Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways

Project Officer: Holly Thomas

Total Project Funding: $499,992

May 12, 2015

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Board of Regents on behalf of University of Nevada, Nevada Bureau of Mines and Geology

Track Name: Play Fairway Analysis

Relevance/Impact of Research

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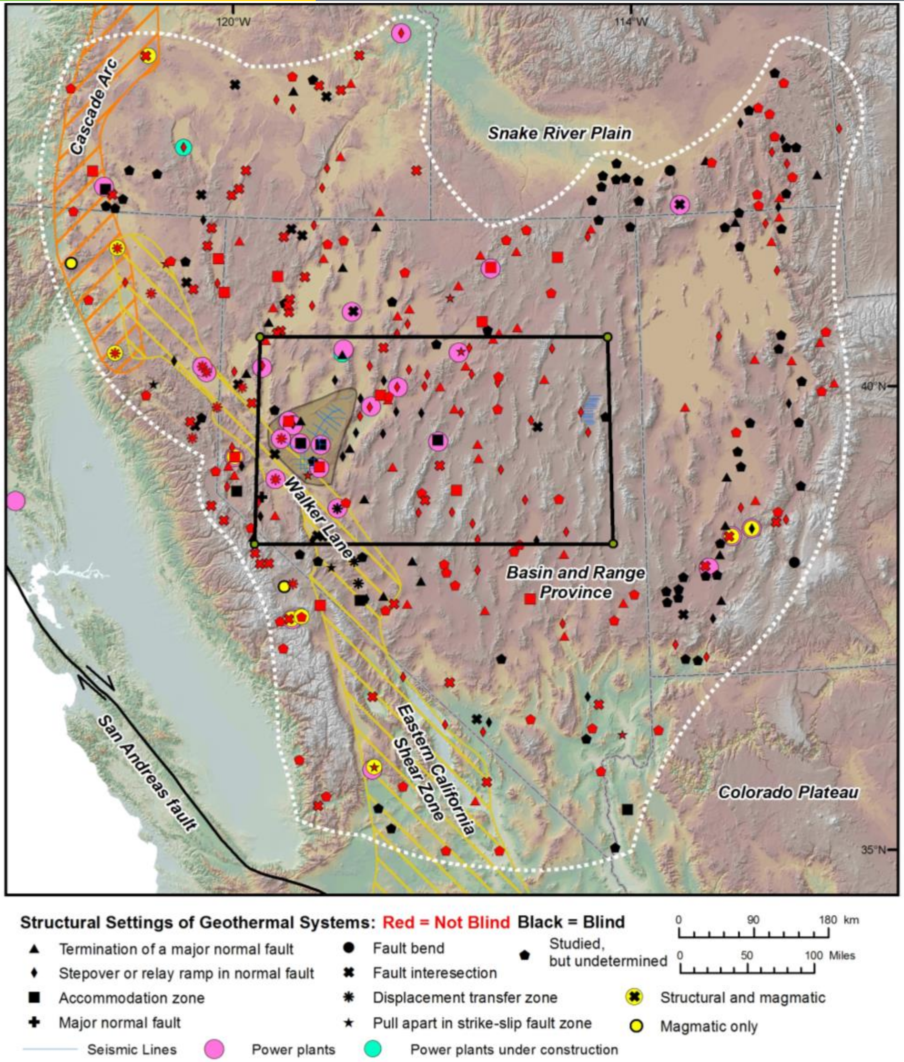
OBJECTIVES

- Synthesize geologic and geophysical characteristics of geothermal fields
- Prepare detailed geothermal potential map
  - 240 km x 400 km transect across Great Basin
  - ~10 parameters incorporated
- Identify areas with high potential for hosting blind systems
- Major deliverables
  - GIS geodatabases of geologic, geophysical, geochemical, and geodetic data
  - Detailed statistically based geothermal potential map
  - 3D models of two promising basins



Map showing structural settings of Great Basin geothermal fields – box surrounds study area

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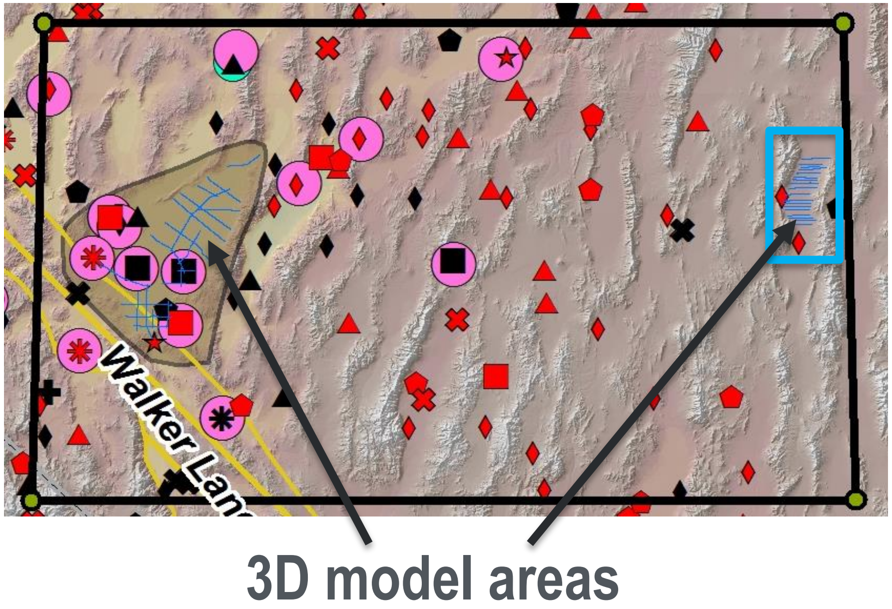
Impacts

- Most detailed geothermal potential map produced to date
- Map may serve as prototype for similar efforts elsewhere
- Accompanying 3D models of two basins provide more detailed maps, further reducing risks in these areas
  - Carson Sink – western part
  - Steptoe basin – eastern part
- Results
  - Will likely stimulate greenfield exploration
  - Reduce risks in drilling
  - Facilitate development of blind geothermal resources

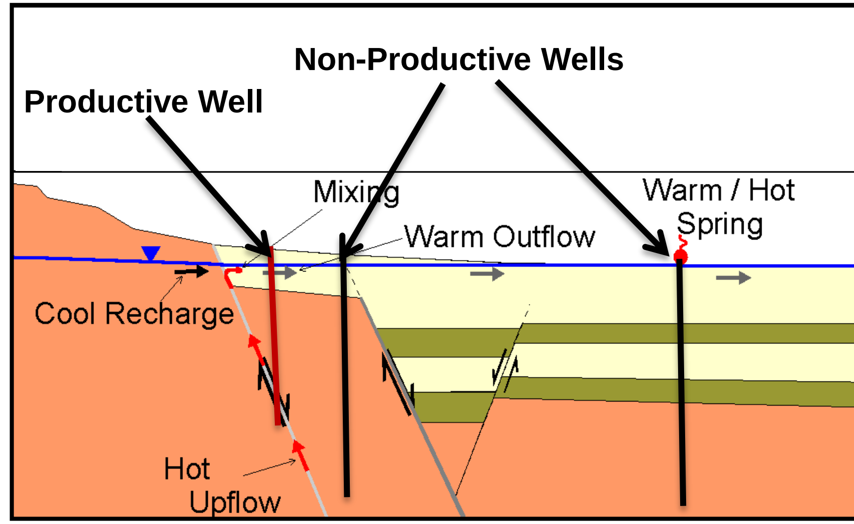
Map showing study area with structural settings of known geothermal systems; symbols same as on previous slide. Thin blue lines show locations of seismic reflection profiles obtained from SEI. Brown shaded area outlines Carson Sink and previously completed detailed gravity survey. Blue box encompasses the Steptoe basin.



Relevance/Impact of Research

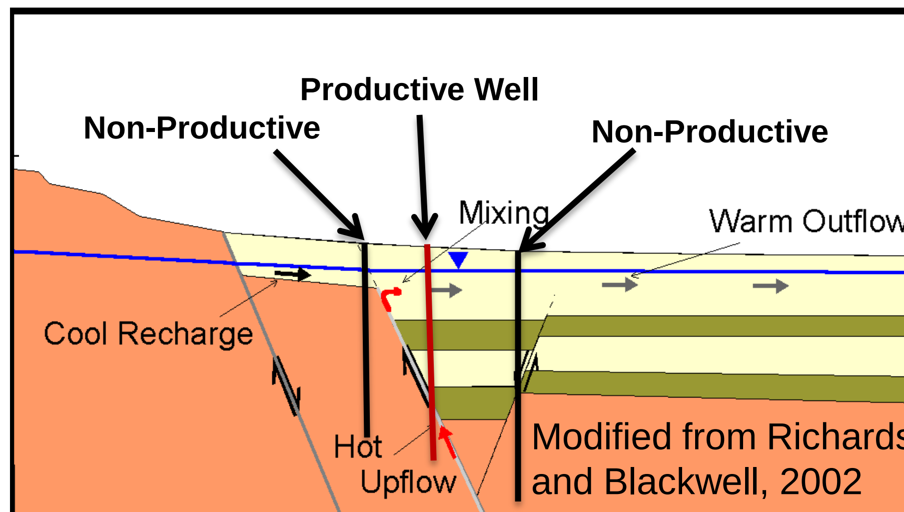
Exploration Challenges

- Spring directly above upflow from deep source (uncommon)
- Outflow from source (common) – drilling in such areas usually results in non-productive well
- Hidden or blind systems (most common)
- Difficult to find permeability sweet spot or play fairway



Barriers

- Assessing potential resources
- Prioritizing sites for exploration and development
- Minimizing risk of expensive drilling



Modified from Richards and Blackwell, 2002

Relevance/Impact of Research

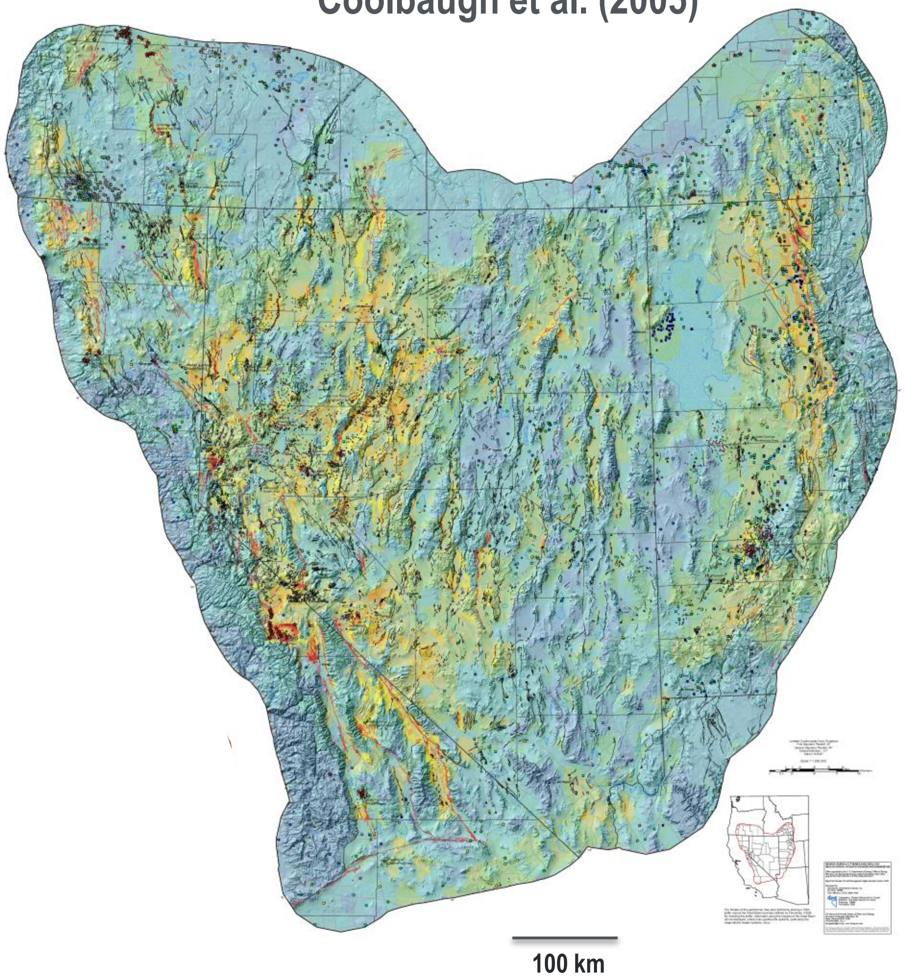
Previous geothermal potential map for Great Basin(Coolbaugh et al., 2005): Limited to 5 parameters

- Gravity gradient data
- Dilational GPS strain rate
- Temperature gradient
- Earthquake frequency
- Quaternary faults

New map with this project incorporates:

- Heat flow/temperature gradient
- Geochemistry from springs and wells
- Structural setting
- Recency (age) of faulting
- Strain rate
- Slip and dilation tendency
- Earthquake frequency and magnitude
- Gravity data
- MT data where available
- Seismic reflection data for two large basins

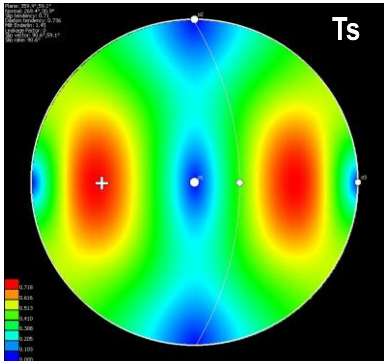
Coolbaugh et al. (2005)

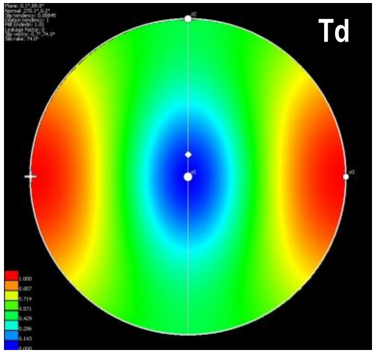


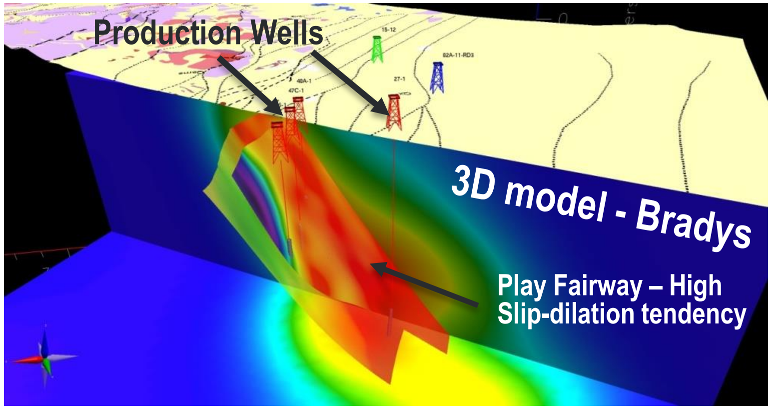
Most detailed geothermal potential map completed for Great Basin region

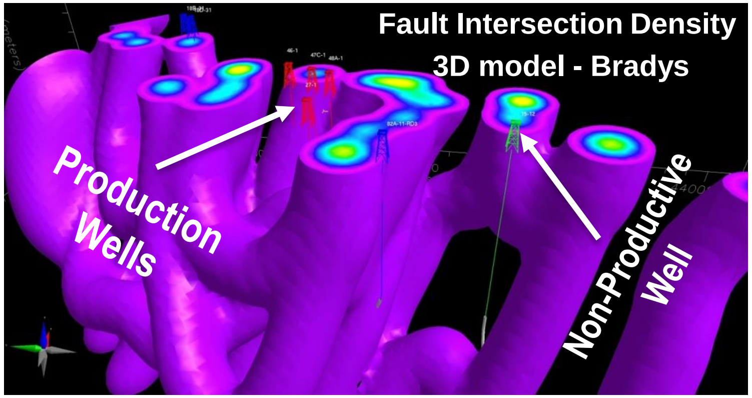
Innovative Aspects to Define Play Fairways

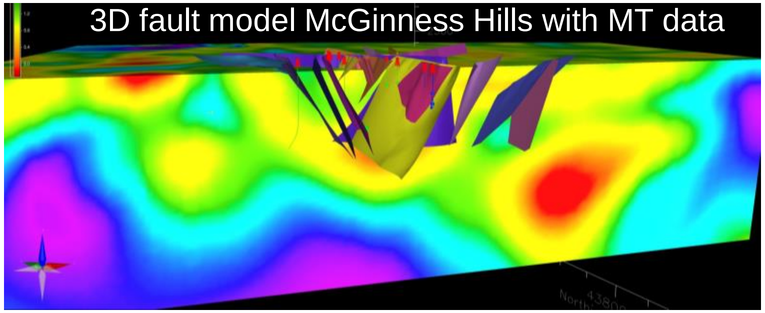
- Slip and dilation tendency - $T_s = \tau / \sigma_n$, $T_d = (\sigma_1 - \sigma_n) / (\sigma_1 - \sigma_3)$
- 3D modeling with slip and dilation tendency
- 3D inversion of MT data
- 3D visualization to define play fairway
- Synthesis of multiple parameters into cohesive assessment of geothermal potential on individual map

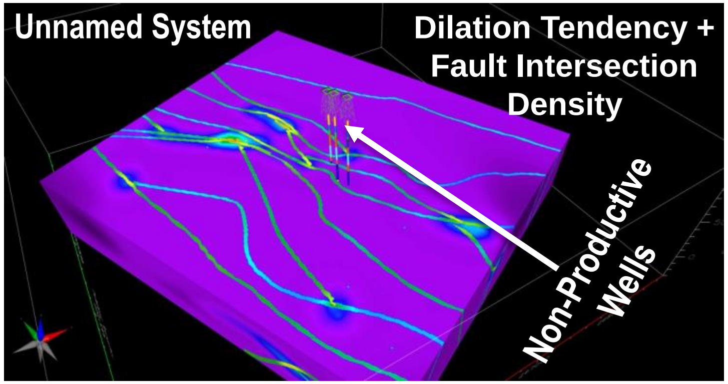












Relevance/Impact of Research: Impact on Geothermal Technologies Goals

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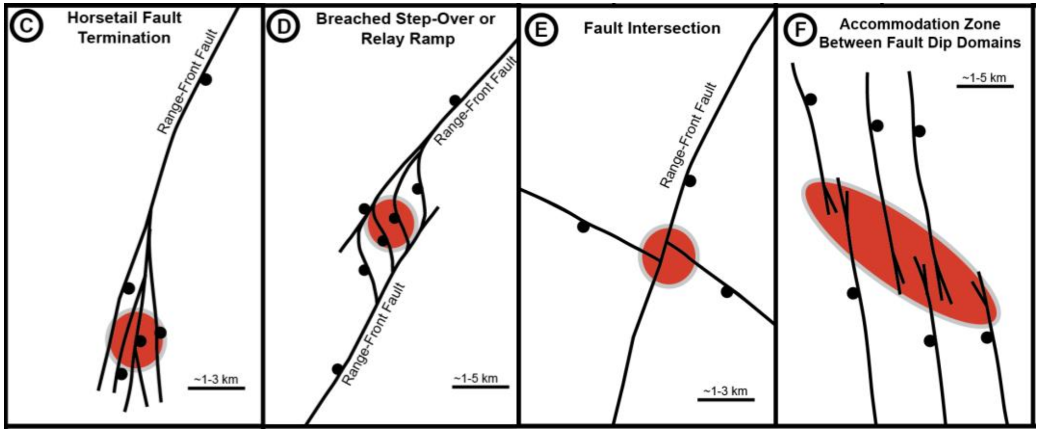
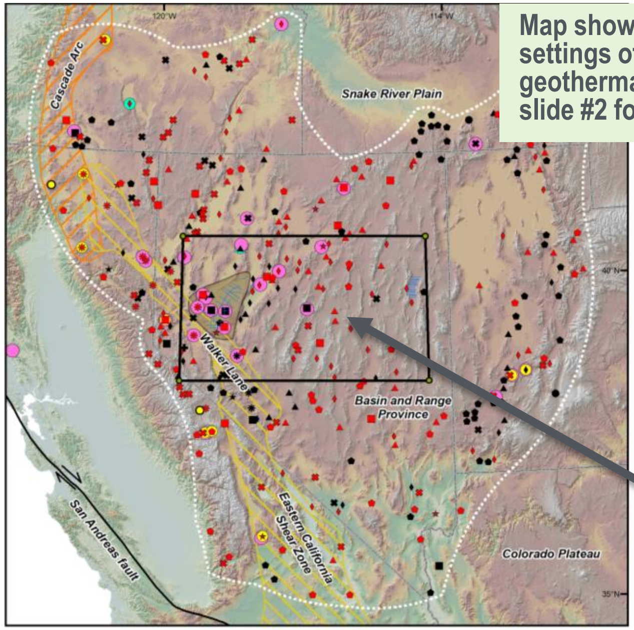
- **GTO Goal – Accelerate Near Term Hydrothermal Growth**
  - Lower risks and costs of development and exploration
  - Lower levelized cost of electricity (LCOE) to 6 cents/kWh by 2020
  - Accelerate development of 30 GWe of undiscovered hydrothermal resources
- Most geothermal resources in Great Basin region are blind
  - 39% of known systems
  - ~75% of total resources estimated to be blind in region (Coolbaugh et al., 2007)
- Must therefore develop methods of identifying play fairways for blind hydrothermal systems and to fully develop potential of region
- Impacts of next generation of detailed geothermal potential maps combined with 3D modeling:
  - Lower risks and costs of development and exploration
  - Improve analytical approach in selection of well sites
  - Resulting cost reductions will lower cost of electricity from geothermal plants
  - May spark greenfield exploration and subsequent acceleration in development of conventional hydrothermal resources
- Relevance to other GTO goals
  - Systems analysis – Resource assessment and data gathering and analysis
  - EGS – enhances understanding of best areas for development and reservoir modeling
  - Low temperature – Enhances understanding of best areas for development

Scientific/Technical Approach

- Recent research indicates that geothermal upwellings in extended terranes focused in certain structural settings – fault interaction areas
  - **High fault density**
  - **Quaternary faults with high slip and dilation tendency**
  - **Geophysical anomalies**
- Need multi-disciplinary geologic and geophysical approach to define play fairways and generate detailed geothermal potential maps
- E-W 240-km-wide, 400-km-long transect across Great Basin chosen area for detailed map because:
  - **High heat flow**
  - **Abundant Quaternary faults and favorable structural settings**
  - **Relatively high extensional to transtensional strain rates with major strain gradient (increase from ~1 mm/yr on east to ~1 cm/yr on west)**
  - **14 geothermal power plants that serve as benchmarks for analysis**

Favorable settings accounting for ~90% of known systems in Great Basin region





Map showing structural settings of Great Basin geothermal fields – see slide #2 for legend

Study area for which geothermal potential map will be produced for this project

Scientific/Technical Approach

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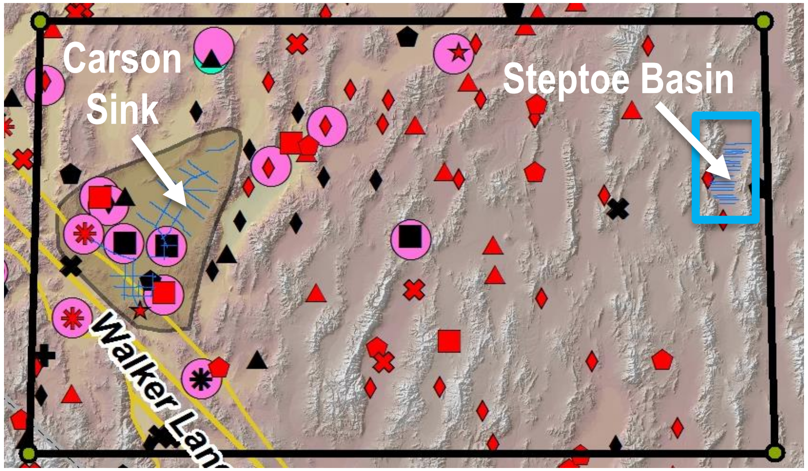
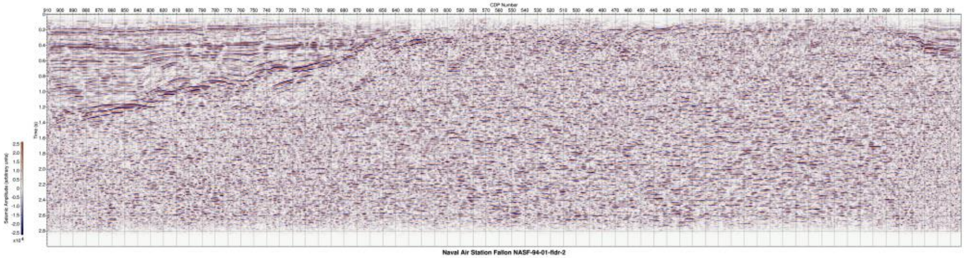
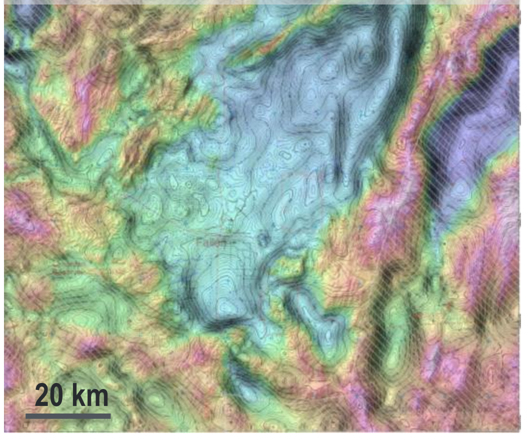
- Transect anchored at west and east ends by more detailed analyses:
  - **Seismic reflection data from multiple profiles – provide insights on subsurface structural settings in large basins**
  - **Detailed gravity for Carson Sink – provides insights on structural setting beneath broad basin**
  - **3D basin-scale models – provide general architecture of basins**
  - **3D slip and dilation tendency analyses – provide locations of play fairways in 3D**
- Carson Sink and Steptoe basins chosen for more detailed study because:
  - **Rich data sets**
  - **Span large strain gradient across region**
  - **High geothermal potential:**
    - **Carson Sink has many power plants and probably hosts additional undiscovered blind systems**
    - **Steptoe basin has probable hydrothermal as well as sedimentary hosted geothermal systems, both fed by upwellings in favorable structural settings**



Map showing study area with structural settings of known systems; symbols same as on slide #2. Thin blue lines show seismic reflection profiles. Brown shaded area outlines Carson Sink and previously completed detailed gravity survey. Blue box encompasses Steptoe basin.



Example of seismic reflection profile from Carson Sink – Fallon Naval Air Station



Map showing existing detailed Bouguer gravity for Carson Sink

Scientific/Technical Approach: Project Tasks and Milestones

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- Major Tasks
  1. Review-interpret geologic data
     - Well and spring data
     - Locations, age, and slip rates on Quaternary faults
     - Heat flow-temperature data
     - Regional stress data
     - Geothermal systems
  2. Review-interpret geophysical data
     - 2.1 – Seismic reflection data - Carson Sink & Steptoe basins
     - 2.2 – Gravity data
     - 2.3 – MT data
     - 2.4 – Seismologic data
  3. Review-interpret geochemical data
  4. Review-interpret geodetic data
  5. GIS database compilation
     - 5.2 Preliminary modeling at end of Q2
     - 5.3 Database management
  6. Identify favorable structural settings
  7. Slip and dilation tendency analysis
  8. 3D modeling of Carson Sink & Steptoe basins
  9. Quantitative ranking of geothermal potential
  10. Detailed geothermal potential maps
  11. Identify data needs for potential Phase II
  12. Final reporting and project review

Task and Milestone Summary

Task #	Task Title or Subtask Title	Milestone	Milestone Description	Milestone Verification	Ant. Qtr
1	Review and Interpretation of Geologic Data	M1.1	Compilation of geologic maps	Maps will include lithologic data and structural data including faults and folds	Q1
2.1	Review and Interpretation of Seismic Reflection Data	M2.1.1	Obtain reflection profiles from Seismic Exchange, Inc.	Purchased profiles per SEI License	Q1
2.1	"	M2.1.2	Analysis of seismic reflection profiles	Interpretation of seismic reflection profiles for 3D modeling in Task 8	Q3
2.1	"	M2.1.3	Characterization of seismic reflection indicators of favorable structural settings	List of characteristics of seismic reflection indicators of favorable structural settings	Q3
2.2	Review and Interpretation of Gravity Data	M2.2.1	Compilation and analysis gravity of anomaly maps	Maps showing gravity data for Great Basin study area	Q1
2.2	"	M2.2.2	Analysis of gravity data	Maps showing interpreted gravity data with inferred faults	Q3
2.2	"	M2.2.3	Identify gravity signatures for favorable structural settings	List of gravity anomaly indicators of favorable structural settings	Q3
2.3	Review & Interpretation of Magnetotelluric Data	M2.3.1	Compilation of MT data	MT data maps for select parts of study area	Q1
2.3	"	M2.3.2	Analysis of MT data	Interpreted MT data and list of characteristics of MT signatures for known systems	Q3
2.4	Review & Interpretation of Seismologic Data	M2.4.1	Analysis of spatial distribution of earthquakes	Maps showing earthquake distribution relative to structural setting and known geothermal systems	Q1
2.4	"	M2.4.2	Characterization of seismologic character of known geothermal areas	Establish seismologic signature of known geothermal systems	Q2
3	Review and Interpretation of Geochemical Data	M3.1	Compilation of geochemical data	Maps showing geochemical data for study area	Q1
3	"	M3.2	Analysis of geochemical data	Characterization of geochemical signatures of known systems and evaluate for additional anomalies	Q2
4	Review and Interpretation of Geodetic Data	M4.1	Compilation of geodetic data	Maps showing geodetic strain for study area	Q1
4	"	M4.2	Analysis of geodetic data	Produce list of geodetic indicators of known systems	Q2
4	"	M4.3	Produce strain maps	Produce velocity gradient and strain rate maps with estimates of slip rates and styles for active faults	Q4
5.1	GIS Database Compilation	M5.1	Compilation of all data into ArcGIS	Produce well organized ArcGIS data sets for study area	Q2
5.2	Preliminary Modeling	M5.2	Prepare preliminary predictive model of geothermal potential	Map showing preliminary geothermal potential	Q2
5.3	Database Management	M5.3	Finalize assembled data sets at end of each quarter	Submit assembled data sets to DOE-GDR and NGDS	Q3, 4
6	Identify and Characterize Structural Settings	M6.1	Complete analysis of structural framework	Maps showing structures that may host blind systems	Q3
7	Slip and Dilation Tendency Analysis	M7.1	Complete slip and dilation tendency analyses	Map showing slip-dilation tendency of faults for study area	Q3
7	"	M7.2	Conduct 3D slip and dilation tendency analysis for Carson Sink and Steptoe basins	Model showing slip and dilation tendency in 3D for Carson Sink and Steptoe basins	Q4
8	3D Geologic Modeling of Selected Basins	M8.1	Construct 3D models of two basins	3D models constructed from geologic map data, seismic reflection profiles, and gravity data	Q4
9	Quantitative Ranking of Blind Geothermal Potential	M9.1	Final rankings table and predictive maps	Database containing rankings and preliminary maps contouring geothermal potential	Q4
10	Complete Geothermal Potential Maps of Study Areas	M10.1	Final geothermal potential maps	Final prediction of known and potential blind geothermal systems	Q4
11	Identify Data Needs for Phase II	M11.1	Robust data sets indicating high potential, comparison with developed areas	Selection of most prospective areas for undiscovered blind geothermal systems for further study	Q4
12	Final Reporting and Project Review	M12.1	Synthesis of project	Submittal of report and databases	Q4

Scientific/Technical Approach: Highlights and Key Issues

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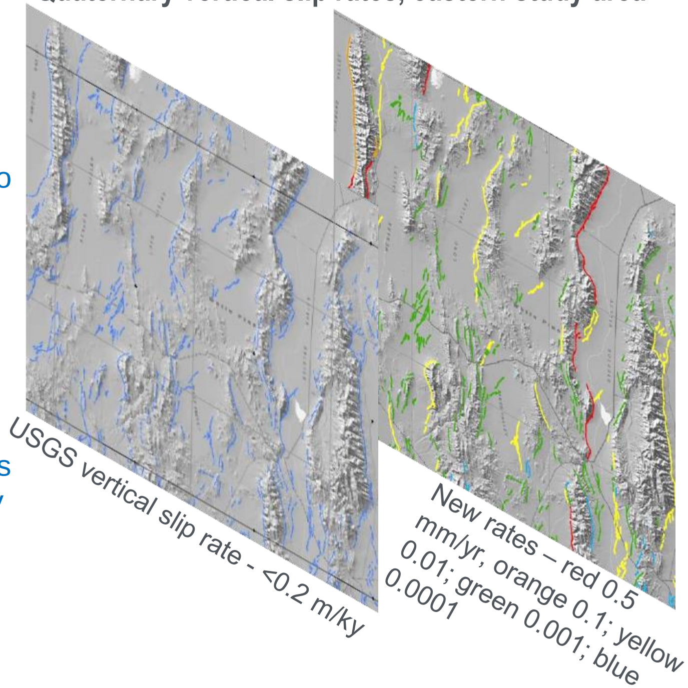
- Task/Organizational Highlights
  - Quarters 1 and 2 (Q1-Q2) – Initially compile then interpret geological, geochemical, and geophysical data sets
  - End of Q2 – Prepare preliminary predictive model with all data sets, determining appropriate groupings and weightings of each parameter
  - End of Q2 – Hold team meeting for feedback on preliminary model and refine accordingly
  - Q3 – Complete interpretation of data sets and initiate detailed analyses and 3D modeling of Carson Sink and Steptoe basins
  - Q4 – Complete detailed geothermal potential map, 3D modeling of Carson Sink and Steptoe basins, and submittal of all data to NGDS and DOE-GDR
- Milestones proceed logically from data compilation to data interpretation to modeling and production of detailed geothermal potential map
- Key Issues
  - Synthesis of multiple data sets into cohesive assessment of geothermal potential on a single map using various weighting factors and statistical methods (e.g., weights of evidence, multivariate statistics, classification and regression tree analysis, etc.)
  - Key hierarchal components include:
    - Permeability – based on structural setting, recency of faulting, slip-dilation tendency, seismicity, gravity, strain rate
    - Temperature – based on heat flow and geochemistry

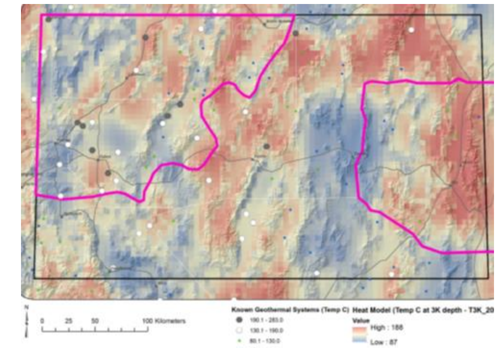
Major Technical Results

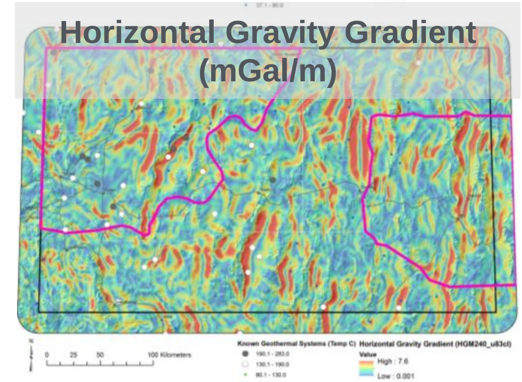
- **Task 1 – Geologic Data**
  - Updating Quaternary fault and fold database for study area
  - High slip rates do not correlate with geothermal activity on main faults but do correlate with activity on nearby stepovers, tips, etc.
- **Task 2.1 – Seismic Reflection Data**
  - Analysis shows many fault tips, stepovers, etc. in Carson Sink; one major stepover in Steptoe basin
- **Task 2.2 – Gravity Data**
  - Large HZ gradients marking major faults do not correlate with geothermal activity but ends/discontinuities in gradients do
- **Task 2.3 – MT Data**
  - Determined best to use both shallow and deep anomalies to gauge geothermal activity

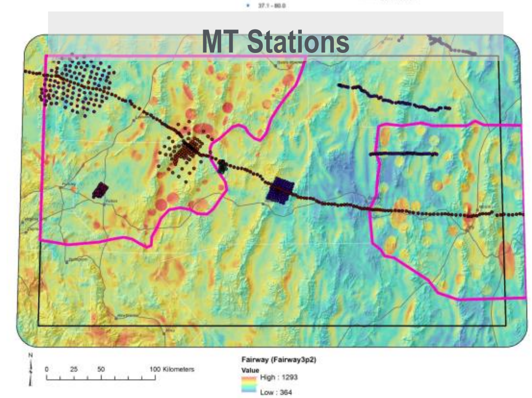
Quaternary vertical slip rates, eastern study area



Heat Flow Data – Temp at 3 km in Study Area





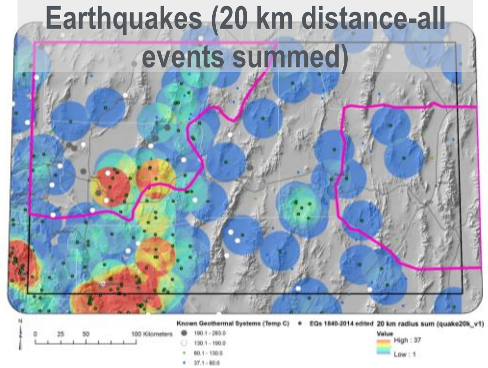


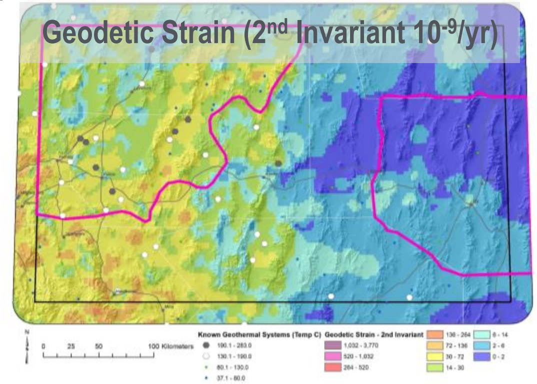
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
M1.1 – Compile and interpret geologic data; planned for Q1	Compiled geologic maps, heat flow, well-spring data, age-slip rates-locations Quaternary faults, regional stress, known geothermal systems	Dec ‘14
M2.1 – Review and interpret seismic reflection data; planned for Q1 to Q3	Reviewed profiles at SEI, purchased 426 miles of profiles, conducted initial analysis	March ’15 & in progress
M2.2 – Compile and interpret gravity data; planned for Q1 to Q3	Compiled available gravity data (44,400 stations); prepared maps showing Bouguer, vertical and horizontal gradients, basin depths	March ‘15 & in progress
M2.3 Compile and interpret MT data; planned for Q1 to Q3	Compiled available MT data from regional transect and 3D arrays	Jan ‘15 & in progress

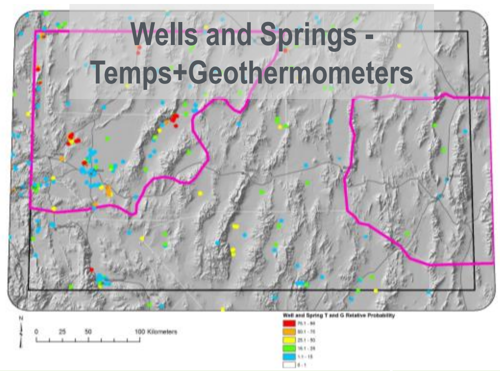
Accomplishments, Results, and Progress

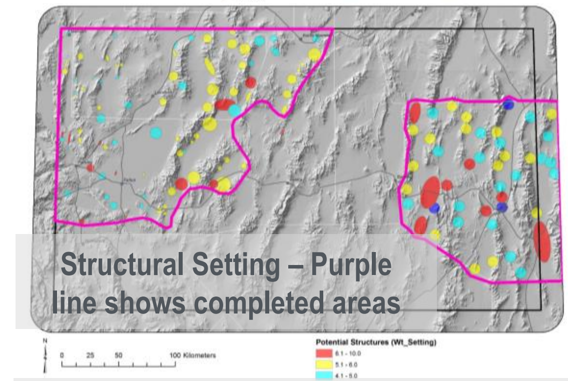
Major Technical Results

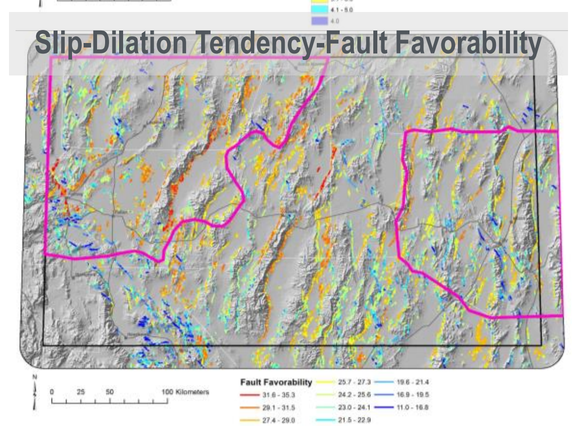
- **Task 2.4 – Seismologic Data**
  - Because density of stations varies across study area, lower threshold of well-located earthquakes also varies
  - Earthquake density rather than magnitude correlates with geothermal activity
- **Task 3 – Geochemical Data**
  - Quality factors – Charge balance (20%), Na-K-Ca minus qtz geothermometer temps (30%), maturity indices (20%), measured temps (20%)
- **Task 4 – Geodetic Data**
  - Higher strain rates correlate with greater density of high enthalpy systems
- **Task 6 – Structural Settings**
  - Concluded that each setting should also be rated based on slip rates + age of linked faults
- **Task 7 – Slip and Dilation Tendency**
  - Value for distance to nearest stress measurement also generated to rate uncertainty of calculation





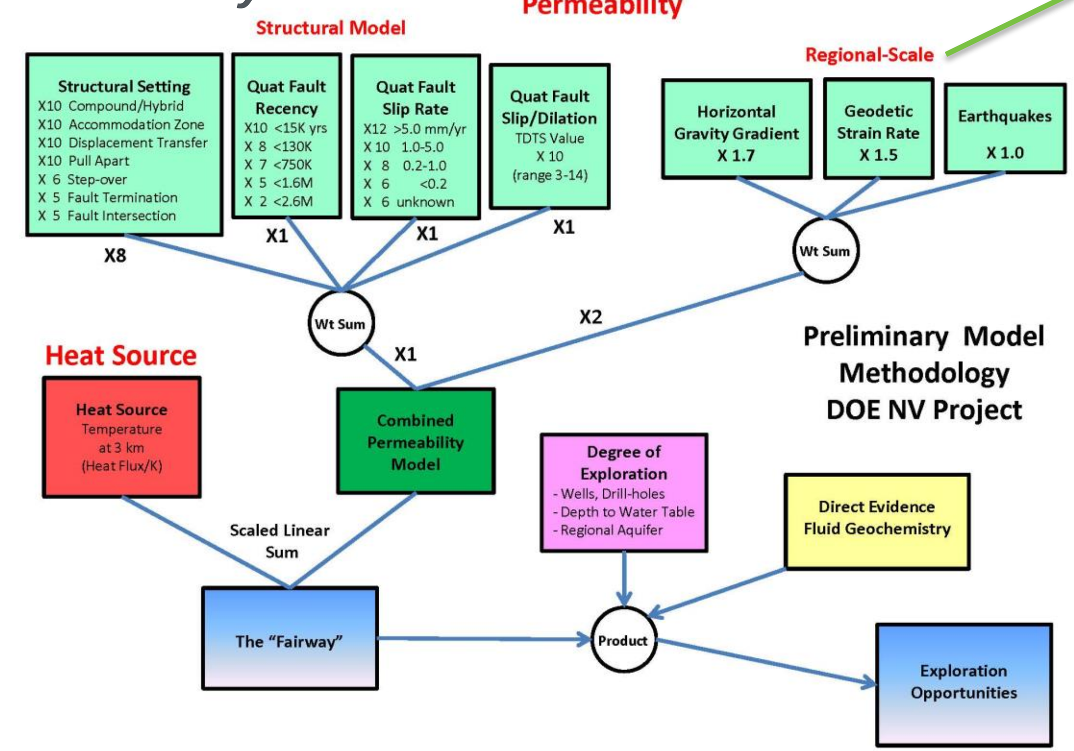


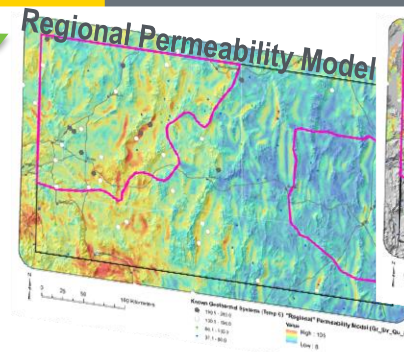


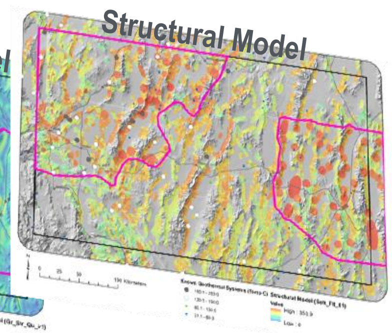


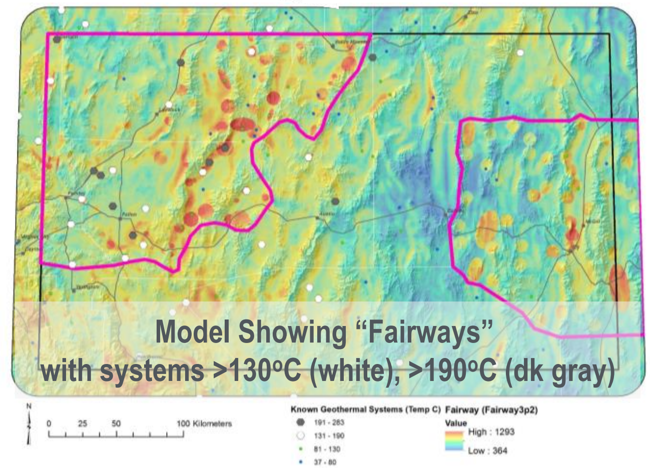
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
M2.4 – Compile and interpret seismologic data; planned for Q1 and Q2	Compiled earthquake locations through Oct 2014 from available catalogues	March '15
M3 – Compile and interpret geochemical data; planned for Q1 and Q2	Calculations compiled for 880 cold and 987 thermal waters; quality factors assigned	March '15
M4 – Compile and interpret geodetic data; produce strain maps; planned for Q1 to Q4	Contoured second invariant and principal strain rate axes calculated from 247 GPS stations	Jan-March '15 & in progress
M6 – Identify and characterize structural settings; planned completion in Q3	~200 favorable settings (fault stepovers, tips, etc.) identified & rated based on certainty + complexity	In progress, ~50% complete
M7 – Slip and dilation tendency analysis; planned for Q3 to Q4	Calculated for Quaternary faults using stress field from borehole breakouts and fault-kinematic data	March '15 & in progress

Preliminary Model









Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
M5.1 – Compilation of all data into ArcGIS; planned for Q2 to Q4	ArcGIS platform developed to incorporate all data sets; all data compiled to date in platform	March '15 & in progress
M5.2 – Preliminary modeling; planned for end of Q2	Preliminary predictive model produced using all data sets	March '15
M5.3 – Database management; planned for each quarter	Data sets assembled by end of each quarter for ultimate submittal to NGDS and DOE-GDR	Jan '15 & in progress

- **Task 5.2 – Preliminary Model**
  - Based on geologic, geochemical, and geophysical principles, preliminary predictive model and geothermal potential map produced
  - Utilized all data sets
  - Permeability based on structural model and regional-scale features
  - Permeability combined with heat flow and geochemistry to define "fairways"

Future Directions

- Key activities to project completion
  - Team meeting (April 2-3) generated constructive feedback leading to refinement of weighting factors - Examples:
    - Rank horizontal gravity gradient lower (than in preliminary model), as major faults generally do not correlate with geothermal activity
    - Structural setting must also be ranked based on recency of faulting, as settings outside active tectonic areas not conducive for high-T systems
    - Fault age categories and rankings revised-multiply: <15ka (x10); <130ka (x5); <750ka (x2), <2.6 Ma (x1); >2.6 Ma (0.1)
    - Slip rate rankings revised-multiply: 2-5 mm (x2); 1-2 mm (x1.75); 0.5-1 mm (x1.5); 0.1-0.5 (x1.25); 0.01-0.1 (x1)
  - Q3 focus (April-June) – Completing compilation and analysis of each data set
    - Identifying characteristics most indicative of geothermal activity for each parameter
    - Identifying characteristics that keep systems blind
  - Q4 focus (July-Sept) – Project completion for all major milestones and deliverables
    - Constructing 3D models of Carson Sink and Steptoe basins
    - Finalize weightings and groupings of all parameters
    - Prepare final geothermal potential map and construct rankings table of areas with high geothermal potential
    - Finalize data sets and submit to NGDS and DOE-GDR
    - Constrain marketability of prospects by denoting distance to transmission and transportation corridors and population centers
- Deployment strategy and expected outcomes
  - Publish predictive geothermal potential map and peer-reviewed papers: Map may serve as prototype for other areas
  - Results will likely stimulate greenfield exploration and development of blind geothermal systems
- Future research
  - Select key areas with highest statistical potential for hosting blind systems for detailed study in Phase II
  - Phase III – Drilling of best targets, as determined from Phase II, with an industry partner

Remaining Milestones (not shown previously)	Status & Expected Completion Date
M8 – 3D modeling of selected basins	Data collection complete; analysis underway – expected completion in Sept '15
M9 – Quantitative ranking of blind geothermal potential	Work underway – expected completion in Sept '15
M10 – Complete geothermal potential maps	Preliminary model demonstrated methodology works; weighting factors being revised; work well underway; expected completion in Sept '15
M11 – Identify data needs for Phase II	Work will begin in Q4; select most prospective areas for further study in Phase II
M12 – Final reporting and project review	On schedule for end of Q4

Mandatory Summary Slide

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- Project progressing well and on schedule
  - Data compilation and analysis largely complete for each parameter
  - All data sets reside in ArcGIS platform
  - Successful preliminary model demonstrated that the multiple data sets can be combined into a predictive geothermal favorability map
  - April team meeting generated constructive feedback and refinement of grouping and weighting of parameters
- Final results and outcomes:
  - Detailed geothermal potential map with more parameters than any other map
  - 3D models and geothermal potential maps for Carson Sink and Steptoe basins
  - Work may stimulate greenfield exploration and development of blind geothermal systems
  - Work may facilitate many discoveries of robust blind geothermal systems like McGinness Hills