Tectonic & Structural Controls of Great Basin Geothermal Systems: Developing Successful Exploration Strategies

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- Why is Nevada in hot water?
- Characterizing structural settings
- Detailed studies
- 3D modeling – lessons learned
- Future directions

Keeping Nevada in Hot Water!

April 23, 2013

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Geothermal = 24/7 Renewable Energy

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UNR Team and Collaborations

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- UNR Team
  - 3 Faculty (Faulds, Cashman, and Bell)
  - 1 post-doc (Siler)
  - 2 research scientists (Hinz and Sadowski)
  - 5 graduate students
  - 2 undergrads
- Project collaborators
  - Industry partners – Ormat, U.S. Geothermal, Gradient Resources, MagmaEnergy, Enel, U.S. Navy
  - Desert Research Institute
  - Zonge Engineering – gravity surveys
- DOE support (EE0002748)

Tectonic Setting:
Why is Nevada in Hot Water?

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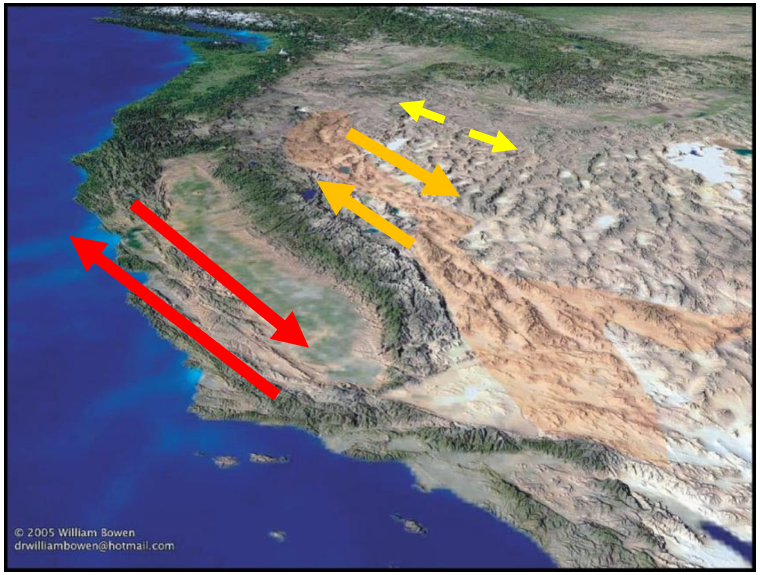
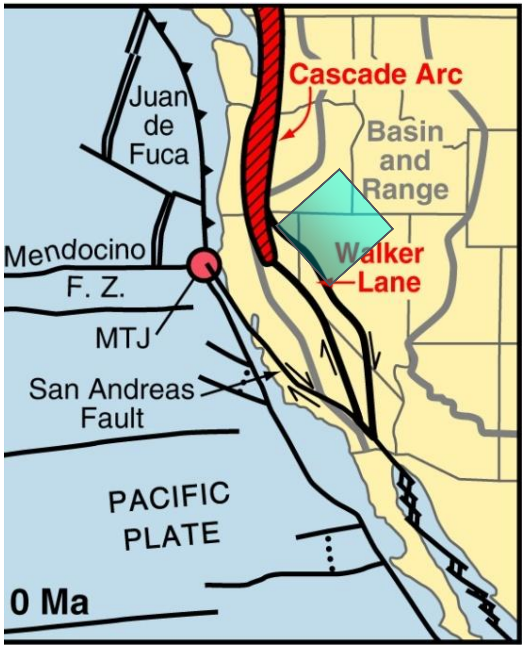
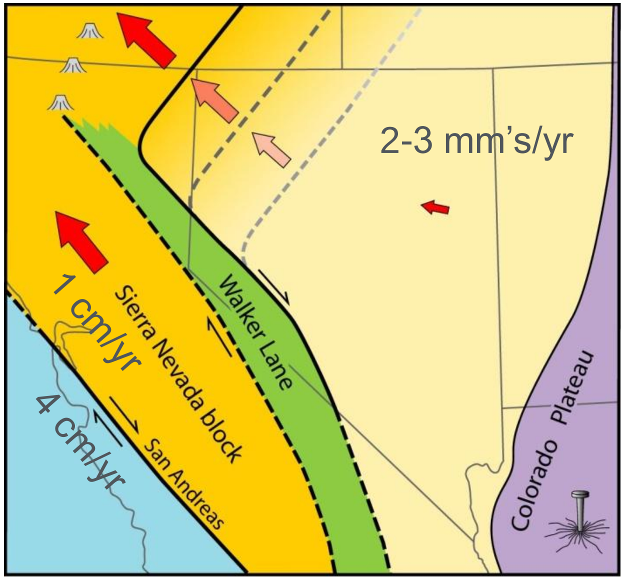
- **Western USA – distributed plate motion**
- **San Andreas – 4 cm/yr right-lateral motion**
- **Walker Lane – 1cm/yr right-lateral motion**
- **Basin and Range – several mm's/year of extension**
- **Transtensional to extensional domains**
- **Volcanism not a major factor**







Distribution of Geothermal Fields and Power Plants

San Andreas Fields

Walker Lane Fields

Basin-Range Fields

- **Does geothermal activity and thus potential correlate with strain rate?**
- **Does power plant capacity correlate with strain rate?**
- **What are the favorable structural settings for geothermal activity?**

Geothermal Activity vs. Strain Rates

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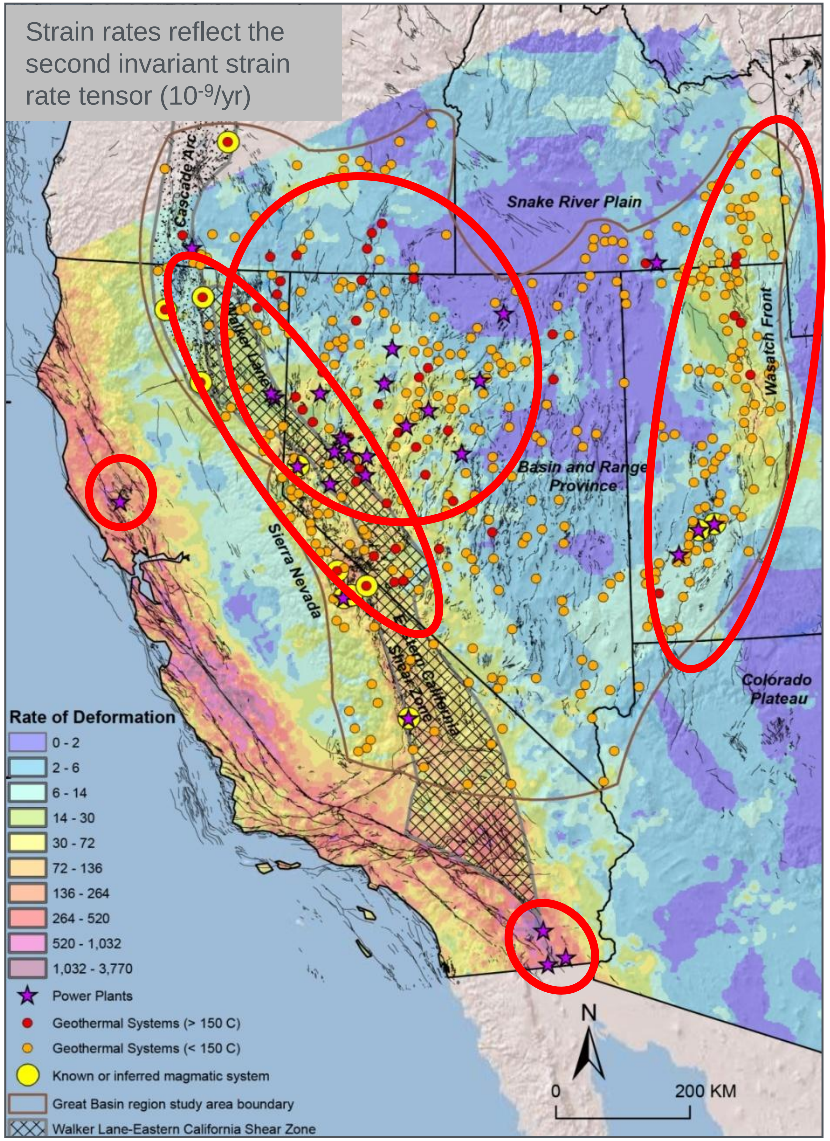
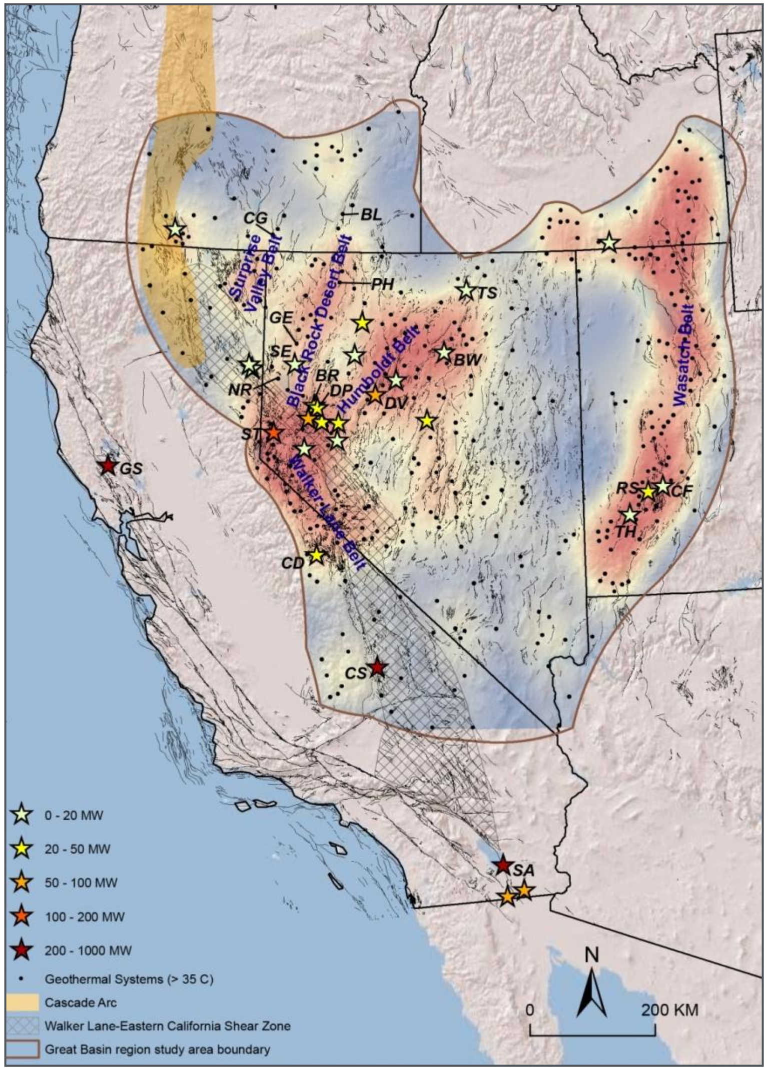
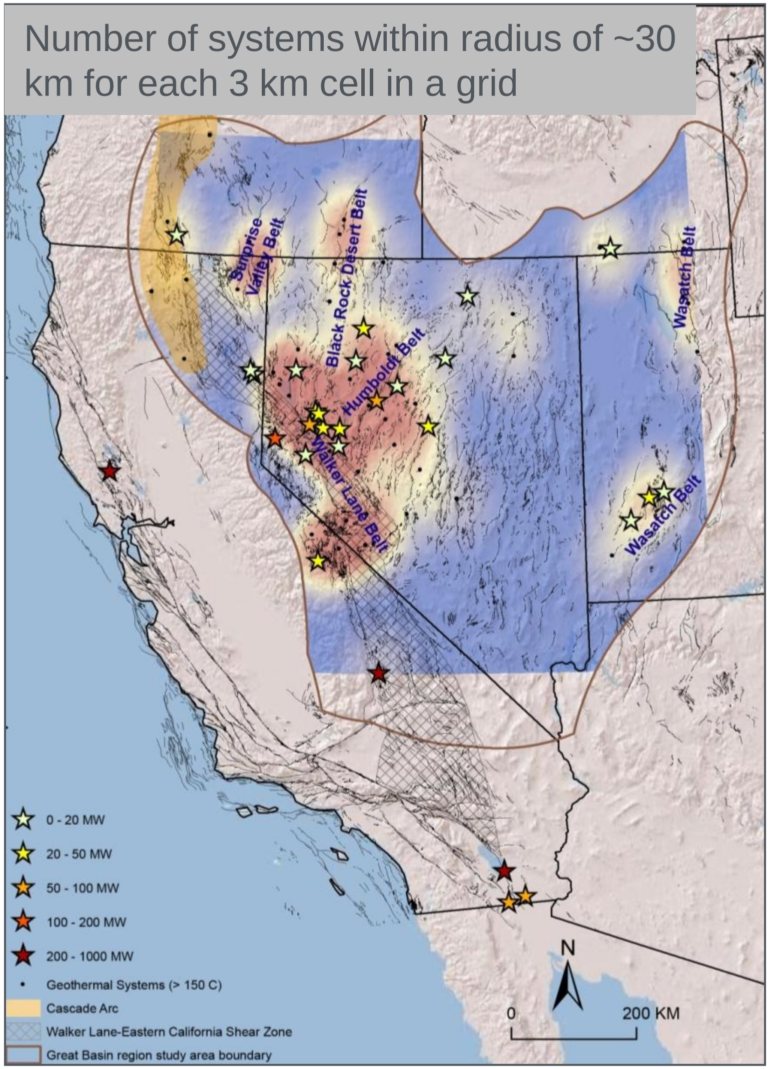
- **Strain decreases to NW as Walker Lane ends**
- **Broad enhanced strain to NE of northern WL**
  - **Dextral shear transferred to extension**
  - **NW Great Basin in broad transtensional region**
- **Fields most abundant in areas of greatest strain**
  - **Eastern Great Basin**
  - **NW Great Basin**
  - **Walker Lane**
- **San Andreas lacks systems except in pull-aparts and magmatic areas**
- **Extension/transtension required**



Distribution of Geothermal Systems



All Systems (>37ºC)



High-Temperature (>150ºC)

Power Potential vs. Strain Rates

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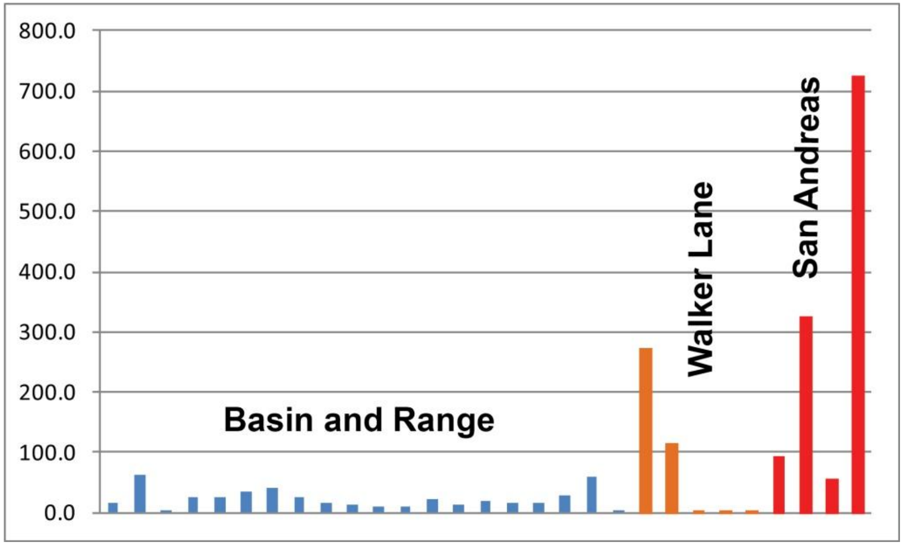
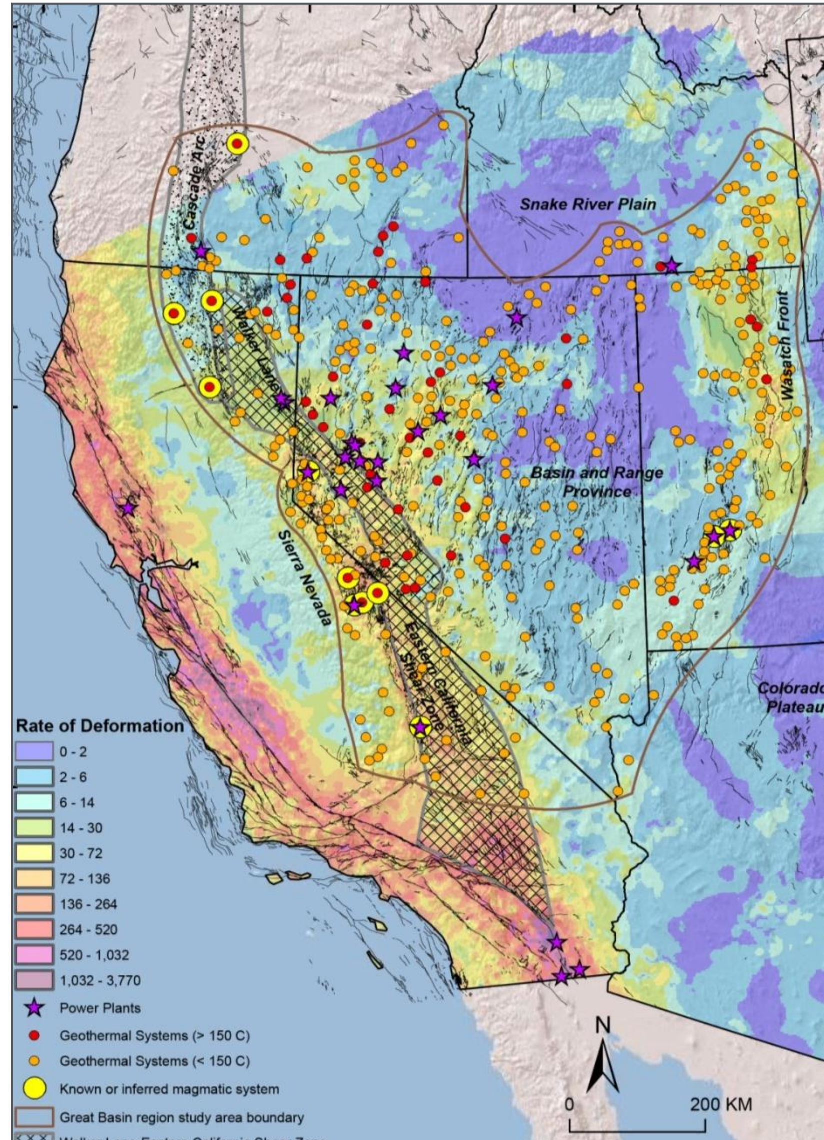


- **Basin and Range – tens of megawatts**
- **Walker Lane – few hundreds of megawatts**
- **San Andreas – several hundreds of megawatts**

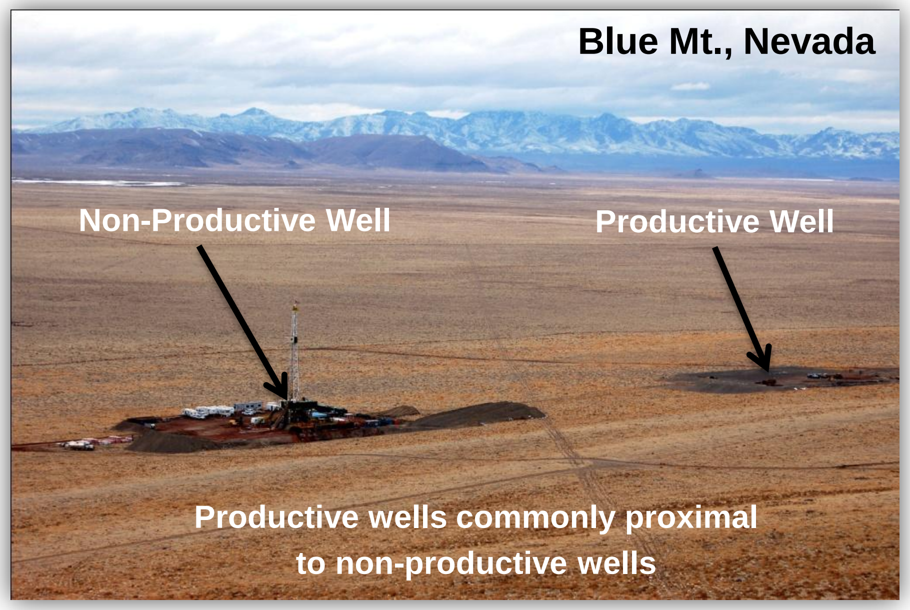


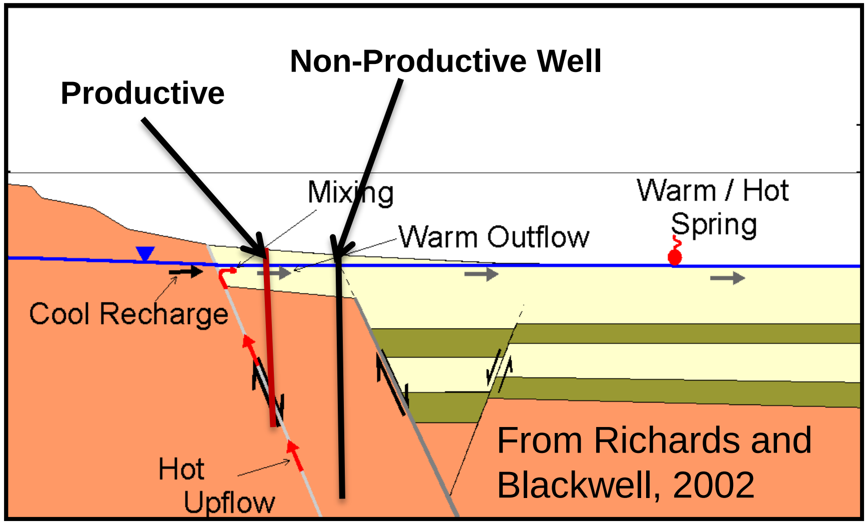
Challenges, Barriers, and Problems Addressed

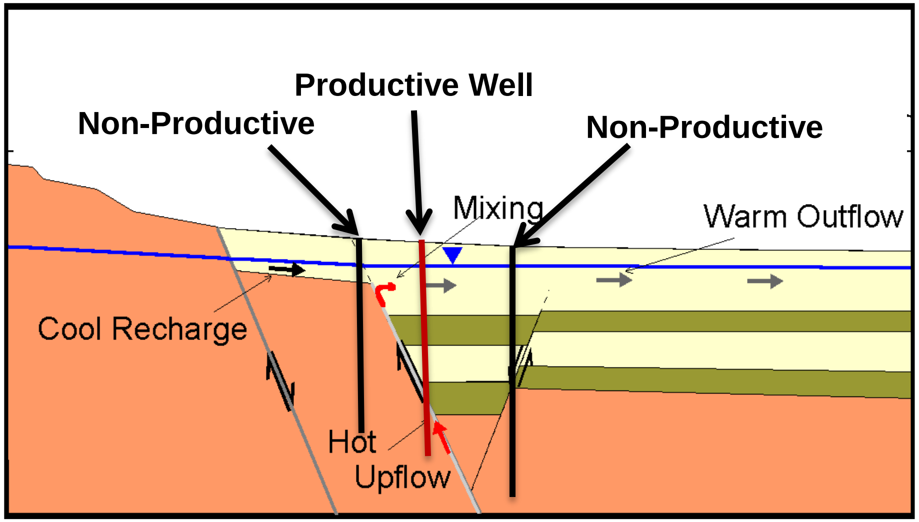
- Current technology cannot identify best geothermal sites with a high degree of certainty without drilling.
  - Permeability
  - Temperature
- Major problems that MYRDD describes:
  - Barrier A - “*the ability has not been sufficiently demonstrated to assess potential EGS resources, prioritize potential sites for EGS, and achieve acceptable levels of site selection risk ahead of expensive drilling investments*”.
  - Barrier B - “*inadequate measuring techniques and knowledge preclude low-risk options to effectively select sites and characterize their physical parameters as potential EGS reservoirs before stimulation*”.
- Better characterization of known systems needed to address these problems.
- Our approach – Characterize structural settings favorable for geothermal activity and develop more comprehensive, conceptual structural models that can facilitate exploration.

Exploration Challenges

- **Exploration Challenges**
  - Spring directly above upflow from deep source (uncommon)
  - Outflow from source (common)
  - Hidden or blind systems (common)
- **Results – significant drilling risk**
  - Hot dry wells
  - Overturn in down-hole temperatures
- **Need better conceptual models to:**
  - Locate areas of upflow
  - Avoid typically less productive outflow zones

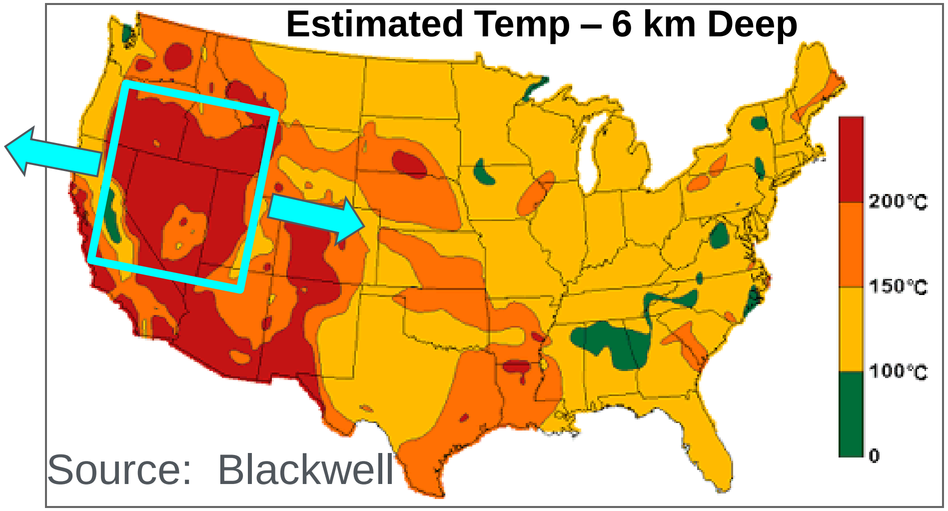


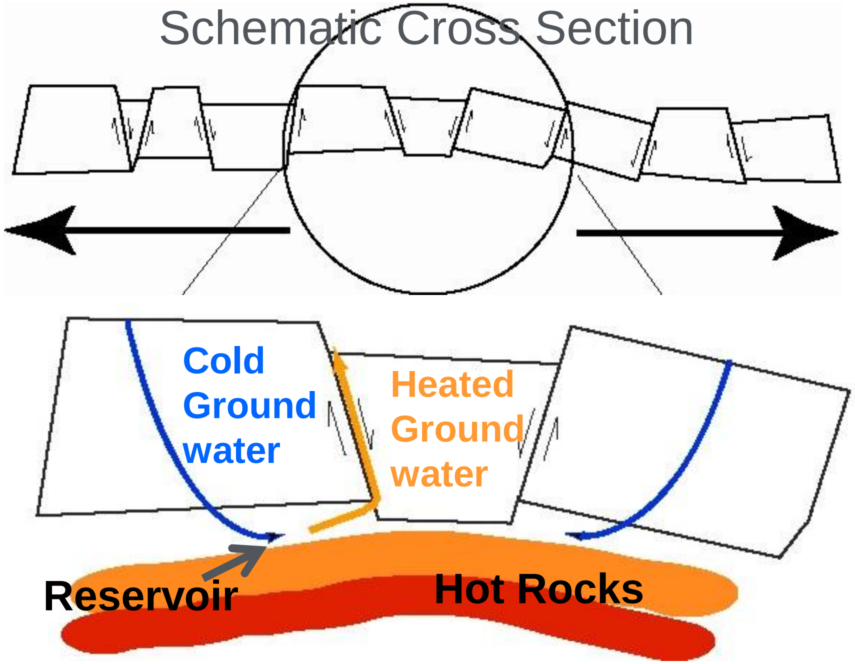




Great Basin Region

- Region of warm crust
- Crust pulling apart or extending
- As crust thins, hot rocks get closer to surface
- Saudi Arabia of geothermal
- Cannot drill 6 km deep (20,000 ft) economically
- Faults allow hot water to reach shallow levels
- Must find hot water pathways using geologic and geophysical techniques





Scientific/Technical Approach

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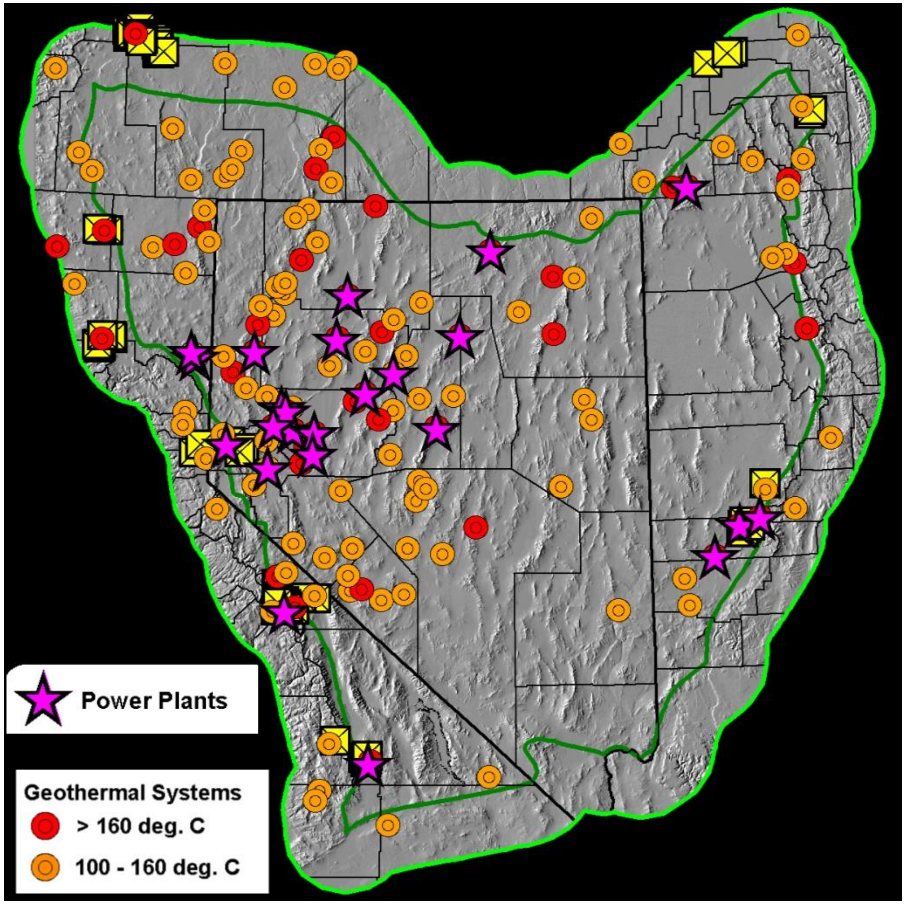
- **Main goal – Characterize structural settings of known systems to better target blind or hidden systems**
- **Approach**
  - **Develop comprehensive catalogue of favorable structural settings and models**
  - **Select 5-6 representative sites for detailed analysis**
  - **3D modeling of several systems**
  - **Slip and dilation tendency analysis**
  - **Synthesize findings**
- **Combine conventional and innovative quantitative techniques to define fluid pathways**
- **Major impacts on exploration strategies:**
  - **Reduce risk of drilling non-productive wells in conventional systems**
  - **Exploration for undiscovered blind systems**
  - **Expansion of conventional systems**
  - **Selecting best sites EGS development**



Great Basin Geothermal Systems: Distribution of known systems long established, but structural settings of systems not systematically defined

Geothermal Education/Field Trips

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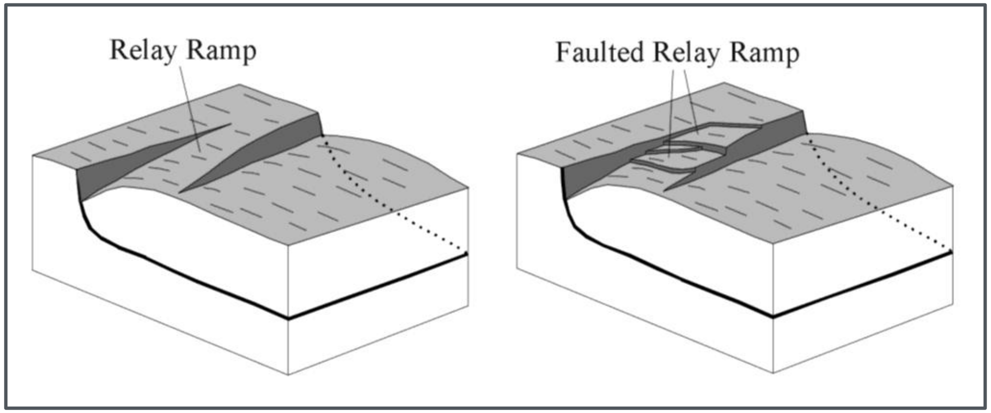
- **Geothermal Exploration Course**
  - **Taught in Spring 2011 – 20 graduate students**
  - **Purpose – training new generation of geoscientists in techniques**
  - **Analyzed geothermal systems in variety of tectonic settings around the world**
- **Reconnaissance trips for structural inventory includes students**
  - **Western Utah**
  - **East-central Nevada**
  - **Southern Oregon**
  - **North-central to NE Nevada**

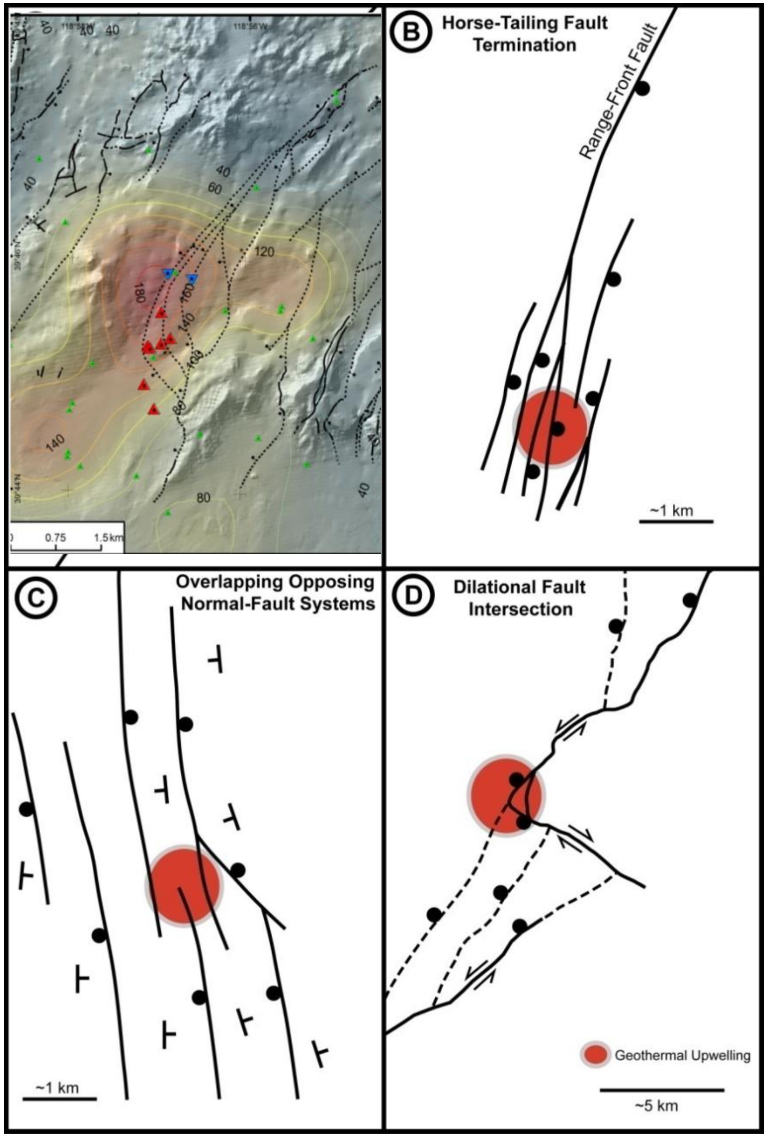
“Educational” Field Trips

Structural Controls Overview

- Most fields not on mid-segments of major faults
- Most on less conspicuous normal faults
- Common occurrences
  - Steps or relay ramps in normal fault zones
  - Fault tips: Terminating, horse-tailing faults
  - Accommodation zones: Overlapping opposing faults
  - Intersecting faults – dilational
  - Pull aparts in strike-slip faults
- Similar findings in other extensional settings
  - TVZ of New Zealand (Rowland & Simmons, 2012)
  - Western Turkey
  - Worldwide (Curewicz and Karson, 1997)

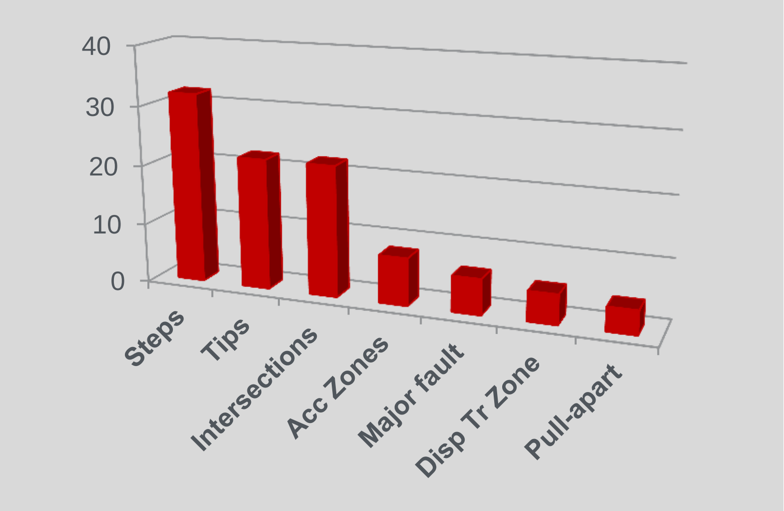


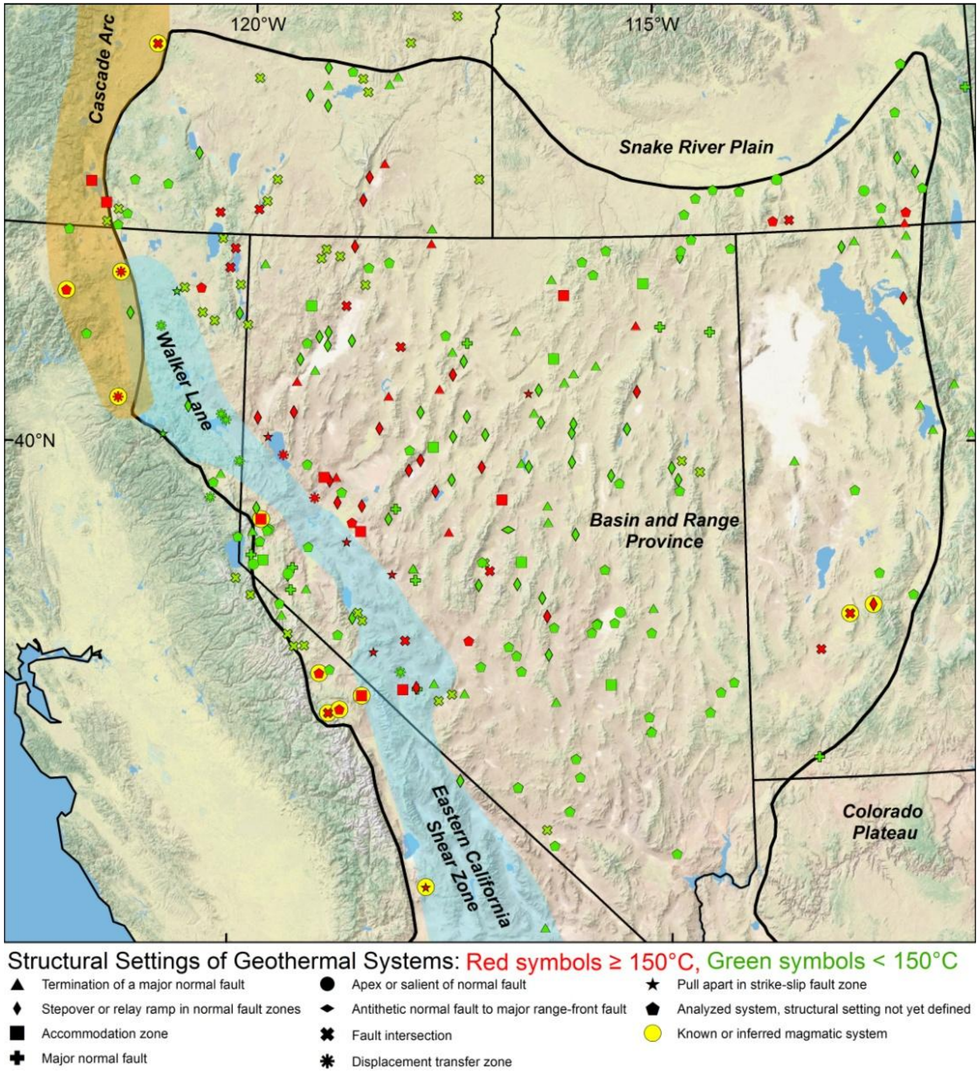
Most Common Setting – Step-Overs or Relay Ramps



Structural Inventory: Major Findings

- Structural settings for geothermal fields:
  - **Major normal fault (~5%)**
  - **Step-over or relay ramp in normal fault (~32%)**
  - **Normal fault tip or termination (~22%)**
  - **Fault intersection-normal and strike-slip or oblique fault (~22%)**
  - **Displacement transfer zone (~5%)**
  - **Accommodation zone (~9%)**
  - **Pull-apart (~4%)**
- Quaternary faults within or near most systems
- Most common settings – critically stressed areas, where fluid pathways more likely to remain open
- Many highly productive systems characterized by >1 type of favorable setting at single locality

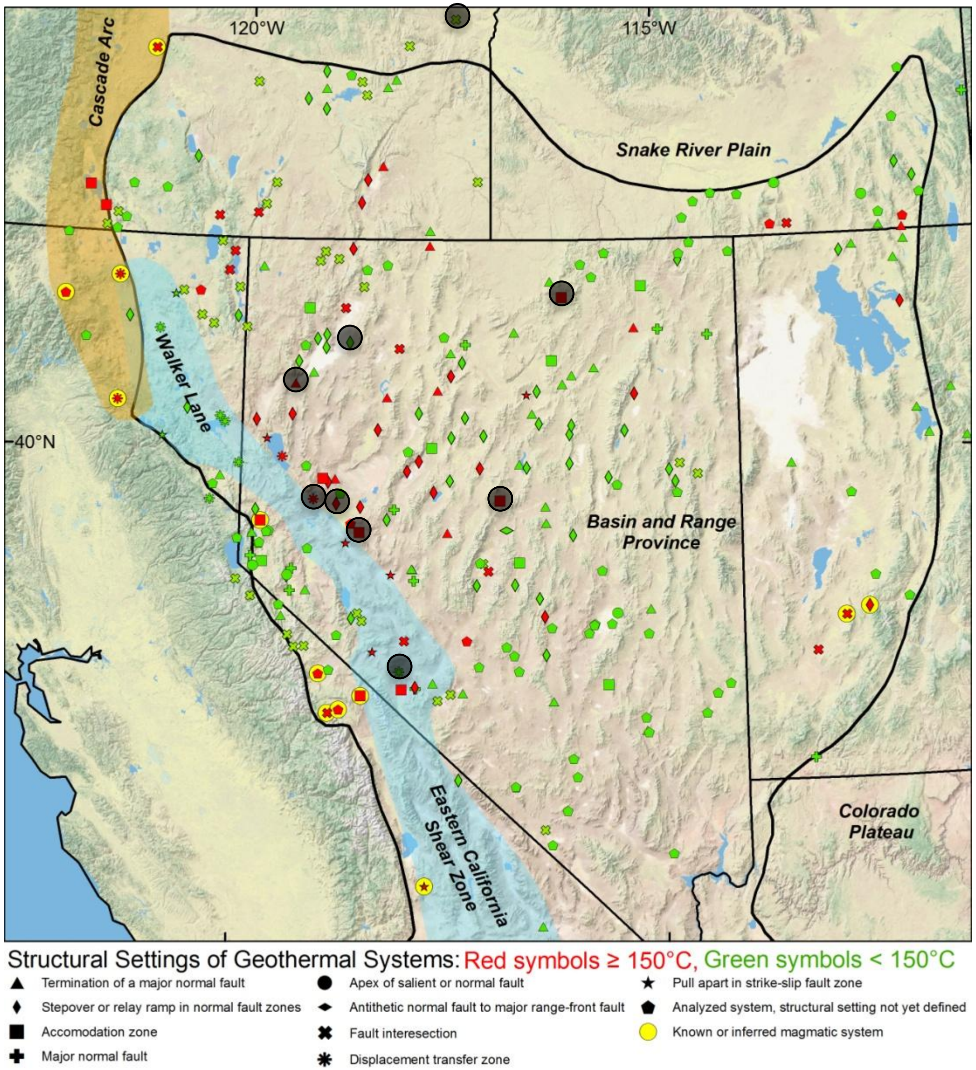




Structural Settings - ~300 Systems Analyzed

Representative Sites for Detailed Study

- **Selected sites for detailed study**
  - Neal Hot Springs, eastern Oregon
  - Tuscarora, northeast Nevada
  - McGuiness Hills, central Nevada
  - Gerlach, northwest Nevada
  - MacFarlane, northwest Nevada
  - Soda Lake, west-central Nevada
  - Salt Wells, west-central Nevada
  - Patua, west-central Nevada
  - Columbus Marsh, southwest Nevada
- **Criteria for selection**
  - Tectonic and structural setting
  - Quality of surface exposure
  - Availability of subsurface data
  - Potential for new or enhanced development



Gray circles denote fields selected for detailed study

Methodology

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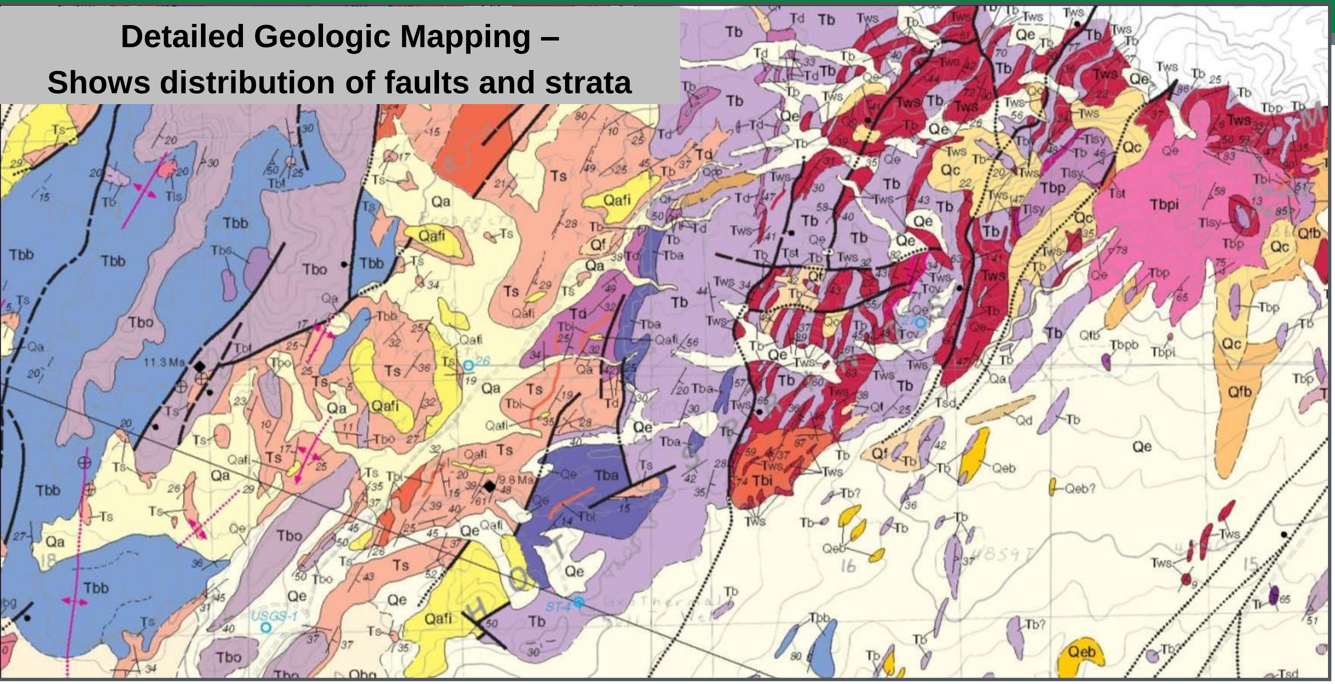
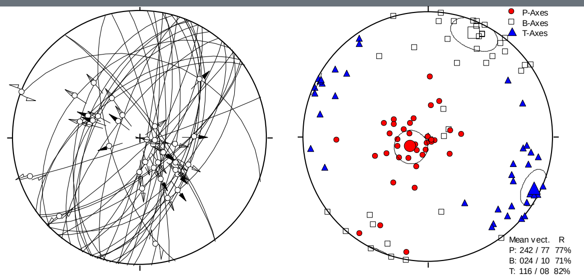
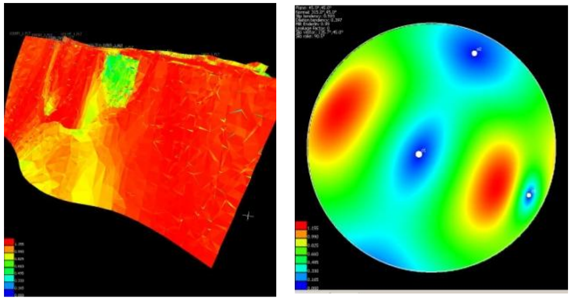


Detailed Geologic Mapping – Shows distribution of faults and strata



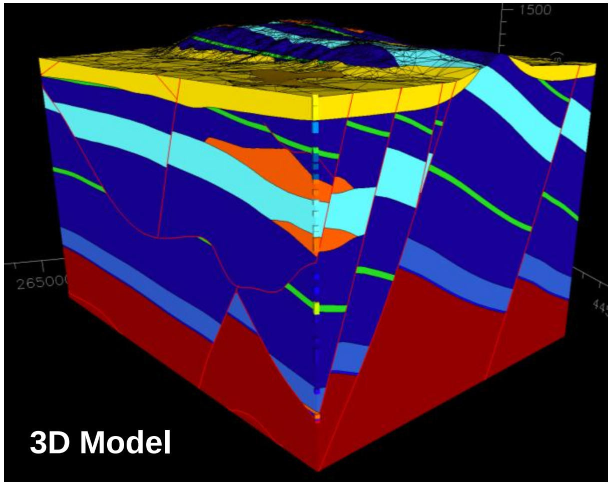
Stress inversion from fault-slip data



Slip-Dilation tendency analysis

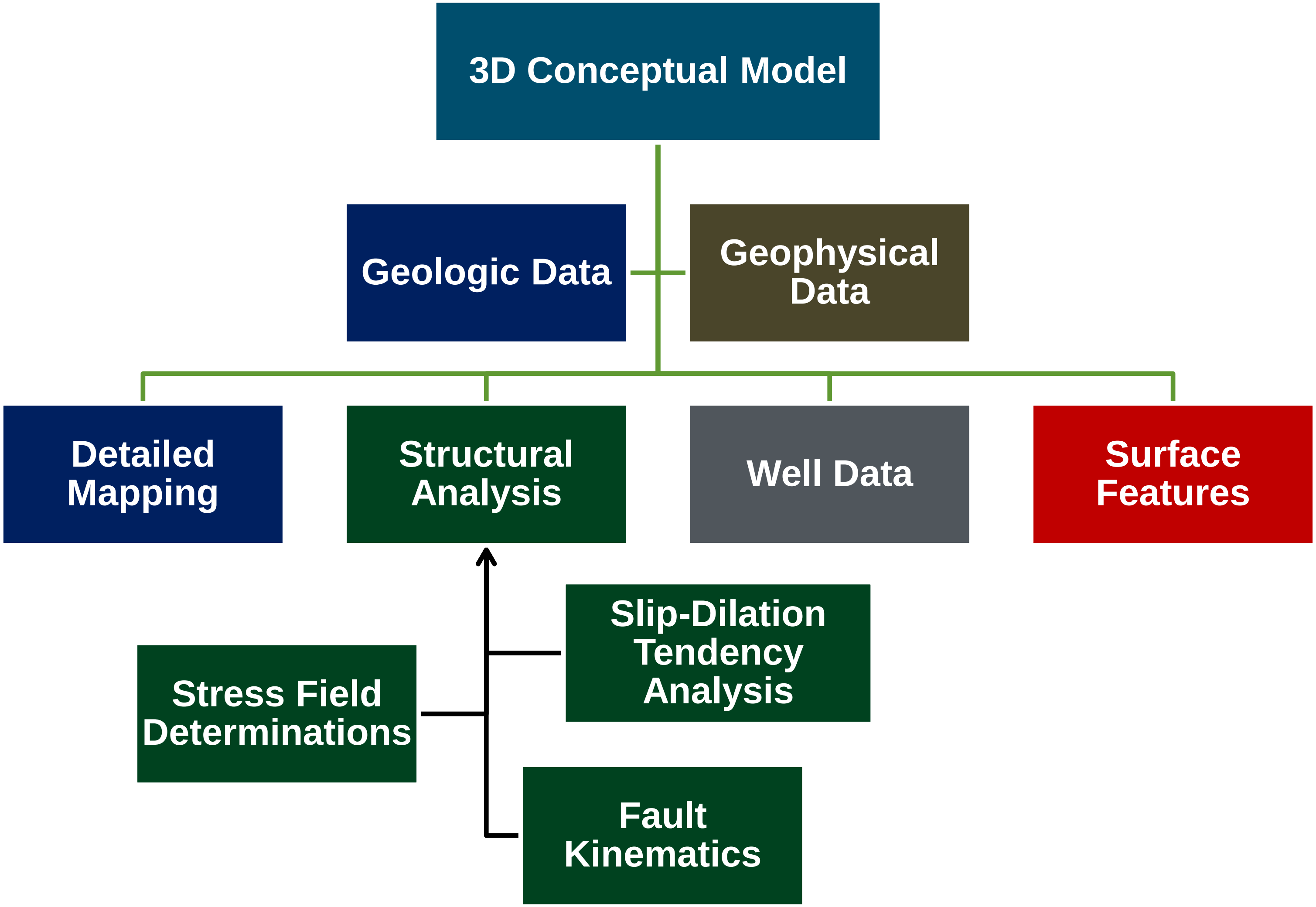
Fault Slip Data

- Detailed mapping
- Structural analysis
  - Fault kinematics
  - Stress determinations
  - Slip-Dilation tendency analyses
- Gravity surveys
- Integrate available geophysics
- 3D Modeling



3D Model

Work Flow


3D Conceptual Model
Geologic Data
Geophysical Data
Detailed Mapping
Structural Analysis
Well Data
Surface Features
Slip-Dilation Tendency Analysis
Stress Field Determinations
Fault Kinematics

Neal Hot Springs, Oregon

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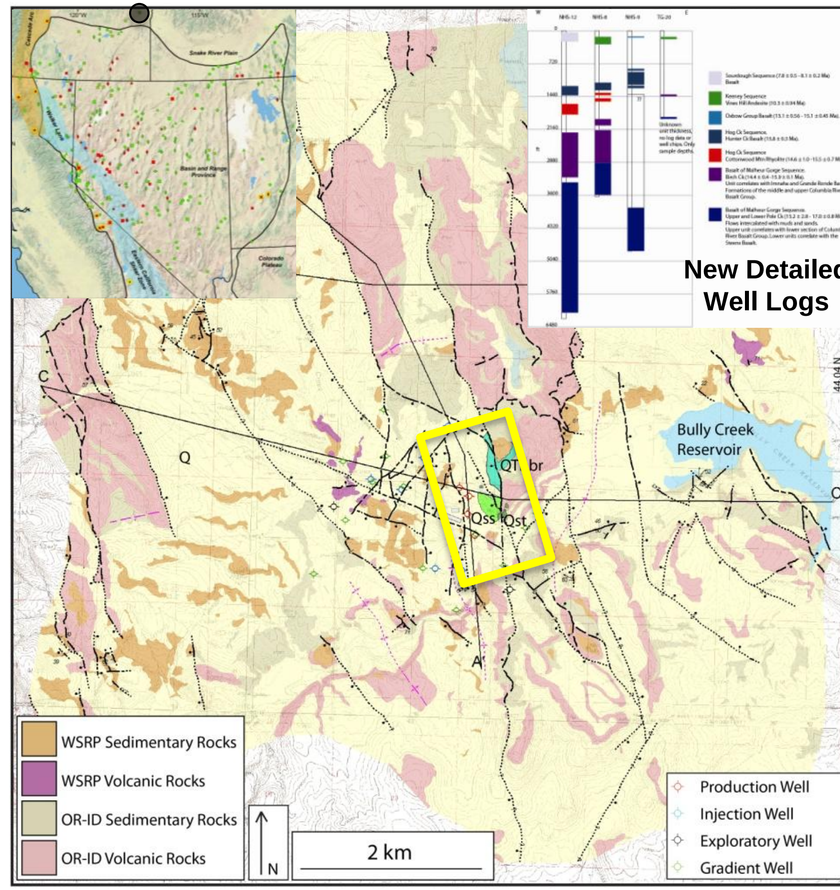
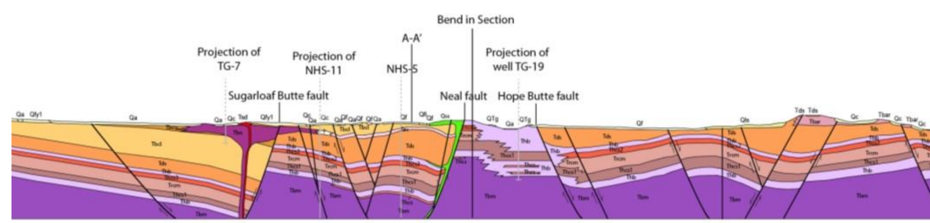
- Selected based on location outside Basin-Range and abundant data
- US Geothermal constructing power plant
- Master's thesis – Joel Edwards
- Methods – detailed mapping, structural analysis, core-chip logging, integration of geophysics, 3D model
- Structural Setting – Step over or relay ramp
- Stress field change from E-W to NE-SE extension





Neal Hot Springs, Oregon Conceptual Model

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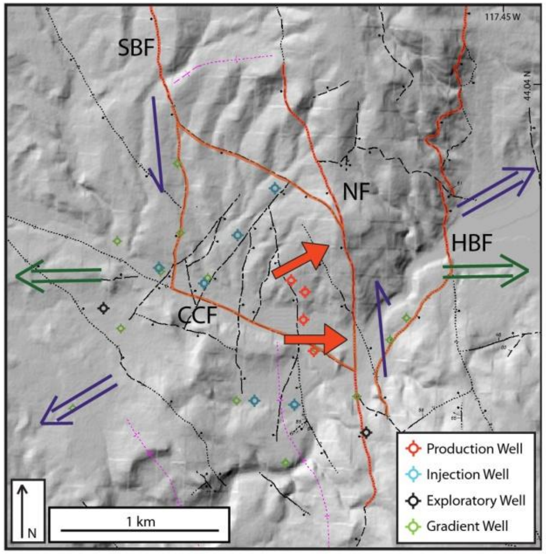
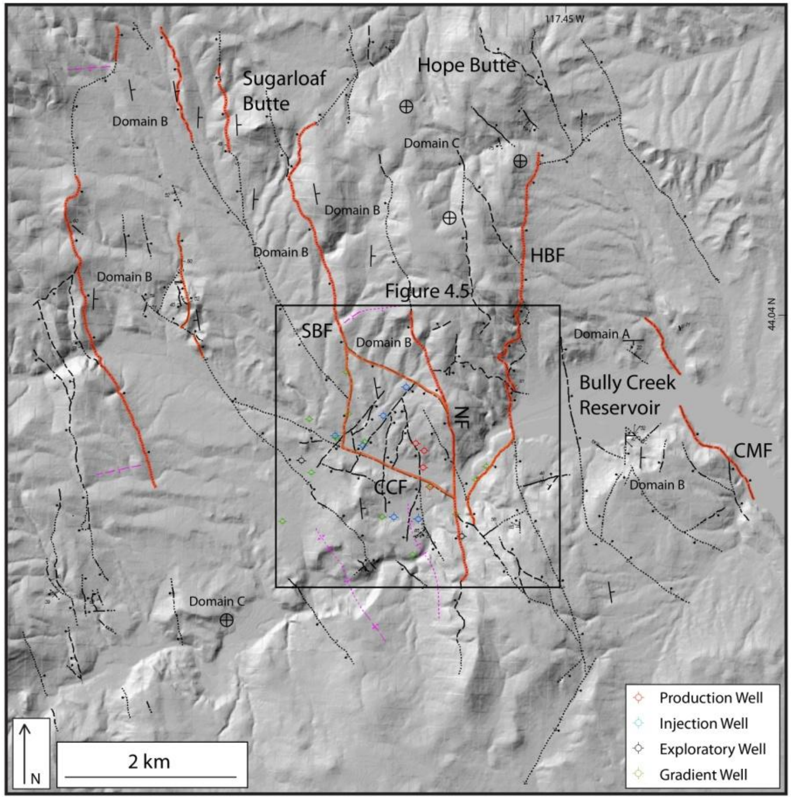
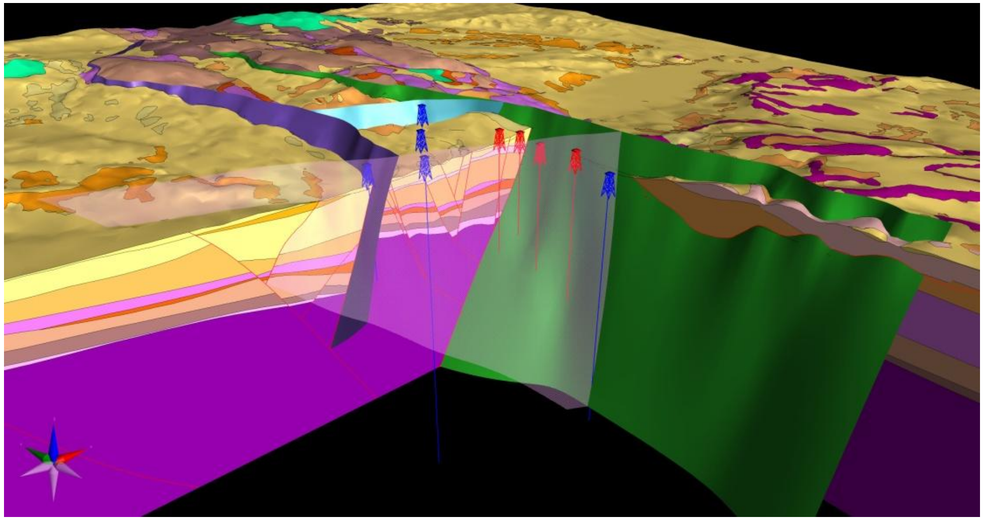
- Step over or relay ramp formed originally in mid to late Miocene E-W extension – left step in normal fault zone
- Reactivated in later NE-SW extension
- Step-over transformed into small pull apart







Tuscarora, Northeastern Nevada

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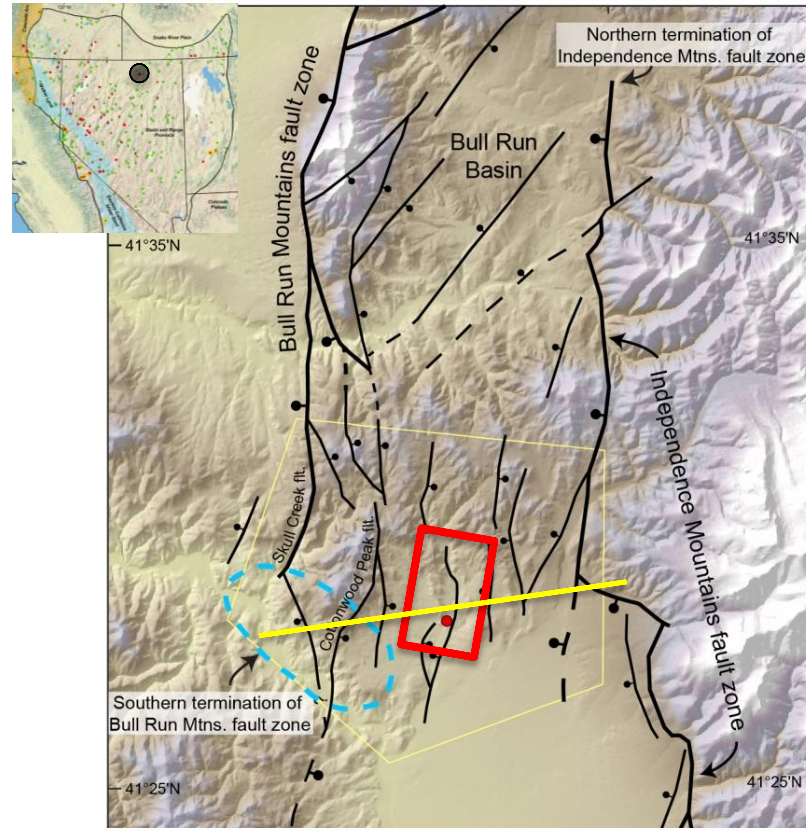
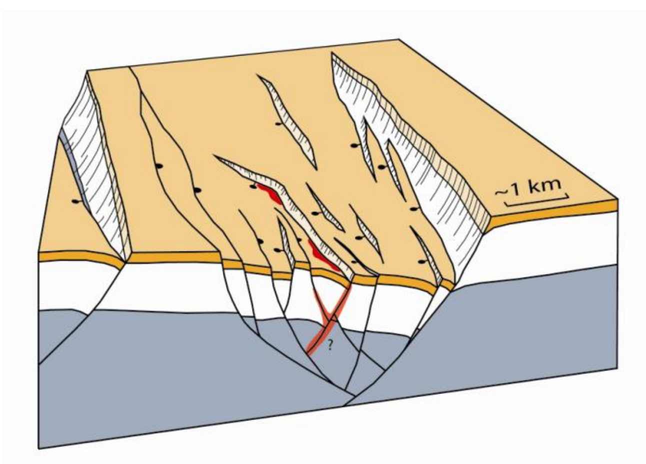
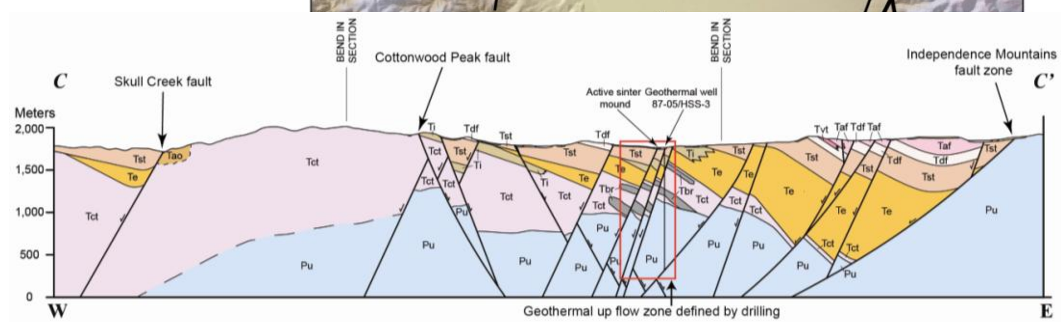
- Selected based on location in NE Nevada, where geothermal systems poorly studied
- Abundant data with new Ormat 18 MWe plant
- Master's thesis – Greg Dering
- Methods – detailed mapping (110 km^2), structural analysis, well logging (1,000 m), integration of geophysics, 3D model
- Structural Setting (two settings)
  - **Broad left step or relay ramp in normal fault system**
  - **Small accommodation zone in step over (intermeshing oppositely dipping faults)**
  - **Reservoir in Paleozoic metasedimentary rocks near margin of Eocene caldera**

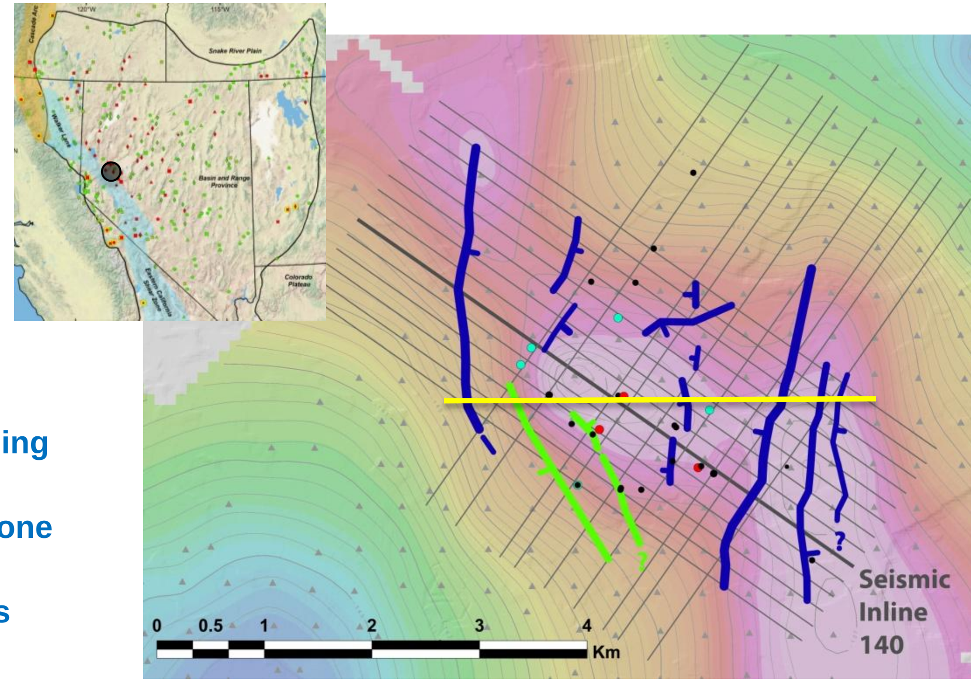


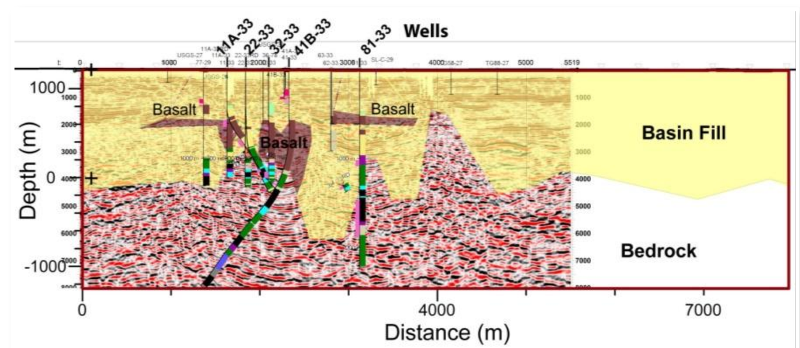




Soda Lake, Western Nevada

- Selected based on blind system in central part of large basin (Carson Sink)
  - **MagmaEnergy expanding power plant**
  - **Abundant geophysical + well data**
- Ph.D. dissertation – Holly McLachlan
- Methods – Well logging, integration of geophysics, and 3D modeling
- Structural Setting
  - **Two NNE-striking, over-lapping, oppositely dipping normal faults**
  - **Best production near oblique accommodation zone formed between graben-bounding faults**
  - **Interaction between overlapping opposing faults generates broad damage zone that provides conduits for upwelling geothermal fluids**





Construction of 3D Models of Representative Fields

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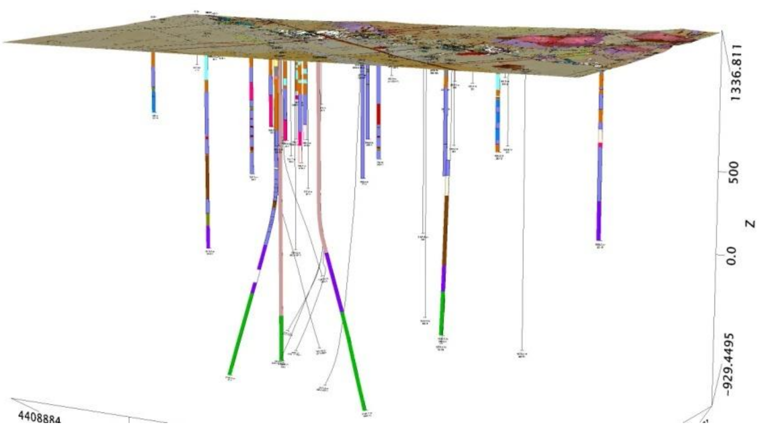
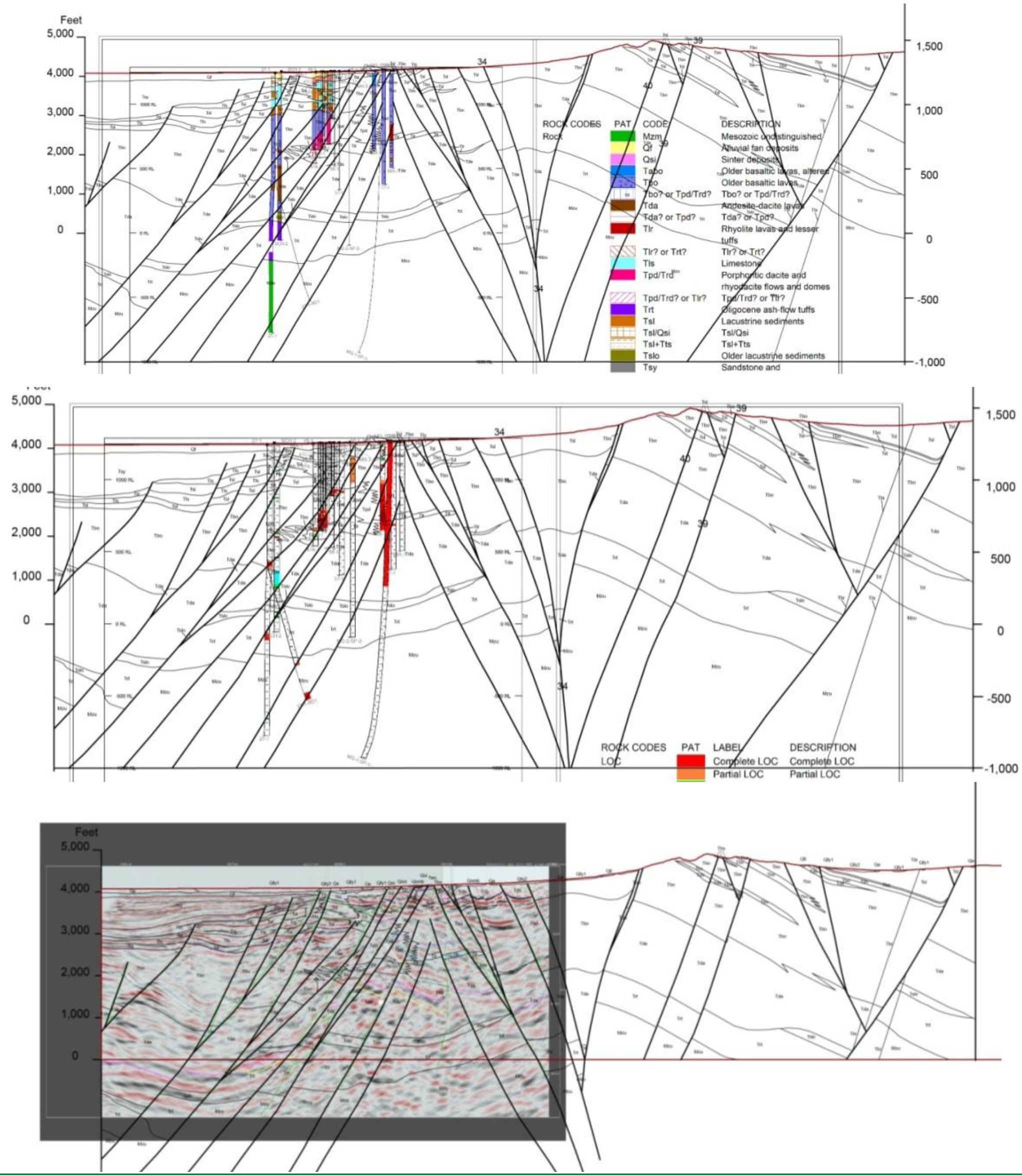
- Detailed mapping of bedrock, Quaternary, and surficial geothermal features
- Incorporate well data
- Interpretation of seismic reflection data
- Construct detailed cross sections





3D Modeling – Enhancing 3D “Thinking”

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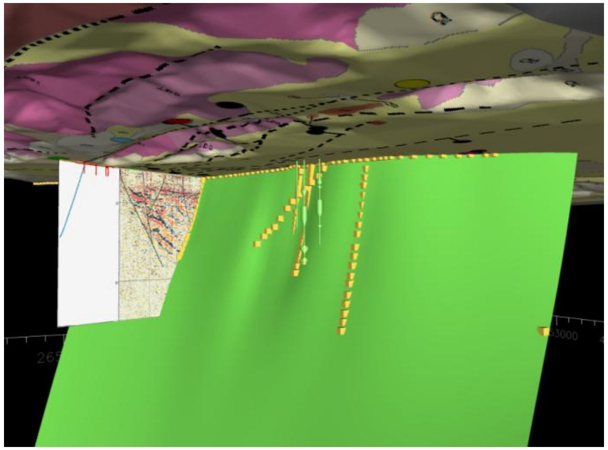
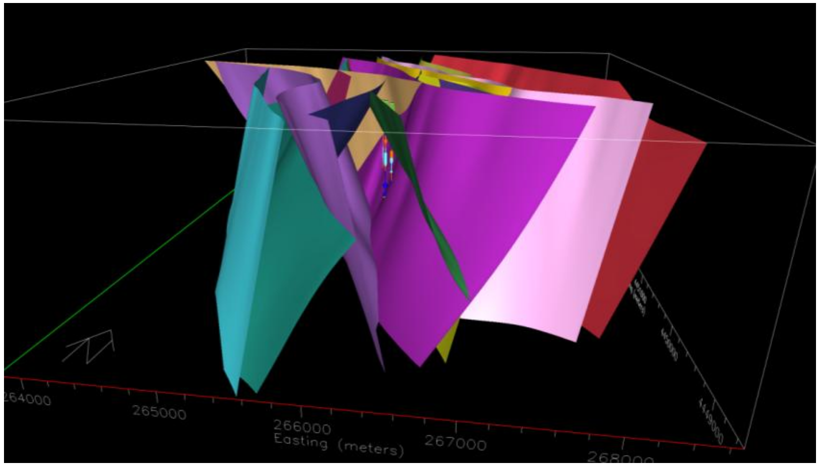
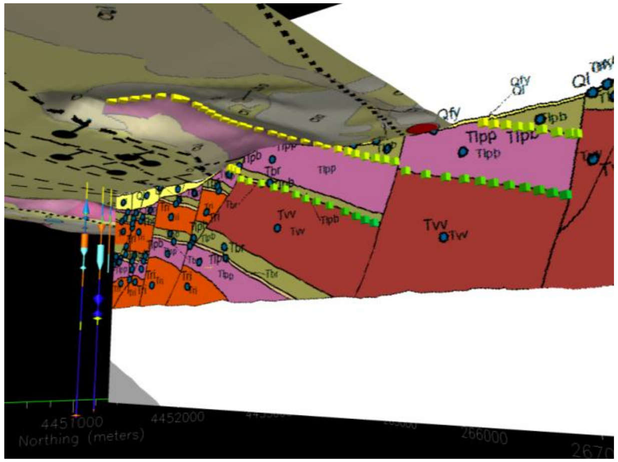
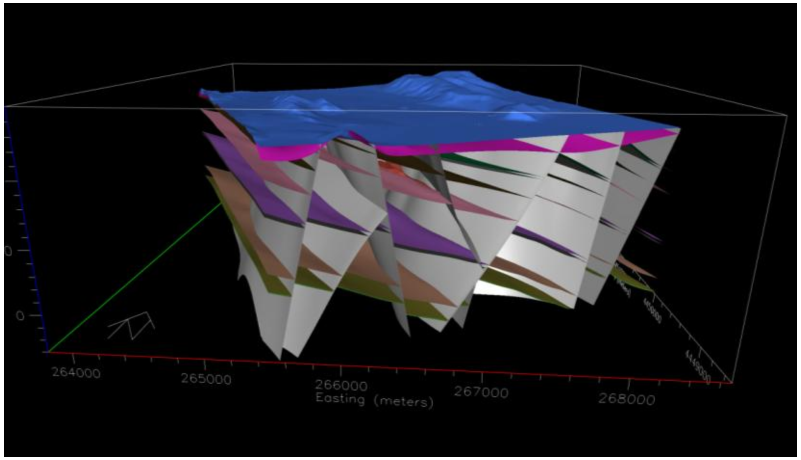


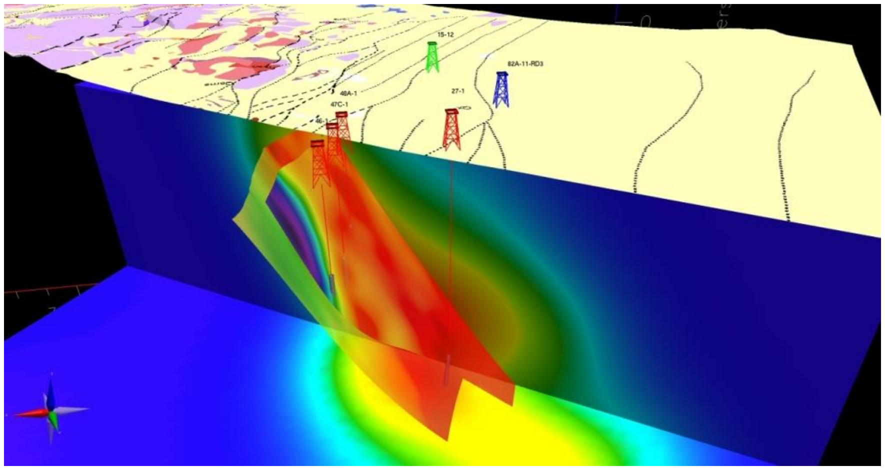




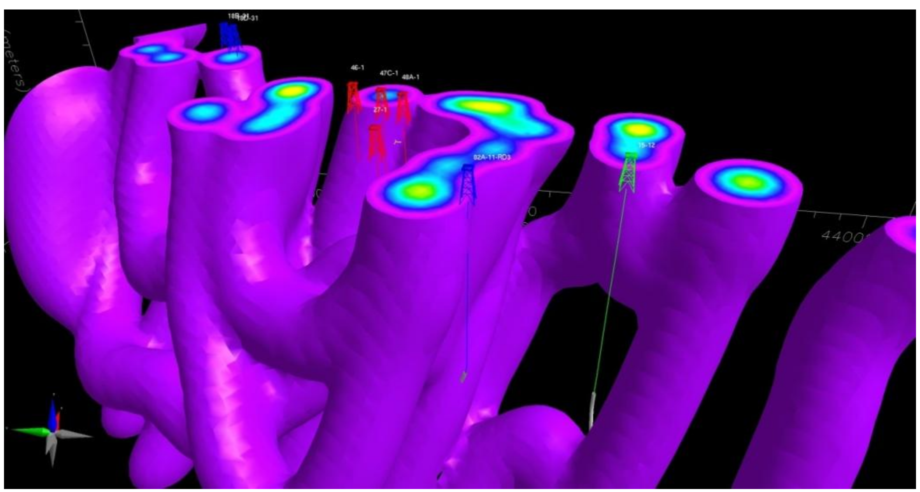


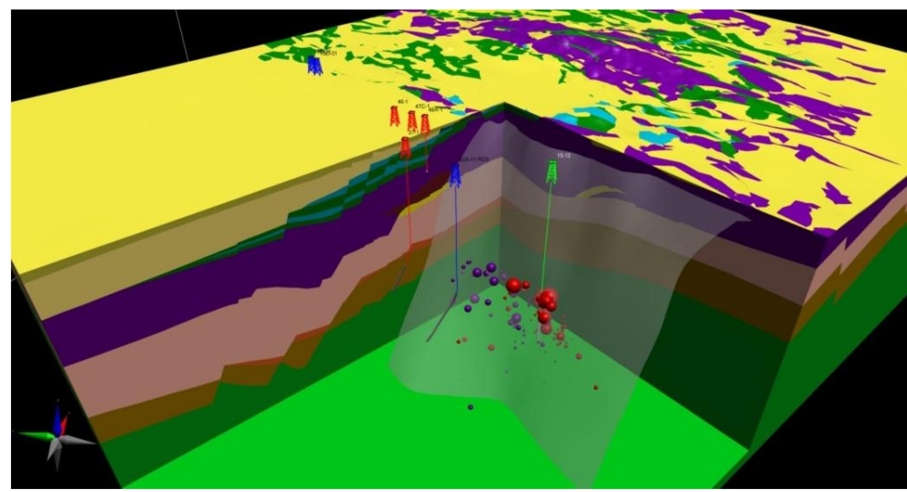
- **Faults and stratigraphic horizons digitized based on maps, cross-sections, seismic interpretations, well data, etc.**
- **Fault hierarchy established to guide model, challenging geoscientist to *think* in 3D**
- **Positive feedback into the original map and cross sections**

3D Modeling: Quantifying and Visualizing Fluid-Flow Fairways



- **Combine with slip and dilation tendency analysis**
- **3D visualization of density of fault intersections**
- **Hitting the target – fluid-flow fairways?**





Fluid-Flow Fairways

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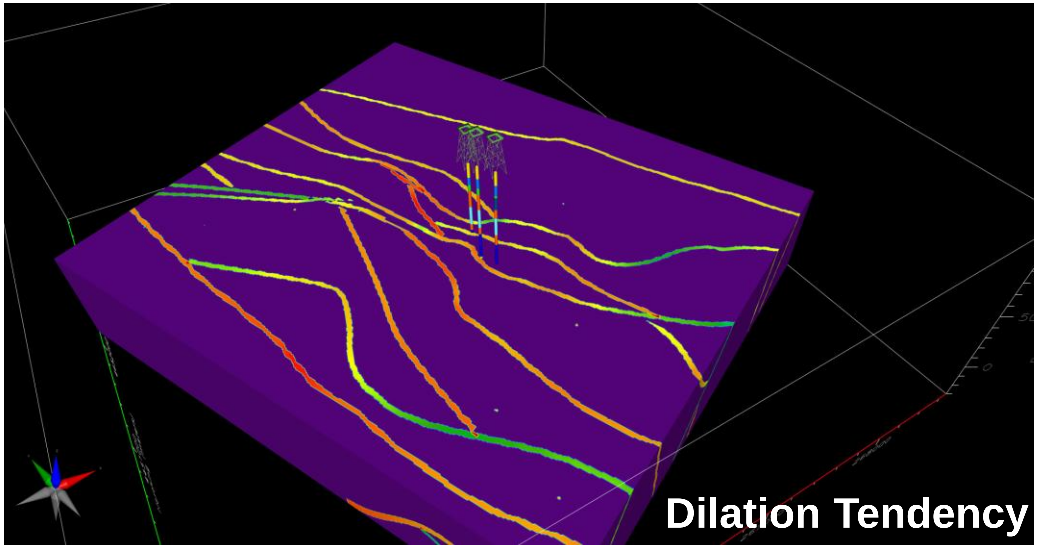
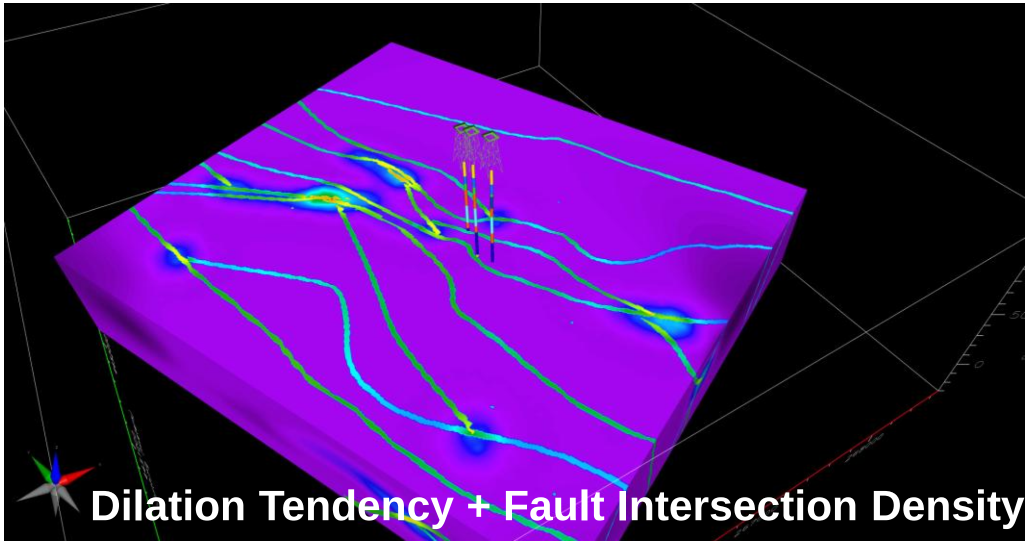
- **Fracture permeability accentuated on fault segments**
  - critically stressed under ambient stress conditions. AND
  - at fault tips and fault intersections where stress concentrations produce and maintain dense fracture networks.
- **Geothermal 'fairway' of high fracture permeability and fluid flow where**
  - collocation of critically stressed fault segments, and
  - high fault intersection density.





Conclusions

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- **Characterization of geothermal systems critical for exploration & development**
  - **Better conceptual models**
  - **Catalogues of key settings and indicators of such settings**
  - **Involves integrated geologic-geophysical work - Structural only one perspective**
- **3D models critical for future development & reducing risks in drilling**
- **Many undiscovered blind geothermal systems**

Future Directions

- Continued characterization of existing systems to find signatures
  - Structural setting
  - MT
  - Gravity
  - Soil gas
- Integrate multiple techniques
  - Geological
  - Geophysical
- Target green-field blind systems
- Apply to EGS development
- ***Develop a "Temperability" Meter!***