Final Research Performance Report

Federal Agency and Organization: DOE EERE – Geothermal Technologies Program

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Project Title: Characterizing Structural Controls of EGS-Candidate and Conventional Geothermal Reservoirs in the Great Basin: Developing Successful Exploration Strategies in Extended Terranes

Project Period: 1/31/2010 to 9/30/2013

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Project Partners: Nicholas Hinz, John Bell, and Pat Cashman (faculty at UNR); Drew Siler, post-doctoral scholar at UNR; Greg Dering, Joel Edwards, and Holly McLachlan (graduate students at UNR); Chris Kratt (subcontract with Desert Research Institute); Zonge Engineering (subcontract for gravity surveys)

DOE Project Team: DOE Contracting Officer – Laura Merrick
DOE Project Officer – Mark Ziegenbein
Project Monitor – Grant Logsdon

DESCRIPTION OF JOBS CREATED

Summary of jobs created with this project:

- Professors:
  - James Faulds (PI) – Professor managing the grant and carrying out major research tasks.
  - John Bell – Professor conducting analysis of relations between Quaternary faulting and geothermal activity.
  - Patricia Cashman – Professor from UNR tasked with analyzing the structural controls of geothermal systems in western and eastern Nevada, as well as northeastern California.
- Research Scientists:
  - Nicholas Hinz – Research Scientist working on and managing several aspects of this project.
  - Andrew Sadowski – Technician assisting in data compilation and management and hired summer 2013 as a Graduate Research Assistant to begin work on a Master's thesis.
- Post-Doctoral Scholars:
  - Drew Siler – Post-doctoral fellow hired to carry out 3D modeling and slip-dilation tendency analysis of geothermal systems.
- Graduate Research Assistants:
  - Greg Dering – Graduate Research Assistant that completed M.S., tasked with analyzing the Tuscarora geothermal field in northeastern Nevada. Finished thesis in May 2013. Hired in summer 2013 as a research scientist.
  - Joel Edwards – Graduate Research Assistant working on a M.S., tasked with analyzing the Neal Hot Springs geothermal field in eastern Oregon. Finished thesis in May 2013.
  - Lyndsay Hazelwood – Graduate Research Assistant working on M.S., tasked with analyzing the Gerlach Hot Springs geothermal field in northwest Nevada.
  - Holly McLachlan – Graduate Research Assistant (GRA) working on a Ph.D. focused on the structural controls of geothermal systems in the Carson Sink region of western Nevada.
- Technicians:
  - Bret Pecoraro – Technician assisting in analysis of core and cuttings.
- Undergraduate Students:
  - Mitch Allen – Undergraduate research assistant tasked with cutting billets for thin sections, preparing mineral separates for Ar/Ar dating, and serving as a field assistant.
  - Kathryn Ryan – Undergraduate research assistant conducting mineral separates on samples for geochronologic dating.
  - Zachary Ward – Undergraduate research assistant preparing billets of rock samples for thin section analysis.

STATUS / ACCOMPLISHMENTS

Project Status Summary:

Project Objectives and Work Plan: We conducted a comprehensive analysis of the structural controls of geothermal systems within the Great Basin and adjacent regions. Our main objectives were to: 1) Produce a catalogue of favorable structural environments and models for geothermal systems. 2) Improve site-specific targeting of geothermal resources through detailed studies of representative sites, which included innovative techniques of slip tendency analysis of faults and 3D modeling. 3) Compare and contrast the structural controls and models in different tectonic settings. 4) Synthesize data and develop methodologies for enhancement of exploration strategies for conventional and EGS systems, reduction in the risk of drilling non-productive wells, and selecting the best EGS sites.

Phase I (Year 1) involved a broad inventory of structural settings of geothermal systems in the Great Basin, Walker Lane, and southern Cascades, with the aim of developing conceptual structural models and a structural catalogue of the most favorable structural environments. This overview permitted selection of 5-6 representative sites for more detailed studies in Years 2 and 3. Sites were selected on the basis of quality of exposure, potential for development, availability of subsurface data, and type of system, so that major types of systems can be evaluated and compared. The detailed investigations included geologic mapping, kinematic analysis, stress determinations, gravity surveys, integration of available geophysical data, slip tendency analysis, and for some areas 3D modeling. In Year 3, the detailed studies were completed and data synthesized to a) compare structural controls in various tectonic settings, b) complete the structural catalogue, and c) apply knowledge to exploration strategies and selection of drilling sites.

Previous Accomplishments (FY 2010):

- Developed master spreadsheet of all known geothermal systems in broad study area. Data components include structural setting, primary structure orientation, Quaternary faulting, reservoir lithology, geothermometry, and magmatism.
- Analyzed over 100 geothermal systems, 65 in detail.
- Prepared major field excursions for next fiscal year.
- Presented talks at geothermal conferences and workshops describing results.

Previous Accomplishments (FY 2011):

- Field excursions were made to dozens of geothermal systems in the Great Basin region to evaluate their structural setting.
- Structural controls of over 200 additional geothermal systems were analyzed either with literature research or field reviews.
- A preliminary catalogue of structural settings was produced. Major findings include: 1) Step-overs or relay ramps in normal faults are the most favorable setting, hosting ~32% of the systems analyzed. 2) Intersections of normal faults and strike-slip or oblique-slip faults host 22%. 3) Normal fault terminations host 22%. 4) Accommodation zones (belts of intermeshing oppositely dipping normal faults) host 8%. 5) Displacement transfer zones, major range-front faults, and pull-aparts in strike-slip faults host 4-6% each.
- Representative sites were selected for detailed study, including Tuscarora, Salt Wells, Soda Lake, Patua, Gerlach, Columbus Marsh, and Neal Hot Springs.

- Detailed studies were conducted at Tuscarora, Salt Wells, Soda Lake, Patua, Columbus Marsh, and Neal Hot Springs.
- Results were presented at the 2010 New Zealand geothermal workshop in Auckland, 2010 GSA annual meeting in Denver, and DOE peer review in Maryland.
- Several papers and abstracts were prepared and accepted for the 2011 GRC and GSA annual meetings.
- A paper describing the applications of structural geology to geothermal exploration and general structural settings was published in the Geological Society of Nevada symposium volume.
- PI Faulds taught a graduate level course in Geothermal Exploration (Geol-702G) during the Spring Semester, 2011. Twenty students were enrolled.

Previous Accomplishments (FY 2012):

- Field excursions were made to ~28 geothermal systems in the Great Basin region to evaluate their structural setting.
- Structural controls of ~100 additional geothermal systems were analyzed either with literature research or field reviews.
- A preliminary catalogue of structural settings was updated. Major findings include: 1) Step-overs or relay ramps in normal faults are the most favorable setting, hosting ~34% of the systems analyzed. 2) Intersections of normal faults and strike-slip or oblique-slip faults host 22%. 3) Normal fault terminations host 23%. 4) Accommodation zones (belts of intermeshing oppositely dipping normal faults) host 7%. 5) Displacement transfer zones, major range-front faults, and pull-aparts in strike-slip faults host 3-4% each.
- Detailed studies continued at Tuscarora, Salt Wells, Soda Lake, Patua, and Neal Hot Springs.
- Detailed studies were initiated at Gerlach and MacFarlane Hot Springs.
- Comparative analysis was carried out to determine if there were regional differences in structural settings.
- Results of this project were presented at the 2011 GRC meeting in San Diego, 2011 GSA annual meeting in Minneapolis, and DOE peer review in Denver.
- Several papers and abstracts were prepared and accepted for the 2012 GRC and AGU annual meetings.
- A paper describing the improved techniques for geothermal exploration gleaned from this study was published in *North American Clean Energy*.
- The research team received training in EarthVision 3D software and began constructing 3D models for some of the systems being analyzed in detail.
- Temperature contour maps were compiled for 10 geothermal systems to better define the relations between thermal anomalies and structural settings.
- Geothermal Inventory Site Relocations – Confirmed and/or relocated most spring and geothermal sites within our database based on imagery, maps, and other information.
- Led pre-meeting field trip for 2012 GRC meeting. The trip was focused on the structural settings of geothermal fields in the Carson Sink area of western Nevada. It filled to capacity and was very well received.

Major Accomplishments in Fiscal Year 2013:

- Field excursions were made to 15 geothermal systems in eastern Nevada and western Utah, including Bartine Hot Spring, Klobe Hot Spring, Fish Creek Springs, and Panaca in eastern Nevada and Newcastle, Veyo Hot Spring, Dixie Hot Spring, Thermo, Roosevelt, Cove Fort, Red Hill Hot Spring, Joseph Hot Spring, Hatton Hot Spring, and Abraham-Baker Hot Springs in western Utah. In addition, ~5 systems were visited in central Nevada in the Big Smokey Valley area.
- Completed development, compilation, and synthesis of data for structural inventory database of geothermal fields in the Great Basin region. This involved completing a review of geothermal site locations, including confirming and/or relocating spring and geothermal sites based on imagery, maps, and other information for master database, as well as expanding and refining database for geothermal systems in western U.S. While some of these areas are outside Great Basin, the distribution and temperature of systems along the San Andreas, Cascades, and Snake River Plain are important for comparisons. In addition, the structural database for geothermal systems was further refined by incorporating geochemical data, with geothermometry added for CA, and additional SMU data, well, spring, TG data collection completed for NV, UT, OR, ID, and CA.
- Structural controls of all known geothermal systems in the Great Basin region (~425 total systems) were reviewed for final calls for the structural catalogue.
- Detailed studies were completed at the Gerlach, MacFarlane Hot Springs, Neal Hot Springs, Patua, Pyramid Lake, Salt Wells, Soda Lake, and Tuscarora geothermal systems. M.S. theses were completed by Joel Edwards and Greg Dering at the Neal and Tuscarora geothermal fields, respectively.
- 3D models were completed for the Neal Hot Springs, Tuscarora, McGinness Hills, and San Emidio geothermal fields.
- Used geothermal database and published maps to assess broad step-overs in fault systems that host geothermal activity. Preliminary conclusions:
    - Geothermal upflow location varies, occurring along, between, and outboard of major fault segments.
    - Small faults and terminations of major fault segments localize activity.
    - Effective exploration requires characterization of subsidiary structures.
- Completed extensive gravity survey of Carson Sink (subcontract to Zonge): Products include Bouguer gravity and depth to basement maps. This involved >34 days of data acquisition, totaling 1,140 stations, and extensive processing.
- Led post-meeting GRC field trip focused on structural settings of fields in NW Nevada.
- Presented 5 papers at the 2012 GRC meeting in San Diego (October).
- Presented 4 papers at the 2012 AGU meeting in San Francisco (December).
- Presented paper at the 2012 New Zealand geothermal workshop in Auckland (November).
- Presented papers on play-fairway analysis, incorporating 3D models and slip-dilation tendency analysis, and Soda Lake geothermal system at the Hedberg Conference in Reno (June 2013).
- Presented at "Geothermal Exploration in 21st Century" workshop for 2013 GRC Meeting in Las Vegas, covering the systematic workflow developed in our detailed studies of geothermal systems.
- Presented 5 papers at 2013 GRC Meeting in Las Vegas on: 1) structural controls of power-generating systems; 2) systematic workflow for exploration of geothermal systems; 3) play-fairway analysis, incorporating 3D models and slip-dilation tendency analysis; 4) MacFarlane geothermal system; and 5) Gerlach geothermal system.

- Presented 3 papers at the 2013 GSA annual meeting in Denver (October).
- Published 3 detailed geologic maps of
- Completed slip-dilation tendency analysis of the entire Great Basin region with data acquired in this project and literature review. This involved delineation of stress provinces in the Great Basin region.
- Completed analysis of relations between Quaternary faulting and all known geothermal systems in the Great Basin region. The highest percentage of high-temp sites are within 2 km of Quaternary faults. This suggests a statistical correlation between proximity to active faults and high-temp resources.
- Hinz and Dering attended advanced EarthVision training course for 3D modeling.
- Prepared text and figures for Journal of Structural Geology paper, summarizing structural controls on geothermal systems in Great Basin region. Involved major effort to research key example systems for figures/text including Coso, Roosevelt, Desert Peak, Brady's, Salt Wells, Jersey Valley, Blue Mountain, and multiple systems in the Salton Trough including Brawley, Salton Sea, and Cerro Prieto.
- Prepared various data sets for incorporation into the National Geothermal Database, including:
    - Structural inventory of ~425 geothermal systems in the Great Basin region.
    - Detailed geologic maps of several geothermal systems (e.g., Neal Hot Springs, Patua, Salt Wells, Tuscarora, and Wabuska).
    - 3D models of several geothermal systems.
    - Regional slip and dilation tendency analysis of Great Basin region.
    - Gravity survey of the Carson Sink in western Nevada.

Professional Contributions through Entire Project:

- 16 published papers.
- 5 published geologic maps.
- 11 published abstracts.
- 53 presentations.
- 2 completed Master's thesis.
- 1 Ph.D. and 2 additional Master's theses nearing completion.

FINAL ACCOMPLISHMENTS FOR EACH TASK

Task 1 – Structural Inventory

1. **Planned Activities**:

- Review the structural settings of geothermal systems throughout the Great Basin region.
- Organize background literature and map data on each system.
- Conduct multiple reconnaissance trips to collect field observations on structural settings.
- Synthesize data for various systems to catalogue according to structural setting.
- Develop catalogue for favorable structural settings in the Great Basin and adjacent regions.
- Summarize results at national meetings and workshops.

2. **Actual Accomplishments**:

- Over the course of the entire project, field visits were made to 117 geothermal systems in the Great Basin region. Major field excursions, incorporating visits to large groups of systems, were conducted in western Nevada, central Nevada, northwestern Nevada, northeastern Nevada, east-central Nevada, eastern California, southern Oregon, and western Utah. For example, field excursions to the following areas included visits of multiple geothermal systems:

- Northwestern Nevada: Baltazor Hot Spring, Blue Mountain, Bog Hot Spring, Dyke Hot Springs, Howard Hot Spring, MacFarlane Hot Spring, McGee Mountain, and Pinto Hot Springs in northwest Nevada.
- North-central to northeastern Nevada: Beowawe, Crescent Valley (Hot Springs Point), Dann Ranch (Hand-me-Down Hot Springs), Golconda, and Pumpernickel Valley (Tipton Hot Springs) in north-central to northeast Nevada.
- Eastern Nevada: Ash Springs, Chimney Hot Spring, Duckwater, Hiko Hot Spring, Hot Creek Butte, Iverson Spring, Moon River Hot Spring, Moorman Spring, Railroad Valley, and Williams Hot Spring in eastern Nevada.
- Southwestern Nevada-eastern California: Walley's Hot Spring, Antelope Valley, Fales Hot Springs, Buckeye Hot Springs, Travertine Hot Springs, Teels Marsh, Rhodes Marsh, Columbus Marsh, Alum-Silver Peak, Fish Lake Valley, Gabbs Valley, Wild Rose, Rawhide-Wedell Hot Springs, Alkali Hot Springs, and Baileys/Hicks/Burrell Hot Springs.
- Southern Oregon: Alvord Hot Spring, Antelope Hot Spring-Hart Mountain, Borax Lake, Crump Geyser, and Mickey Hot Spring in southern Oregon.
- Western Utah: Newcastle, Veyo Hot Spring, Dixie Hot Spring, Thermo, Roosevelt, Cove Fort, Red Hill Hot Spring, Joseph Hot Spring, Hatton Hot Spring, and Abraham-Baker Hot Springs.

- Structural controls of 426 geothermal systems were analyzed with literature research, air photos, google-Earth imagery, and/or field reviews (Figures 1 and 2). Of the systems analyzed, we were able to determine the structural settings of more than 240 sites. However, we found that many "systems" consisted of little more than a warm or hot well in the central part of a basin. Such "systems" were difficult to evaluate in terms of structural setting in areas lacking in geophysical data.
- Developed database for structural catalogue in a master spreadsheet. Data components include structural setting, primary fault orientation, presence or absence of Quaternary faulting, reservoir lithology, geothermometry, presence or absence of recent magmatism, and distinguishing blind systems from those that have surface expressions.
- Reviewed site locations for all 426 geothermal systems– Confirmed and/or relocated spring and geothermal sites based on imagery, maps, and other information for master database. Many systems were mislocated in the original database. In addition, some systems that included several separate springs spread over large areas were divided into two or more distinct systems. Further, all hot wells were assigned names based on their location to facilitate subsequent analyses.
- Results were presented at the following:
    - Initial results in FY 2011 were presented at the 2010 New Zealand geothermal workshop in Auckland, 2010 GSA annual meeting in Denver, and 2011 DOE peer review in Maryland.
    - For FY 2012, results were presented at:
        - Geological Society of America Annual Meeting, Minneapolis, Minnesota (October 9, 2011).
        - Geothermal Resources Council Annual Meeting, San Diego, California (October 24, 2011).

- Congressional briefing in Washington DC (March 27, 2012).
- University of Edinburgh in Scotland (April 13, 2012).
- Department of Energy Geothermal Technologies Program 2012 Peer Review: Denver, Colorado (May 8, 2012). Won peer-review award for best project.
- Ad Hoc discussion of mineral and geothermal resource development in Nevada: Roundtable for Nevada Business Magazine, Reno, Nevada (July 10, 2012).
- Geothermal Energy Association Summit, Sacramento, CA (August 8, 2012).

o For FY 2013, results were presented at:
- Geothermal Resources Council Meeting, San Diego, CA (October 2012).
- Association of Engineering Geologists monthly meeting, Las Vegas (October 9, 2012).
- New Zealand geothermal workshop, Auckland (November 18, 2012).
- American Geophysical Union, San Francisco (December 4, 2012).
- Nevada Mining Oversight and Advisory Committee, Carson City, NV (December 12, 2012).
- Western Washington University, Bellingham, WA (February 5, 2013).
- Weather Channel filming at Fly Geyser, NV for segment on Secrets of the Earth (aired in August, 2013).
- Keynote address: DOE peer review, Denver, CO (April 23, 2013).
- JASON geothermal research meeting, La Jolla, CA (June 20, 2013).
- Geothermal Energy Association Summit, Reno, NV (June 27, 2013).
- Hedberg Conference, Reno, NV (June 26, 2013).
- Geothermal Resources Council Meeting, Las Vegas (September 27 to October 1, 2013).
- Nevada Mineral Exploration Coalition Meeting (October 15, 2013).
- Keynote address: Penrose Conference, Park City, Utah (October 20, 2013).
- Geological Society of America annual meeting, Denver, CO (October 28, 2013).

3. **Explanation of Variance**: Not applicable.

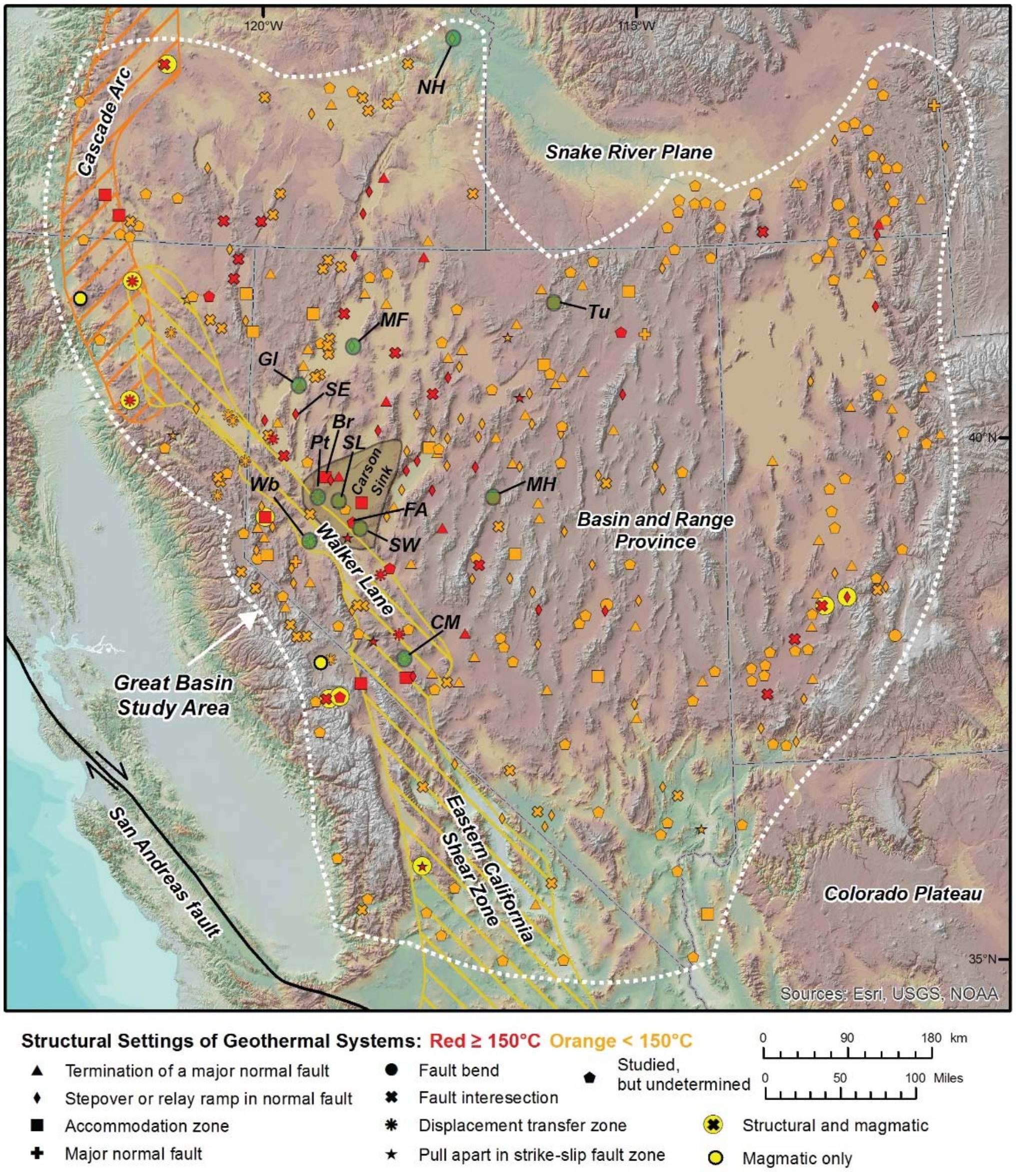

Figure 1. Structural settings of geothermal systems in the Great Basin region, as deduced in this study. Major types of structural settings are shown on digital elevation model of the Great Basin and adjacent regions. Red symbols – high-temperature systems (≥150°C); orange symbols – low-temperature systems (<150°C); yellow circles represent known or inferred magmatic systems. Green transparent circles delineate geothermal systems studied in detail in this project. Geothermal systems discussed in text include: Br, Brady's Hot Springs; CM, Columbus Marsh; FA, Fallon Airbase; Gl, Gerlach; MF, MacFarlane Hot Springs; MH, McGinness Hills; NH, Neal Hot Springs; Pt, Patua; SE, San Emidio; SL, Soda Lake; SW, Salt Wells (Eight-Mile Flat); Tu, Tuscarora; Wb, Wabuska. Brown shaded area outlines Carson Sink gravity survey.

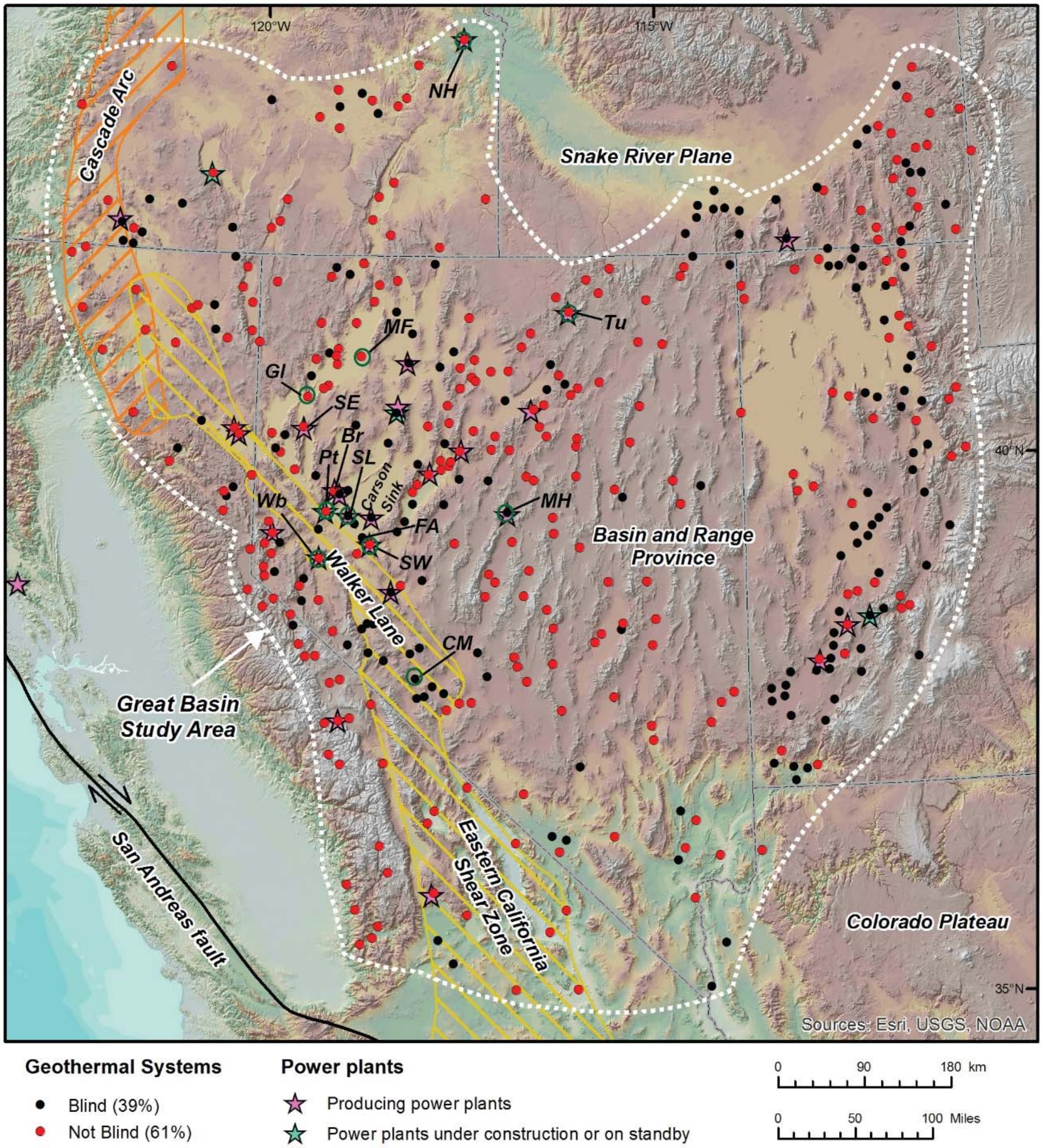

Figure 2. Blind (black) geothermal systems versus systems with surface hot springs or fumaroles (not blind, red) in the Great Basin region shown on digital elevation model. Green circles delineate geothermal systems studied in detail in this project. Abbreviations same as in Figure 1.

Task 2 – Define Favorable Structural Settings

1. **Planned Activities**: Based on the inventory of structural settings for geothermal systems, the most favorable types of systems will be defined.

2. **Actual Accomplishments**:

- We catalogued systems into the following eight major groups, based on the dominant pattern of faulting (Figure 1):
  - Major normal fault segments (i.e., near displacement maxima).
  - Fault bends.
  - Fault terminations or tips.
  - Step-overs or relay ramps in normal faults.
  - Fault intersections.
  - Accommodation zones (i.e., belts of intermeshing oppositely dipping normal faults),
  - Displacement transfer zones whereby strike-slip faults terminate in arrays of normal faults.
  - Transtensional pull-aparts.
- These settings form a hierarchal pattern with respect to fault complexity.
  - Major normal faults and fault bends are the simplest.
  - Fault terminations are typically more complex than mid-segments, as faults commonly break up into multiple strands or horsetail near their ends.
  - A fault intersection is generally more complex, as it generally contains both multiple fault strands and can include discrete dilational quadrants.
  - A step-over consists of two overlapping fault terminations and thus involves additional complexity, especially where the relay ramp is breached by multiple fault splays between the main overlapping faults and thus contains multiple fault intersections.
  - Accommodation zones involve further complexity, as they contain multiple fault terminations and fault intersections.
- Of the 426 fields analyzed, major findings include (Figures 1 and 2):
  - 39% of the known systems are blind or hidden (Figure 1), with no surface hot springs or fumaroles.
  - The structural setting for ~25% of the systems could not be determined (Figure 2). In most cases, undetermined systems reside in the central part of a basin (commonly warm wells) that lacks adequate geophysical data for elucidating the subsurface structure.
  - Step-overs or relay ramps in normal faults are the most favorable setting (Figure 2), hosting ~32% of the systems analyzed. Such areas are characterized by multiple, commonly overlapping fault strands, increased fracture density, and thus enhanced permeability.
  - Normal fault terminations host 25%.
  - Intersections of normal faults and strike-slip or oblique-slip faults host 22%.
  - Accommodation zones (belts of intermeshing oppositely dipping normal faults) host 9%.
  - Displacement transfer zones host 5%.
  - Pull-aparts in strike-slip faults host 3%.
  - Bends in major normal faults host 2%.
  - Major range-front faults host 1% of the known systems.

- Some of the more robust systems contain more than one type of structural setting. These include Steamboat, Coso, and Dixie Valley. About 21% of the fields are hybrid or compound systems.
- Pull-aparts and displacement transfer zones are more abundant in the transtensional western part of the Great Basin.
- An analysis of the relations between Quaternary faulting and geothermal systems was completed for the Great Basin region. The 426 localities were overlain on USGS Quaternary fault database in GoogleEarth to evaluate proximity to mapped faults and look for unrecognized faults.
    - Quaternary faults typically lie within or near most of the geothermal systems.
    - Geothermal fields were evaluated with proximity to Quaternary faults classified in 4 categories: <1 km, 1-2 km, 1-5 km, 1-10 km.
    - Fault ages were classified as historical, Holocene, late Pleistocene, mid-Pleistocene, and Quaternary undivided.
    - The highest percentage of high-temp sites are within 2 km of Quaternary faults. This suggests a statistical correlation between proximity to active faults and high-temp resources.
- Geothermal systems are rare along major range-front faults, possibly due to both reduced permeability in thick zones of clay gouge and periodic release of stress in major earthquakes.
- Step-overs, terminations, intersections, and accommodation zones correspond to long-term, critically stressed areas, where fluid pathways would more likely remain open in networks of closely-spaced, breccia-dominated fractures.
- Temperature contour maps were compiled for 10 geothermal systems to better define the relations between thermal anomalies and structural settings.
- These data were synthesized and summarized in multiple papers presented at GRC, GSA, and AGU meetings.

3. **Explanation of Variance**: Not applicable.

Task 3 – Regional Slip Tendency Analysis

1. **Planned Activities**: Based on the configuration of the regional stress field, slip and dilation tendencies will be calculated for major faults in the Great Basin region. Subcontract funds, originally budgeted to the GFZ in Germany, for this work were re-budgeted for post-doctoral scholar Siler at UNR. Dr. Drew Siler joined our team in November 2011. This re-budgeting was approved by DOE. Dr. Siler completed the regional slip tendency analysis in FY2013.

   Background: Critically stressed fault segments have a relatively high likelihood of acting as fluid flow conduits (Sibson, 1994). As such, the tendency of a fault segment to slip (slip tendency; Ts; Morris et al., 1996) or to dilate (dilation tendency; Td; Ferrill et al., 1999) provides an indication of which faults or fault segments within a geothermal system are critically stressed and therefore likely to transmit geothermal fluids. The slip tendency (Ts) of a surface is defined by the ratio of shear stress to normal stress on that surface: $Ts = \tau / \sigma n$ (Morris et al., 1996).

   Dilation tendency (Td) is defined by the stress acting normal to a given surface:
   $Td = (\sigma 1 - \sigma n) / (\sigma 1 - \sigma 3)$ (Ferrill et al., 1999).

2. **Actual Accomplishments**:

- Slip and dilation tendency on the Great Basin fault surfaces (from the USGS Quaternary Fault Database) were calculated using 3DStress (software produced by Southwest Research Institute).
- Slip and dilation tendency are both unitless ratios of the resolved stresses applied to the fault plane by the measured ambient stress field.
    - Values range from a maximum of 1 (a fault plane ideally oriented to slip or dilate under ambient stress conditions) to zero (a fault plane with no potential to slip or dilate).
    - Slip and dilation tendency values were calculated for each fault in the Great Basin. As dip is unknown for many faults in the USGS Quaternary Fault Database, we made these calculations using the dip for each fault that would yield the maximum slip or dilation tendency. As such, these results should be viewed as maximum slip and dilation tendency.
    - The resulting along-fault and fault-to-fault variation in slip or dilation potential is a proxy for along fault and fault-to-fault variation in fluid flow conduit potential.
- Stress Magnitudes and directions were calculated across the entire Great Basin. Stress field variation within each focus area was approximated based on regional published data and the world stress database (Hickman et al., 2000; Hickman et al., 1998 Robertson-Tait et al., 2004; Hickman and Davatzes, 2010; Davatzes and Hickman, 2006; Blake and Davatzes 2011; Blake and Davatzes, 2012; Moeck et al., 2010; Moos and Ronne, 2010 and Reinecker et al., 2005).
- The minimum horizontal stress direction (Shmin) was contoured, and spatial bins with common Shmin directions were calculated. Based on this technique, we subdivided the Great Basin into nine regions (Shmin <070, 070<Shmin<080, 080<Shmin<090, 090<Shmin<100, 100<Shmin<110, 110<Shmin<120, 120<Shmin<130, 130<Shmin<140, Shmin>140). Slip and dilation tendency were calculated using 3DStress for the faults within each region using the mean Shmin for the region. Shmin variation throughout Great Basin are shown on Figure 3.
- For faults within the Great Basin proper, we applied a normal faulting stress regime, where the vertical stress (sv) is larger than the maximum horizontal stress (shmax), which is larger than the minimum horizontal stress (sv>shmax>shmin). Based on visual inspection of the limited stress magnitude data in the Great Basin, we used magnitudes such that shmin/shmax = .527 and shmin/sv= .46. These values are consistent with stress magnitude data at both Dixie Valley (Hickman et al., 2000) and Yucca Mountain (Stock et al., 1985).
- For faults within the Walker Lane/Eastern California Shear Zone, we applied a strike-slip faulting stress, where shmax > sv > shmin. Upon visual inspection of limited stress magnitude data from the Walker Lane and Eastern California Shear zone, we chose values such that SHmin/SHmax = .46 and Shmin/Sv= .527 representative of the region.
- Results: The results of our slip and dilation tendency analysis are shown in Figures 4 (dilation tendency), 5 (slip tendency) and 6 (slip tendency + dilation tendency). Shmin varies from northwest to east-west trending throughout much of the Great Basin. As such, north- to northeast-striking faults have the highest tendency to slip and to dilate, depending on the local trend of shmin. These results provide a first order filter on faults and fault systems in the Great Basin, affording focusing of local-scale exploration efforts for blind or hidden geothermal resources.

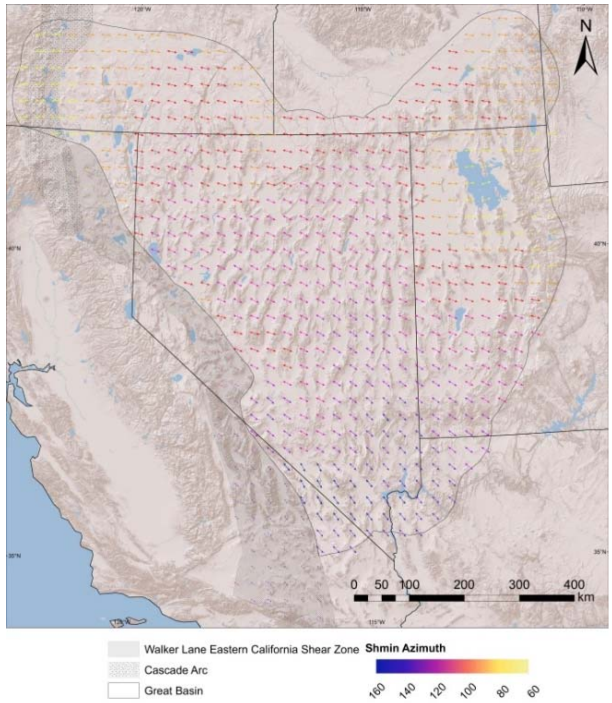

Figure 3. Shmin azimuth throughout the Great Basin. These shmin azimuths, along with an orthogonal shmax and a vertical principle stress, were used to calculate slip and dilation tendency values for all Quaternary faults in the Great Basin.

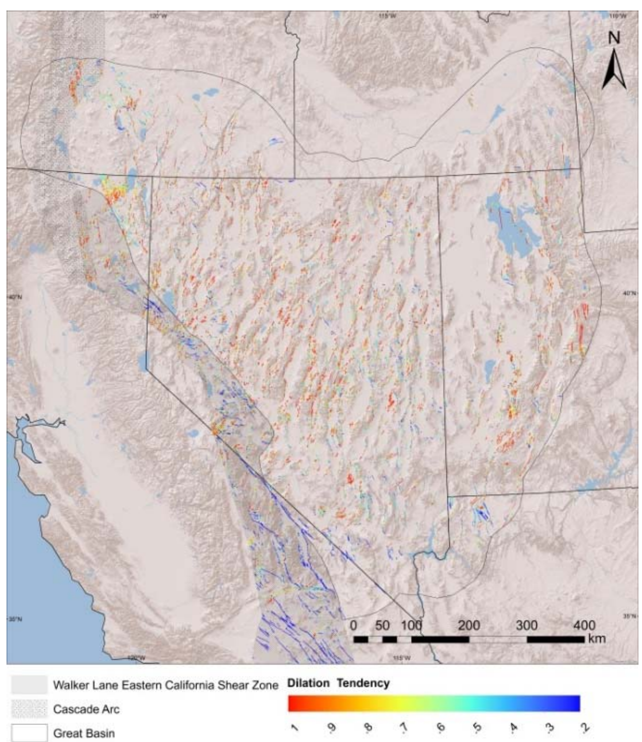

Figure 4. Dilation tendency of Quaternary faults in the Great Basin region.

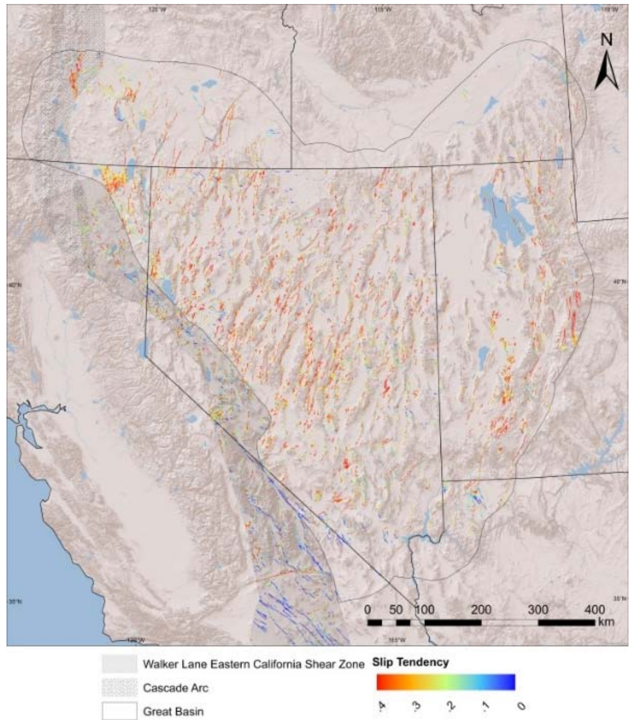

Figure 5. Slip tendency of Quaternary faults in the Great Basin region.

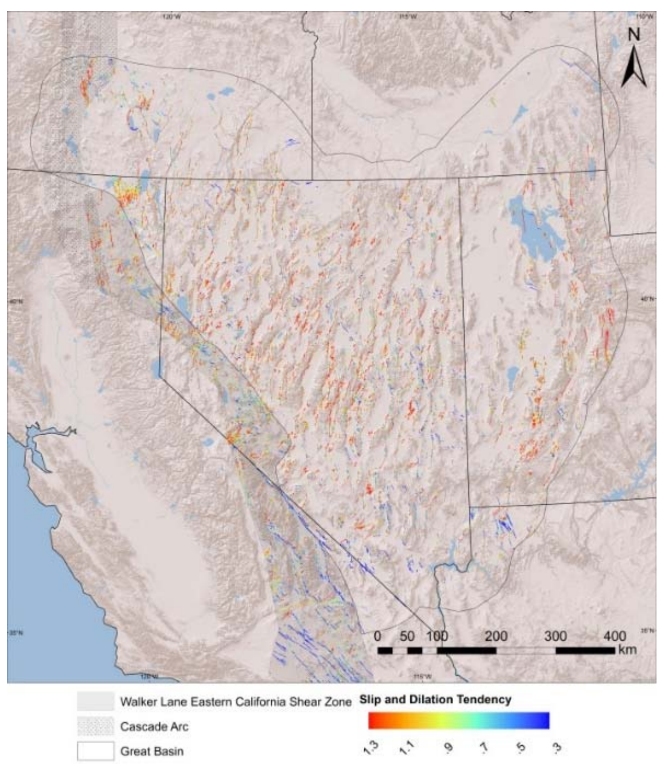

Figure 6. Slip tendency + dilation tendency of Quaternary faults in the Great Basin region.

3. **Explanation of Variance**: Not applicable.

Task 4 – Selection of Sites for Detailed Study

1. **Planned Activities**: Several representative sites (5-6 originally planned) were selected for detailed study. Site selection was based on 1) general location, such that fields in different parts of the Great Basin region are studied in this project; 2) type of structural setting such that a variety of settings are analyzed in this project, and 3) availability of subsurface and geophysical data, which will facilitate 3D modeling of some fields.

2. **Actual Accomplishments**:

- Ten geothermal systems were analyzed in detail for this project, several more than originally planned. In addition, this project also supported additional work on several other systems that had been previously studied or that were being analyzed in complementary studies.
- The following representative fields were selected for detailed study (in alphabetical order):
    - Columbus Marsh in southwestern Nevada due to its location within a displacement transfer zone, where a system of left-lateral faults in the Mina deflection of the Walker Lane diffuses into a system of northerly striking normal faults.
    - Gerlach Hot Springs in northwest Nevada due to its location along a fault termination and availability of geophysical and well data based on exploration by U.S. Geothermal. M.S. candidate Lyndsay Hazelwood is studying this area.
    - MacFarlane Hot Springs in northwest Nevada due to its location in a step-over or relay ramp of Quaternary faults. M.S. candidate Sabina Kraushaar is studying this area.
    - McGinness Hills in central Nevada due to is location in the central part of the Great Basin, as well as within a broad accommodation zone containing more localized fault intersections and step overs.
    - Neal Hot Springs in eastern Oregon due to its location directly north of the Great Basin adjacent to the Snake River Plain along a step-over and fault termination. Abundant geophysical and well data exist due to development by U.S. Geothermal. Joel Edwards completed his M.S. thesis in this area.
    - Patua in west-central Nevada due to its apparent location in a small pull apart or displacement transfer zone adjacent to the Walker Lane and abundant well and geophysical data due to development by Gradient Resources, Inc.
    - Salt Wells in western Nevada due to its location within an accommodation zone and abundant well and gravity data due to development of a power plant by Enel.
    - Soda Lake in west-central Nevada due to the blind nature of the system in the central part of a large basin and ample well and geophysical data due to development by MagmaEnergy. Ph.D. Candidate Holly McLachlan is studying this area.
    - Tuscarora due to its location in northeast Nevada, residing in a small accommodation within a broad step over and available geophysical and well data due to development of a power plant by Ormat. Greg Dering completed his M.S. thesis for this area.
    - Wabuska due to its location in the Walker Lane along a system of ENE-striking left-lateral faults, where they intersect NW-striking dextral faults and also appear to merge into a system of northerly striking normal faults.
- This project also supported some work on the following systems, which had been previously studied or were being analyzed in complementary projects:

- o Brady's in northwestern Nevada: Due to robust data sets of geological, geophysical, and well data, this field became the prime test case for the application of play fairway analysis.
- o San Emidio in northwestern Nevada: This area had been studied in detail on a complementary DOE grant in collaboration with U.S. Geothermal. Funds on the other DOE grant were expended prior to finalizing the 3D model. Thus, this grant supported completion of the 3D model.

3. **Explanation of Variance**: Not applicable.

Task 5 – Detailed Studies

1. **Planned Activities**: Detailed studies of 5-6 representative sites were planned. Detailed studies of 10 sites were actually carried out.

2. **Actual Accomplishments**: Detailed studies of 10 representative sites were conducted and are described below in alphabetical order.

- Columbus Marsh (SW Nevada) – Chris Kratt (subcontract to Desert Research Institute) conducted detailed analysis of the Columbus Marsh geothermal system. Major accomplishments included:
    - o Detailed geologic mapping of ~30 km^2 was completed in the vicinity of the Columbus Marsh geothermal field to obtain critical structural data that would elucidate the structural controls of this field.
    - o Documenting E- to ENE-striking left lateral faults and N- to NNE-striking normal faults.
    - o Some faults cut Quaternary basalts.
    - o This field appears to occupy a displacement transfer zone near the eastern end of a system of left-lateral faults. ENE-striking sinistral faults diffuse into a system of N- to NNE-striking normal faults within the displacement transfer zone.
    - o Columbus Marsh therefore corresponds to an area of enhanced extension and contains a nexus of fault intersections, both conducive for geothermal activity.
- Gerlach Hot Springs (NW Nevada) – M.S. candidate Lyndsay Hazelwood (Advisor-Pat Cashman) has been conducting detailed analysis of the Gerlach Hot Springs. This work is still in progress, with expected completion in Spring 2014. To date, major accomplishments have included:
    - o Geologic mapping of nearby granitic bedrock, Quaternary units, geothermal features (e.g., sinter and mudpots), and alteration zones.
    - o Measuring orientations of joints and calcite and silica veins in granitic rocks exposed directly west of the hot springs in the footwall of a major normal fault. Many of the veins are probably related to the active geothermal system. The exposed granite may reflect conditions in the geothermal reservoir at depth.
    - o Prepared ArcGIS database of geologic data.
    - o Conducted 2-m temperature survey.
    - o Obtained geophysical and down-hole temperature data from U.S. Geothermal.
    - o Began digitizing geologic map and interpretation of geophysical data.
    - o Published GRC paper describing structural controls of the Gerlach geothermal system (Hazelwood et al., 2013).

- MacFarlane Hot Springs (NW Nevada) – M.S. candidate Sabina Kraushaar (Advisor-Pat Cashman) has been conducting detailed analysis of MacFarlane Hot Springs. This work is still in progress, with expected completion in Spring 2014. To date, major accomplishments have included:
    - Completed detailed geologic map of ~100 km^2, including surficial geothermal features, Quaternary units, and Miocene volcanic rocks.
    - Digitized geologic map.
    - Completed 2-m temperature survey.
    - Prepared geodatabase of geologic data.
    - Measured fault scarp profiles.
    - Published GRC paper describing setting and structural controls (Kraushaar and Cashman, 2013).
- McGinness Hills (central Nevada) – Post-doctoral scholar Drew Siler conducted detailed studies of the McGinness Hills geothermal system. This project was partly supported by another DOE project, but substantial funding and work were carried out as part of this grant. Major accomplishments included:
    - Completion of ~ xx km^2 of detailed geologic mapping, including Paleozoic basement rocks, Tertiary volcanic rocks, and Quaternary deposits.
    - Determined that primary geothermal upwellings are controlled by intersections between NNE- and NW-striking faults that within both a step over in a northerly striking normal fault zone as well as broad accommodation zone between two oppositely dipping Quaternary range-front fault zones.
    - Synthesized well and magnetotelluric data to develop several detailed cross sections.
    - Cross-sections were used to produce a 3D model. Incorporated down-hole fracture data provided by Ormat into the 3D model.
- Neal Hot Springs (eastern Oregon) – Joel Edwards (advisor-Jim Faulds) completed a M.S. focused on the structural controls of Neal Hot Springs in Spring 2013 (Edwards, 2013). Major accomplishments included:
    - Completion of ~90 km^2 of detailed geologic mapping, including Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features (e.g., sinter).
    - Analysis of 25 thin sections to aid in stratigraphic correlations.
    - Obtaining geochemical data for 108 samples of cuttings to facilitate stratigraphic correlations at depth.
    - Compilation and digitizing of the geologic map.
    - Preparation of 7 samples for 40Ar/39Ar dating.
    - Analysis of cuttings from three wells. Logs revealed ~200 m of offset across the producing fault.
    - Synthesizing data for GRC, AGU, and DOE EERE 2012 Student Geothermal Competition.
    - Publishing GRC paper and AGU abstract summarizing results (Edwards et al., 2012a, b). Edwards was awarded best paper for his presentation in the GRC session.
    - Estimating stress orientations from fault kinematic data.
    - Conceptual structural model was developed with Neal occupying a left step-over and small pull-apart in a steep W-dipping normal-oblique-slip fault zone.
    - Completed several cross sections.
    - Completed 3D model.
- Patua (W Nevada) – PI Faulds and Ph.D. candidate McLachlan (advisor Jim Faulds) analyzed the Patua geothermal field. Major accomplishments included:

  - PI Faulds completed detailed mapping and published a geologic map of the area as NBMG open-file report (Faulds et al., 2011; http://www.nbmg.unr.edu/dox/of118.pdf).
  - Detailed mapping and gravity data suggest that the geothermal field occupies a poorly exposed, structurally complex area that may correspond to a small right step in an obscure NW-striking dextral fault zone.
  - Thin sections were prepared of exposed stratigraphic units and core from wells.
  - Seismic reflection data were obtained from Gradient Resources and loaded into OpenDetect software.
  - McLachlan analyzed cuttings and core from 9 wells and completed stratigraphic columns for several coreholes.
  - Drill-hole database was built in Target software.
  - Gravity data and well locations were incorporated into modeling database.
- Salt Wells (W Nevada) – Hinz analyzed the Salt Wells geothermal system. Major accomplishments included:
  - A detailed geologic map was completed and published as NBMG open-file report (Hinz et al., 2011; http://www.nbmg.unr.edu/dox/of119.pdf).
  - Thin sections were prepared.
  - A comprehensive drill-hole spreadsheet was compiled.
  - Logging of all available core (one drill-hole) completed.
  - Two geologic cross-sections have been completed and two more have been started.
  - Results for 40Ar/39Ar analysis were obtained and indicate that the volcanic rocks exposed in the Bunejug Mountains and Cocoon Mountains range in age from ~12-16 Ma and correlate with those exposed at Rainbow Mountain to the north.
  - Developed conceptual structural model based on new detailed mapping, drill-hole data, gravity data, and distribution of active and paleo-spring deposits.
    i. Hybrid structural setting composed of a synclinal accommodation zone and the southward termination of the Rainbow Mountain fault zone.
    ii. The Rainbow Mountain fault zone has ruptured 3 times in the past ~15,000 years, including the historic rupture in 1954. Late Pleistocene, Holocene, and historic 1954 scarps are associated with much of the Rainbow Mountain fault zone but have not been observed within the production well field at the southern end of the fault zone. This may show the importance of local fault segments (particularly near the tips of fault zones) that haven't recently ruptured as these may be critically stressed for dilation and fluid flow.
- Soda Lake (western Nevada) – Ph.D. candidate McLachlan (advisor Jim Faulds) analyzed the Soda Lake geothermal field. Major accomplishments included:
  - Prepared LiDAR and DEM mosaics of the study area.
  - Logged cuttings from 17 wells and updated well database.
  - Analyzed thin sections of cuttings to aid in stratigraphic correlations.
  - Reviewed borehole geophysics.
  - Extracted seismic reflection lines from SMT Kingdom and registered them in ArcMap.
  - Interpreted faults based on well and seismic reflection data. Gravity + lith-log cross-sections were matched to seismic profiles to allow interpretation of faults.
  - Optimized nine 2D profiles using gravity data.

  - Obtained 40Ar/39Ar date of ~5 Ma on prominent basalt penetrated by several wells. Due to the presence of Holocene maars in the area, the plug-like body of basalt was originally interpreted as Quaternary in age, but the Ar/Ar date demonstrates an early Pliocene age, similar to other basalts in the region.
  - Drafted 13 cross-sections, incorporating well data, gravity models, and seismic reflection data.
  - Presented paper at the 2011 GRC annual meeting.
  - Presented paper summarizing results at AGU 2012 Fall Meeting and 2013 Hedberg Conference.
- Tuscarora (NE Nevada) – Greg Dering (advisor Jim Faulds) completed M.S. thesis focused on the structural controls of the Tuscarora geothermal field in Spring 2013 (Dering, 2013). Major accomplishments included:
  - Detailed mapping of ~113 km^2 was completed, and the geologic map was published as an NBMG open-file report (Faulds and Dering, 2013).
  - A new Quaternary fault was discovered ~2 km south of the power plant.
  - Thin sections of 32 samples were obtained and analyzed.
  - Core and cuttings were logged in detail from 7 wells. This work elucidated the stratigraphic-structural framework.
  - 40Ar/39Ar dates were obtained from three samples.
  - Established geodatabase to consolidate imagery, well data, mapping, sample locations, and structural data.
  - Estimated stress orientations based on fault kinematic data.
  - Conceptual structural model was developed. The Tuscarora field lies in a zone where two W-dipping range-front fault zones overlap. Discontinuous and minor normal faults that dip both east and west connect the two major fault zones. The geothermal field lies within a small accommodation zone, where these oppositely dipping faults intermesh. Thus, the geothermal field occupies a small accommodation zone within a broader step-over or relay ramp.
  - Five cross sections were prepared based on the geologic mapping. Well data were incorporated into the cross sections.
  - 3D model was completed for geothermal field. Cross sections were used to build 3D model.
  - Published GRC paper describing the structural setting at Tuscarora. Dering was awarded best paper for his presentation at the GRC session.
  - Presented paper at 2012 AGU meeting.
  - Presented talk to Nevada Petroleum and Geothermal Society and Winnemucca chapter of the Geological Society of Nevada.
  - Assisted Ormat in selecting well sites for new resources, including targeting an E-dipping fault identified by our mapping.
- Wabuska (W Nevada) – Hinz completed detailed analysis of the Wabuska geothermal field. Major accomplishments included:
  - A detailed geologic map was completed and published as NBMG open-file report (Hinz et al., 2013; http://www.nbmg.unr.edu/dox/of138.pdf).
  - One geologic cross-section was constructed and published with the geologic map.

- Thin sections were prepared.
- Samples for 40Ar/39Ar analysis have been selected.
- Developed a conceptual structural model based on new detailed mapping and published data on the fluid geochemistry and production well temperatures.
    i. The reservoir is probably associated with a cluster of fault intersections within a broad displacement transfer zone along a major strand of the sinistral-normal Wabuska fault zone.
    ii. In a similar pattern to Salt Wells, the Wabuska geothermal system resides along a major fault zone with numerous late Pleistocene and Holocene fault scarps, but the well field is locally devoid of any evidence for recent fault slip (no fault scarps), suggesting that it lies in a critically stressed area.

3. **Explanation of Variance**: Not applicable.

Task 5.1 Detailed Mapping

1. **Planned Activities**: Detailed mapping was planned for several representative geothermal systems.

2. **Actual Accomplishments**: Detailed mapping was conducted at eight representative sites:

- Columbus Marsh – About 30 km^2 of detailed mapping was completed directly west of Columbus Marsh by Chris Kratt through a subcontract with the Desert Research Institute. This primarily included collection of structural data, such as attitudes of faults and strata and slickenlines on faults, in order to elucidate the subsurface structural framework of the adjacent Columbus Marsh.
- Gerlach – Detailed mapping of ~12 km^2 of granitic bedrock, Quaternary deposits, and surficial geothermal features was carried out by M.S. candidate Lyndsay Hazelwood.
- MacFarlane – About 100 km^2 of detailed mapping of Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features was completed by M.S. candidate Sabina Kraushaar.
- McGinness Hills – Approximately 60 km^2 of detailed mapping and three cross sections were completed at McGinness Hills by post-doctoral scholar Drew Siler. The geologic map included Paleozoic-Mesozoic basement rocks, Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features. This project was partially funded by another DOE grant awarded to Dr. Phil Wannamaker at the University of Utah, with a subcontract to UNR.
- Neal Hot Springs – A total of ~90 km^2 of detailed mapping, three detailed cross sections, and detailed unit descriptions were completed by Joel Edwards as part of his Master's thesis (Edwards, 2013). This included Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features. The map is being considered for publication by the Oregon Department of Geology and Mineral Industries.
- Patua – A total of ~140 km^2 of detailed mapping was completed by PI Faulds. This included Mesozoic basement, Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features. A detailed geologic map of the area was published by the Nevada Bureau of Mines and Geology (Faulds et al., 2011).
- Salt Wells – A total of ~140 km^2 of detailed mapping was completed by Hinz. This mapping included Miocene volcanic and sedimentary rocks, Quaternary deposits, and surficial

geothermal features. The detailed geologic map of the area was published by the Nevada Bureau of Mines and Geology (Hinz et al., 2011).

- Tuscarora – A total of ~113 km^2 of detailed mapping and 4 cross sections were completed by Greg Dering as part of his Master's thesis (Dering, 2013). The geologic map includes Paleozoic basement rocks, Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features. A detailed geologic map, including cross sections and detailed unit descriptions, was published by the Nevada Bureau of Mines and Geology (Dering and Faulds, 2013).
- Wabuska – A total of ~140 km^2 of detailed mapping was completed by Hinz. The geologic mapping included Mesozoic basement, Tertiary volcanic and sedimentary rocks, Quaternary deposits, and surficial geothermal features. The map was published by the Nevada Bureau of Mines and Geology (Hinz et al., 2013).

3. **Explanation of Variance**: Not applicable.

Task 5.2 Structural Analysis-Fault Kinematics

1. **Planned Activities**: In conjunction with the detailed mapping, structural analysis of faults and folds was planned, including kinematic analysis of exposed fault surfaces to determine slip sense.

2. **Actual Accomplishments**: Abundant data on the orientations of bedding and layering were acquired from all detailed study areas (e.g., Faulds et al., 2011; Hinz et al., 2011, 2013; Dering, 2013; Edwards, 2013). Exposed fault surfaces were sparse in some of the geothermal fields, such as Gerlach, Salt Wells, and McGinness Hills, limiting insights into fault kinematics in these areas. Structural analyses of faults and fractures were completed at the following geothermal fields:

- Gerlach – Fault surfaces were scarce in this area, but abundant veins and joints were measured in hydrothermally altered Mesozoic granite directly west of the geothermal field. Most of the veins and joints strike NNE (Figure 7), which indicates extension on N- to NNE-striking faults in the area.
- Neal Hot Springs – Kinematic data (Figure 8) suggest that the extension direction has changed from about ~E-W to ~NE-SW over the past several million years. This is compatible with regional geologic relations. The later NE-SW extension is probably associated with development of the western Snake River Plain.
- Patua – Kinematic data from this region indicate NW-SE extension and essentially dip-slip motion on NNE-striking normal faults (Figure 9), which is compatible with regional geologic relations and GPS geodetic data.
- Salt Wells – Kinematic analyses of fault and vein sets are still underway. Provisional results indicate that the extension direction has changed from ~E-W to WNW-ESE over the past several million years along N- to NNE-striking normal faults. The WNW-ESE extension direction is also broadly fitting with dextral-oblique offset observed across many of the historic 1954 fault scarps.
- Tuscarora – Kinematic analysis of fault slip data reveal normal dip-slip motion on northerly striking normal faults (Figure 10).

3. **Explanation of Variance**: Not applicable.

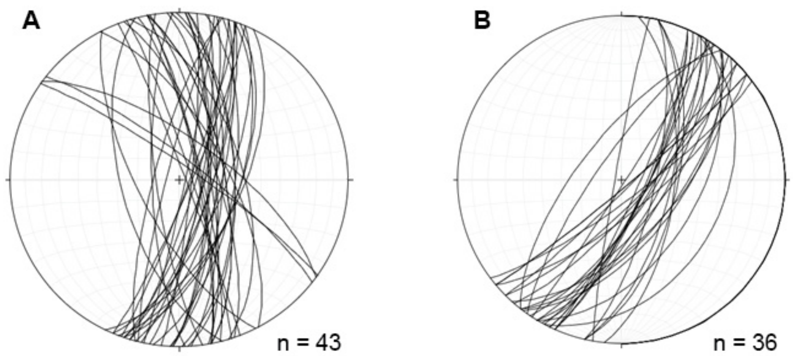

Figure 7. Lower hemisphere, equal-area projections of great circles for calcite veins (A) and joints (B) measured in hydrothermally altered Mesozoic granite directly west of the Gerlach geothermal field. These data indicate extension and dilation on N- to NNE-striking faults and fractures. n = number of measurements.

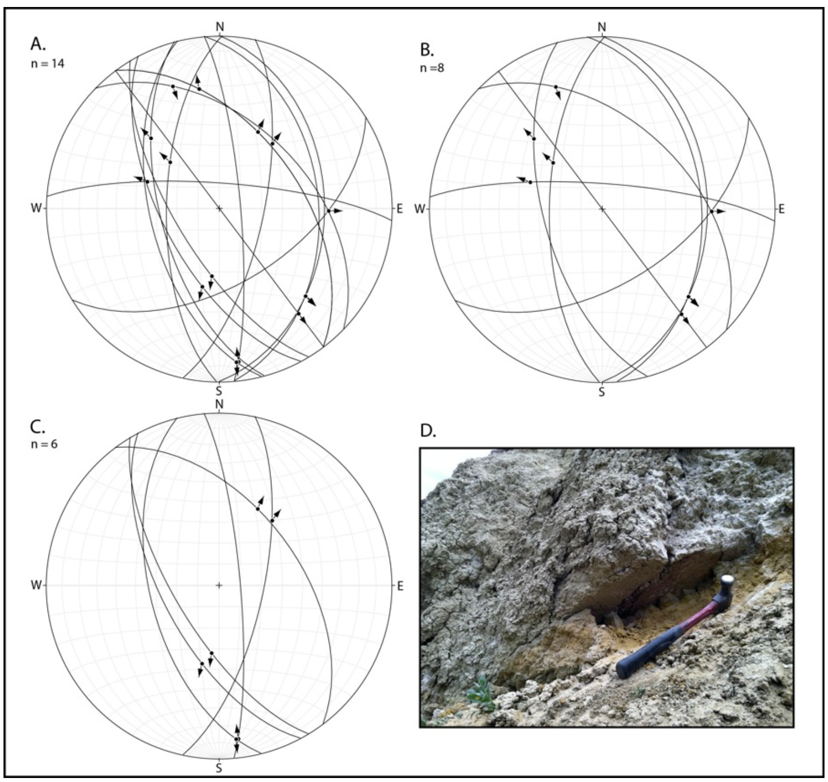

Figure 8. Lower-hemisphere, stereographic projections of fault planes (great circles) and slip vectors (arrows) from the Neal Hot Springs geothermal area, as measured from kinematic indicators (e.g., slickenlines, rough facets, and Riedel shears) from Edwards (2013). A. All fault measurements (minus one measurement with little confidence). B. Faults indicating northwest-southeast slip direction. C. Faults indicating south-northeast slip direction. D. Representative fault surface. n = number of measurements.

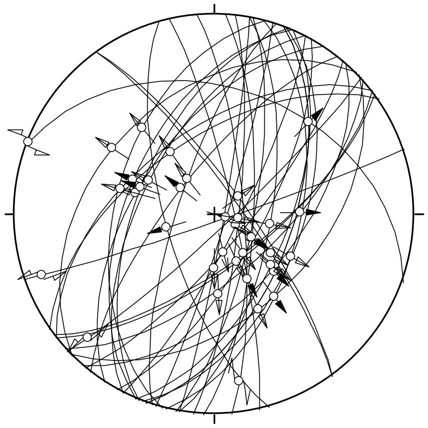

Figure 9. Lower-hemisphere, stereographic projections of 37 fault planes (great circles) and slip vectors (arrows), as measured from kinematic indicators (e.g., slickenlines, rough facets, and Riedel shears) in the Hot Springs Mountains. These data indicate dip-slip normal displacement on NNE-striking faults.

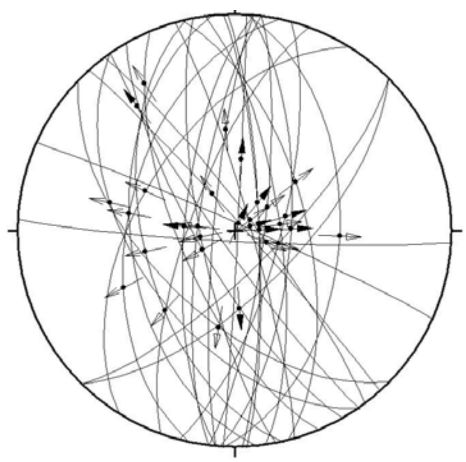

Figure 10. Lower-hemisphere, stereographic projections of 30 fault planes (great circles) and slip vectors (arrows), as measured from kinematic indicators (e.g., slickenlines, rough facets, and Riedel shears) in the vicinity of the Tuscarora geothermal field (from Dering, 2013). These data indicate normal displacement on northerly striking faults.

Task 5.3 Stress Determinations

1. **Planned Activities**: Stress determinations will be made for several of the sites selected for detailed study.
2. **Actual Accomplishments**:

- Fault kinematic data were acquired from the sites of detailed study and formed the basis of estimating stress orientations.
  - Neal Hot Springs: Fault kinematic data were inverted to obtain the local stress field (e.g., Marrett and Allmendinger, 1990; Figures 8 and 11). These data suggest that the stress field has changed since the late Miocene, with an earlier ~E-W least principal stress and present-day NE-SW-trending least principal stress (H_{min}). This suggests that earlier N-S-striking normal faults are now accommodating oblique

normal-sinistral slip and that the geothermal field lies within a small pull-apart zone in a left-stepping, northerly striking normal-sinistral fault zone. Borehole breakout data were not available for the Neal area.

- Patua – Fault kinematic data from this area were inverted to establish the stress field (Figures 9 and 12). These data indicate NW-trending least principal stress and essentially dip-slip motion on NNE-striking normal faults, which is compatible with regional geologic relations, GPS geodetic data, and borehole breakout data from the nearby Desert Peak and Brady's geothermal fields.
- Soda Lake: Slip data are not available for Soda Lake, because the geothermal field lies within the central part of a large basin. However, slip data from the nearby Hot Springs Mountains were inverted to estimate the stress field (Figure 12). These data indicate a NW-trending least principal stress, which is also compatible with borehole breakout data from Desert Peak.
- Tuscarora: Fault kinematic data were inverted to obtain the local stress field (Figures 10 and 13). Data suggest an E-W-trending least principal stress. However, extension has been occurring episodically in the Tuscarora area since the Miocene. Thus, the fault kinematic data and stress inversion may average out several episodes of extension and not fully reflect the present-day stress field. Borehole breakout data were not available for the Tuscarora area.

- Assessments were carried out to determine the availability of borehole breakout data in the detailed study areas, because such data would provide a more accurate view of current stresses, as compared to fault kinematic data since it is difficult to determine the ages of some fault surfaces.

3. **Explanation of Variance**: Not applicable.

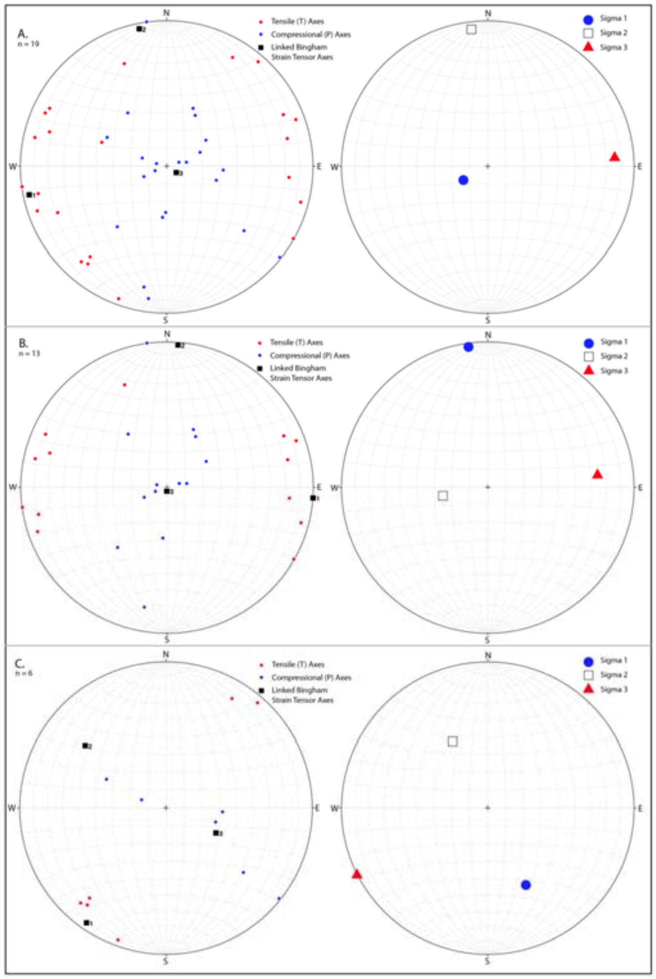

Figure 11. Stress field calculations for Neal Hot Springs shown on lower-hemisphere, equal area stereographic projections of P-compressional (blue dots) and T-tensile (red dots) axes, calculated linked Bingham strain axes (black squares), and average principal stress orientations (sigma 1: blue circle; sigma 2: square; sigma 3: red triangle), as derived from kinematic data (Edwards, 2013). A. All faults indicating west-trending (~260°) extension axis and least principal stress. B. Main fault population indicating west-trending extension axis and least principal stress. C. Fault subpopulation suggesting a southwest-trending extension axis and least principal stress. n = number of measurements.

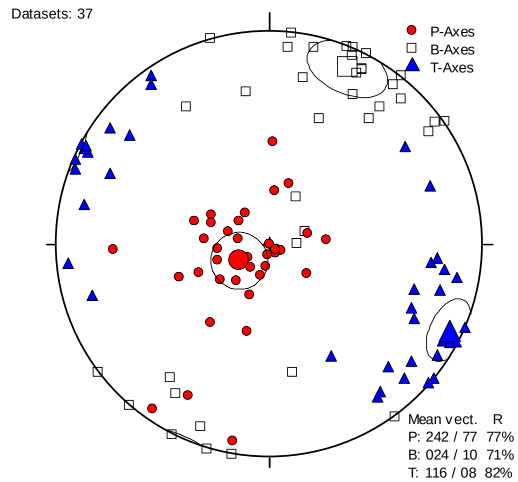

Figure 12. Stress field determination for Hot Springs Mountains and Patua geothermal field, as derived from fault kinematic data. Lower-hemisphere, equal area stereographic projections of P-compressional (red dots) and T-tensile (blue triangles) axes. Data indicate a WNW-trending least principal stress (~296°).

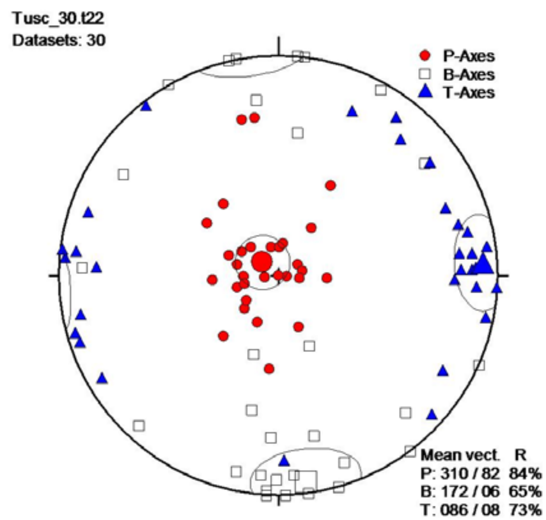

Figure 13. Stress field determination for the Tuscarora geothermal field, as derived from fault kinematic data (Dering, 2013). Lower-hemisphere, equal area stereographic projections of P-compressional (red dots) and T-tensile (blue triangles) axes. Data indicate an E-W-trending least principal stress.

Task 5.4 Gravity Surveys

1. **Planned Activities**: Gravity surveys were to accompany some of the detailed studies.

2. **Actual Accomplishments**: A detailed gravity survey was carried out for the entire Carson Sink in western Nevada (Figure 1) through a subcontract to Zonge Engineering, Inc. The Carson Sink is a large composite basin containing three known, blind high-temperature geothermal systems (Fallon Airbase, Stillwater, and Soda Lake). This area was chosen for a detailed gravity survey in order to characterize the gravity signature of the known geothermal systems and to identify other potential blind systems based on the structural setting indicated by the gravity data.

   Data: Data were acquired at approximately 400, 800, and 1600 meter intervals for a total of 1,243 stations. The project location and station location points are presented in Figure 14. The station distribution for this survey was designed to complete regional gravity coverage in the Carson Sink area without duplication of available public and private gravity coverage. Gravity data were acquired using a Scintrex CG-5 gravimeter and a LaCoste and Romberg (L&R) Model-G gravimeter. The CG-5 gravity meter has a reading resolution of 0.001 milligals and a typical repeatability of less than 0.005 milligals. The L&R gravity meter has a reading resolution of 0.01 milligals and a typical repeatability of 0.02 milligals. The basic processing of gravimeter readings to calculate through to the Complete Bouguer Anomaly was made using the Gravity and Terrain Correction software version 7.1 for Oasis Montaj by Geosoft LTD.

   Results: The gravity survey of the Carson Sink yielded the following products.
   - Project location and station location map (Figure 14).
   - Complete Bouguer Anomaly @ 2.67 gm/cc reduction density.
   - Gravity Complete Bouguer Anomaly at 2.50 g/cc Contour Map (Figure 15).
   - Gravity Horizontal Gradient Magnitude Shaded Color Contour Map.
   - Gravity 1st Vertical Derivative Color Contour Map.
   - Interpreted Depth to Mesozoic Basement (Figure 16), incorporating drill-hole intercept values.

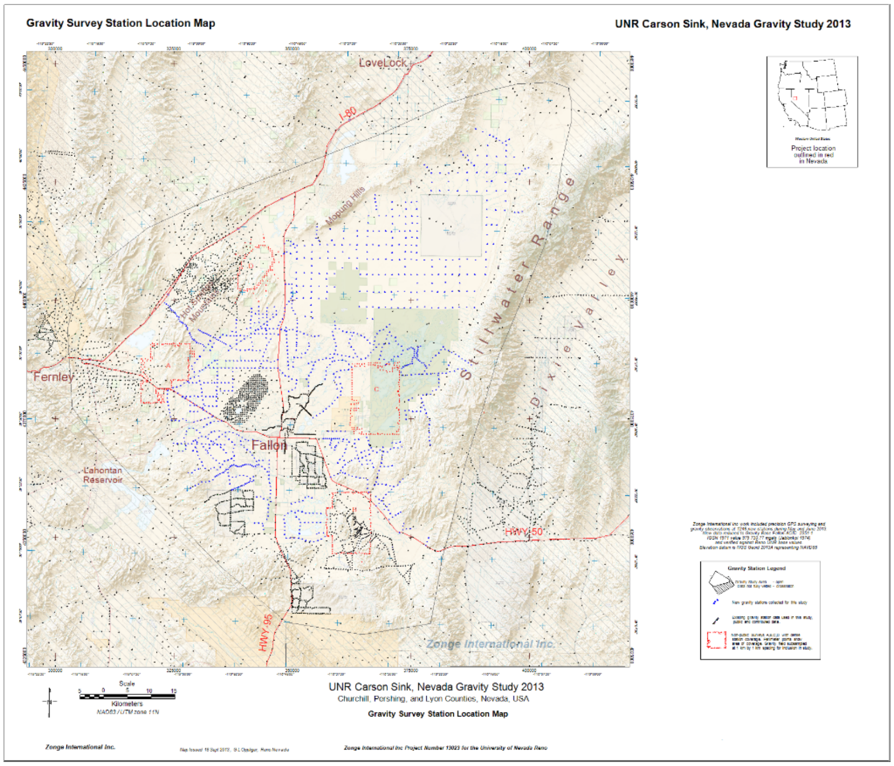

Figure 14. Project and station location map. A total of 1,246 new gravity stations were acquired in this study.

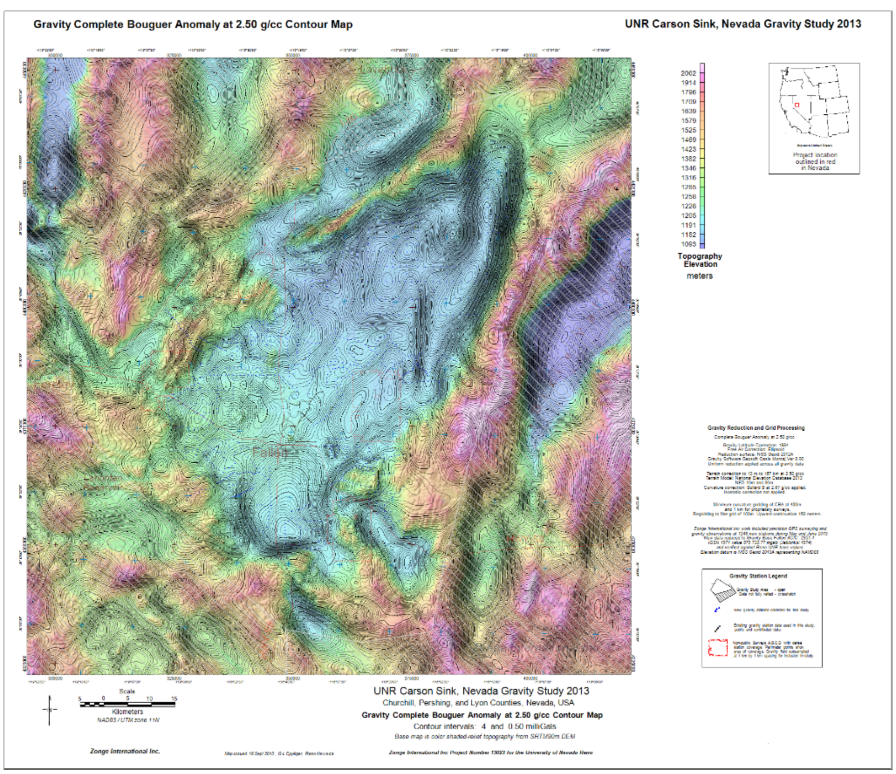

Figure 15. Gravity complete Bouguer anomaly at 2.50 g/cc contour map.

Preliminary Interpretation of Results:

- The Carson Sink is a complex composite basin with several major depocenters (Figures 15 and 16).
- Major depocenters are present in the south-central, east-central, and northeastern parts of the basin.
- The distribution of gravity anomalies suggests a complex pattern of faulting in the subsurface of the basin, with many fault terminations, step-overs, and accommodation zones.
- The pattern of faulting implies that other, previously undiscovered blind geothermal systems are likely in the Carson Sink.
- The gravity survey was completed near the end of this project. Thus, more thorough analysis of the data and potential locations of blind geothermal systems is planned for future work.

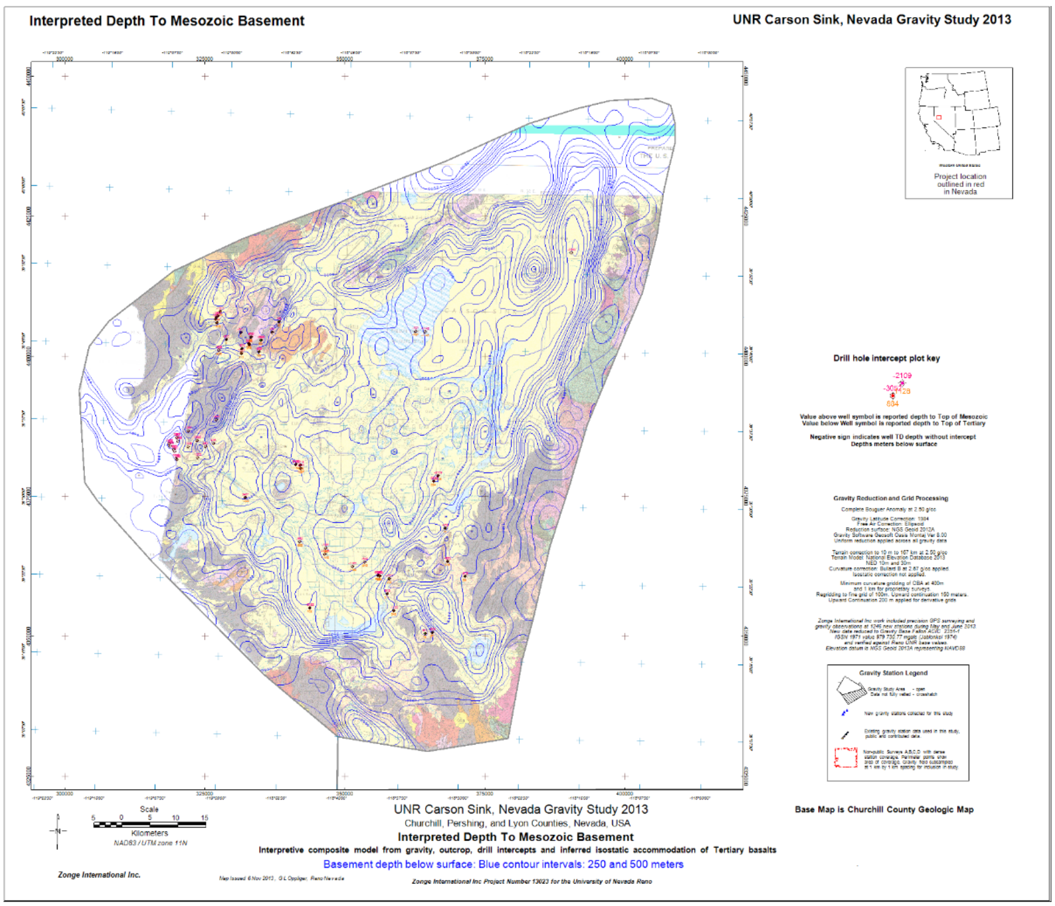

Figure 16. Interpreted depth to Mesozoic basement.

3. **Explanation of Variance**: Gravity surveys have not been needed in as many areas as originally planned, because industry has already completed such surveys at most of our sites selected for detailed study, including Tuscarora, Soda Lake, Gerlach, and Patua.

Task 5.5 Three-Dimensional Modeling

1. **Planned Activities**: Preliminary 3D modeling of 2-3 of the sites studied in detail was planned.

2. **Actual Accomplishments**: 3D models were completed by post-doctoral scholar Drew Siler for 4 geothermal systems – McGinness Hills, Neal Hot Springs, San Emidio, and Tuscarora. In addition, 3D models for two other systems, Salt Wells and Soda Lake, are in progress.

   Background: The 3D geologic models were built using EarthVision by Dynamic Graphics Inc. (Alameda, CA), using methods similar to that described by previous workers (Moeck et al., 2009 a, b, 2010; Jolie et al., 2012; Siler et al., 2012). The models were constructed based on 1:24,000 scale geologic maps and cross sections, lithologic analysis of well cuttings, locations of lost circulation during well drilling, interpretation of seismic reflection data, and gravity data and magnetic data (depending on data availability in each study). Faults were modeled based on mapped surface traces, seismic reflection interpretation, geologic cross-sections, presence of slickenlines and/or fault gouge in the well cuttings, and the depths of major zones of lost circulation during drilling.

   McGinness Hills, central Nevada:

- Structural Setting: This geothermal system lies in a ~8.5 km wide, north-northeast trending accommodation zone defined by east-dipping normal faults bounding the Toiyabe Range to the west and west-dipping normal faults bounding the Simpson Park Mountains to the east. Within this broad accommodation zone lies a fault step-over defined by north-northeast striking, west-dipping normal faults which step to the left at the McGinness Hills geothermal system.
- The McGinness Hills 3D model consists of 9 geologic units and 41 faults (Figure 17).
  - The basal geologic units are metasedimentary rocks of the Ordovician Valmy and Vininni Formations (undivided in model), which are intruded by Jurassic granite.
  - Unconformably overlying is a ~100s m-thick section of Tertiary andesitic lava flows and four Oligocene-to-Miocene ash-flow tuffs: The Rattlesnake Canyon Tuff, tuff of Sutcliffe, the Campbell Creek Tuff, and the Nine Hill tuff.
  - Overlying are sequences of pre-to-syn-extensional Quaternary alluvium and post-extensional Quaternary alluvium.
  - 10-15º eastward dip of the Tertiary stratigraphy is controlled by the predominant west-dipping fault set.
- Geothermal production is from two west-dipping normal faults in the northern limb of the step-over.
- Injection is into west-dipping faults in the southern limb of the step over. Production and injection sites are in hydrologic communication, but at a deep level, as the northwest-striking fault that links the southern and northern limbs of the step-over has no permeability.

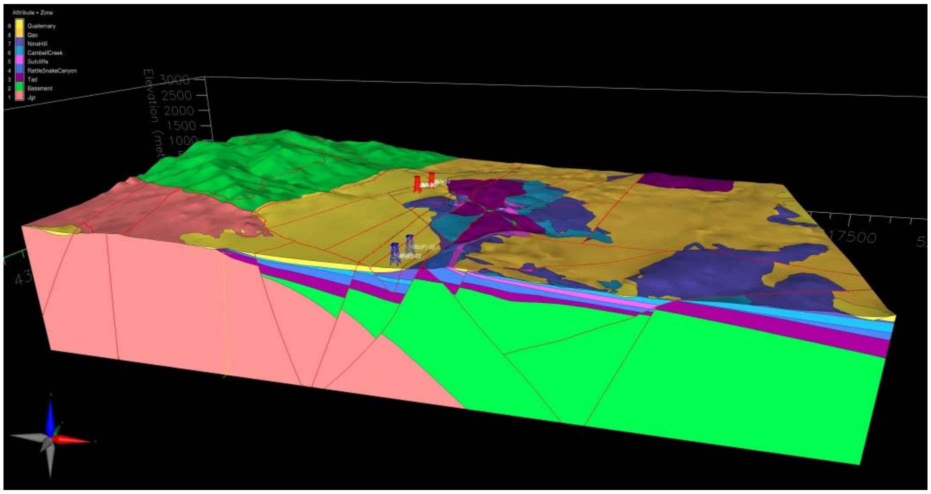

Figure 17. View looking north at the 3D model of the McGinness geothermal system. Production wells are shown in red; injection wells in blue.

Neal Hot Springs, eastern Oregon:

- Structural Setting: The Neal Hot Springs geothermal system lies in a left-step in a north-striking, west-dipping normal fault system, consisting of the Neal fault to the south and the Sugarloaf Butte fault to the north (Edwards, 2013). The step-over may be accommodating sinistral-normal oblique slip and thus also acting a small pull-apart zone.
- The 3D geologic model consists of 104 faults and 13 stratigraphic units (Figure 18).
  - The stratigraphy consists of Miocene to Pliocene volcanic and sedimentary rocks overlain by Quaternary alluvial fan deposits.
  - Strata are subhorizontal to gently dipping (<15°) with tilts to both the east and west.
- Geothermal production is exclusively from the Neal fault south of, and within the step-over.
- Geothermal injection is into both the Neal fault to the south of the step-over and faults within the step-over.

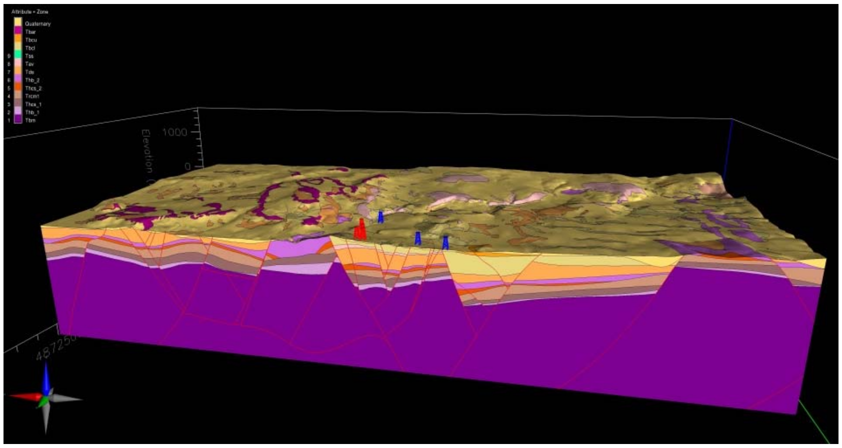

Figure 18. View looking south at the 3D model of the Neal geothermal system. Production wells are shown in red; injection wells in blue.

San Emidio, northwestern Nevada:

- Structural Setting: The San Emidio geothermal system is characterized by a right-step in a west-dipping normal fault zone that bounds the western side of the Lake Range.
- The 3D geologic model consists of 5 geologic units and 55 faults (Figure 19).
  - The basement consists of Jurassic-Triassic metasedimentary basement.
  - The basement is overlain by a ~500-1000 m thick section of middle Miocene mafic volcanic rocks and intercalated sedimentary lenses.
  - Quaternary sedimentary deposits mantle all older rock units.
  - The 15-30º eastward dip of the fault blocks is controlled by the predominant west-dipping fault set.
- Both geothermal production and injection are concentrated north of the step over in an area of closely-spaced west-dipping normal faults.

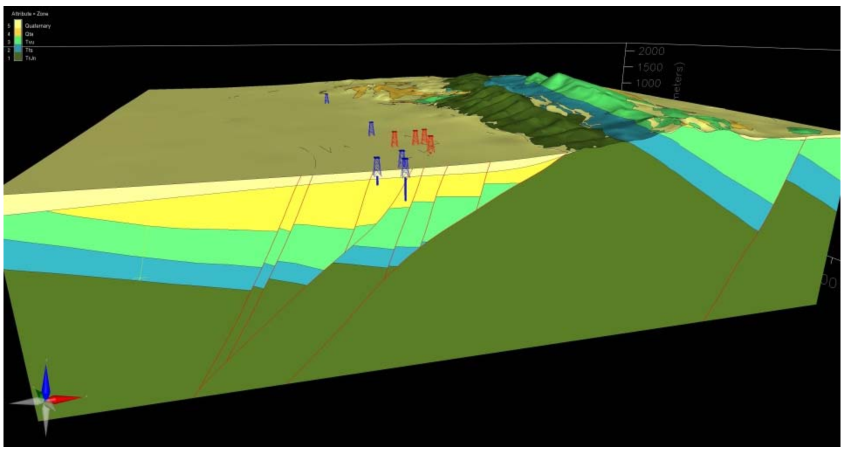

Figure 19. View looking north at the 3D model of the San Emidio geothermal system. Production wells are shown in red; injection wells in blue.

Tuscarora, northeast Nevada:

- Structural Setting: The Tuscarora geothermal system sits within a ~15 km wide left-step in a major west-dipping, range-bounding normal fault system. The step-over is defined by the Independence Mountains fault zone and the Bull Runs Mountains fault zone which overlap along strike. Strain is transferred between these major fault segments via an array of northerly striking normal faults with offsets of 10s to 100s of meters and strike lengths of less than 5 km. These faults within the step-over are one to two orders of magnitude smaller than the range-bounding fault zones between which they reside. Faults within the broad step define an anticlinal accommodation zone, wherein east-dipping faults mainly occupy the western half of the accommodation zone and west-dipping faults lie in the eastern half of the accommodation zone. The geothermal system resides in the axial part of the accommodation, straddling the two fault dip domains.
- The 3D model of Tuscarora encompasses 70 small-offset normal faults that define the accommodation zone and a portion of the Independence Mountains fault zone, which dips beneath the geothermal field.
- The Tuscarora 3D geologic model consists of 10 stratigraphic units (Figure 20).
  - Paleozoic basement of consists metasedimentary and metavolcanic rocks, dominated by argillite, siltstone, limestone, quartzite, and metabasalt of the Schoonover and Snow Canyon Formations. Paleozoic formations are lumped in a single basement unit

in the model.
  - Eocene felsic volcanic rocks of the Big Cottonwood Canyon caldera overlie the Paleozoic basement. These units are modeled as intracaldera deposits, including domes, flows, and thick tuffaceous deposits that change in thickness and locally pinch out.
  - The youngest and stratigraphically highest bedrock units are middle Miocene rhyolite and dacite flows, regionally correlated with the Jarbidge Rhyolite and modeled with uniform cumulative thickness of ~350 m.
  - Unconsolidated Quaternary alluvium overlies all older rock units.
  - Fault blocks in the eastern portion of the model are tilted 5-30° east toward the Independence Mountains fault zone. Fault blocks in the western portion of the model are tilted west toward steeply east-dipping normal faults. These opposing fault block define a narrow extensional anticline.
- Geothermal production is from 4 closely-spaced wells that exploit a west-dipping, NNE-striking fault zone near the axial part of the accommodation zone.

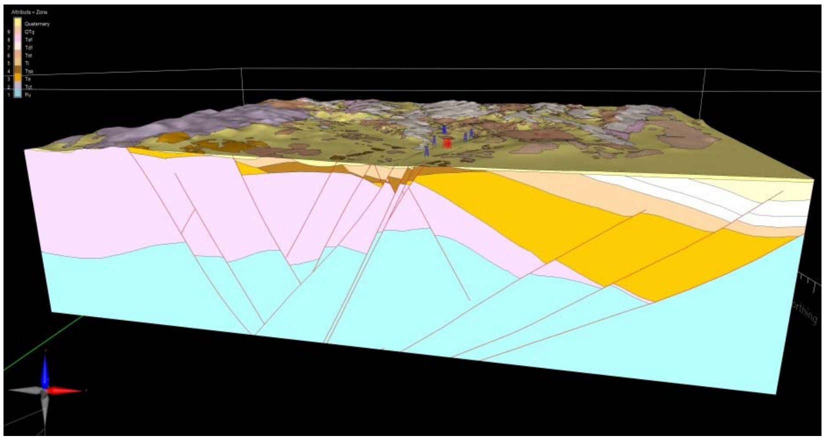

Figure 20. View looking north at the 3D model of the Tuscarora geothermal system. Production wells are shown in red; injection wells in blue.

3. **Explanation of Variance**: Not applicable. However, the GFZ in Germany was originally scheduled to carry out this task, but could not do the work, because Dr. Inga Moeck obtained another position and had no time for this project. The subcontract funds to the GFZ were therefore re-budgeted for post-doc Siler at UNR.

Task 5.6 Slip Tendency Analysis

1. **Planned Activities**: Slip and dilation tendency analysis was planned for representative geothermal fields in the Great Basin region selected for detailed study.

2. **Actual Accomplishments**: Based on available data generated either in this study or from previous studies, slip and dilation tendency analyses were completed for the McGinness Hills, Neal, Patua, Salt Wells, San Emidio, and Tuscarora geothermal fields. Methods and results are discussed below.

   Background: Critically stressed fault segments have a relatively high likelihood of acting as fluid flow conduits (Sibson, 1994). As such, the tendency of a fault segment to slip (slip tendency; Ts; Morris et al., 1996) or to dilate (dilation tendency; Td; Ferrill et al., 1999) provides an indication of which faults or fault segments within a geothermal system are critically stressed and therefore likely to transmit geothermal fluids.

The slip tendency of a surface is defined by the ratio of shear stress to normal stress on that surface: $T_s = \tau / \sigma_n$ (Morris et al., 1996).

Dilation tendency is defined by the stress acting normal to a given surface:
$T_d = (\sigma_1 - \sigma_n) / (\sigma_1 - \sigma_3)$ (Ferrill et al., 1999).

Slip and dilation were calculated using 3DStress (Southwest Research Institute). Slip and dilation tendency are both unit-less ratios of the resolved stresses applied to the fault plane by ambient stress conditions. Values range from a maximum of 1 (a fault plane ideally oriented to slip or dilate under ambient stress conditions) to zero (fault plane with no potential to slip or dilate).

Slip and dilation tendency values were calculated for each fault in the focus study areas at McGinness Hills, Neal Hot Springs, Patua, Salt Wells, San Emidio, and Tuscarora on fault traces. As dip is not well constrained or unknown for many faults mapped within these areas, the calculations used the dip for each fault that would yield the maximum slip tendency or dilation tendency. As such, these results should be viewed as maximum tendency of each fault to slip or dilate. The resulting along-fault and fault-to-fault variation in slip or dilation potential is a proxy for along fault and fault-to-fault variation in fluid flow conduit potential.

The stress field variation within each focus area was approximated based on regional published data and the world stress database (Hickman et al., 2000; Hickman et al., 1998 Robertson-Tait et al., 2004; Hickman and Davatzes, 2010; Davatzes and Hickman, 2006; Blake and Davatzes 2011; Blake and Davatzes, 2012; Moeck et al., 2010; Moos and Ronne, 2010 and Reinecker et al., 2005), as well as local stress information if applicable. For faults within these focus systems, we applied either 1) a normal faulting stress regime, where the vertical stress (sv) is larger than the maximum horizontal stress (shmax), which is larger than the minimum horizontal stress (sv>shmax>shmin); or 2) a strike-slip faulting stress regime, where the maximum horizontal stress (shmax) is larger than the vertical stress (sv), which is larger than the minimum horizontal stress (shmax >sv>shmin) depending on the general tectonic province of the system. Based on visual inspection of the limited stress magnitude data in the Great Basin, we used magnitudes such that shmin/shmax = .527 and shmin/sv= .46, which are consistent with complete and partial stress field determinations from Desert Peak, Coso, the Fallon area, and Dixie valley (Hickman et al., 2000; Hickman et al., 1998 Robertson-Tait et al., 2004; Hickman and Davatzes, 2011; Davatzes and Hickman, 2006; Blake and Davatzes 2011; Blake and Davatzes, 2012).

McGinness Hills, central Nevada:

- Slip and dilation tendency for the McGinness Hills geothermal field (Figure 21) were calculated based on geologic mapping by Siler (unpublished, 2012).
- Because the McGinness Hills area lies in the Basin and Range Province, we applied a normal faulting stress regime, with a minimum horizontal stress direction oriented

115, based on inspection of local and regional stress determinations, as explained above.

- Under these stress conditions, NNE-striking, steeply dipping fault segments have the highest dilation tendency, whereas NNE-striking 60° dipping fault segments have the highest tendency to slip.
- The McGinness Hills geothermal system is characterized by a left-step in a NNE-striking, W-dipping fault system within a north NE-trending accommodation zone. As such, the normal faults that define these two structures are well oriented for both slip and dilation, including the W-dipping faults exploited for both production and injection.
- Interestingly, although there is pressure communication between production and injection wells at McGinness Hills (B. Delwiche, personal comm.), the NW-striking fault, which generates hard linkage between the production and injection locations, is poorly oriented for both slip and dilation and therefore unlikely to host permeability.

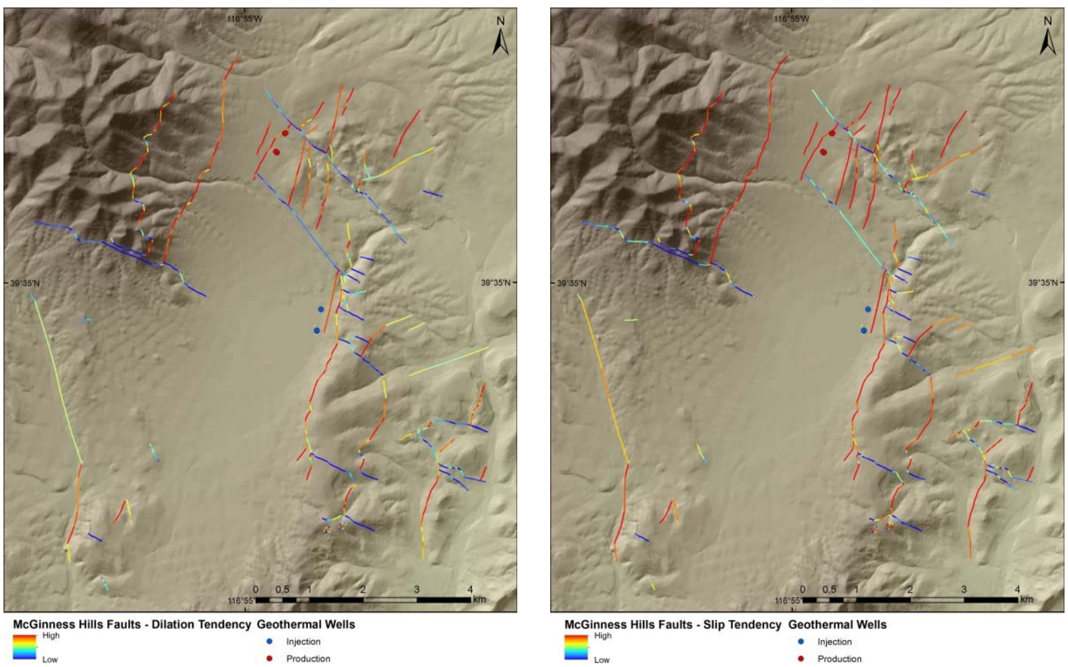

Figure 21. Dilation tendency (left) and slip tendency (right) at McGinness Hills, central Nevada. Warmer colors correspond to higher dilation and slip tendencies on area faults. Small circles show locations of production (red) and injection wells (blue).

Neal Hot Springs, eastern Oregon:

- Based on inversion of fault kinematic data, Edwards (2013) concluded that two discrete stress fields are recorded at Neal Hot Springs—An older episode of east-west directed extension and a younger episode of southwest-northeast directed extension. This interpretation is consistent with the evolution of Cenozoic tectonics in the region (Edwards, 2013).

- As such, we applied a southwest-northeast (060) directed normal faulting stress regime, consistent with the younger extensional episode, to the Neal Hot Springs faults.
- Under these stress conditions, NE-striking steeply dipping fault segments have the highest tendency to dilate, and NE-striking 60° dipping fault segments have the highest tendency to slip (Figure 22).
- Under these stress conditions, both the Neal Fault and Sugarloaf Butte faults are well-oriented for both slip and dilation and thus for fracture permeability.
- In addition, several subsidiary faults on the eastern side and within the step-over between the Neal and Sugarloaf Butte faults are well oriented for slip and dilation.

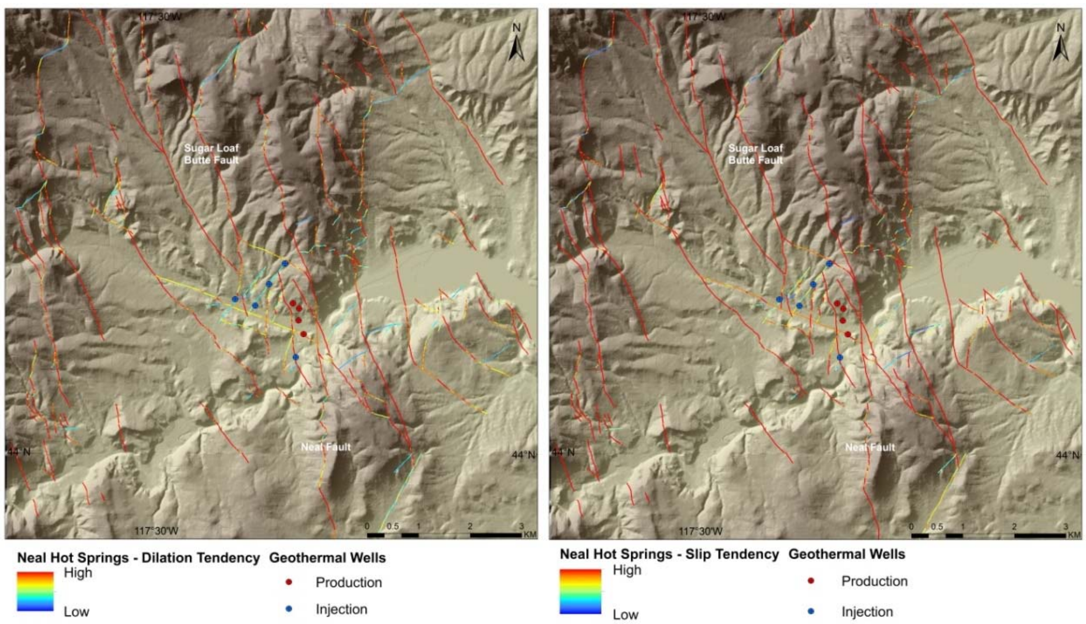

Figure 22. Dilation tendency (left) and slip tendency (right) at Neal Hot Springs, eastern Oregon. Warmer colors correspond to higher dilation and slip tendencies on area faults. Small circles show locations of production (red) and injection wells (blue). Faults were mapped by Edwards (2013).

Patua, western Nevada:

- Slip and dilation tendency for the Patua geothermal system (Figure 23) were calculated based on faults mapped in the Hazen Quadrangle by Faulds et al. (2011).
- Patua lies near the boundary between the Basin and Range province, characterized by west-northwest directed extension, and the Walker Lane belt, characterized by west-northwest directed dextral shear. As such, the Patua area likely has been affected by tectonic stress associated with both stress regimes.
- In order to characterize this stress variation, we calculated slip tendency at Patua for both normal and strike-slip faulting stress regimes. Based on examination of regional and local stress data (as explained above), we applied an shmin direction of 105° to Patua.
- Whether the vertical stress (sv) magnitude is larger than the maximum horizontal stress (shmax), as in a normal faulting stress regime, or the maximum horizontal

stress (shmax) magnitude is larger than the vertical stress (sv), as in a strike-slip faulting stress regime, has very little effect on the dilation tendency, which is controlled by the stresses acting normal to fault planes. Thus, the dilation tendency results for a strike-slip faulting stress regime and for a normal faulting stress regime are virtually identical.

- We therefore present one result for dilation tendency applicable to both strike-slip and normal faulting stress conditions along with slip tendency for both a normal faulting and a strike-slip faulting stress regime.
  - Under these stress conditions, NNE- striking steeply dipping fault segments have the highest dilation tendency.
  - Under the strike-slip faulting stress regime, NNW- and ENE-striking, steeply dipping faults have the highest slip tendency, whereas under normal faulting conditions NNE-striking, 60° dipping faults have the highest slip tendency.

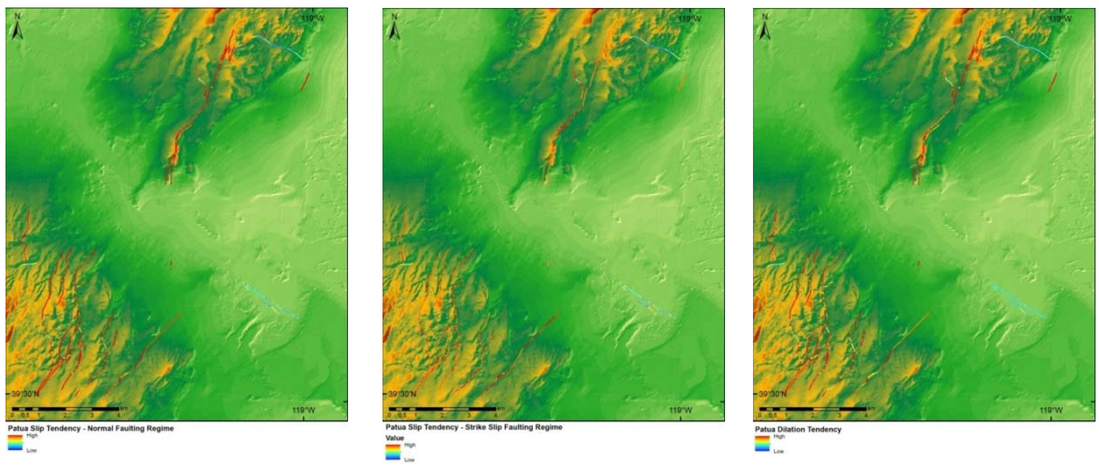

Figure 23. Slip and dilation tendency at Patua geothermal field, western Nevada. Slip tendency in a normal faulting regime is shown on left; slip tendency in a strike-slip faulting regime is shown in middle; dilation tendency for both normal and strike-slip regimes is shown on right. Warmer colors correspond to higher dilation and slip tendencies on area faults. Faults were mapped by Faulds et al. (2011).

Salt Wells, western Nevada:

- Slip and dilation tendency for the Salt Wells geothermal field (Figure 24) were calculated based on faults mapped in the Bunejug Mountains Quadrangle by Hinz et al. (2011).
- The Salt Wells area lies in the Basin and Range province. As such, we applied a normal faulting stress regime to area faults, with a minimum horizontal stress oriented 105° based on inspection of local and regional stress determinations.
- Under these stress conditions, NNE- striking, steeply dipping fault segments have the highest dilation tendency.
- NNE-striking 60° dipping fault segments have the highest tendency to slip.
- Several such faults intersect in high density in the axial part of the accommodation zone within and proximal to the Salt Wells geothermal field.

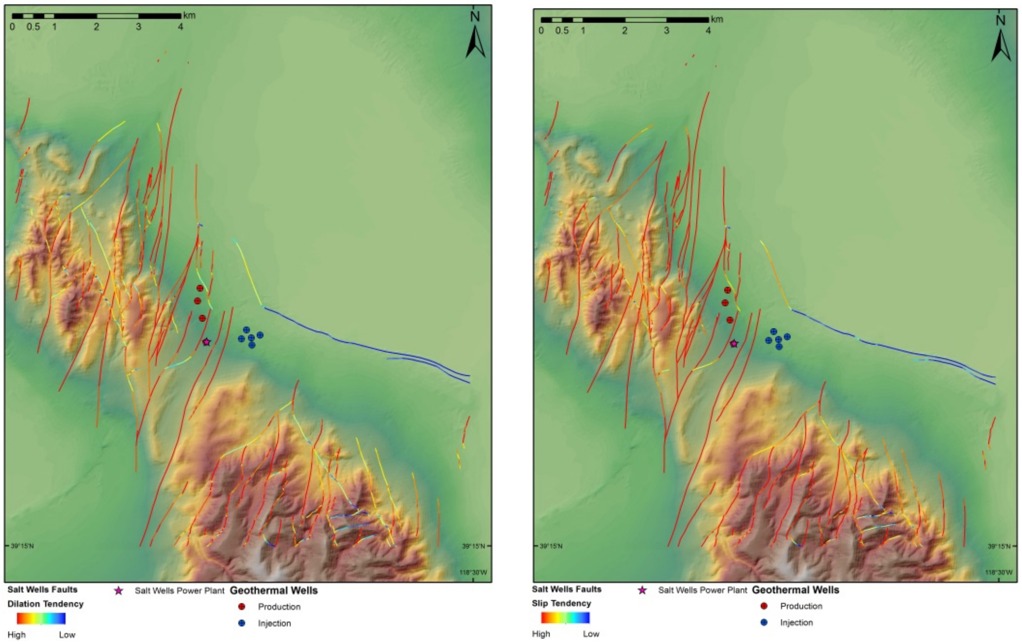

Figure 24. Dilation tendency (left) and slip tendency (right) at Salt Wells, western Nevada. Warmer colors correspond to higher dilation and slip tendencies on area faults. Small circles show locations of production (red) and injection wells (blue). Faults were mapped by Hinz et al. (2011).

San Emidio, northwest Nevada:

- Slip and dilation tendency for the San Emidio geothermal field (Figure 25) were calculated based on the faults mapped by Rhodes et al. (2012).
- The San Emidio area lies in the Basin and Range province. We therefore applied a normal faulting stress regime to area faults, with a minimum horizontal stress direction oriented 115°, based on inspection of local and regional stress determinations, as explained above. This is consistent with the shmin determined through inversion of fault data by Rhodes (2011).
- Under these stress conditions, NNE-striking, steeply dipping fault segments have the highest dilation tendency, whereas NNE-striking 60° dipping fault segments have the highest tendency to slip.
- Interestingly, the San Emidio geothermal field lies in an area of primarily N-striking faults, which have moderate dilation tendency and moderate to low slip tendency.

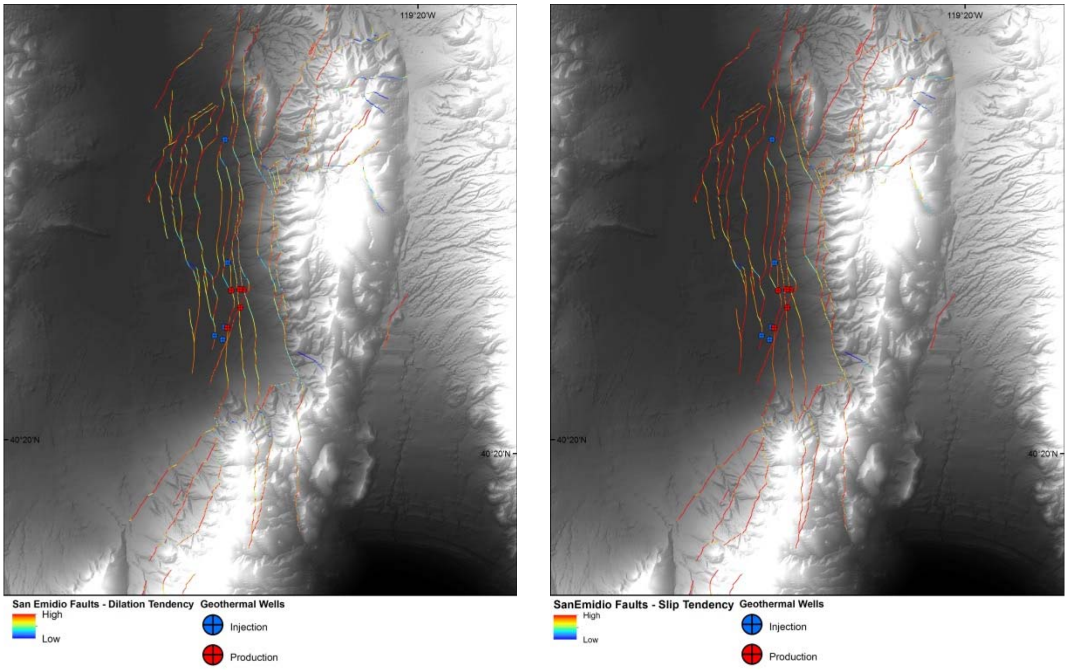

Figure 25. Dilation tendency (left) and slip tendency (right) at San Emidio, northwestern Nevada. Warmer colors correspond to higher dilation and slip tendencies on area faults. Small circles show locations of production (red) and injection wells (blue). Faults were mapped by Rhodes et al. (2012).

Tuscarora:

- Slip and dilation tendency for the Tuscarora geothermal field (Figure 26) were calculated based on the geologic mapping of Dering and Faulds (2013).
- The Tuscarora area lies in the Basin and Range province. Thus, we applied a normal faulting stress regime to the Tuscarora area faults, with a minimum horizontal stress oriented 115°, based on inspection of local and regional stress determinations.
- Under these stress conditions, NNE-striking, steeply dipping fault segments have the highest dilation tendency, whereas NNE-striking 60° dipping fault segments have the highest tendency to slip.
- Tuscarora is defined by a left-step in a major N- to NNE-striking, W-dipping range-bounding normal fault system.
- Faults within the broad step define an anticlinal accommodation zone wherein E-dipping faults mainly occupy the western half of the accommodation zone, and W-dipping faults lie in the eastern half of the accommodation zone.
- The geothermal system resides in the axial part of the accommodation zone, straddling the two fault-dip domains.
- Within the axial part of the accommodation zone several W-dipping, NNE-striking faults are well oriented for both slip and dilation, including fault strands exploited for both production and injection for the Tuscarora geothermal power plant.

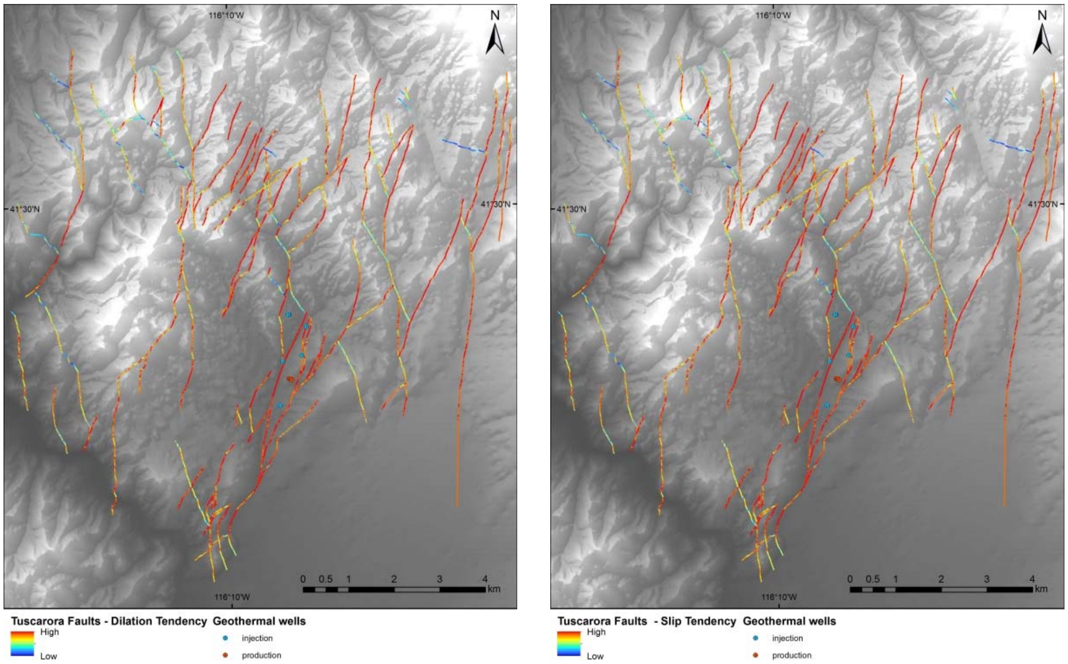

Figure 26. Dilation tendency (left) and slip tendency (right) at Tuscarora, northeast Nevada. Warmer colors correspond to higher dilation and slip tendencies on area faults. Small circles show locations of production (red) and injection wells (blue). Faults were mapped by Dering and Faulds (2013).

3. **Explanation of Variance**: Not applicable. However, the GFZ in Germany was originally scheduled to carry out this task, but could no longer do the work as Dr. Inga Moeck obtained another position and had no time for this project. The subcontract funds to the GFZ were therefore re-budgeted for post-doc Siler at UNR to carry out this work.

Task 5.7 GIS Database Compilation

1. **Planned Activities**: Generate geodatabases, shapefiles, and spreadsheets of geological and geophysical data for sites undergoing detailed studies.

2. **Actual Accomplishments**: For the following geothermal fields, geologic maps, cross-sections, geochronologic data, geochemical data, and well data were compiled in geodatabase format and combined with available geophysical data.

- MacFarlane Hot Springs —ESRI geodatabase (ArcGeology v1.3):
  - Geologic map data in shapefile format that includes faults, unit contacts, unit polygons, attitudes of strata and faults, and surficial geothermal features, including travertine fissure ridges and travertine deposits.
  - 2 m temperature probe data.
  - Historic temperature gradient hole data.
- Neal Hot Springs—ESRI geodatabase (ArcGeology v1.3):
  - Contains all the geologic map data, including faults, contacts, folds, unit polygons, and attitudes of strata and faults.
  - List of stratigraphic units and stratigraphic correlation diagram.

  - Three cross-sections.
  - Locations of production, injection, and exploration wells.
  - Locations of 40Ar/39Ar samples.
  - Location of XRF geochemical samples.
  - 3D model constructed with EarthVision using geologic map data, cross-sections, drill-hole data, and geophysics (model not in the ESRI geodatabase).
- Patua—ESRI geodatabase (ArcGeology v1.3):
  - Contains all the geologic map data, including faults, contacts, folds, veins, dikes, unit polygons, and attitudes of strata and faults.
  - List of stratigraphic units.
  - Locations of geothermal wells.
  - Locations of 40Ar/39Ar and tephra samples.
- Salt Wells—ESRI geodatabase (ArcGeology v1.3):
  - Contains all the geologic map data, including faults, contacts, folds, dikes, unit polygons, and attitudes of strata and faults.
  - List of stratigraphic units and stratigraphic correlation diagram.
  - Locations of 40Ar/39Ar samples.
- Tuscarora—ESRI geodatabase (ArcGeology v1.3):
  - Contains all the geologic map data, including faults, contacts, folds, unit polygons, and attitudes of strata and faults.
  - List of stratigraphic units and stratigraphic correlation diagram.
  - Detailed unit descriptions of stratigraphic units.
  - Five cross-sections.
  - Locations of production, injection, and monitor wells.
  - 3D model constructed with EarthVision using geologic map data, cross-sections, drill-hole data, and geophysics (model not in the ESRI geodatabase).
- Wabuska—ESRI geodatabase (ArcGeology v1.3):
  - Contains all the geologic map data, including faults, contacts, folds, veins, dikes, unit polygons, and attitudes of strata.
  - List of stratigraphic units and stratigraphic correlation diagram.
  - One cross-section.

For the following geothermal fields, geologic map data, well data, and structural data were compiled in shapefiles and spreadsheets.

- Columbus Marsh:
  - Shapefile and spreadsheet of structural data, including attitudes of faults and strata and slip orientations of faults.
- Gerlach:
  - Spreadsheet of structural data, including faults, joints, and veins.
  - Spreadsheet of 2m temperature probe data.
- McGinness Hills:
  - Geologic map data in shapefile format that includes faults, unit contacts, unit polygons, attitudes of strata and faults, and surficial geothermal features.
  - 5 cross-sections in Adobe Illustrator format.
  - Comprehensive catalogue of drill-hole data in spreadsheet, shapefile, and Geosoft database formats. Includes XYZ locations of well heads, year drilled, type of well,

operator, total depths, well path data (deviations), lithology logs, and temperature data.
    - 3D model constructed with EarthVision using geologic map data, cross-sections, drill-hole data, and geophysics.
- Soda Lake:
    - Comprehensive catalogue of drill-hole data in spreadsheet, shapefile, and Geosoft database formats. Includes XYZ locations of well heads, year drilled, type of well, operator, total depths, well path data (deviations), lithology logs, and temperature data.
    - 13 cross-sections in Adobe Illustrator format.

3. **Explanation of Variance**: Not applicable.

Task 6 – Develop and Teach Geothermal Exploration Class

1. **Planned Activities**: A graduate level class in geothermal exploration (Geol-702G) will be prepared and taught at UNR during Spring Semester, 2011.

2. **Actual Accomplishments**: PI Faulds taught a graduate level course in Geothermal Exploration (Geol-702G) during the Spring Semester, 2011. Twenty students attended the course, and evaluations were excellent. The course included an overview of geothermal systems from various tectonic settings throughout the world (e.g., Turkey, Italy, New Zealand, Indonesia, and the western U.S.), three major field trips, and term papers that focused on the structural setting of geothermal fields in the western U.S. This was the first course in geothermal exploration taught at UNR and first such course taught by Faulds.

3. **Explanation of Variance**: Not applicable.

Task 7 – Completion of Detailed Studies

1. **Planned Activities**: Detailed studies of 5-6 representative sites were planned. Detailed studies of 10 sites were actually carried out.

2. **Actual Accomplishments**: Studies were completed for 6/7 of the 10 sites chosen for analysis. Details are described under Task 5 above.

- Detailed studies were completed for the following geothermal systems:
    - Columbus Marsh in west-central Nevada.
    - MacFarlane Hot Springs in northwest Nevada.
    - McGinness Hills in central Nevada.
    - Neal Hot Springs in eastern Oregon.
    - Salt Wells in western Nevada.
    - Tuscarora in northeastern Nevada.
    - Wabuska in western Nevada.
- Substantial work was completed on the following systems, but full completion of the detailed studies is slated for Spring 2014, as graduate students complete their thesis work and/or research geologists have time to finalize models.
    - Gerlach – awaiting the completion of M.S. thesis by Lyndsay Hazelwood.

  - Patua – awaiting integration of geologic and geophysical data, when the latter is provided by Gradient Resources, Inc.
  - Salt Wells – essentially complete, but a 3D model will be prepared by Hinz after completion of additional cross sections.
  - Soda Lake – Ph.D. candidate Holly McLachlan will complete final integration of geologic and geophysical data and generate a 3D model.

3. **Explanation of Variance**: Not applicable.

Task 8 – Comparative Analysis

1. **Planned Activities**: On the basis of the inventory of structural settings of geothermal systems throughout the Great Basin, initial comparative analysis on the relative proportions of certain settings in different regions was conducted.

2. **Actual Accomplishments**:

- Regional variations in favorable structural settings were analyzed. The dominant structural controls on geothermal systems differ between regions, suggesting guidelines for geothermal exploration. Findings include:
  - Faults related to geothermal systems in southeastern Oregon preferentially strike northwest (an anomaly true only of this study area); step-overs and fault intersections are the most common structural controls.
  - The Basin and Range of central Nevada has the strongest preferred fault orientation, NNE. The most common settings are step-overs, fault terminations, and accommodation zones (in that order).
  - Faults related to geothermal systems in western Utah have a N to NE preferred orientation, but there are subsidiary faults at a high angle to these. Fault intersections are the most common structural control in Utah and are more prevalent here than in any other parts of the Great Basin region.
  - The Walker Lane of western Nevada exhibits the most diverse range of fault orientations and of structural controls on geothermal systems. Pull-aparts are the most common, with fault intersections and fault terminations also in abundance.
  - A GRC paper describing these results was presented at the 2012 GRC meeting (Cashman et al., 2012).
- The abundance of geothermal fields was compared to strain rates in various parts of the Great Basin region. A direct correlation between strain rates and the density of geothermal systems, particularly high-temperature systems, was observed. We also found that power plant capacity directly correlates with strain rate. A paper describing these results was presented at the 2012 GRC meeting (Faulds et al., 2012).

3. **Explanation of Variance**: Not applicable.

Task 9 – Completion of Structural Catalogue

1. **Planned Activities**: Completion of the structural catalogue was scheduled for Phase III as the project ended and all data sets were complete.

2. **Actual Accomplishments**: A structural catalogue was completed for the 426 known geothermal systems in the Great Basin region study area. This list of systems in spreadsheet format was initially populated with data from Coolbaugh et al. (2003), including the names of the geothermal systems, measured temperature, geothermometry, and association with magmatism. Names were modified for a number of systems based on common names now widely accepted by industry (e.g., Salt Wells and Wild Rose). Temperature and geothermometry data were updated from field measurements conducted in this study, published reports, and public data archives. Some systems were removed from the initial list and some were added based on availability of better quality data than available for the original study (Coolbaugh et al., 2003). Specific data fields in this structural catalogue spreadsheet include the following general categories of data:
   - Name (plus unique GIS ID #).
   - Temperature (measured and geothermometry).
   - Field Visit (Yes/No).
   - Structural setting (Primary and Secondary categories).
   - Strike direction of major controlling faults.
   - Blind (Yes/No).
   - Magmatic (Yes/No).
   - Association with Quaternary faulting (age of faulting and distance).
   - Latitude/Longitude location in decimal degrees, NAD 1983.

3. **Explanation of Variance**: Not applicable.

Task 10 – Development of Exploration Strategies

1. **Planned Activities**: Based on our compilation of structural settings of geothermal systems in the Great Basin, the implications on exploration strategies will be addressed in various papers and presentations.

2. **Actual Accomplishments**: The implications of our findings on geothermal exploration strategies were presented at various meetings and workshops throughout the period of this project. This includes publication of 16 papers, 11 abstracts, and >50 presentations.

   Major implications on exploration strategies include:
   - Nearly all known geothermal systems occur within eight types of structural settings.
   - ~90% of known systems reside in four types of structural settings.
   - Our data suggest that exploration for blind geothermal systems should focus on only a handful of structural settings, with the most common being fault step overs, fault terminations, fault intersections, and accommodation zones.
   - Some of the most robust high-enthalpy geothermal systems, including many that host power plants (e.g., Steamboat, Dixie Valley, Brady's, and McGinness Hills) are hybrid systems and contain more than one favorable structural setting (Faulds et al., 2013).
   - Systematic exploration strategies should focus both on the regional level (where to look in the first place) and then on the site-specific scale (detailed investigations of individual systems, e.g. play-fairway analysis.

- Within broad structural settings, such as accommodation zones, the most favorable localities for geothermal activity appear to be those areas with the greatest density of faulting.
- Play-fairway analysis integrates structure, lithology, temperature, fault intersection density, and slip and dilation tendency analysis. It is absolutely critical for selecting the best drilling targets.
- 3D modeling indicates that fault controlled geothermal reservoirs occur along fault segments that have high slip and dilation tendency.
- 3D modeling indicates that most geothermal wells produce from areas with high fault density.
- Where good exposures are present, detailed geologic mapping and structural analysis in the initial exploration phase can greatly reduce the risks in drilling successful wells and thus greatly improve the economics of developing a geothermal system.
- A recommended workflow involves detailed geologic mapping, structural analysis (e.g., fault kinematic studies, estimation of stress field, slip and dilation tendency analysis), geochemical analysis, analysis of cuttings and/or core, and integration of geophysical data, 3D modeling, and play fairway analysis (Figure 27).

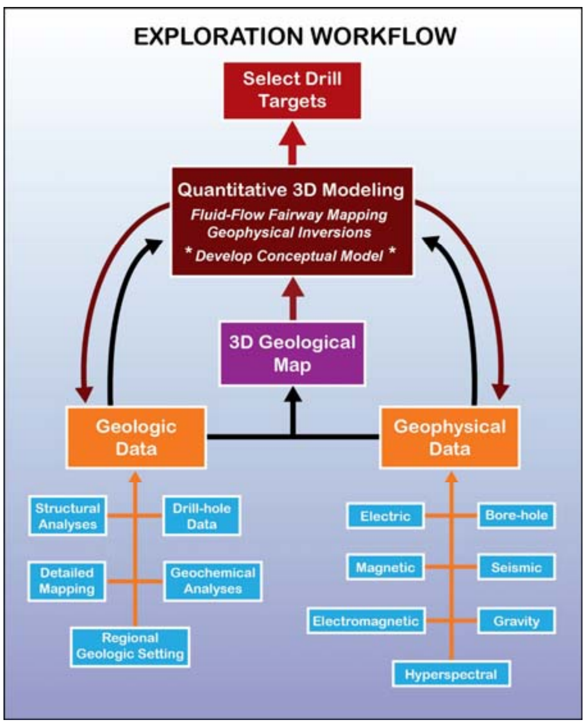

Figure 27. Recommended workflow for analyses of geothermal systems.

3. **Explanation of Variance**: Not applicable.

Task 11 – Project Management and Reporting

1. **Planned Activities**: In addition to providing the required quarterly and annual reports, results will be presented at various meetings and workshops. Periodic meetings between project personnel will occur to keep the tasks on track.

2. **Actual Accomplishments**:
- All quarterly and annual reports were submitted.
- Periodic meetings took place with project personnel to keep the project on track.
- Discussions took place with the Arizona Geological Survey to determine how to incorporate results of this study (including 3D models) into the National Geothermal Database.
- Results were published in 16 papers and 11 abstracts. Results were also given in >50 presentations at professional meetings, including GRC, AGU, GSA, DOE peer reviews, GEA summit meetings, and the New Zealand geothermal workshop.

3. **Explanation of Variance:** Not applicable.

Task 12 – Technology Transfer/Commercialization

1. **Planned Activities**: In addition to providing the required quarterly and annual reports, results will be presented at various meetings and workshops. A course in geothermal exploration was taught in Spring Semester, 2011. In addition, all data produced in this project will be submitted and incorporated into the National Geothermal Data System.

2. **Actual Accomplishments**:
- All quarterly and annual reports were submitted.
- We are submitting our deliverables from this project to the National Geothermal Database System (NDGS) with the help of the Arizona Geological Survey (AGS). The AGS has a wealth of recent experience with data contributions to the NGDS and are helping to ensure a smooth and accurate process of submitting our data.
    - All data are submitted with appropriate metadata records.
    - Specific types of data submitted from this project include, but are not limited to published papers, abstracts, M.S. theses, structural inventory database of all known systems in the Great Basin region, gravity data for the Carson Sink, geologic maps and accompanying geodatabases, 3D models, and results of stress inversions and slip and dilation tendency analyses.
- Course in geothermal exploration was taught in Spring 2011. In addition to transferring knowledge to the next generation of geothermal geoscientists, some of those taking the course were professionals currently holding positions in industry.
- Led pre-meeting and post-meeting field trips for 2012 GRC meeting. These trips were focused on structural settings of geothermal fields in the Carson Sink area of western Nevada. They filled to capacity and were very well received.
- Presented a half-day module of a two-day pre-meeting workshop at the 2013 GRC meeting.

3. **Explanation of Variance**: Not applicable.

PRODUCTS / DELIVERABLES

Training and Professional Development:

Advising of Graduate Students Supported by this Project:

Dering, Greg, M.S. candidate: Structural controls of the Tuscarora geothermal system, northeastern Nevada. Began in January 2011; completed in Spring 2013.

Edwards, Joel, M.S. candidate: Structural controls of the Neal Hot Springs geothermal field, eastern Oregon: Began in January 2011; completed in Spring 2013.

Hazelwood, Lyndsay, M.S. candidate: Structural controls on the Gerlach Hot Springs, northwestern Nevada: Began in Fall 2011; probable completion in Spring 2014.

Kraushaar, Sabina, M.S. candidate: Structural controls of the MacFarlane Hot Springs, northwestern Nevada: Began in Spring 2012; probable completion in Spring 2014.

Mayhew, Brett, M.S. candidate: Structural setting and 3D modeling of the Astor Pass geothermal system on the Paiute Indian Reservation, western Nevada: Began in January 2011; completion in Summer 2013. Partially supported by this project during year-1 of studies for assistance with the structural inventory.

McLachlan, Holly, Ph.D. candidate: Structural controls of geothermal systems in the Carson Sink, western Nevada. Began in Fall 2009; probable completion in Fall 2014.

Field Trips:

- National Geothermal Academy: Led field trip focused on the structural controls of geothermal systems in western Nevada (July 8, 2011)
- GRC 2012 Annual Meeting: Led two field trips for the GRC meeting reviewing the structural controls of geothermal systems in the western Great Basin region. Both trips filled to capacity and were very well received (September-October 2012).

Geothermal Exploration Class: Taught Geothermal Exploration Class during the Spring Semester 2011, which benefitted all of the graduate students working on this project.

Professional Training: Attended multiple training courses in Alameda, CA for EarthVision 3D modeling software. Participants in these courses have included Dering, Faulds, Hinz, Mayhew, and Siler.

Theses Completed:

Dering, G.M., 2013, Structural controls of the Tuscarora geothermal field, Elko County, Nevada [M.S. thesis]: University of Nevada, Reno, 82 p.

Edwards, J.H., 2013, Structural controls of the Neal Hot Springs geothermal system, eastern Oregon [M.S. thesis]: University of Nevada, Reno, 84 p.

Workshops:

Geothermal Exploration: Integrated Field and Modeling Techniques: Workshop on geothermal exploration for Geothermal Resources Council Annual Meeting, Las Vegas, NV (September 27, 2013).

Publications and Presentations:

Published Papers:

Cashman, P., Faulds, J.E., and Hinz, N.H., 2012, Regional variations in structural controls on geothermal systems in the Great Basin: Geothermal Resources Council Transactions, v. 36, p. 25-30.

Dering, G. and Faulds, J., 2012, Structural controls of the Tuscarora geothermal field, Elko County, Nevada: Geothermal Resources Council Transactions, v. 36, p. 41-46. [Won best paper award for session]

Edwards, J., and Faulds, J.E., 2012, Preliminary assessment of the structural controls of Neal Hot Springs geothermal field, Malheur County, Oregon: Geothermal Resources Council Transactions, v. 36, p. 891-896. [Won best paper award for session]

Faulds, J.E., 2011, Improved techniques for geothermal exploration (byline article): North American Clean Energy, v. 5, no. 6, p. 73-74.

Faulds, J.E., Hinz, N.H., and Coolbaugh, M.F., 2011, Structural investigations of Great Basin geothermal fields: Applications and implications, in Steininger, R., and Pennell, B., eds., Great Basin evolution and metallogeny: Geological Society of Nevada 2010 Symposium Volume, p. 361-372.

Faulds, J.E., Coolbaugh, M.F., Hinz, N.H., Cashman, P.H., and Kratt, C., Dering, G., Edwards, J., Mayhew, B., and McLachlan, H., 2011, Assessment of favorable structural settings of geothermal systems in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 35, p. 777-784.

Faulds, J.E., Hinz, N.H., Kreemer, C., and Coolbaugh, M.F., 2012, Regional patterns of geothermal activity in the Great Basin region, western USA: Correlation with strain rates: Geothermal Resources Council Transactions, v. 36, p. 897-902.

Faulds, J. E., Hinz, N. H., Kreemer, C. W., 2012, Structural and tectonic controls of geothermal activity in the Basin and Range province, western USA: New Zealand Geothermal Workshop 2012 Proceedings, Auckland, 5 p.

Faulds, J.E., Hinz, N.H., Dering, G.M., Drew, S.L., 2013, The hybrid model – the most accommodating structural setting for geothermal power generation in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 37, p. 3-10.

Hazelwood, L.A., Cashman, P.H., and Faulds, J.E., 2013, Structural controls on the geothermal system at Gerlach, Washoe County, Nevada: Geothermal Resources Council Transactions, v. 37, p. 463-468.

Hinz, N.H., Faulds, J.E., and Stroup, C., 2011, Stratigraphic and structural framework of the Reese River geothermal area, Lander County, Nevada: A new conceptual structural model: Geothermal Resources Council Transactions, v. 35, p. 827-832.

Hinz, N. H., Faulds, J. E., Siler, D. L., 2013, Developing systematic workflow from field work to quantitative 3D modeling for successful exploration of structurally controlled geothermal systems: Geothermal Resources Council Transactions, v. 37, p. 275-280.

Kraushaar, S., and Cashman, P.H., 2013, Structural controls of the MacFarlane geothermal system, Humboldt County, Nevada: A progress report: Geothermal Resources Council Transactions, v. 37, p. 17-23.

McLachlan, H., and Benoit, W.R., and Faulds, J.E., 2011, Structural framework of the Soda Lake geothermal area, Churchill County, Nevada: Geothermal Resources Council Transactions, v. 35, p. 925-930.

Siler, D., Mayhew, B., and Faulds, J.E., 2012, Three-dimensional geologic characterization of geothermal systems: Astor Pass, Nevada, USA: Geothermal Resources Council Transactions, v. 36, p. 783-786. [Won best paper award for session]

Siler, D.L., and Faulds, J.E., 2013, Three-dimensional geothermal fairway mapping: Examples from the western Great Basin, USA: Geothermal Resources Council Transactions, v. 37, p. 327-332.

Geologic Maps:

Dering, G.M., and Faulds, J.E., Preliminary geologic map of the Tuscarora geothermal area, Elko County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 13-5, scale 1:24,000.

Faulds, J.E., Ramelli, A.R., and Perkins, M.E., 2011, Preliminary geologic map of the Hazen Quadrangle, Lyon and Churchill Counties, Nevada: Nevada Bureau of Mines and Geology Open-File Report 11-8, scale 1:24,000.

Faulds, J.E., Ramelli, A.R., Garside, L.J., Coolbaugh, M.F., and Green, H.L., 2012, Preliminary geologic map of the Desert Peak Quadrangle, Churchill County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 12-5, scale 1:24,000.

Hinz, N.H., Faulds, J.E., and Bell, J.W., 2011, Preliminary geologic map of the Bunejug Mountains Quadrangle, Churchill County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 11-9, scale 1:24,000.

Hinz, N. H., Ramelli, A. R., Faulds, J. E., 2013, Preliminary geologic map of the Wabuska Quadrangle, Lyon County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 13-08, 1 sheet, 1:24,000 scale.

Published Abstracts:

Dering, G., and Faulds, J.E., 2012, Structural controls of the Tuscarora geothermal field, Elko County, Nevada: American Geophysical Union Transactions, V13C-2864.

Edwards, J.H., and Faulds, J.E., 2012, Structural controls of Neal Hot Springs geothermal field, Malheur County, Oregon: American Geophysical Union Transactions, V13A-2830.

Faulds, J.E., Coolbaugh, M.F., Moeck, I., and Hinz, N.H., 2010, Structural Investigations of geothermal fields: Applications and Implications: Geological Society of America Abstract with Programs, v. 42, no. 5, p. 673.

Faulds, J.E., Coolbaugh, M.F., and Hinz, N.H., 2010, Characterizing favorable structural settings of geothermal reservoirs in extensional regions: Enhancing exploration strategies *in* Eccles, J.D., Grigor, M.R., Hoskin, P.W.O., and Hikuroa, D.C.H., eds., Abstract Volume, GeoNZ 2010 Conference, New Zealand, Geological Society of New Zealand Miscellaneous Publication 129A, p. 94.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Cashman, P.H., Kratt, C., Dering, G., Edwards, J., Mayhew, B., and McLachlan, H., 2011, Assessment of favorable structural settings of geothermal systems in the Great Basin region, western USA: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 39.

Faulds, J.E., Hinz, N.H., and Kreemer, C.W., 2012, Tectonic and structural controls on geothermal activity in the Great Basin region, western USA: American Geophysical Union Transactions, V24-01.

Faulds, J.E., Hinz, N.H., Siler, D.L., Coolbaugh, M.F., Queen, J.H., Zemach, E., 2013, Structural controls on the Brady's geothermal system, western Nevada: Insights from integrated geologic, geophysical, and 3D characterization: Geological Society of America Abstract with Programs, v. 45, no. 7, p. 653.

Hinz, N.H., Faulds, J.E., Siler, D.L., 2013, Exploration of structurally controlled geothermal systems - systematic and integrated workflow from field work to quantitative 3D mapping, modeling, and drill targeting: Geological Society of America Abstract with Programs, v. 45, no. 7, p. 653.

McLachlan, H.S., and Faulds, J.E., 2012, Some new constraints on the stratigraphic and structural setting of the Soda Lake geothermal field, Churchill County, Nevada: American Geophysical Union Transactions, V13A-2817.

Siler, D.L., Mayhew, B., and Faulds, J.E., 2012, 3D characterization of a Great Basin geothermal system: Astor Pass, NV: American Geophysical Union Transactions, V13A-2828.

Siler, D.L., Faulds, J.E., 2013, Play-fairway analysis for geothermal exploration: examples from the great basin, western USA: Geological Society of America Abstract with Programs, v. 45, no. 7, p. 653.

Presentations:

PI Faulds:

Structural controls of geothermal activity in the northern Hot Springs Mountains, western Nevada: The tale of three geothermal systems (Brady's, Desert Perk, and Desert Queen): Geothermal Resources Council Annual Meeting, Sacramento, California (October 27, 2010).

Structural Investigations of Geothermal Fields: Applications and Implications: Geological Society of America Annual Meeting, Denver, Colorado (November 3, 2010).

Structural Investigations of Geothermal Fields in Extended Terranes: Applications and Implications: Lecture in Dr. Dave Boden's class on Geothermal Energy, Truckee Meadows Community College, Reno, Nevada (November 10, 2010).

Characterizing Favorable Structural Settings of Geothermal Reservoirs in Extensional Regions: Enhancing Exploration Strategies: GeoNZ2010 Geoscience-Geothermal Conference, Auckland, New Zealand (November 21, 2010).

Characterizing Favorable Structural Settings of Geothermal Reservoirs in Extensional Regions: Enhancing Exploration Strategies: Geological Society of Nevada, Winnemucca Chapter, monthly meeting (February 9, 2011).

Characterizing Structural Controls of EGS Candidate and Conventional Geothermal Reservoirs in the Great Basin: Developing Successful Exploration Strategies in Extended Terranes: Department of Energy Geothermal Technologies Program 2011 Peer Review: Bethesda, Maryland (June 8, 2011).

Structural Investigations of Geothermal Fields in Extended Terranes: Applications and Implications: National Geothermal Academy, Reno, Nevada (July 8, 2011). Lecture and field trip for class.

Structural Controls of Geothermal Systems in the Great Basin: Unlocking Nevada's Vast Hidden Geothermal Resources: Nevada Geothermal Council, Reno, Nevada (July 21, 2011).

Assessment of favorable structural settings of geothermal systems in the Great Basin region, western USA: Invited talk in special session on geothermal resources; Geological Society of America Annual Meeting, Minneapolis, Minnesota (October 9, 2011).

Assessment of favorable structural settings of geothermal systems in the Great Basin, western USA: Geothermal Resources Council Annual Meeting, San Diego, California (October 24, 2011).

Assessment of Favorable Structural Settings of Geothermal Systems in the Great Basin, Western USA: Lecture in Dr. Dave Boden's class on Geothermal Energy, Truckee Meadows Community College, Reno, Nevada (November 3, 2011).

Strategies for Developing Vast Geothermal Resources in the Great Basin: Congressional Briefing Luncheon entitled "The Road to the New Energy Economy" sponsored by Discover Magazine and the National Science Foundation, Washington, DC (March 27, 2012).

Characterizing Favorable Structural Settings of Geothermal Reservoirs in Extensional Regions: Enhancing Exploration Strategies: University of Edinburgh, Scotland (April 13, 2012).

Characterizing Structural Controls of EGS Candidate and Conventional Geothermal Reservoirs in the Great Basin: Developing Successful Exploration Strategies in Extended Terranes: Department of

Energy Geothermal Technologies Program 2012 Peer Review: Denver, Colorado (May 8, 2012). Won award for best project.

Assessment of Structural Favorable Structural Settings of Geothermal Systems in the Great Basin, Western USA: National Geothermal Academy, Reno, Nevada (July 9, 2012). Lecture for class.

Ad Hoc discussion of resource development in Nevada: Mining Roundtable for Nevada Business Magazine, Reno, Nevada (July 10, 2012).

Keeping Nevada in Hot Water: Strategies for Reducing Risks in Geothermal Development: Geothermal Energy Association Summit, Sacramento, CA (August 8, 2012).

Regional Patterns of Geothermal Activity in the Great Basin Region: Correlation with Strain Rates: Geothermal Resources Council Annual Meeting, Reno, Nevada (October 1, 2012).

Structural and Tectonic Controls of Geothermal Activity in the Great Basin Region, Western USA: Association of Engineering Geologists monthly meeting, Las Vegas, Nevada (October 9, 2012).

Structural and Tectonic Controls of Geothermal Activity in the Basin & Range Province, Western USA: New Zealand Geothermal Workshop, Auckland, New Zealand (November 18, 2012).

Tectonic and Structural Controls of Geothermal Activity in the Great Basin Region, Western USA: American Geophysical Union annual meeting, San Francisco, California (December 4, 2012).

Why is Nevada in Hot Water?: Geothermal Activity and Development: Mining Oversight and Advisory Committee, Carson City, Nevada (December 12, 2012).

Why is Nevada in Hot Water: Structural and Tectonic Controls of Geothermal Activity in the Great Basin Region: Western Washington University, Bellingham, WA (February 5, 2013).

Keynote Address-Luncheon Talk: Tectonic and Structural Controls of Great Basin Geothermal Systems: Developing Successful Exploration Strategies: Department of Energy Peer Review Meeting, Denver, CO (April 23, 2013).

Structural and Tectonic Controls on Geothermal Activity in the Great Basin Region: Conventional and EGS Systems: JASON Research Meeting, Department of Energy, La Jolla, CA (June 20, 2013).

Fault Controls on Geothermal Activity in the Great Basin Region: Conventional and EGS Systems: Served on Panel for Geothermal Energy Association Summit Meeting, Reno, NV (June 27, 2013).

The hybrid model – the most accommodating structural setting for geothermal power generation in the Great Basin, western USA: Geothermal Resources Council Annual Meeting, Las Vegas, NV (October 1, 2013).

Keynote Address: Structural Controls on Permeability and Fluid Flow in Extensional Settings: Penrose Conference on "*Predicting and Detecting Natural and Induced Flow Paths for Geothermal Fluids in Deep Sedimentary Basins",* Park City, Utah (October 20, 2013).

Cashman:

Regional variations in structural controls on geothermal systems in the Great Basin: Geothermal Resources Council Annual Meeting, Reno, NV (October, 2012).

Dering:

Tuscarora geothermal field: Nevada Petroleum and Geothermal Society, Reno, Nevada (May, 2012).

Structural controls of the Tuscarora geothermal field: Gordon Research Conference—Geochemistry of Ore Deposits: Andover, NH (July, 2012).

Structural controls of the Tuscarora geothermal field, Elko County, Nevada: Geothermal Resources Council Annual Meeting, Reno, NV (October, 2012).

Structural controls of the Tuscarora geothermal field, Elko County, Nevada: American Geophysical Union Annual Meeting, San Francisco, CA (December, 2012).

Tuscarora geothermal field: Geological Society of Nevada, Winnemucca, Nevada (September, 2013).

Edwards:

Preliminary assessment of the structural controls of Neal Hot Springs geothermal field, Malheur County, Oregon: Geothermal Resources Council Annual Meeting, Reno, NV (October, 2012).

Structural controls of Neal Hot Springs geothermal field, Malheur County, Oregon: American Geophysical Union Annual Meeting, San Francisco, CA (December, 2012).

Hazelwood:

Structural controls on the geothermal system at Gerlach, Washoe County, Nevada: Geothermal Resources Council Annual Meeting, Las Vegas, NV (October, 2013).

Hinz:

Stratigraphic and structural framework of the Reese River geothermal area, Lander County, Nevada: A new conceptual structural model: Geothermal Resources Council Annual Meeting, San Diego, CA (October, 2011).

Structural controls of three blind geothermal resources at the Hawthorne Ammunition Depot: Summary of 2009-2010 project: Energy Initiatives Task Force, U.S. Army, Reno, NV (February 8, 2012).

Workflow methodology for 3-Dimensional geologic mapping with examples from structural characterization of geothermal systems: Digital Mapping Techniques 2012, Champaign-Urbana, IL (May 22, 2012).

Developing systematic workflow from field work to quantitative 3D modeling for successful exploration of structurally controlled geothermal systems: Geothermal Resources Council Annual Meeting, Las Vegas, NV (October, 2013).

Exploration of structurally controlled geothermal systems - systematic and integrated workflow from field work to quantitative 3D mapping, modeling, and drill targeting: Geological Society of America Annual Meeting, Denver, CO (October, 2013).

Structural controls of three blind geothermal systems at Hawthorne plus Lee-Allen and Wabuska: Nevada Petroleum and Geothermal Society, Reno, NV (January, 2014).

Kraushaar:

Structural controls of the MacFarlane geothermal system, Humboldt County, Nevada: A progress report: Geothermal Resources Council Annual Meeting, Las Vegas, NV (October, 2013).

McLachlan:

Structural framework of the Soda Lake geothermal area, Churchill County, Nevada: Geothermal Resources Council Annual Meeting, San Diego, CA (October, 2011).

Some new constraints on the stratigraphic and structural setting of the Soda Lake geothermal field, Churchill County, Nevada: American Geophysical Union Annual Meeting, San Francisco, CA (December, 2012).

Structural Framework of the Soda Lake Geothermal Field: An Optimized Composite Model Based on Well Lithology, Gravity, and Seismic Data: AAPG Hedberg Research Conference, 3D Structural Geologic Interpretation, Reno, NV (June 23-27, 2013).

Siler:

3-Dimensional Geologic Modeling Applied to the Structural Characterization of Geothermal Systems: Astor Pass, Nevada, USA: US-New Zealand Joint Geothermal Workshop, New Zealand (April 16-19, 2012).

Three-dimensional geologic characterization of geothermal systems: Astor Pass, Nevada, USA: Geothermal Resources Council Annual Meeting, Reno, NV (October, 2012).
3D characterization of a Great Basin geothermal system: Astor Pass, NV: American Geophysical Union Annual Meeting, San Francisco, CA (December, 2012).
Advancements in 3D Structural Analysis of Geothermal Systems: AAPG Hedberg Research Conference, 3D Structural Geologic Interpretation, Reno, NV (June 23-27, 2013).
Three-dimensional geothermal fairway mapping: Examples from the western Great Basin, USA: Geothermal Resources Council Annual Meeting, Las Vegas, NV (October, 2013).
Play-fairway analysis for geothermal exploration: examples from the great basin, western USA: Geological Society of America Annual Meeting, Denver, CO (October, 2013).

Patents and IP: Not applicable.

Other Products / Deliverables: Great Basin Center for Geothermal Energy – several papers and presentations shown at http://www.unr.edu/geothermal/meetings_pres.html.