

# Targeting of Potential Geothermal Resources in the Great Basin from Regional to Basin-Scale Relationships between Geodetic Strain and Geological Structures

**Short Title:** Geothermal Targeting from Strain and Structure

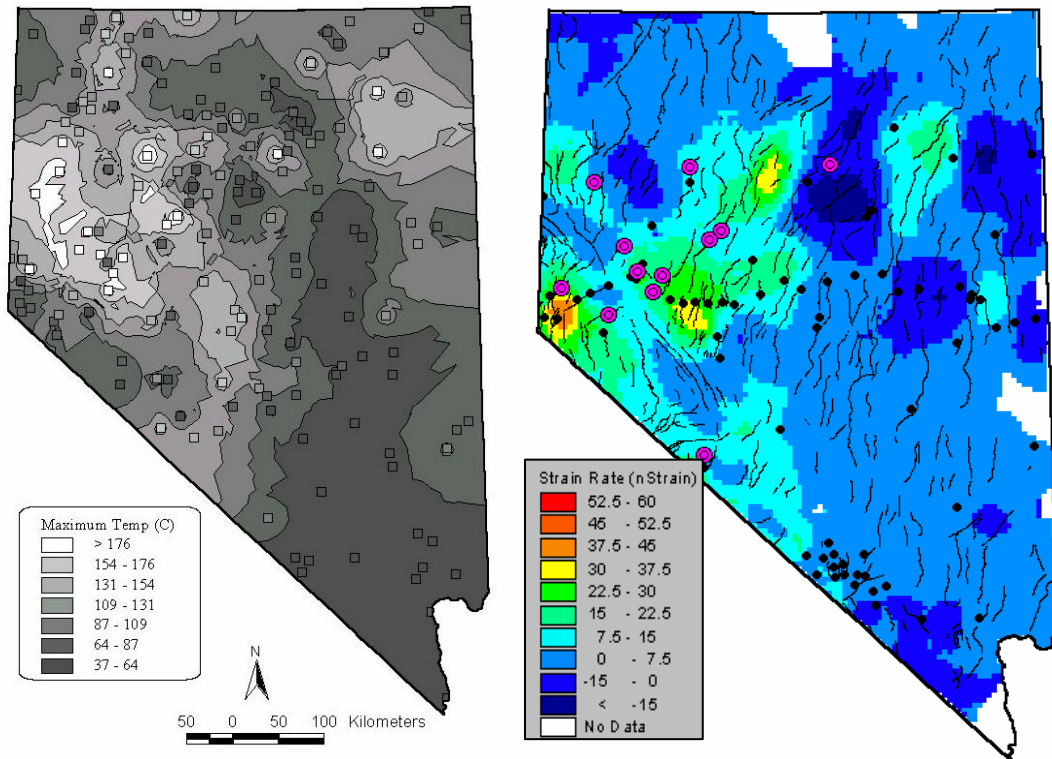
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Nevada Bureau of Mines and Geology, and Nevada Seismological Laboratory  
MS 178, University of Nevada, Reno

**Abstract.** This is a follow-on two-year proposal from a currently funded project of the same name, which has the goal of assessing a new method to target potential geothermal resources on the regional scale by seeking relationships between geologic structures and GPS-geodetic observations of regional tectonic strain. On a regional scale we have found that the locations of existing power-producing plants together with the spatial pattern of geothermal well temperatures is strongly correlated with GPS-measured rates of tectonic trans-tensional strain, indicating that geothermal plumbing systems might in some regions be controlled by fault planes acting as conduits that are continuously being stressed apart by tectonic activity. Following from this discovery in 2003-2004, we installed a GPS network (“MAGNET”) with the objective to map crustal strain rates with basin-scale (~15 km) spatial resolution, and 1 mm/yr accuracy. To date, 56 stations have been installed and measured using 34 GPS receivers that we move from site to site around the network. MAGNET 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 in the east. MAGNET covers a broad region that has relatively high geothermal well temperatures, and is well posed to investigate crustal strain-rates around the economic geothermal fields at Brady’s/Desert Peak, and Dixie Valley. These GPS data will enable testing of the hypothesis that the controlling tectonic features that are favorable for geothermal targeting are abrupt changes in the strike of faults within the regional strain field. As originally proposed, the results from these GPS data will take 3–4 years before precise strain rate maps can be resolved with a precision of <1 mm/yr. The initial results now from ~1 year of data acquisition indicate that the quality of the data is on target to meet this specification. Therefore this proposal is to continue to measure the installed network so that we can achieve our originally stated goal. By the end of this 2-year follow-on project, strain rates of sufficient accuracy and spatial resolution are predicted to be at the level required to discriminate hypotheses from each test area regarding which structures are tectonically active, and to invert for tectonic parameters that are relevant to geothermal models. Two internationally recognized co-PIs are brought into this project at this stage: Corné Kreemer who is an expert on strain modeling, and William Hammond who is an expert on visco-elastic modeling. Kreemer will develop more refined strain modeling techniques and explore the relationship between strain and geological structures. Hammond will model post-seismic visco-elastic relaxation from large 19<sup>th</sup> century earthquakes in the region, which we predict will dominate the strain rate field in specific areas, including Dixie Valley. The outcome of this project will be identification at the basin-scale of specific structures which might be targeted for geothermal exploitation.

# Description of Project

## Goal and Objectives

This is a follow-on proposal from a currently funded project of the same name, which has the goal of assessing a new geodetic method to target potential geothermal resources in the Great Basin. As such, it addresses “Identification and Characterization of New Potential Geothermal Resource Targets.” Our objective is to seek relationships between geologic structures and GPS-geodetic observations of regional tectonic strain. Our driving scientific question is: “How do we explain so much geothermal activity within the largely non-magmatic setting of the Great Basin?” From the first year of the current project in 2002 (Fig. 1) it was discovered that, on a regional scale, the locations of existing power-producing plants together with the spatial pattern of geothermal well temperatures is strongly correlated with GPS-measured rates of tectonic trans-tensional strain, indicating that geothermal plumbing systems might in some regions be controlled by fault planes acting as conduits that are continuously being stressed apart by tectonic activity [Blewitt *et al.*, 2003].



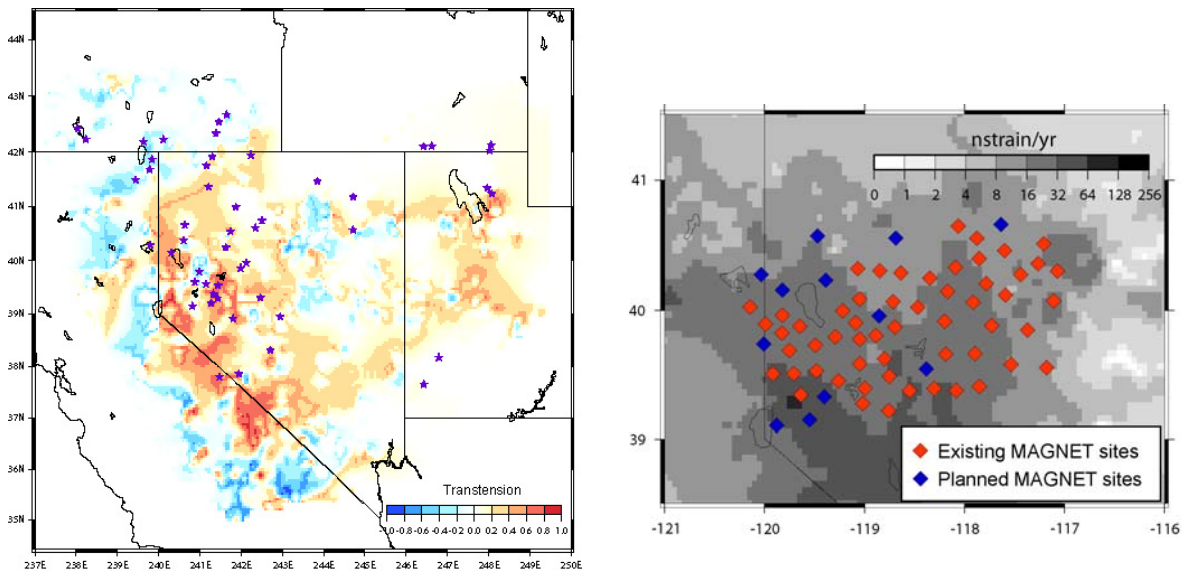
**Figure 1. (Left)** Trend surface of maximum geothermal temperatures. Locations of geothermal systems used for contouring are shown with squares [courtesy of *M. Coolbaugh*]. **(Right)** Rates of extensional strain normal to fault strikes derived using available GPS data (black dots), not yet including the data proposed to be acquired and analyzed here [Blewitt *et al.*, 2002, 2003]. Also plotted are economic and sub-economic geothermal fields that are believed to be non-magmatic.

## Working Conceptual Model

Based on our discovery of tectonic-temperature correlations, our working conceptual model to explain geothermal activity in non-magmatic settings is based on heat flow and fluid flow, and their interaction with tectonic activity. (1) GPS data show that the Basin and Range province is extending [Bennett *et al.*, 1999; Hammond and Thatcher, 2004], which would lead to crustal thinning. The shorter depth to Moho

implies a regional enhancement in the thermal gradient. From GPS and microseismicity we recently discovered current deep magmatic intrusion into the lower crust [Smith *et al.*, 2004] in the western Great Basin, which might also explain enhanced heat flow [Blewitt, 2004]. (2) From a fluid flow perspective [Barton, 1995; Hickman *et al.*, 1997], faults and fractures can act as conduits to transport heat efficiently to the surface. However, sustainable fluid flow (in long term equilibrium) requires active tectonics. From this type of model, we would predict that areas undergoing extensional tectonics would tend to pull-apart fractures that would enhance fluid and heat flow [Faulds *et al.*, 2004]. Moreover, we would predict that deeply dipping faults might be more efficient at transporting fluid and heat over larger vertical distances (thus strike-slip faulting may play an important role). We would also predict 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.

From these considerations, our objective is to use GPS to test aspects of this conceptual model, (1) by identifying locations that are more tectonically active; and (2) by identifying locations where the style of strain implies extension *and* complexity. One measure of complexity is “transtension”, which we define as the admixture of shear deformational strain and positive dilatational strain. In geologic terms, we would expect to find transtension in regions that have both normal faulting and strike-slip faulting. Conceptually these conditions satisfy our working model. Figure 2 shows an example of how such measures might be used to help target geothermal fields.



**Figure 2.** (left) Map of “transtension” which indicates complexity in the strain field, derived from available GPS data (not the data proposed here). The stars show locations of geothermal fields. Our conceptual model would predict that transtension should be a good indicator of geothermal potential. (right) Map of current GPS sites (red) in our network “MAGNET”, also showing proposed additional sites (blue). The greyscale contours indicate strain magnitude (not style). Note the two maps are of different scales. Without the GPS data from this project, such strain maps will be too inaccurate to be useful for geothermal exploration, and so the above maps should only be regarded as indicative of broader regional characteristics. By the end of 2006, maps with  $\sim 2$  nstrain/yr accuracy, with  $\sim 20$  km resolution, and including the style of strain will be available from this project.

### **MAGNET: Mobile Array of GPS for Nevada Transtension**

Since 2003, the project built on this initial discovery with an ambitious plan to install a GPS network “MAGNET” with the objective to map crustal strain rates with basin-scale ( $\sim 15$  km) spatial resolution, and 1 mm/yr accuracy. Network reconnaissance and siting, and GPS system design started September 2003, and data acquisition from the first few stations began in January 2004. To date (January 2005), 56

stations have been installed and 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 in the east. The network spans a broad region that has relatively high geothermal well temperatures, and is well posed to investigate crustal strain-rates around the economic geothermal fields at Brady's/Desert Peak, and Dixie Valley. These GPS data will enable testing of the hypothesis that the controlling tectonic features that are favorable for geothermal targeting are abrupt changes in the strike of faults within the regional strain field. Examples of this include step-over geometries in strike-slip faults which create pull-apart tectonics, or trans-tensional systems.

As originally proposed, the results from these GPS data will take 3–4 years before precise strain rate maps can be resolved with a precision of <1 mm/yr. The initial results now from ~1 year of data acquisition indicate that the quality of the data is on target to meet this specification. Therefore this proposal is to continue to measure the installed network so that we can achieve our originally stated goal. By the end of this 2-year follow-on project, strain rates of sufficient accuracy and spatial resolution are predicted to be at the level required to discriminate hypotheses from each test area regarding which structures are tectonically active, and to invert for tectonic parameters that are relevant to geothermal models (such as the depth of locking and 3-d slip-rate vectors on active fault planes, which theoretically can be used to model dilatation around fault zones which might be accommodated by fracturing).

Here we propose to expand the current 56-station network to double the number of (34) receivers, that is to 68 stations. The additional 12 stations will be installed in 2005. Note that the original proposal only promised 40 stations, however more stations were installed due to 15 additional GPS receivers being available from *non-geothermal* funding. However, these “non-geothermal” GPS receivers are planned to be used for seismic research purposes elsewhere in Nevada for about 50% of the time over the next 2 years due to obligations on other contracts. We therefore propose to purchase an additional 10 GPS receivers with funds from this project so that the network in Figure 2 can be maintained at the current level of support. Without these additional receivers we would have to scale back the above network close to the original proposed size of 40 stations (Fig. 2 minus 28 stations), which would significantly impact spatial resolution of strain. The additional receivers will also increase our likelihood of detecting possible strain transients associated with lower-crustal magmatic intrusion [Smith *et al.*, 2004; Blewitt, 2004].

## **Modeling**

Two internationally recognized experts are now proposed to be co-PI's on this project: (1) Corné Kreemer who is an expert on strain modeling [Kreemer *et al.*, 2000], and (2) William Hammond who is an expert on Basin and Range tectonics and visco-elastic modeling [Hammond and Thatcher, 2004]. Both have been actively involved in the project since they were hired as soft-funded researchers in the geodesy group at UNR in July 2004. Kreemer will develop more refined strain modeling techniques and explore the relationship between geodetic strain and geological structures. Hammond will model post-seismic visco-elastic relaxation from large 19<sup>th</sup> century earthquakes in the region, which we predict should dominate the strain rate field in specific areas, including Dixie Valley. Understanding this effect is important so that we can calculate how much strain is really transient, and how much is secular on the geological time scale. We could therefore test the hypothesis that strain on the longer time scale is more important for geothermal activity (as crustal-scale heat flow is a long-term process). Given the highly precise GPS data we are collecting and the strong capabilities of the team to model the data, we are confident that the final outcome of this project will be identification at the basin-scale of specific structures which might be targeted for geothermal exploitation.

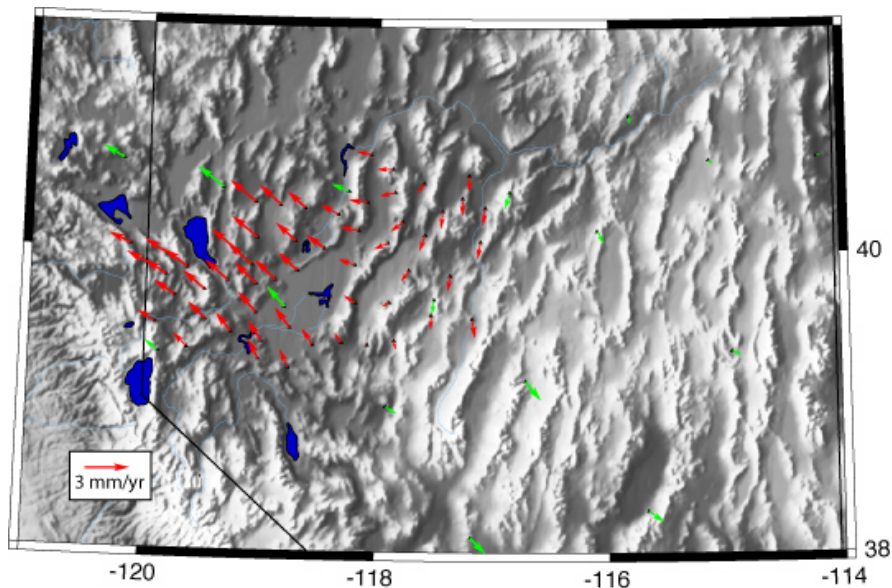
### *Incorporating geologic data into geodetic strain rate interpretation*

The strain rate tensor field inferred from GPS velocity measurements is non unique [Kreemer *et al.*, 2000]. However, fault parameters can place important constraints on how strain rate can and can not be

accommodated. Vice versa, the geodetic strain rate field can constrain what type of slip to expect on existing fault structures. Thus the fault parameters and geodetic strain rate field are mutually beneficiary to one another. Until recently most of the fault parameters were relatively unknown, but with the release of the USGS 2002 Fault and Fold database (Haller et al., 2002), a complete and consistent database exists for the slip rate, age, dip, and orientation of most important Quaternary faults in the Great Basin. The only important unknown is the slip direction on the fault plane and is largely dependent on the surrounding strain rate field. Besides evaluating the favorability of fault orientations given the geodetic strain rate field, we propose to evaluate several levels of geologic constraints in the inversion for the geodetic strain rate field. These constraints could consist of incorporating zones of weakness where faults are present, to including limits on the expected style of deformation. An actual simultaneous inversion of the geologic deformation rates and the GPS velocities will be explored as well. However, the latter should be performed with care because uncertainties in fault slip rates are often large. Moreover, it will be essential that the GPS velocities used have any significant postseismic relaxation signal removed from the observed velocity.

### *Central Great Basin Postseismic Relaxation and Estimating Geothermal Favorability*

In the 20<sup>th</sup> century, Central Nevada experienced a cluster of large ( $M_{6.5-7.5}$ ) earthquakes, near a region where geothermal favorability today is almost the highest in the state [Blewitt et al., 2002]. The largest of these were the Pleasant Valley 1915  $M_{7.7}$ , 1932 Cedar Mountain  $M_{7.2}$ , 1954 Fairview Peak  $M_{7.2}$ , and 1872 Owens Valley  $M_{7.7}$  events [Caskey et al., 2000]. Many studies have shown that following large earthquakes the stresses that are induced in the lower crust and upper mantle relax over periods of weeks to decades [e.g. Savage and Prescott, 1978; Pollitz, 1997; Pollitz et al., 2000, Pollitz, 2003; Deng et al., 1998]. The amount of postseismic response observed depends on the viscosity stratification of the lithosphere, and the amount of time that has passed since the event. Recent developments in space-based geodesy have been instrumental in identifying and measuring this important part of the earthquake cycle.



**Figure 3.** Modeled postseismic relaxation following the sequence of earthquakes at the Central Nevada Seismic Belt shown on Basin and Range topography. Expected geodetic velocity given a viscoelastic lower crust with viscosity of  $3 \times 10^{18}$  Pa s is shown for our existing MAGNET GPS sites (red) and other existing GPS sites (green). Fault segments from north to south are the 1915 Pleasant Valley ( $M_{7.7}$ ), 1954 Rainbow Mountain - Stillwater sequence ( $M_w$  7.0), 1954 Dixie Valley ( $M_s$  6.8), 1954 Gold King-West Gate sequence ( $M_w$  6.5), 1954 Fairview Peak ( $M_s$  7.2), 1932 Cedar Mountain ( $M_s$  7.2) events.

Some recent studies using campaign GPS results [Hetland and Hager, 2003] or campaign GPS and Interferometric Synthetic Aperture Radar (InSAR) [Gourmelen and Amelung, 2003] have modeled the modern geodetic velocity field based on the earthquakes of the Central Nevada Seismic Belt. Their results suggest that a significant fraction of the deformation seen today is attributable to postseismic relaxation (e.g. Figure 3). However, these studies used older, less precise GPS results and were not spatially focused near the earthquakes. The MAGNET network offers a significant advantage over previous campaign GPS based studies because of its tighter site density around the CNSB, its greater horizontal and vertical precision, and greater quantity of data collected. Earlier studies also did not take into account that part of the geodetic signal is attributable to time invariant secular loading, and assigned all deformation to transients. It is important to realize that transient postseismic processes do not represent elastic loading of the seismogenic crust in the traditional sense. In particular, over time the deformation field from relaxation becomes broader and less localized near the fault of origin. Thus modern deformation up to 100s of km from the past earthquake could be mistaken for seismogenic loading of faults far to the east or west of the earthquake, giving the false impression of fault activity and geothermal favorability. If, on the other hand, we have knowledge of the past earthquakes, we can adjust our estimation by taking into account this distribution of strain.

To better estimate the activity rates on faults that are an indication of geothermal favorability, we must take into account the effects of postseismic relaxation on the modern geodetic velocities. Since decades to a century have elapsed since the earthquakes, we need to develop a new modeling strategy that will allow us to recognize the spatial pattern of relaxation in the present-day deformation. We will achieve this by employing an integrated modeling approach that uses Kreemer's strain rate map, the U.S. Geological Survey Quaternary Fault and Fold database, and Hammond's geodynamic modeling of the earthquake process. Essentially we will subtract the estimated postseismic velocities from the observed geodetic velocities, and use the residual to improve the estimates of slip rates on faults. The approach is iterative, since the new slip rates may imply a different postseismic response. We will develop an efficient computational process for estimating slip rates and a viscosity structure that fit both the geodetic and paleoseismic data. We will begin with a rheological model determined from more recent earthquakes [Pollitz *et al.*, 2000; Pollitz, 2003] and post-glacial rebound [Bills *et al.*, 1994].

### **Summary of Proposed Workplan and Deliverables.**

The following presents a convenient summary of the proposed activities that have been detailed above:

- (1) Continue to acquire data from the existing 56-station MAGNET GPS network (technician + Co-Is).
- (2) Install 12 additional stations to the network = 68 stations (technician + Co-Is).
- (3) Purchase 10 additional GPS receivers to make up for the shortfall, in that 15 of our current 34-receiver pool are funded by other grants and will be used elsewhere for seismic research (Blewitt).
- (4) Produce GPS station position solutions with ~ 1 mm accuracy (Blewitt + Hammond).
- (5) Search for strain transients associated with lower-crustal magmatic intrusion (Blewitt).
- (6) Produce a station velocity solution with ~ 1 mm/yr accuracy (Blewitt).
- (7) Model the station velocities as a continuous strain field (Kreemer)
- (8) Investigate using geological constraints in strain modeling (Kreemer; with Rick Zehner, GBCGE).
- (9) Model relaxation from 19<sup>th</sup> century earthquakes, to calibrate the secular strain field (Hammond).
- (10) Investigate joint model inversion of secular and transient strain (Hammond and Kreemer).
- (11) Investigate strain indicators of geothermal potential, guided by our working conceptual model and produce final maps. (Co-Is; with Mark Coolbaugh, GBCGE).
- (12) Improve conceptual model with improved understanding that results from the analysis (Co-Is).
- (13) Present our findings at conferences, workshops, in quarterly reports, and in journals (Co-Is).

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## Milestones

<b>Task</b>	<b>Geothermal Targeting from Strain and Structure</b>	<b>Completion</b>
01	Acquire data from MAGNET GPS network.	Weekly
02	Install 12 additional stations	09/30/2005
03	Purchase and test 10 additional GPS receivers	10/31/2005
04	Produce GPS station position solutions	Quarterly
05	Produce GPS station velocity solutions	06/30/06+07
06	Strain transient analysis (temporal)	06/30/06+07
07	Strain modeling with geological constraints (spatial)	09/30/06+07
08	Visco-elastic relaxation correction of strain maps	09/30/2006+07
09	Produce maps of strain indicators	09/30/2006+07
10	Reports to DOE	Quarterly
11	Conference presentations	Regularly

## Budget Justification

The work will be conducted by the co-P.I.s Blewitt, Hammond, and Kreemer, together with a technician. The estimated dedicated time for Blewitt is approximately 2 months per year, most of which is cost shared. The estimated dedicated time for each of the Hammond and Kreemer on this project is 3 weeks per year. A technician is required at 50% FTE to conduct fieldwork, at 2 x 10 hour days per week. Estimated fieldwork mileage costs are based on current experience, at an average of 8 trips per month, 250 miles per trip @\$0.45 per mile = \$900 per month. Computing facilities already exist and come at no cost to this project. Estimated GPS equipment cost is \$6,000 per set for 10 sets = \$60,000. GPS equipment cost estimates are based on the assumption that we can receive significant discounts through the UNAVCO community bulk purchases <http://www.unavco.org> (UNR is a UNAVCO member). Maintenance of existing GPS sets is estimated to be \$300 per site per year for solar panel, cabling, and batteries (due to ageing, wind and rodent damage, and battery life times). For the 19 existing geothermal GPS sets, the total maintenance cost is therefore estimated to be \$5,700 per year.

## **Biographical Sketch: Geoffrey Blewitt**

### **EDUCATION**

B.Sc. (1st Class Hons) Physics, Queen Mary College, University of London, 1981  
Ph.D. Physics, California Institute of Technology, 1986

### **PROFESSIONAL WORK EXPERIENCE**

1999–present, Research Professor, jointly at Nevada Bureau of Mines and Geology and Nevada Seismological Laboratory, University of Nevada, Reno.  
1999–present, Visiting Professorship, University of Newcastle, UK.  
1994–1999, Professor, Department of Geomatics, University of Newcastle upon Tyne, England.  
1985–1994, Group Supervisor, Space Geodesy and Geodynamics Systems Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena.  
1981–1985 Graduate Research Assistant, Department of Physics, Caltech.

### **HONORS AND AWARDS**

American Geophysical Union Fellow, 2005  
The Space Foundation's Space Technology Hall of Fame, Certificate of Commendation, 2004  
E.B. Burwell Jr. Award, Geological Society of America, Engineering Geology Division, 2004  
Mackay Faculty Achievement Award, Mackay School of Earth Science and Engineering, 2004.  
UNAVCO Inc. Certificate of Recognition, 2004.  
**Geothermal Resources Council Best Paper Award, 2003.**  
American Geophysical Union Featured Lecture: December 2002.  
Association of Engineering Geologists Publication Award, 2002.  
Certificate of Appreciation for Outstanding Service from the International GPS Service, 2001.  
Co-Inventor on U.S. Patent Number 6,295,021, California Institute of Technology, Sept. 25, 2001.  
Co-Inventor on U.S. Patent Number 5,963,167, California Institute of Technology, Oct. 5, 1999.  
NASA Group Achievement Award "Earth-rotation measurement system based on GPS," 1999.  
Elected Fellow of the International Association of Geodesy, 1999.  
Shell Innovation Award, 1997.  
NASA Certificate of Recognition "GIPSY OASIS II," 1996.  
NASA Software of the Year Competition, Runner up, 1995.  
NASA Group Achievement Award for "Global reference frame accurate to 1 cm," 1994.  
NASA Certificate of Recognition "Precise determination of Earth's center of mass using GPS," 1993.  
NASA Certificate of Recognition "Daily estimates of the Earth's pole position with GPS," 1993.  
NASA Certificate of Recognition "Global geodesy using GPS without fiducial sites," 1993.  
NASA Group Achievement Award "Development of pioneering OASIS/GIPSY software," 1992.  
NASA Certificate of Recognition "Precise regional baseline estimation" 1991.  
Jet Propulsion Laboratory Director's Research Achievement Award, 1989.  
American Astronomical Society Bruno Rossi Prize, "Detection of Neutrinos from SN1987A," 1987.  
Queen Mary College, University of London, Best Physics Student Award, 1981.

### **RECENT PROFESSIONAL ACTIVITIES**

Proposal Review Panel, NSF EarthScope Program (2003-present).  
Chair, UNAVCO/NAREF Working Group on Stable North America Reference Frame (2003-present).  
Scientific Organizing Committee, Workshop on GPS Vertical, Luxembourg (April 2003).  
Proposal Review Panel, NASA Solid Earth and Natural Hazards Applications (2002).  
Member, Special Bureau for Loading, Global Geophysical Fluids Center, IERS (2002-present).  
Vice Chair, Global Strain Rate Map, International Lithosphere Program (1999–2002).  
Chair of Board of Directors, UNAVCO Inc., (2000–2004).  
Governing Board, International GPS Service (IGS), (1996–2001; 2004-present).

## **SAMPLE OF RECENT REFEREED JOURNAL PUBLICATIONS (from 70 total refereed pubs)**

- Smith, K.D., D. von Seggern, G. Blewitt, L. Preston, J.G. Anderson, B.P. Wernicke, J.L. Davis, Evidence for deep magma injection beneath Lake Tahoe, Nevada-California, *Science*, doi:10.1126/science.1101304, 2004.
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- Kreemer, C. Haines J., Holt W.E., Blewitt, G., and Lavallée D., On the determination of a global strain rate model: *Earth, Planets and Space*, v. 52, p. 765-770, 2000.

## **CURRENT AND PENDING SUPPORT**

- |  |          |
|--|----------|
| 1. Pending: This proposal. DOE. 6/05-9/07.   | 2 months |
| 2. Current: "Earth's Shape, Geoid, Rheology, and Water Storage." NASA. 10/04-9/07. | 2 months |
| 3. Current: "Geodetic Monitoring of Yucca Mountain using GPS", DOE, 10/03-9-08.    | 2 months |
| 4. Current: "Terrestrial Reference Frame Theory and Practice," NASA, 10/03-9/06.   | 2 months |

## Biographical Sketch: William C. Hammond

### EDUCATION

1985-1989, B.A. Applied Mathematics, University of California, Berkeley.  
1994-2000, Ph.D. University of Oregon, Eugene, Department of Geological Sciences.

### PROFESSIONAL EXPERIENCE

1990-1994, Project Manager, Fair, Isaac Company, Business Analytics and Consulting.  
2001–2004, Postdoctoral Research Geophysicist, U.S. Geological Survey, Earthquake Hazards Team.  
2004 – present, Assistant Research Professor/Research Scientist in Geophysics/Space Geodesy.

### HONORS AND AWARDS

Young Scientist Travel Award, G.P.S. Vertical Workshop, Luxembourg, April 2003.  
Outstanding Achievement Award, U.S.G.S. Earthquake Hazards Team, November 2002.  
The Thayer Scholarship, Univ. of Oregon Dept. of Geological Sciences, May 1999.  
Paul and Helen Weiser Scholarship, Univ. of Oregon Dept. of Geological Sciences, June 1996.

### PROFESSIONAL SERVICE

2003-2005 Site Selection Working Group Member, EarthScope/Plate Boundary Observatory  
1996-1997 Graduate Student Representative, Univ. of Oregon Dept. of Geological Sciences

### PEER-REVIEWED PUBLICATIONS

- Hammond, W.C. and W. Thatcher, 2005, Northwest Basin and Range tectonic deformation observed with the Global Positioning System, 1999-2003, in review at J. Geophys. Res.
- 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, J. Geophys. Res. 109(B8), 8403, doi:10.1029/2003JB002746.
- Hammond, W.C., 2004, Vertical motion of the Basin and Range, western United States from 10 Years of Campaign GPS, Cahiers du Centre Européen de Géodynamique et de Séismologie, Proceedings of the workshop: The state of GPS vertical positioning precision: Separation of earth processes by space geodesy, ed T. van Dam, v. 23, p 131-136.
- Hammond, W.C., and D.R. Toomey, 2003, Seismic velocity anisotropy and heterogeneity beneath the Mantle Electromagnetic and Tomography Experiment (MELT) region of the East Pacific Rise from analysis of P and S body waves, J. Geophys. Res., 108(B4), 2176, doi:10.1029/2002JB001789.
- Toomey, D.R., W.S.D. Wilcock, J.A. Conder, D.W. Forsyth, J.D. Blundy, E.M. Parmentier, W.C. Hammond, 2002, Asymmetric mantle dynamics in the MELT region of the East Pacific Rise, Earth and Planet. Sci. Lett., 200, 287-295.
- Hammond, W.C., and E.D. Humphreys, 2000, Upper mantle seismic wave velocity: The effect of realistic partial melt geometries, J. Geophys. Res., 105, 10,975-10,986.
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- Toomey, D.R., W.S.D. Wilcock, S.C. Solomon, W.C. Hammond, J.A. Orcutt, 1998, Mantle seismic structure beneath the MELT region of the East Pacific Rise from P and S wave tomography, Science, 280, 1224-1227.

### SELECTED ABSTRACTS

- Hammond, W.C. and C. Kreemer 2005, Anomalous geodetic dilatation at the Central Nevada Seismic Belt: Inferring secular and transient contributions, EOS Trans. AGU, 86, Fall Meet. Suppl. [INVITED].
- Kreemer, C. and W.C. Hammond 2005, Using a western United States geodetic strain rate model to improve our understanding of the driving forces in continental extension zones, EGU meeting, Vienna, [INVITED].

Kreemer, C, and W.C. Hammond 2005, AGU Joint Assembly, [INVITED].

Blewitt, G., H.-P. Plag, C. Kreemer, W.C. Hammond, V. V. Titov, 2005, Effects of the  $M_w$  9.0 Sumatra earthquake and tsunami on Earth's shape, AGU Joint Assembly [INVITED].

Hammond, W.C. and Kreemer, C 2005, Using geodetic data to estimate seismic hazard in the western Great Basin, SSA Annual Meeting.

Hammond, W.C., Blewitt, G., Kreemer, C. 2005, Geodetic constraints on the rate and style of contemporary deformation in the northern Walker Lane, SSA Annual Meeting, [INVITED].

Plag, H.-P., Blewitt, G., Kreemer, C., and Hammond, W.C. 2005, Effects of the Sumatra Earthquake and Tsunami on Earth Shape, SSA meeting.

Hammond, W.C., W. Thatcher, G. Blewitt, 2004, Crustal Deformation across the Sierra Nevada-Northern Walker Lane, Basin and Range Transition, Western United States Measured with GPS, 2000-2004, Eos Trans. AGU, 85(47) Fall Meet. Suppl.

Kreemer, C., G. Blewitt, W.C. Hammond, M.F. Coolbaugh, 2004, A new strain rate model for the Great Basin and its implications to tectonic and geodynamic studies, Eos Trans. AGU, 85(47) Fall Meet. Suppl.

Hammond, W.C., 2004, Constraints on Basin and Range lithospheric dynamics from the Global Positioning System, Earthscope Workshop: Great BREAK, Reno, NV.

Hammond, W.C., 2004, Recognizing postseismic relaxation at the Central Nevada Seismic Belt, Basin and Range Seismic Hazard Summit, II, Reno, NV.

Thatcher, W., and W.C. Hammond, 2004, Present-day deformation of the Great Basin and its implications for seismic hazard assessment, Reno Basin and Range Seismic Hazards Summit II, Reno, NV.

Hammond, W.C., 2004, How well can GPS data constrain variations in lithospheric rheology? A Basin and Range case study, UNAVCO Annual Meeting, Boulder CO, February 26-27.

Hammond, W.C., 2003, and W. Thatcher, Crustal Deformation of the Northern Basin and Range [Northern California, Oregon, Northern Nevada] from Measurement with the Global Positioning System Eos Trans. AGU, 84, Fall Meet. Suppl.

Poland, M., D. Dzurisin, W. C. Hammond, E. Endo, E. Iwatsubo, M. Lisowski, 2003, New results from a proposed PBO Cascade volcano cluster I: Deformation in the Medicine Lake region of northeast California from leveling, GPS, and INSAR, Geol. Soc. Am. Abstr. with Progr., vol 35.

Hammond, W.C., and W. Thatcher, 2003, Crustal deformation across the Basin and Range province [Nevada and Utah], western United States, measured with the Global Positioning System, 1992-2002, EGS-AGU-EUG Joint Assembly, Nice, France, Geophys. Res. Abs., vol. 5.

Hammond, W.C., and W. Thatcher, 2002, GPS Measurement of deformation of the Basin and Range province, western United States, Eos Trans. AGU, 83, Fall Meet Suppl.

M. Nyst and W.C. Hammond, 2002, Present-day kinematics of crustal deformation of the Walker Lane and central Nevada, derived from GPS data, Eos Trans. AGU, 83, Fall Meet Suppl.

Hammond, W.C. and W. Thatcher, 2001, Integrated kinematic analysis of GPS and fault slip data in the Eastern California Shear Zone, Walker Lane and Sierra Nevada., Eos Trans. AGU, 82, Fall Meet Suppl.

Hammond, W.C., and W. Thatcher, 2001, The dynamics of western United States tectonism, Earthscope Workshop, Making and Breaking a Continent, Snowbird, UT.

Barclay, A.H., D.R. Toomey, W.S.D. Wilcock, W.C. Hammond, 2001, Geodynamic and seismic modeling of the MELT region of the East Pacific Rise: An example of plate scale hotspot-ridge interaction, Eos Trans. AGU, 82, Fall Meet Suppl.

Toomey, D.R., W.S.D. Wilcock, J. Blundy, W.C. Hammond, 1999, Asymmetric mantle dynamics in the MELT region of the East Pacific Rise: A result of hot, asthenospheric return flow, Eos Trans. AGU, 80.

#### **CURRENT AND PENDING SUPPORT**

Current: "Geodetic Monitoring of Yucca Mountain using GPS", DOE 10/03 – 09/08. 9 mos/yr  
 Pending: This proposal. DOE. 6/03-9/05. 1 mos/yr

## Biographical Sketch: Cornelis Kreemer

Postdoctoral Fellow, Nevada Bureau of Mines and Geology, UNR

- EDUCATION:**
- Ph.D., 2001 Geosciences, SUNY - Stony Brook, NY, USA  
*Thesis: 'A global strain rate model'*  
*Advisor: Dr. W. Holt*
  - M.S. (Drs.), 1997 Geophysics, Utrecht University, The Netherlands  
*Thesis: 'Plate boundary deformation in the Explorer region'*  
*Advisor: Dr. R. Govers*
- RESEARCH INTERESTS:** Plate tectonics; Crustal deformation; Application of space-geodesy in geophysics; Plate boundary dynamics
- RESEARCH AND PROFESSIONAL EXPERIENCE:**
- 07/2004 – Present Postdoctoral Fellow, Nevada Bureau of Mines & Geology  
*Contributions to team efforts on quantifying crustal deformation by space-geodesy in Great Basin.*  
*Supervisor: Dr. G. Blewitt*
  - 09/2002 – 08/2004 Postdoctoral Fellow, Collège de France, Aix en Provence  
*Kinematic investigations of Aegean and Myanmar in particular, and of oceanic transform and other strike-slip faults in general. Supervisor: Dr. X. Le Pichon*
  - 12/2001 – 08/2002 Postdoctoral Fellow, Laboratoire de Géologie, ENS, Paris  
*Regional modelling of deformation fields in the Mediterranean. Funded by Exxon and Total-Elf. Supervisor: Dr. X. Le Pichon*
  - 06/1998 – 11/2001 Research Assistant, SUNY - Stony Brook  
*Global modelling of crustal strain rates and velocities using geodetic, geologic and seismological data; Work under guidance of Dr. W. Holt in close collaboration with Dr. A.J. Haines, Dr. G. Blewitt, and the UNAVCO consortium. Project is under auspices of International Lithosphere Program and supported by NASA.*
  - 08/1996 – 10/1996 Research Scholar, Geodynamics Lab, Pennsylvania State University, College Park  
*Modelling of seismic strain rates offshore Vancouver Island; Work in collaboration with Dr. K. Furlong, and supported by International Relation Office, Utrecht University.*
- FIELD EXPERIENCE:**
- 2004 – Present Member, MAGNET Geodetic Team  
*Maintenance of semi-permanent GPS network and acquisition of data in western Nevada*
  - 07/1996 Member, Scientific Cruise  
*Collection of seismic and bathymetric data offshore Vancouver Island to provide additional evidence of localised plate boundary deformation.*
- TEACHING EXPERIENCE:**
- 02/2001 – 06/2001 Co-lecturer, SUNY - Stony Brook  
*Seismology Project 'Women in Science and Engineering'*

- 09/1997 – 05/1998 Teaching Assistant, SUNY - Stony Brook  
*Structural Geology - Geophysics - Natural Hazards*
- 02/1996 – 05/1996 Teaching Assistant, Utrecht University  
*Math II - Complex numbers & Fourier Series/Transforms*
- 1995 – Present Regular contributor to 'Astruim', Dutch educational periodical on astronomy and planetary sciences

- AWARDS:**
- Travel Award, awarded by GPS99 meeting committee to attend meeting in Tsukuba, Japan, 10/1999
  - Excellence in Teaching Award, SUNY - Stony Brook, 05/1998

**REFEREED PAPERS:**

- Le Pichon, X., **C. Kreemer**, and N. Chamot-Rooke, Asymmetry in elastic properties and the evolution of large continental strike-slip faults, submitted to *J. geophys. Res.*, in press, 2005.
- Kreemer, C.**, N. Chamot-Rooke, and X. Le Pichon, Constraints on the evolution and vertical coherency of deformation in the Northern Aegean from a comparison of geodetic, geologic, and seismologic data, *Earth planet. Sci. Lett.*, 225, 329-346, 2004.
- Kreemer, C.**, and N. Chamot-Rooke, Contemporary kinematics of the southern Aegean and the Mediterranean Ridge, *Geophys. J. Int.*, 157, 1377-1392, 2004.
- Kreemer, C.**, W.E. Holt, and A.J. Haines, An integrated global model of present-day plate motions and plate boundary deformation, *Geophys. J. Int.*, 154, 8-34, 2003
- Kreemer, C.**, W.E. Holt, and A.J. Haines, The global moment rate distribution within plate boundary zones, in *Plate Boundary Zones*, eds. S. Stein and J.T. Freymueller, *Geodynamics Series*, 30, pp. 173-190, doi:10/1029/030GD10, AGU, Washington, D.C., 2002.
- Kreemer, C.**, and W.E. Holt, A no-net-rotation model of present-day surface motions, *Geophys. Res. Lett.*, 28, 4407-4410, 2001.
- Kreemer, C.**, J. Haines, W.E. Holt, G. Blewitt, and D. Lavallée, On the determination of a global strain rate model, *Earth Planets Space*, 52, 765-770, 2000.
- Kreemer, C.**, and W.E. Holt, What caused the March 25, 1998 Antarctic plate earthquake?; Inferences from regional stress and strain rate fields, *Geophys. Res. Lett.*, 27, 2297-2300, 2000.
- Kreemer, C.**, W.E. Holt, S. Goes, and R. Govers, Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data, *J. geophys. Res.*, 105, 663-680, 2000.
- Kreemer, C.**, R. Govers, K.P. Furlong, and W.E. Holt, Plate boundary deformation between the Pacific and North America in the Explorer region, *Tectonophysics*, 293, 225-238, 1998.

**WEBSITE**

Meertens, C.M., L. Estey, C. Kreemer, and W. Holt, Interactive web interface to the global strain rate map project, 2004, <http://www.world-strain-map.org>

**CONFERENCE ABSTRACTS:**

~ 50 papers (presentations and posters) at international conferences

**CURRENT AND PENDING SUPPORT**

Current: "Geodetic Monitoring of Yucca Mountain using GPS", DOE 10/03 – 09/08. 9 mos/yr  
 Pending: This proposal. DOE. 6/03-9/05. 1 mos/yr