Blewitt, 1989]. See Blewitt, *et al*. [2006] for more details. From the determined time-series a velocity estimate was derived. A preliminary MAGNET GPS velocity field is presented here relative to the Stable North American Reference Frame (SNARF [Blewitt, *et al.*, 2005b]) (Figure 1a). Shown are velocities for all stations with over 0.8 yr of data coverage. The longest running sites have over 2 years of data acquisition. A comparison with velocities from the continuously operated BARGEN geodetic network indicates that MAGNET velocities are nearly everywhere close in amplitude and direction. A direct comparison can be made between BARGEN site UPSA and MAGNET site UHOG, which are collocated (within ~20 m): the velocities differ by 0.3 mm/yr and 0.4 mm/yr in east and north component, respectively. This is an encouraging agreement considering the difference in time span of observation for MAGNET (maximum 2 yrs) and BARGEN (maximum 6 years).

In the remainder of this paper we discuss how the GPS velocities constrain tectonic deformation rates and how these may relate to geothermal potential. Because results are preliminary we supplement the MAGNET and BARGEN velocities in our study area with USGS campaign-style velocities that have originally been reported by Hammond and Thatcher [2004; 2005; 2006] and Svarc, *et al.* [2002]. In order to infer the secular tectonic deformation rates (which we presume to be related to geothermal activity), any effect on the geodetic velocities of transient deformation needs to be removed. One such transient is the postseismic relaxation that is caused by a series of large earthquakes along the Central Nevada Seismic Belt (CNSB) in the 20th century. Hammond, *et al.* [2006] and Hammond [2005] presented the effects of this relaxation on the present-day surface velocities by estimating visco-elastic parameters for the mantle and lower crust from GPS velocities, Interferometric Synthetic Aperture Radar data, and seismic and geologic measurements of the earthquakes. The postseismic model suggests that a large portion (up to 1.5 mm yr^{-1}) of the geodetically-inferred extension across the CNSB can be accounted for by relaxation effects. In the remainder of this paper we use the GPS velocities after correction for postseismic relaxation according to the model of Hammond, *et al.* [2006]. This correction has a significant impact on the distribution of secular strain in the western Great Basin.

For the purposes of strain modeling, we multiply the formal uncertainties in the MAGNET and BARGEN velocities by a factor of 11.8. This factor is chosen such that the reduced χ^2 is similar for the campaign, semi-continuous and continuous site velocities.

From Velocities to Deformation Rates

In order to relate the geodetic velocities to crustal deformation rates we adopt two different approaches. In the first approach we model the crustal horizontal strain rate field under the assumption that the crust deforms as a continuum. In the second approach we divide the region in fault-bounded blocks and solve for the rotation of the blocks and the magnitude and style of slip on the bounding faults. One advantage of the continuum strain rate modeling approach is that no knowledge of the location and geometries of blocks and faults is needed, and a smooth estimate of the deformation field is provided. The drawback of the continuum approach is that many processes, including earthquakes and geothermal activity, may be constrained to faults. In a block modeling approach all deformation is attributed to slip on block-bounding faults. Unlike the strain rate modeling approach, the estimate of slip is insensitive to an anomalous velocity of any particular station. In order for the block modeling approach to be useful in understanding the relationship between tectonic and geothermal activity most existing economic and sub-economic geothermal fields need to be located along or near potential block boundaries.

Strain Rate Modeling

Here, we characterize the regional deformation field on the assumption that most of the crust in the Great Basin deforms in a spatially continuous fashion. To derive a continuous velocity gradient tensor field we apply a spline interpolation technique [e.g., Haines and Holt, 1993; Holt, *et al.*, 2000]. In this method model velocities are fitted to the observed geodetic velocities in a least-squares sense, using the full data covariance matrix. Model velocities are then interpolated using bi-cubic Bessel spline functions to derive a continuous velocity gradient tensor field, which provides estimates of strain rate, interpolated velocity, and vertical axis rotation for any point in our model grid. We use grid cells of 0.2° by 0.2° in dimension, which allow us to take advantage of our spatially dense velocity data to quantify the velocity gradients in higher detail than previously possible. We excluded site LEWI which may show mining related motion [Gourmelen and Amelung, 2005], as well as sites BAMO, BATT and BUFF which we suspect to be affected by anthropogenic activity as well.

Figure 1b shows the strain rate model expressed as contours of the second invariant of strain rate and as principal axes of the average strain rate tensor for each 0.2° by 0.2° grid cell. The strain rate field has several broad characteristics. Strain rates are largest along the Walker Lane belt and diminish in a direction roughly perpendicular to the strike of that belt to reach near plate-like rigidity in the Battle Mountain area. The style of strain indicates a combination of shear and transtension along the Walker Lane belt and roughly east-west oriented uni-axial extension in the Basin and Range east of Pyramid Lake and the Carson Sink. According to our model result, the known geothermal systems (≥150°C), including all existing power plants and those under construction [Coolbaugh, *et al.* 2005], are located within areas that exhibit various tectonic styles of deformation. From an analysis of earlier data Blewitt, *et al.* [2005a] had inferred a positive correlation between the locations of geothermal systems and areas that showed a significant transtensional strain rate. To test this hypothesis against the model using our new data we plot the estimate of transtension, as defined by Blewitt, *et al.* [2005a] (Figure 2a). Scaled by strain rate, the largest transtension can be found in the northern Walker Lane. However, the model also predicts two significant areas of transpression (i.e., a combination of shortening and shear): one located north of Lake Tahoe, and another one in the Carson Sink region. Many geothermal systems, including several plants seem to be situated at the transition from transtension to transpression. The same transition seems to also take place, albeit locally, for the Empire plant near Gerlach (northeast of Pyramid Lake) and the Rye Patch system along the Humboldt Range.

To further test that geothermal activity is enhanced at places where there is a rapid lateral change in style of strain, we quantitatively define the style of the average strain rate tensor for each grid area and then calculate the spatial derivative. We define the style to vary between 0.0 (for bi-axial uniform extension) to 1.0 (for uni-axial extension), 2.0 (for shear), 3.0 (for uni-axial compression), and 4.0 (for bi-axial uniform compression). Figure 2b shows the spatial derivatives of those values (with spatial distance between two grid cells set to 1). We find elevated values for rapid change in style in the Reno – Tahoe region, in the Carson sink area continuing to the area northeast of Pyramid Lake, and in the Humboldt Range region. Most power plants and other geothermal systems are located where there is a spatially rapid change in deformation style. Exceptions are the systems along Pyramid Lake, where there is spatially uniform transtension, and those in Dixie Valley, where strain rates are very small and slightly transtensional.

Block Modeling

The association of geodetically inferred transtension with the presence of hydrothermal systems suggests that geodetic strain is related to slip on active transtensional fault systems

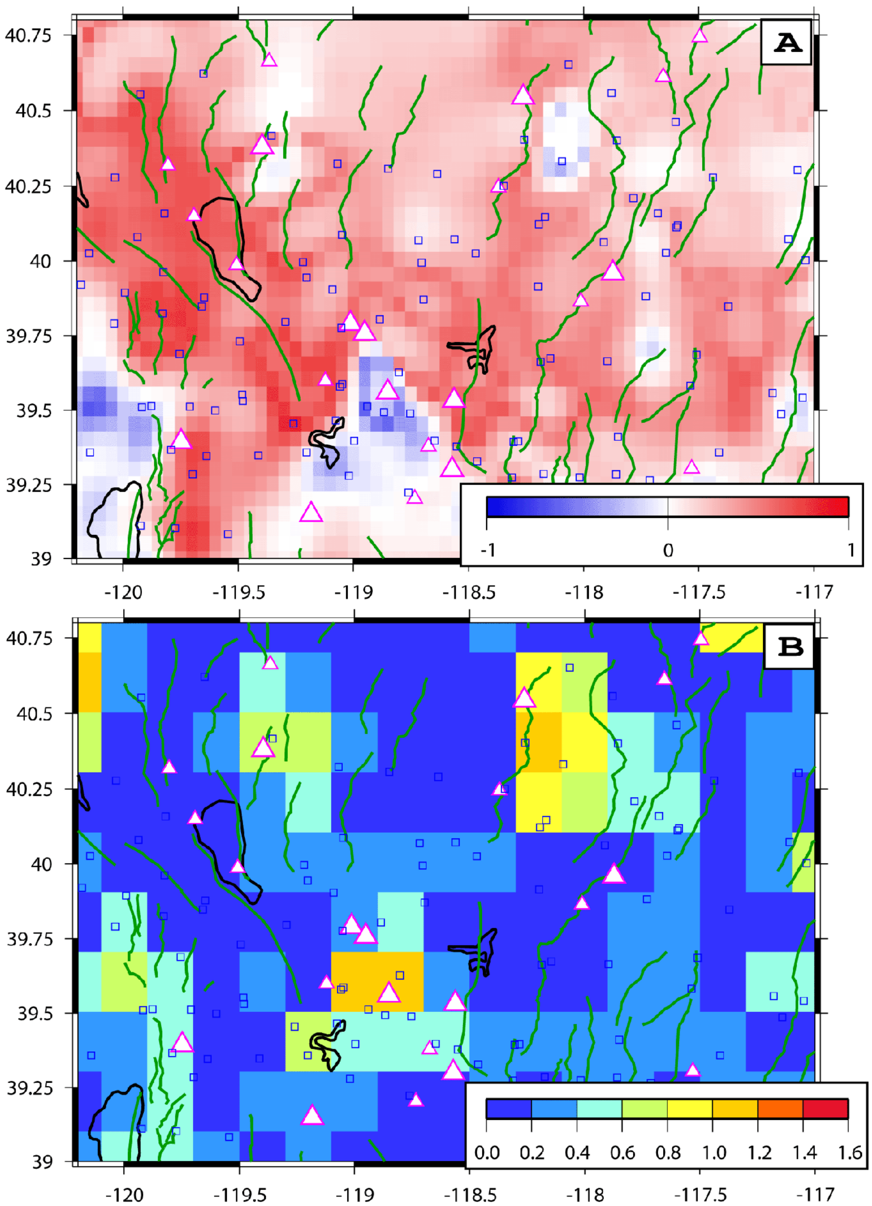

Figure 2. Large triangles are locations of geothermal power plants (existing and under construction). Small triangles are all other geothermal systems (≥150°C). Green lines are major Quaternary faults. A) Contour plot of the transtensional quality of the model strain rate field, weighted by relative regional strain rate values. Positive values (red) indicate transtension, where as negative values (blue) indicate transpression. B) Color coded gradient of strain rate style for each 0.2° by 0.2° area overlapping the grid cells for which the tensor style is defined (see text on the definition). Blue colors reflect that the style of the model strain rate tensor is constant regionally. Green to orange colors indicate rapid spatial change in style of strain.

that can focus fluid flow. Most permanent tectonic deformation is expressed in crustal faulting, and thus long-term deformation will be focused at the boundary of non-deforming crustal blocks that are bounded by faults. To focus on what geodesy can say about slip on faults, we use a block modeling analytical framework. Block modeling assumes that GPS stations record motions of crustal blocks that are bounded by faults that are locked at the surface and experience infrequent earthquakes, but slip continuously at depth during the interseismic time period [e.g., McCaffrey 2005; Meade and Hagar, 2005]. The details of our representation are discussed in Hammond and Thatcher [2006].

We have constructed a block model (Figure 3a) that uses geologically recent (Quaternary, Holocene and Historic) surface ruptures and geologic estimates of slip rates as a guide for drawing connected boundaries (mostly from the USGS Quaternary Fault and Fold database, Haller, *et al.* [2002]). The great number of active faults in the Basin and Range Province can make this a challenging exercise, since not all faults contribute equally to the accommodation of long-term strain. In addition, recently active faults do not always connect end-to-end to form the contiguous boundaries of closely adjoining blocks. Our model, nonetheless, represents the essential elements of fault patterns in the western Basin and Range.

The results of this modeling (Figure 3a) provide estimates of the motion of each block and hence estimates of the strike slip and dip-slip rate on each faults segment in the model. Here we are concerned primarily with the presence of oblique normal slip, related to transtension. We define a transtension value in similar fashion as defined by Blewitt, et al. [2005a] but based on slip rates rather than principal strain rate axes.

Figure 3b shows that transtension is insignificant on the northwest trending faults in the westernmost part of our study area, in northeast California, despite the rapid rate at which these faults slip, since they are predominantly dextral slip. In Nevada, most of the normal faults exhibit some transtensional character. Notable exceptions are the northeast trending faults near the northern and western edge of the Carson Sink (e.g., near the Brady's geothermal field). Although this local transpressional deformation is also seen in the continuum model approach (Figure 2b), it should be noted that these particular block boundaries surrounding the Carson Sink are tentatively assigned, as no clear through-going faults exists there, and other alternatives to the presented block geometries need to be further investigated. As a whole, however, it appears there is a qualitative correlation between transtension and the distribution of geothermal systems, consistent with the strain rate modeling.

Discussion

At present our results should be interpreted with caution. Currently all MAGNET velocities have been determined from data spanning less than 2.2 years. Ideally, all velocities should be derived from at least 2.5 yr of data in order for seasonal signals to not significantly affect the estimate of a constant velocity [Blewitt and Lavallée, 2002]. In other words, many or all of the MAGNET velocities estimates may deviate from a

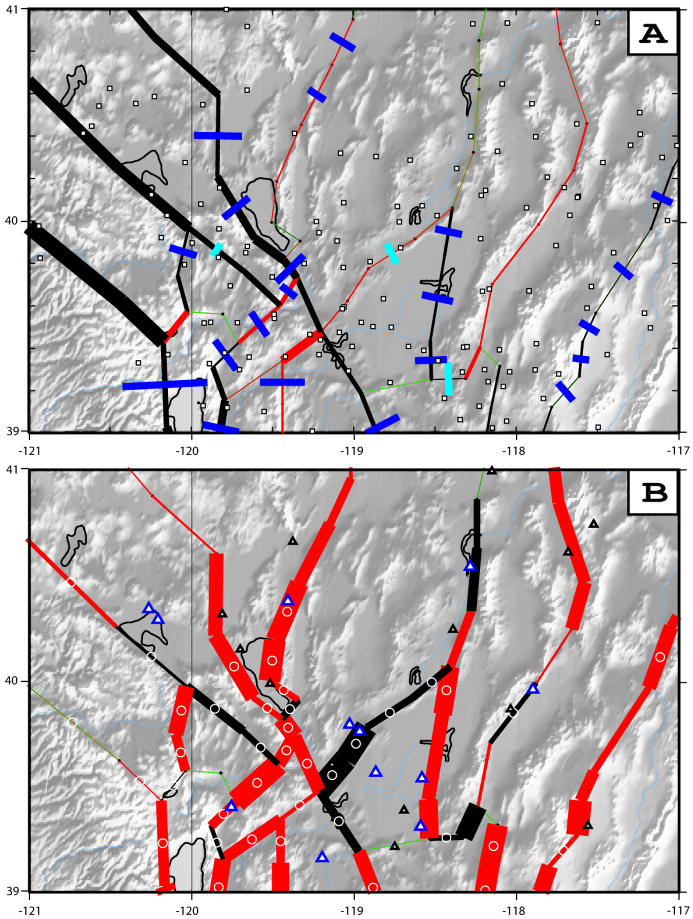

Figure 3. A) Model block boundaries and slip rate estimates in our study area. The block boundaries extend beyond the limits of the figure. Thickness of the block bounding line segment indicates the dextral (black), or sinistral (red) slip rate. Fault bisecting bars indicate the rate of normal (blue) or reverse (cyan) slip. Green lines indicate boundaries where no fault slip rate was inferred. Squares are the GPS station locations. B) Transtension value is indicated by thickness of line segment, red for transtension, black for transpression. Large blue-lined triangles are locations of geothermal power plants (existing and under construction). Small black-lined triangles are all other geothermal systems (≥150°C).

"true" constant velocity because of seasonal effects. Another point of concern is the proper assessment of uncertainties in the velocities, which control uncertainty in the strain and transtension estimates. Because we combine continuous BARGEN data with semi-continuous MAGNET data and campaign-style USGS data, it is crucial that the velocity uncertainties are properly scaled and correctly reflect the time-span, number of data, and type of acquisition used to obtain each velocity. For example, our strain rate model suggests rapid spatial variation in strain style northeast of Pyramid Lake and along the Humboldt Range. This is the location of two BARGEN sites (GARL and TUNG), whose very accurate velocities put strong constraints on the local strain rate field. If the assigned uncertainties are not scaled similarly as the uncertainties of nearby MAGNET or USGS sites, then we may predict spurious strain rates near the BARGEN sites. The results of the block modeling are less sensitive to velocity uncertainties than the continuous model. Uncertainty in the block modeling is introduced from uncertainty in block geometries, and assumed fault parameters.

At face value our strain rate and block modeling results suggest that transtension is an important aspect of the strain rate field against which to relate geothermal potential. However, we show here that perhaps even more important is the apparent correlation between geothermal systems and the rapid spatial change in style of strain, such as in the Carson Sink region. A combined evaluation of the strain rate and block modeling results suggest that most geothermal systems, including all plants (except Dixie Valley) are either in a region of significant transtension or of spatial strain style change. Dixie Valley may not fit this correlation because of uncertainty in our postseismic relaxation predictions, which were themselves based on an earlier version of the velocity field. This uncertainty particularly affects our ability to constrain the long-term deformation near Dixie Valley, where the postseismic signal is expected to be largest. We plan to revisit the study done by Hammond, *et al.* [2006] by including the MAGNET velocities in constraining the postseismic model, which we anticipate will improve the correction. Another explanation for the anomalous result for Dixie Valley relates to the general limitations of this study: i.e., there is a non-uniqueness in using our modeling results to make predictions on the actual style of slip on faults when fault orientations and dips vary rapidly over short length scales. Faulds, *et al.* [2004] suggested, for example, that fluid and heat flow would be enhanced where fracturing is complex, such as in a pull-apart structure, or a kink in fault-strike. This complexity is probably related to the fact that there is local partitioning of a regional constant state of strain, which appears to be transtensional in most of our study area. In essence our conclusion that favorability is increased in areas with rapid spatial variation in style of change can be interpreted as a large scale analogy to the small-scale examples reported by Faulds, *et al.* [2004].

Given our preliminary results on the style of strain and its spatial variation we can start to identify regions with predicted but yet unexplored high geothermal favorability, such as the Carson City Valley, and northeastern Carson Sink.

Conclusions

We present geodetic velocities from the MAGNET network that we use to infer relationships between the spatial variation in the style of geodetically inferred crustal deformation and the locations of existing geothermal systems. Although MAGNET time-series are at present relatively short, and any interpretation thereof should be performed with caution, the velocity results are consistent and close to expectations. We use the velocities, supplemented with those from the BARGEN and USGS networks, to model the deformation field with two different, but supplemental approaches. One in which we determine the strain rate tensor field everywhere in our study area, and another where we solve for rotations of defined crustal blocks and the slip on the blocks' fault boundaries. We conclude from the preliminary results that there is a positive correlation between existing geothermal systems and areas that are either under transtension or that are at the transition of areas with different deformation styles, such as in the Carson Sink area. The only exception to these inferred correlations is the geothermal activity in Dixie Valley. We speculate that this discrepancy may be because our model results are locally incorrect due to the imperfect postseismic relaxation model that is used to correct the observed velocities with. Our preliminary results suggest high favorability in some yet unexplored regions such as the Carson City Valley and the northeastern Carson Sink. A detailed quantitative correlation between the characteristics of the geodetic deformation field and the proximity to hydrothermal systems will be the continuing study of future work when our GPS velocities are more precise near the conclusion of this project. Such studies should use a formal spatial analysis approach to document and quantify the kind of correlations that now start to emerge visually.

Acknowledgments

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References

Blewitt, G., 1989, Carrier phase ambiguity resolution for the Global Positioning System applied to geodetic baselines up to 2000 km, Journal of Geophysical Research, v. 94, p. 10,187-10,283.

Blewitt, G., 1990, An automatic editing algorithm for GPS data, Geophysical Research Letters, v. 17, p. 199-202.

Blewitt, G., and D. Lavallée, 2002. Effects of annual signals on geodetic velocity: Journal of Geophysical Research, v. 107, 10.1029/2001JB000570.

Blewitt, G., M. Coolbaugh, W.E. Holt, C. Kreemer, J.L. Davis, and R.A. Bennett, 2002. Targeting of potential geothermal resources in the Great Basin from regional relationships between geodetic strain and geological structures, Geothermal Resources Council Transactions, v. 26, p. 523-526.

Blewitt, G., M. Coolbaugh, W. Holt, J. Davis, and R. Bennett, 2003. Targeting of potential geothermal resources in the Great Basin from regional- to basin-scale relationships between geodetic strain and geological structures, Geothermal Resources Council Transactions, v. 27, p. 3-7.

Blewitt, G., W.C. Hammond, and C. Kreemer, 2005a. Relating geothermal resources to Great Basin tectonics using GPS: Geothermal Resource Council Transactions, v. 29, p. 331–336.

Blewitt, G., D. Argus, R. Bennett, Y. Bock, E. Calais, M. Craymer, J. Davis, T. Dixon, J. Freymueller, T. Herring, D. Johnson, K. Larson, M. Miller, G. Sella, R. Snay, and M. Tamisiea, 2005b. A stable North America reference frame (SNARF): First release, UNAVCO-IRIS Joint Workshop: Stevenson, Washington.

Blewitt, G., W.C. Hammond, and C. Kreemer, 2006. Geodetic constraint on contemporary deformation in the northern Walker Lane: 1. Semi-permanent GPS strategy , in J.S. Oldow, and P.H. Cashman, eds. , Late Cenozoic Structure and Evolution of the Great Basin Sierra Nevada Transition, Geological Society of America Special Volume, submitted.

Coolbaugh, M., R. Zehner, C. Kreemer, D. Blackwell, G. Oppliger, D. Sawatzky, G. Blewitt, A. Pancha, M. Richards, C. Helm-Clark, L. Shevenell, G. Raines, G. Johnson, T Minor, and T. Boyd, 2005. Geothermal potential map of the Great Basin, western United States: Nevada Bureau of Mines and Geology Map, v. 151.

Faulds, J.E., M. Coolbaugh, G. Blewitt, and C.D. Henry, 2004. Why is Nevada in hot water? Structural controls and tectonic model of geothermal systems in the northwestern Great Basin: Geothermal Resources Council Transactions, v. 28, p. 649-654.

Gourmelen, N., and F. Amelung, 2005. Towards a continental scale deformation map of the western Basin and Range from InSAR, *Eos Transactions AGU, v. 86,* Fall Meeting Supplement, Abstract G51C-0845.

Haines, A.J., and W.E. Holt, 1993. A procedure for obtaining the complete horizontal motions within zones of distributed deformation from the inversion of strain rate data: Journal of Geophysical Research, v. 98, p. 12,057-12,082.

Haller, K.M., R.L. Wheeler, and K.S. Rukstales, 2002. Document of changes in fault parameters for the 2002 National Seismic Hazard Maps - Conterminous United States except California, USGS open file report 02-467.

Hammond, W.C. and W. Thatcher, 2004. Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the Global Positioning System, Journal of Geophysical Research, v. 109, 8403, doi:10.1029/2003JB002746.

Hammond, W.C., 2005. The ghost of an earthquake, Science v. 310, p. 1440-1442.

Hammond, W.C. and W. Thatcher, 2005. Northwest Basin and Range tectonic deformation observed with the Global Positioning System, 1999-2003, Journal of Geophysical Research, v. 110, B10405, doi:10.1029, 2005JB003678.

Hammond, W.C. and W. Thatcher, 2006. Crustal deformation across the Sierra Nevada, Northern Walker Lane, Basin and Range transition, Western United States, measured with GPS, 2000-2004, Journal of Geophysical Research, in prep.

Hammond, W.C., C. Kreemer, and G. Blewitt, 2006. Geodetic constraint on contemporary deformation in the northern Walker Lane: 3. Central Nevada seismic belt postseismic relaxation, in J.S. Oldow, and P.H. Cashman, eds., Late Cenozoic Structure and Evolution of the Great Basin Sierra Nevada Transition, Geological Society of America Special Volume, submitted.

Holt, W.E., B. Shen-Tu, J. Haines, and J. Jackson, 2000. On the determination of self-consistent strain rate fields within zones of distributed deformation, in M.A. Richards, R.G. Gordon, and R.D., van der Hilst eds., The History and Dynamics of Global Plate Motions, v. 121, Geophysical Monograph: Washington, D.C., AGU, p. 113-141.

McCaffrey, R., 2005. Block kinematics of the Pacific-North America plate boundary in the southwestern United States from inversion of GPS, seismological and geologic data, Journal Geophys. Res., v. 110, B07401, doi:10.1029/2004JB002207.

Meade, B.J., and B.H. Hagar, 2005. Spatial localization of moment deficit in southern California, Journal Geophysical Research, v. 100, B04402, doi:10.1029/2004JB003331.

Svarc, J.L., J.C. Savage, W.H. Prescott, and A.R. Ramelli, 2002. Strain accumulation and rotation in western Nevada, 1993-2000, Journal of Geophysical Research, v. 107, p. 2090, doi:10.1029/2001JB000579.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., Webb,,F.H. 1997, Precise point positioning for the efficient and robust analysis of GPS data from large networks, Journal of Geophysical Research, v. 102, p. 5005-5018.