Satellite InSAR (Interferometric Synthetic Aperture Radar) Ground Displacement Analysis for Geothermal Reservoir Management and Development

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Proposal submitted in response to a REQUEST FOR PROPOSALS from the Great Basin Center for Geothermal Energy
Proposal Deadline: Feb. 18, 2005

ABSTRACT

Ground deformations mapped with InSAR are beginning to be recognized as having utility for monitoring production induced changes in geothermal reservoirs, but better understanding of the sources of the deformation signals is required to improve confidence in data use. Building on our previous time-series InSAR work at the Bradys and Desert Peak areas, we propose to develop a more sensitive and time resolved Interferometric Synthetic Aperture Radar (InSAR) displacement observation sequence to identify previously unrecognized reservoir production signals and possibly seasonal recharge effects. We will employ the newest technology from the European Space Agency's ENVISAT ASAR radar to achieve this signal improvement by acquiring a relatively dense data sequence covering two years. To advance the general understanding of types of useful and unwanted signals contained in these surface deformation observations will test a set of hypothesis developed from our InSAR previous work by using hydrologic flow and elastic deformation modeling and other consistency tests. We will use time-sequence 3-D elastic deformation modeling to develop a "best fitting" description of how reservoir volume change is modified by changes in production and injection well patterns. Finally we will integrate the InSAR observations, insights from modeling, and our knowledge of the field environment to develop useful conclusions.

This study directly promotes increased utilization of geothermal resources in the Western United States by developing methods and knowledge that will assist reservoir management and expansion at Bradys and Desert Peak and that will also serve as technology templates for other Great Basin geothermal fields.

Total Federal Funds Requested: **$208,785**

[1] Associate Research Professor, Arthur Brant Laboratory for Exploration Geophysics, Department of Geological Sciences, UNR.
[2] Associate Research Professor, Great Basin Center for Geothermal Energy, UNR.
[3] Research Professor, Nevada Bureau of Mines and Geology, UNR.
[4] Hydrology PhD candidate, Department of Geological Sciences, and Washoe County Department of Water Resources Hydrologist

DESCRIPTION OF PROJECT

Relevance and Background

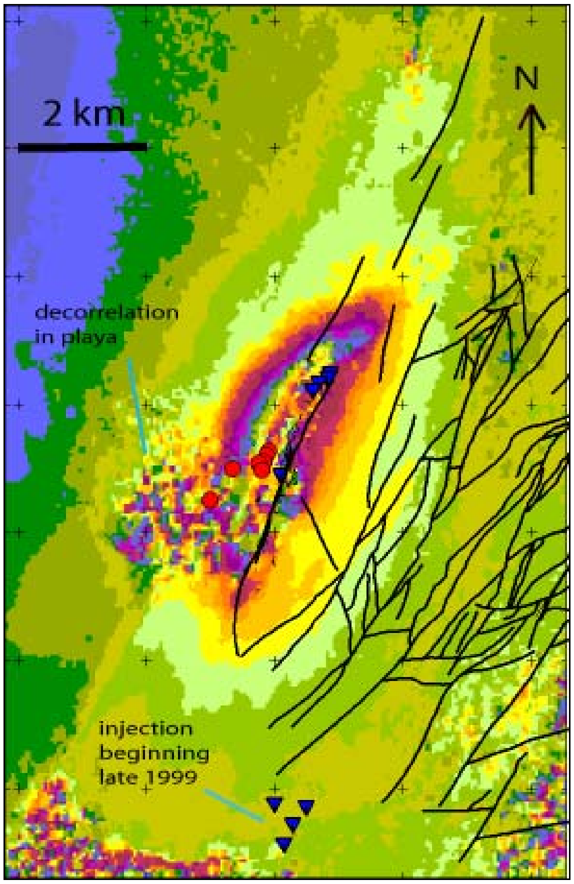
This study supports increased development of geothermal based energy in the Great Basin through its three objectives: 1) Developing and demonstrating InSAR surface deformation observation and interpretation methods that are directly useful to the expansion and management of many producing geothermal reservoirs. 2) Identifying the effective boundaries of the Bradys and Desert Peak geothermal fields to guide future production and inject well placement. 3) Elucidating how the reservoir interacts with the surrounding aquifer systems on a long term and seasonal basis to improve resource management.

For many geothermal fields, incomplete knowledge of the actual reservoir boundaries adds to the risk of new development and exploration work. Commonly, groundwater-level and pressure data are insufficient to delineate the complete geothermal field. In this context, ground deformations mapped with InSAR provide valuable new information on the extent of the reservoir system beyond the known field and on the effectiveness of injection wells. In a geothermal field, surface deformation will occur as a consequence of the production of geothermal fluids even if the reservoir is deep and isolated from shallow groundwater (Vasco, 2002).

Reservoir deformation is largely driven by pressure reduction, which reduces the reservoir's compressive strength and allows subsidence of overlying strata into the reservoir; but other factors contribute - including contraction by cooling. Where coupling into a shallow groundwater aquifer occurs, the surface deformation response will contain additional elements (Poland, 1984). These include strain from the newly added weight of deposits that have lost buoyant support, and the simple dehydration shrinkage of clayey deposits. Because all of the above effects are typically associated with production and are centered on the most favored fluid flow axis they are not easily separable. Use of additional data such as ground-water levels and reservoir modeling may help determine their relative significance in a particular case.

Introduced only twelve years ago as a research method with the launch of the European Space Agency's (ESA) ERS 1 satellite, repeat-orbit differential InSAR (InSAR for short) has been showcased for its ability to image earth surface deformation related to earthquakes and volcanic intrusions and more recently ground deformation related to groundwater use, geothermal and petroleum production (Massonnet, 1998). InSAR is a surface displacement change detection method with unprecedented millimeter level sensitivity. Surface displacements that occur in the time interval between the acquisitions of two radar scenes are inferred by comparing the travel times of the radar waves. This is accomplished through combining the two radar scenes to form an interferogram or phase interference image. The anomalous phase patterns represent travel time delay features that include contributions from changes in surface displacement and atmospheric water vapor.

InSAR offers two distinct advantages over traditional optical leveling and GPS methods for vertical surface change detection. First it can provide map-like images at resolutions of 20-40 meters covering 100 km by 100 km regions. Second, it can be applied in retrospective change studies by using the 10 year archive of ERS 1/2 scenes. InSAR's ability to monitor surface deformation at geothermal fields has been established on some of the largest fields, e.g. Coso (Fialko, 2000) and models for inversion of reservoir volume strain have been developed and applied (Vasco, 2002).



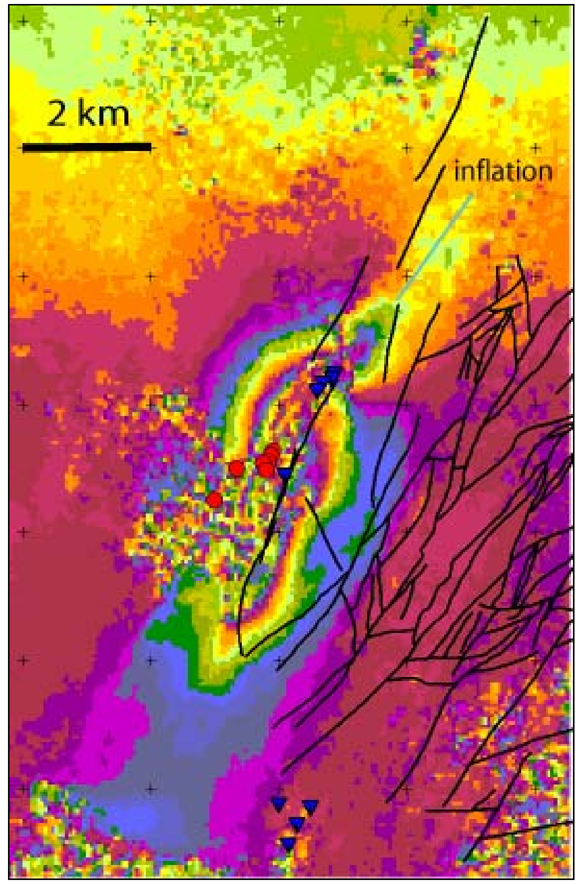


Figure 1: Interferogram A - 2.96 years: 92-11-26 to 95-11-04. Each color change represents 0.16 cm line-of-sight LOS distance change. 18 color changes represent one color cycle or fringe cycle of 2.83 cm LOS or 3.07 cm projected on the vertical. Surface faults: heavy black lines. Symbols: Production wells: circles. Injection wells: triangles. Geologic surface faults: heavy black lines from Benoit, 1982, and Churchill County, Nevada geologic maps.

Figure 2: Interferogram B - 4.78 years: 95-11-04 to 00-09-24. Surface faults: heavy black lines. Symbols: as in Figure 1.

Relocation of injection wells in 1999 coincides with southwestward migration of the reservoir surface deformation pattern.

RESULTS FROM PREVIOUS AWARD

Although our previous Bradys InSAR study (to be completed September 2005), was only minimally funded at $71K total for a two year period, it produced significant results which we have published. See Oppliger 2004a, Oppliger 2004b. The study achieved its primary objective by clearly demonstrating that InSAR observations prepared from archived historical radar scenes can provide valuable reservoir monitoring information for mid-capacity (10-30 MWe) fields. Previously to this only the largest producing geothermal fields had been examined with InSAR. Our study showed the InSAR response over the Bradys field migrates several kilometers in response to production and injection changes over a several year period. These InSAR observations also identified lateral recharge flow barriers (faults) which delimit the produced reservoir block from the surrounding aquifer systems. This work also showed that we could observe coherent millimeter level patterns of surface displacements up to 10 km from the producing field for periods of 3, 5 and 9 years. Fortunately we were able to work past some problems produced by variable data quality to get these useful results.

Figures 1 and 2 show the Bradys geothermal field InSAR differential surface deformation changes over the 1992-1995 and 1995-2000 time periods. A strong southwestward growth of the reservoir response is evident in all of our measurements that include 1999 or later dates. This corresponds in time to the beginning of relocation of injection to the new well field. This pattern is interpreted as indicating lateral growth (with associated pressure reduction and fluid flow) of the active reservoir along a previously weakly coupled segment of the reservoir fault system.

Publications and Presentations produced from the previous award:

Publications:

Oppliger, G., Coolbaugh, M., Foxall, W., 2004a, Imaging structure with fluid fluxes at the Bradys geothermal field with satellite interferometric radar (InSAR): New insights into reservoir extent and structural controls. Geothermal Resources Council Transactions, v.28, pp:37-40.

Oppliger, G., Coolbaugh, M., 2004b, Imaging structure with fluid fluxes at the Brady, Nevada, U.S.A, geothermal field with satellite interferometric radar (InSAR), Society of Exploration Geophysicists, 74th Annual International Meeting, Oct. 10-15, Denver, Colorado., Extended abstracts volume, 4 pages, 3 figures.

Oppliger G., 2004c InSAR Ground Displacement Analysis in INEEL Federal Geothermal Research Program Update Fiscal Year 2004: Geothermal Technologies Program, Resource Development, Remote Sensing Techniques, http://geothermal.id.doe.gov/publications.shtml (in press).

Presentations at professional meetings

Oppliger, G, Coolbaugh M., Foxall, W., 2004 Imaging structure with fluid fluxes at the Bradys geothermal field with satellite interferometric radar (InSAR) Geothermal Resources Council Annual Meeting, Palm Springs, CA., Aug. 29-Sep.1.

Oppliger, G., 2004, The potential role of satellite radar (D-InSAR) monitoring of groundwater level change in the Truckee Meadows Region, Public meeting of the Washoe County Regional Water Planning Commission, Reno, Nevada, Sept 18.

Oppliger, G., Coolbaugh, M., 2004, Imaging structure with fluid fluxes at the Brady, Nevada, U.S.A, geothermal field with satellite interferometric radar (InSAR): Society of Exploration Geophysicists, 74th Annual International Meeting, Denver, Colorado, Oct. 10-15.

Oppliger, G., Coolbaugh, M., 2004, Mapping Geothermal Reservoir Structural Controls with Satellite Interferometric Radar – Examples from Bradys and Steamboat Hills, Nevada, Great Basin Geothermal Workshop, University of Nevada Reno, Nov 5.

Proposed Research

Because an unexpectedly high level of spatial and temporal detail was identified in our first study we propose further investigation to understand how to best apply this detail to reservoir definition and management.

In this study we will retain our focus on the Bradys-Desert Peak study area because: a) these two geothermal fields present a good range of production and InSAR related issues that can be extrapolated to many other Great Basin geothermal fields, b) we have there established significant supporting geologic and geophysical data sets that allow improved assessment of the results and c) we have developed a compelling set of interferograms using the available data covering the years 1992 to 2002.

Our new objectives are to:

1) Improve the quality of the InSAR observations for reliability of data interpretation and identification of previously unrecognized reservoir signals. We will enhance the InSAR observations over a forward looking two year test period by acquiring 8-10 new radar scenes per year using the new advanced ENVISAT ASAR radar satellite system. Our objective is to improve the reliability of the reservoir interpretation and possible isolate previously unrecognized reservoir signals.

2) Deepen our analysis and understanding of the reservoir related InSAR surface deformation signals by model testing of specific deformation scenarios. Here we seek to improve our understanding of how to interpret InSAR observations in terms of significant reservoir processes. This requires that we estimate the relative importance to InSAR of a number of potentially over-printing hydrologic, lithologic, geo-mechanical, tectonic, and surface process active at the study site. Additionally, this requires that we understand what aspects, if any, of a reservoir volume change model are compromised when these factors are ignored. We also seek to better understand the effective boundaries of the Bradys and Desert Peak geothermal fields and elucidate how these reservoirs interacts with the surrounding aquifer system on a multi-year and seasonal basis.

And, 3) Interpret the InSAR surface deformation time-series by fitting a series of volume change source distributions along the plane the reservoir fault system. This reservoir time-series model is expected to reflect how the geometry of the produced reservoir system has evolved in response to changes in production and injection rates. We will try to constrain the maximum and minimum depths of volume change, the lateral and vertical distribution of volume change and the lateral growth rate of volume change.

Reservoir volume change modeling approaches

Deformation Source Types Which deformation source type is best suited to model volume loss in a fault control reservoir? We will explore the suitability of two classic deformation sources that can be applied to modeling volume changes - the Mogi's point source (Mogi, 1958) and Okada's planar dislocation source (Okada, 1985). These sources have both been used extensively in the literature to interpret InSAR displacement anomalies in terms of causative subsurface volume change. Most of these studies model volcanic processes but some have investigated geothermal and hydrothermal deformation processes (Vasco 2005). The two sources have different one-over-distance power law behaviors. Mogi is $1/R^2$, Okada is $1/R^4$ and both represent different deformation processes.

Volume vs. Planar Distributed Reservoir Volume Change: The Bradys geothermal system is controlled by the NW Bradys fault system in which a few faults have very high hydrologic conductivity, but is it physically possible to source all reservoir volume change in the partial closure of these few faults? Another possibility is that volume change is occurring in a lower permeability, kilometer wide bedrock reservoir zone in response to pressure reductions. We will use parallel planar distributions of Okada's tensile dislocation sources and Mogi sources to determine if these models can be distinguished.

Cooling Response: What is the relative contribution of cooling contraction to the total reservoir response? We will constrain the solutions in two ways: First by estimating the delta-temperature reservoir volume product and then by estimating the rate that is energy extracted from the reservoir fluid by its delta-T volume product. Thermal contraction is largely an isotropic process so it would appear to be better modeled as a distribution of Mogi volume change sources, but we will investigate this.

Regional Water-Table Coupling: Is the presence of a long wavelength (10 km) signal in a geothermal InSAR response indicative of a deep possibly magmatic related volume change (dewatering of magma) as has been inferred from the long wavelength InSAR response at Coso and Long Valley, or are these long wavelength signals more reasonably modeled by regional-scale water-table cone-of-depression effects. We will answer this question by modeling a cone-of-depression developed in a layered regional aquifer. The Bradys-Desert Peak production history with source geometries will be used in a MODFLOW groundwater flow simulation. The resulting cone-of-depression will be expressed in terms of its effect on aquifer shrinkage and associated surface depression related to InSAR observations. Aquifer permeability typically decreases significantly in lower sedimentary and bedrock units so that the theoretical 3-D radial flow around a fluid sink becomes a 2-D radial flow at a few kilometers from the source. The transformation from 3-D volume to 2-D layered flow might be expected to expand the cone-of-depression, altering its behavior as a function of distance from $1/R^2$ to $1/R$. This simple effect is expected to strengthen long wavelengths components in geothermal production InSAR observations. As a consequence of this, modeling of geothermal InSAR observations with source functions that have $1/R^2$ (Mogi) or $1/R^4$ (Okada) may be expected to over estimate the source depth. We will fit these sources to the cone-of-depression model to determine if depths are over estimated. Mike Widmer will design and run required groundwater models using the MODFLOW flow modeling package with assistance from a graduate student.

Contributions of slip on faults: Are strike-slip or dip-slip fault displacements contributing to the Bradys InSAR response? This is an important question considering the Bradys system is interpreted as localized by an active left step in a left lateral fault. To investigate this we will model strike-slip and dip-slip displacements on the Bradys fault system using Okada's displacing solutions.

Dehydration Shrinkage of Clays: Is sufficient hydrothermally produced clay present along the Brady's fault to contribute to the InSAR response as it dehydrates above a dropping water level? We will attempt to estimate the volume and type of clays along the near the Bradys fault and estimate its possible contribution.

Project Resources

Only limited new hardware and software resources are required to undertake this study. The purchase of additional computer disk capacity is budgeted and modifications to our deformation modeling codes are required to implement some of the proposed modeling scenarios. The PI maintains a radar processing capability in the Arthur Brant Laboratory for Exploration Geophysics which includes a Linux 2.8 GHz, 1GB RAM, 1.5 Terra bytes disk system with JPL's ROI_PAC, radar interferometry processing software, ENVISAT ASAR raw preprocessors. DIMOT surface displacement modeling code, and other deformation codes, RSI's IDL and ENVI programming and image processing software are all available. Mike Widmer will develop and execute the MODFLOW simulations using his Department of Water Resources desktop computer.

DELIVERABLES

Deliverables include DOE Quarterly reports over the project period, DOE fiscal year annual reports plus annual updates for year (usually in December) 2005, 2006, 2007. GRC annual meeting transactions paper and meeting presentation on current results (usually in the Fall) for 2005, 2006, 2007. Preparation and submittal of a paper on the study's key findings for publication in a professional journal by Sept 2007. Web based publication of results and GIS data layers through the Great Basin Center site in Sept 2006 and Sept 2007. Web published movie of the time depend surface deformation response showing changes in production and injection well locations Feb 2007.

Student Involvement: A graduate student (to be named) will be employed approximately half time to assist with Hydrologic and Deformation modeling. Additionally, Dr. Oppliger maintains a radar processing capability in the Arthur Brant Laboratory for Exploration Geophysics (since 2003) that he utilizes to teach a graduate radar imaging course (twice since 2003) and facilitate graduate student InSAR research projects. Results and data from this study will be used to facilitate student training in radar methods.

MILESTONES

Description	People		Completed
Place order new radar acquisitions	GO		July 2005
Contributions of slip on faults evaluation	GO		Sept 2005
Regional Water-Table Coupling evaluation	MW, GO,LS		Dec 2005
Cooling Response evaluation	GO		Feb 2005
Submit results for GRC paper	GO		April 2006
Year 1 interferogram processing	GO		June 2006
Year 1 GIS synthesis with production data	MC, GO, LS		July 2006
Clay dehydration shrinkage evaluation	GO, MC		Sept 2006
Volume vs. Planar Distributed Reservoir Volume Change evaluation	GO		Dec 2006
Time-series 3-D reservoir model with animation	GO, MC, LS		Feb 2007
Submit results for GRC paper	GO		April 2007
Year 2 interferogram processing	GO		June 2007
Final GIS synthesis with production data	MC, GO		Aug 2007
Submit of key results to professional journal for publication	GO, MC		Sept 2007

BUDGET EXPLANATION AND JUSTIFICATION

Salaries: G. Oppliger will provide overall project management, coordinate with other researchers, conduct the InSAR processing and deformation modeling, and will lead the preparation of publications and reports. M. Coolbaugh will integrate the existing geologic, geophysical, well production, InSAR deformation fields, and 3-D reservoir volume change models into a three dimensional GIS. L. Shevenell develops methodologies for the use of hydrologic data and models and provides interpretive guidance in working with the results. The unnamed graduate student will assist with the hydrologic and deformation modeling.

Collaborators (no DOE budgeted salary) : Mike Widmer, although a Hydrology PhD candidate, is also a hydrologist with Washoe County's Department of Water Resources. Mike will provide his expertise and software to conduct the regional cone-of-depression modeling.

Field Work: Vehicle mileage will cover the costs of sampling surface clays and other field anomaly checking.

Meeting Registration: These funds cover part of the cost of presenting study results at one meeting per year.

Additional details on the roles of individual researchers can be found in the preceding "Milestones" table.

Gary L. Oppliger

Research Associate Professor
Arthur Brant Laboratory for Exploration Geophysics
Dept. of Geological Sciences and Engineering, University of Nevada, Reno
Tel (775) 784-7056, Email: oppliger@mines.unr,edu

Education

Ph.D. Engineering Geoscience, (1982) University of California, Berkeley, CA, Electromagnetic methods, instrumentation and digital signal processing. Dissertation Advisor: H. Frank Morrison.
M.S. Engineering Geoscience, (1977) University of California, Berkeley, CA
B.S. Engineering Geoscience, (1975) University of California, Berkeley, CA

Areas of Expertise

Satellite radar interferometry and GPS applications, Potential fields and electrical methods for water, mineral and geothermal exploration, Local gravimetric geoid computation for geodetic applications.

Academic Experience

Nov 1999 - present, Associate Research Professor, Arthur Brant Laboratory for Exploration Geophysics, Department of Geological Sciences and Engineering, University of Nevada, Reno.

Industry Experience

1997-1999, District Geophysicist, Kennecott Exploration Co., Reno NV.
1995-1996, Sr. Research Geophysicist, Electromagnetic Instruments Inc, Berkeley, CA.
1990-1995, Sr. Geophysicist, Western Mining Corp. North America, Reno, NV
1980-1989, Research Geophysicist, Newmont Exploration Ltd, Tucson. AZ.

Professional Activities

Session organizer and chair: Great Basin Center for Geothermal Energy, Workshop, University of Nevada, Reno, Nov 5, 2004.
Reviewer: Society of Exploration Geophysicist annual meeting 2004.
Member: American Geophysical Union; Member, Geological Society of America, Society of Exploration Geophysicist

Representative Journal Publications

Murphy, B. J., **Oppliger, G. L**., Brimhall Jr., G., and Hynes, A. J., 1999. Mantle Plumes and Mountains: *American Scientist*, v. 87, p. 146-153.
Murphy, B. J., **Oppliger G. L.**, Brimhall Jr., G., and Hynes, A. J., 1998. Plume Modified Orogeny: an example from the southwestern United States: *Geology* 26:731-734.
Oppliger, G. L., Murphy, B. J., Brimhall Jr., G., 1997. Is the ancestral Yellowstone hotspot responsible for the Tertiary "Carlin mineralization in the Great Basin of Nevada?: *Geology* 25:627-30.
Oppliger, G. L., 1984, Three-Dimensional Terrain Corrections for Mise-a-la-masse and Magnetometric Resistivity Surveys: *Geophysics*, Vol. 49, No. 10; P. 1718-1729,

Representative Conference Publications

Oppliger, G., Coolbaugh, M., Foxall, W., 2004, Imaging structure with fluid fluxes at the Bradys geothermal field with satellite interferometric radar (InSAR): New insights into reservoir extent and structural controls. *Geothermal Resources Council Transactions*, Vol. 28, pages:37-40.

Oppliger, G., Coolbaugh, M., 2004, Imaging structure with fluid fluxes at the Brady, Nevada, U.S.A, geothermal field with satellite interferometric radar (InSAR), *Society of Exploration Geophysicists*, 74th Annual International Meeting, Oct. 10-15, Denver, Colorado., Extended Abstracts Volume, 4 pages, 3 figs.

Faulds, J., Garside, L., **Oppliger, G.**, 2003, Structural Analysis of the Desert Peak-Brady Geothermal Fields, Northwestern Nevada: Implications for Understanding Linkages between Northeast-Trending Structures and Geothermal Reservoirs in the Humboldt Structural Zone, *Geothermal Resources Council Transactions* Vol. 27, pages: 859-864.

Coolbaugh, M., Sawatzky, D., **Oppliger, G**., Minor, T., Raines, G., Shevenell, L., Blewitt, G., 2003, Geothermal GIS Coverage of the Great Basin, USA: Defining Regional Controls and Favorable Exploration Terrains, *Geothermal Resources Council Transactions* Vol. 27, pages: 9-13.

Current Research Support

Washoe County Department of Water Resources and Regional Water Planning Commission: A cooperative study of the relation between satellite radar differential interferometry (D-InSAR) ground deformation observations and groundwater production and level data in the South Truckee Meadows, (PI $18k 10/2004-7/2005.) G. Oppliger.

U.S. Department of Energy: Investigating the relation between geothermal reservoir compaction, geometry and production rates from a ten-year InSAR ground displacement history at the Bradys and Desert Peak Fields, (PI $72k 7/2003-9/2005) G. Oppliger M. Coolbaugh.

U.S. Department of Energy: Regional assessment of exploration potential for geothermal systems in the Great Basin using a geographic information system (GIS) – Part II, (co-PI, $93K, 7/2003- 6/ 2005), M. Coolbaugh, G. Raines, Shevenell, T. Minor, D. Sawatzky, G. Oppliger.

Recent Research Support

NASA EPSCoR core: InSAR-GPS Investigation of Seasonal Groundwater Response in Reno, (PI $8k for 3/2003-8/2004.) G. Oppliger.

U.S. Department of Energy: Geologic and Geophysical Analysis of the Desert Peak-Brady Geothermal Fields: Part II - Structural Controls on Geothermal Reservoirs in the Humboldt Structural Zone (co-PI $98K, 7/2003- 6/2004), J. Faulds, L. Garside, G. Oppliger, R. Anooshehpoor.

Current Dissertation/Thesis committee member for:

Cheryl Goudy, Ph.D. student in Geology

Jim Scott, Ph.D. student in Geophysics Seismology

Jessica Muelhberg, M.S. student in Geology

Blake Morrow M.S. student in Geology

Richard Redd, M.S. student in Hydrology

Kurt Katzenstein, Ph. D. student in Geo Engineering

Recent Collaborators: (not listed above)

Jim Carr, Jim Trexler, Pat Cashman.

Dr. Mark F. Coolbaugh

Research Assistant Professor
Great Basin Center for Geothermal Energy, University of Nevada, Reno
Geological Sciences Department, MS 172, Reno, Nevada 89557-0138
Tel: (775) 784-1415; E-mail: cool.78@alum.mines.edu

Professional Preparation

Ph. D., Geology, 2003
University of Nevada, Reno, Mackay School of Mines, Reno, Nevada
M. S., Geological Engineering, 1985
University of Arizona, College of Mines, Tucson, Arizona
B. S., Geological Engineering, 1978
Colorado School of Mines, Golden, Colorado

Professional Assignments

Research Assistant Professor, March 2002 to Present
Great Basin Center for Geothermal Energy, University of Nevada, Reno. Research on modern geothermal systems using a GIS, spatial statistics, remote sensing, aqueous and gas geochemistry, and GPS-based crustal strain measurements. (For more detail, see research projects listed below.)

Research Assistant and Teaching Assistant, August 1998 – March 2002

Arthur Brant Laboratory for Exploration Geophysics, Dept. of Geological Sciences, UNR. Dissertation research develops geothermal and mineral exploration models using a GIS, spatial statistics (weights-of-evidence and logistic regression), and remote sensing imagery (including ASTER, TIMS, and AVIRIS). Additional research included the use of a GIS to assess natural sources of mercury to the atmosphere.

Exploration Manager – Mongolia, September 1996 - February 1998
Cascadia Chemicals & Minerals Corp., Ulaanbaatar, Mongolia
Developed and managed all corporate exploration programs for copper and gold.

Research Assistant and Teaching Assistant, **July 1995 - August 1996**
University of British Columbia, Vancouver, B.C., Canada
Development of new lithogeochemical exploration tools in the search for mineral deposits, particularly Carlin-type, sediment-hosted gold deposits.

Chief Geologist, April 1994 - June 1995
Carson Gold Corp., Vancouver, B. C., Canada
Designed and managed all corporate overseas exploration programs, with projects in South and Central America, the Philippines, and Mongolia.

Senior Exploration Geologist/Geological Engineer, November 1991 - January 1994
Coeur Rochester, Inc., Lovelock, Nevada, USA
Development of district-wide gold exploration program. Assistance with open-pit mine geology, ore control, and engineering.

Consultant, February 1991 - October 1991
Mine and Exploration Services, Monte Vista, Colorado, USA
Mine permitting and compliance issues, exploration programs, production geology, and ore reserve development.

Chief Geologist/Manager/Senior Geologist, June 1984 - January 1991
Summitville Consolidated Mining Co., Inc., Del Norte, Colorado, USA
Supervision of mine geology and exploration departments responsible for development of ore reserves, open-pit ore control, regional exploration, and land acquisition.

Geologist, **June 1983 - June 1984**
Pegasus Gold Corporation, Reno, Nevada, USA
Management of district exploration program.

Associate Geologist, **June 1980 - Dec. 1982, summers of 1977 - 1979**
Climax Molybdenum Co., div. of AMAX, Golden, Colorado, USA
Geologic mapping and field work for molybdenum exploration and mining.

Underground Motorman's Assistant, **June 1976 - September 1976**
ASARCO, Inc., Leadville, Colorado, USA
Track haulage of ore, equipment, and supplies in an underground lead-zinc-silver mine.

Selected Publications and Presentations

Coolbaugh, M.F. and Bedell, R., 2005, A Simplification of weights of evidence using a density function and fuzzy distributions: a comparison of probability modeling techniques in the designation of geothermal systems in Nevada; Geol. Assoc. Canada Special Paper "GIS applications in the Earth Sciences", *in press*.

Coolbaugh, M.F., Arehart, G.B., Faulds, J.E., and Garside, L.J., 2005, Geothermal systems in the Great Basin: modern analogues to the roles of magmatism, structure, and regional tectonics in the formation of mineral deposits; *in* Geological Society of Nevada Symposium Proceedings, May 11-21, 2005, *under review*.

Coolbaugh, M. F., Gustin, M. S., and Rytuba, J. J., 2002, Annual emissions of mercury to the atmosphere from natural sources in Nevada and California: Environmental Geology, v. 42, n. 4., p. 338-349.

Coolbaugh, M.F. and Shevenell, L.A., 2004, A method for estimating undiscovered geothermal resources in Nevada and the Great Basin: Proceedings, Annual Meeting, Palm Springs, CA, Aug. 29-Sep. 1, 2004, Geothermal Resources Council Transactions, v. 28, p. 13-18.

Coolbaugh, M. F., Taranik, J. V., and Kruse, F. A., 2000, Mapping of surface geothermal anomalies at Steamboat Springs, NV. using NASA Thermal Infrared Multispectral Scanner (TIMS) and Advanced Visible and Infrared Imaging Spectrometer (AVIRIS) data; *In:* Proceedings, 14th Thematic Conference, Applied Geologic Remote Sensing, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI., p. 623-630.

Coolbaugh, M. F. and Stanley, C. R., 1996, A lithogeochemical evaluation of feldspar hydrolysis, decarbonatization and jasperoid alteration from the Jerritt Canyon district, Nevada, using Pearce element ratio analysis; Technical Document #11, MDRU Lithogeochemical Exploration Research Project, Annual Technical Report, year 1, Dept. of Geol. Sciences, University of British Columbia.

Gray, J. E., and Coolbaugh, M. F., 1994, Geology and geochemistry of Summitville, Colorado: An epithermal acid sulfate deposit in a volcanic dome: Economic Geology, Special Issue on Volcanic Centers as Targets for Mineral Exploration, v. 89, no. 8, p. 1906-1923.

Gray, J. E., Coolbaugh, M.F., Plumlee, G. S., and Atkinson, W. W., 1994, Environmental geology of the Summitville Mine, Colorado: Economic Geology, Special Issue on Volcanic Centers as Targets for Mineral Exploration, v. 89, no. 8, p. 2006-2014.

Current and Past Geothermal Research

1) <u>Regional Assessment of Exploration Potential for Geothermal Systems in the Great Basin using a Geographic Information System (GIS)</u>: Collaborators: Mark F. Coolbaugh, Gary L. Raines, Lisa A. Shevenell, Tim B. Minor, Don L. Sawatzky, and Gary Oppliger: funded by DOE.

A geographic information system (GIS) is being used to integrate diverse types of geologic, chemical, and physical information to predict where high-temperature geothermal systems are most likely to occur in the Great Basin of western North America. Spatial analysis using weights-of-evidence and logistic regression is being used to quantify relationships between geothermal systems and the map data and clarify the conditions necessary for the formation of high-temperature geothermal systems.

2) <u>Remote Sensing for Exploration and Mapping of Geothermal Resources</u>: Collaborators: Wendy Calvin and Mark F. Coolbaugh: funded by DOE.

Hyperspectral and multispectral remote sensing, in the visible, near-infrared, and thermal infrared ranges, is being used to identify anomalous surface features related to active geothermal systems. These features include areas of high heat flow (thermal anomalies), diagnostic rocks (sinter and evaporite assemblages), hydrothermal alteration (alunite and clay minerals), and vegetation anomalies.

3) <u>Geochemical Characterization of Magmatic-related vs. Extension-related Geothermal Systems in the Great Basin: Implications for Exploration, Exploitation, and Environmental Issues</u>: Collaborators: Greg B. Arehart, Mark F. Coolbaugh, and Simon R. Poulson: funded by DOE.

This research will identify the distinguishing chemical characteristics of magmatic and extensional geothermal systems, and relate those differences to differences in host rock lithologies, magma compositions, or other physical and chemical parameters. The significance those differences have for exploration, exploitation, and effects on the environment is being reviewed.

4) <u>Targeting of potential geothermal resources in the Great Basin from regional relationships between geodetic strain and geological structures</u>: Collaborators: Geoff Blewitt and Mark F. Coolbaugh: funded by DOE.

The ability of GPS-based measurements of geodetic strain to identify zones of crustal extension, and the role those zones of extension play in controlling geothermal activity, is being investigated. The Quaternary structural fabric of Nevada is being used to help constrain the mode and location of strain.

Dr. Lisa Shevenell

Education

New Mexico Institute of Mining and Technology	Geology	B.S.	1984
University of Nevada, Reno	Hydrogeology	Ph.D.	1990

Areas of Expertise

Groundwater hydrology, geothermal systems, isotope hydrology, aqueous geochemistry

Research Grants

Thirty (12 geothermal) funded research projects for a total of $5.5 million

Positions

Director, Great Basin Center for Geothermal Energy, UNR, 2004 – present
Associate Director, Great Basin Center for Geothermal Energy, UNR, 2001 – 2004
Research Professor, Nevada Bureau of Mines and Geology, 1993 –present
Research Associate, Oak Ridge National Laboratory, 1990-1993.
Research Assistant, Desert Research Institute, Reno, Nevada 1987-1990.
Research Assistant, Los Alamos National Laboratory, 1984-1987.

Selected Publications (of 27 refereed journal articles, 22 peer reviewed publications, 20 symposium papers, 13 other articles, 75 abstracts, and 78 contract reports)

Coolbaugh, M., and **Shevenell,** L., 2004. A method for estimating undiscovered geothermal resources in Nevada and the Great Basin. Geothermal Resources Council *Transactions*, v. 28 (Best Paper Award)

Shevenell, L., and Garside, L., 2003, Nevada Geothermal Resources. Nevada Bureau of Mines and Geology Map 141.

Skalbeck, J.D., **Shevenell**, L., and Widmer, M., 2002, Mixing of thermal and non-thermal waters in the Steamboat Hills area, Nevada: Geothermics, v. 31, no. 1, p. 69–90.

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Long, J.C.S., and **Shevenell**, L., 2001. The Potential of Geothermal Energy. Testimony prepared for the Secretaries of the Departments of Interior and Energy, presented on November 29, 2001, 6 p.

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Shevenell, L., and F. Goff, 1995, Evolution of geothermal waters at Mount St. Helens, Washington, U.S.A. J. Vol. Geoth. Res., 69(1/2): 73-93.

Shevenell, L., and F. Goff, 1993, Addition of magmatic volatiles into the hot spring waters of Loowit Canyon, Mount St. Helens, Washington, U.S.A. Bull. Vol., 55(7): 489-503.

Shevenell, L., 1991, Tritium in the thermal waters discharging in Loowit Canyon, Mount St. Helens, Washington, U.S.A. Chem. Geol. (Isotope Geoscience Section) 94: 123-135.

Shevenell, L., 1990, Chemical and Isotopic Investigation of the New Hydrothermal System at Mt. St. Helens, Washington: University of Nevada, Reno, 282 p.

Goff, F., **Shevenell**, L., Gardner, J.N., Vuataz, F.D., and Grigsby, C.O., 1988, The hydrothermal outflow plume of Valles caldera, New Mexico and a comparison with other outflow plumes: Journal of Geophysical Research, v. 93, no. B6, p. 6041–6058.

Shevenell, L., Goff, F., Grigsby, C.O., Janik, C.J., Trujillo, P.E., Jr., and Counce, D., 1987, Chemical and isotopic characteristics of thermal fluids in the Long Valley Caldera Lateral Flow System, California. Trans. Geoth. Res. Council 11: 195-202.

Goff, F., and **Shevenell**, L., 1987, Travertine deposits at Soda Dam, New Mexico and their implications for the age and evolution of the Valles Caldera hydrothermal system. Bull. Geol. Soc. of Am. 99: 292-302.

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Summary of Professional Experience
Mr. Widmer has over 20 years of professional experience in ground water exploration and development including water well construction, aquifer testing, surface and groundwater resource analysis, numerical modeling of aquifers, geophysical processing and interpretations, and hydrogeologic investigations in support of water rights.

Professional Affiliations
Assoc. of Ground Water Scientists & Engineers
Nevada Water Resources Association
Geological Society of America
American Geophysical Union

Education
B.Sc., Geology, University of Washington, Seattle, 1980
Graduate Studies, University of Nevada, Reno, 1982-1983, 1996-present

PROJECT MANAGER EXPERIENCE

Drilling: contracting, construction, design and testing of numerous exploratory and municipal water wells.
Groundwater modeling: construction and interpretation of both steady state and transient models for water resource investigations and long-range resource management.
Geophysics: design, coordination, processing and interpretation of various land and airborne geophysical surveys used to define geologic structure and aquifer delineation for ground water resource investigations and for groundwater modeling input. Recent work includes Satellite Radar Imaging.
Groundwater resource investigations: Use of various methods and techniques for analysis of water resources including surface and airborne geophysics, isotope and geochemistry analysis, aquifer hydraulic analysis, field mapping and extensive exploratory drilling and testing.
Construction of Truckee Meadows Early Warning Flood ALERT System: Network of 26 meteorological remote stations used in monitoring real time weather and stream data for flood forecasting and precipitation recording.
Surface water evaluations: construction and maintenance of stream gauging and monitoring devices, surface water resource evaluation, and synthetic record generation.
Watershed assessment: Conduct watershed assessment surveys, make recommendations on management and protection.

PUBLICATIONS AND TECHNICAL REPORTS

Taylor, K., **Widmer, M**., and Chesley, M. *Use of transient electromagnetics to define local hydrogeology in an arid alluvial environment*. Geophysics Vol. 57, No. 2, Feb. 1992.

Widmer, Michael and McKay, Alan., 1994. *Ground Water Contamination from Septic Tank Effluent in a Closed Basin, Washoe County, Nevada*. Washoe County Department of Public Works, Reno, Nevada.

Widmer, Michael C., 1997. *Steady-State and Transient Ground-Water Modeling of Washoe Valley, Washoe County, Nevada*. Washoe County Department of Water Resources, Reno, Nevada.

Skalbeck, J., **Widmer, M**., Karlin, R., 1998. The application of potential fields and electromagnetic methods to delineate the hydrogeologic heterogeneity in the Steamboat Hills area, Reno, Nevada. EOS Tans., American Geophysical Union, vol. 79, No.45, p243.

Widmer, Michael C., 2000. *Statistical Generation and Analysis of Streamflow Data for Galena, Whites, Thomas and Hunter Creeks, Truckee Meadows, Washoe County, Nevada*. Washoe County Department of Water Resources, Reno, Nevada.

Widmer, Michael C., 2000. *Geophysical Analysis of Cold Springs and Lemmon Valleys, Washoe County, Nevada*. Washoe County Department of Water Resources, Reno, Nevada.

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Vasco, D.W., Wicks, C., Jr. , and Karasaki, K., 2002, Geodetic imaging: High-resolution reservoir monitoring using satellite interferometry, Geophysical Journal International, v. 149, p. 555-571.

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