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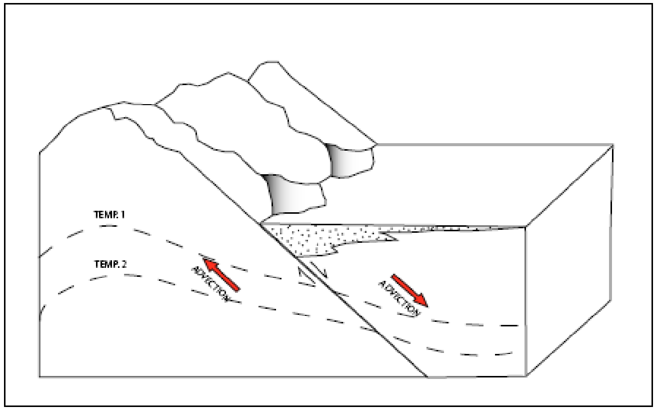

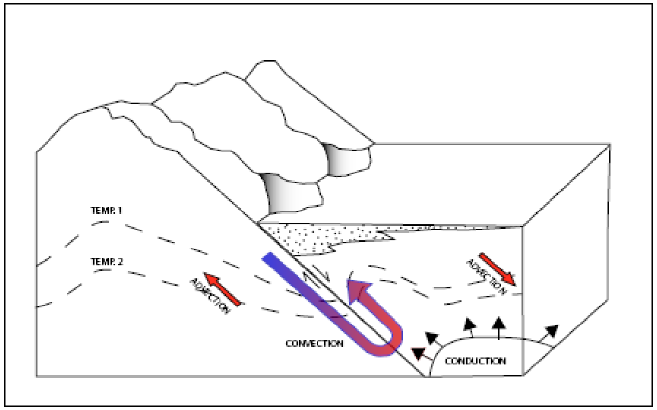

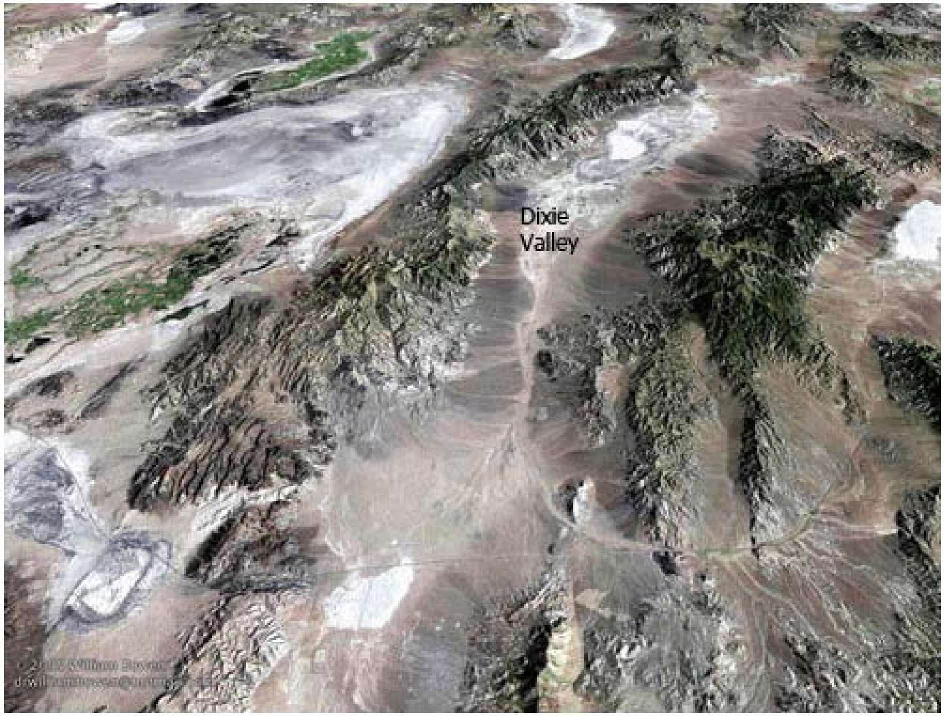

Novel Coupled Thermochronometric and Geochemical Investigation of Blind Geothermal Resources in Fault-Controlled Dilational Corners

April 23, 2013

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University of Texas at Austin
Jackson School of Geosciences

Novel Coupled Thermochronometric and Geochemical Investigation of Blind Geothermal Resources in Fault-Controlled Dilational Corners

- Timeline
  - Project start 01/31/2012 - 01/31/2014 (50% complete)
- Budget
  - Total project funding $ 845,409
  - DOE $ 845,409
- This project is a Phase I Prove of Concept project only (no Phase II)
- Partners: LBNL (Drs. Kennedy and Lewicki) and the University of Kansas (Dr. Walker)

Summary of project management plan

Stockli is the project leader; UT team (Stockli, Dr. Andrew (postdoctoral scholar), and Alison MacNamee (UT graduate students) will carry out all structural, geological, geochemical and thermochronometric analyses during all Phases of the project.

The structural work will be carried out in collaboration with Dr. J.D. Walker (University of Kansas)

Soil gas and noble gas work will be carried out by LBNL scientists Dr. Kennedy and Dr. Lewicki.

Stockli will spearhead the data integration and interpretation in concert with the UT and LBNL teams.

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Objective of Dixie Valley Innovative Geochemistry Project

Geothermal plays in extensional and transtensional tectonic environments have long been a major target in the exploration of geothermal resources and the Dixie Valley area has served as a classic natural laboratory for this type of geothermal plays. In recent years, the **interactions between normal faults and strike-slip faults, acting either as strain relay zones have attracted significant interest in geothermal exploration as they commonly result in fault-controlled dilational corners with enhanced fracture permeability** and thus have the potential to host blind geothermal prospects.

Structural ambiguity, complications in fault linkage, etc. often make the selection for geothermal exploration drilling targets complicated and risky. Though simplistic, the three main ingredients of a viable utility-grade geothermal resource are **heat**, **fluids**, and **permeability**. In light of this, in this Proof of Concept study, we propose a novel integrated approach combining (U-Th)/He and $^4He/^3He$ **thermochronometry** and **soil-gas geochemistry** to pin-point **heat and geothermal fluids** in a well-characterized **structural context** (permeability and alteration) in order to minimize these ambiguities, reduce the geothermal exploration risks, and improve the feasibility evaluation of blind geothermal exploration.

Summary of scientific/technical approach

(1) Structural and geological analysis of “dilational corners” (interaction of transcurrent and extensional faults)

(2) Conventional (U-Th)/He Thermochronometry

(3) Novel $^4He/^3He$ Thermochronometry

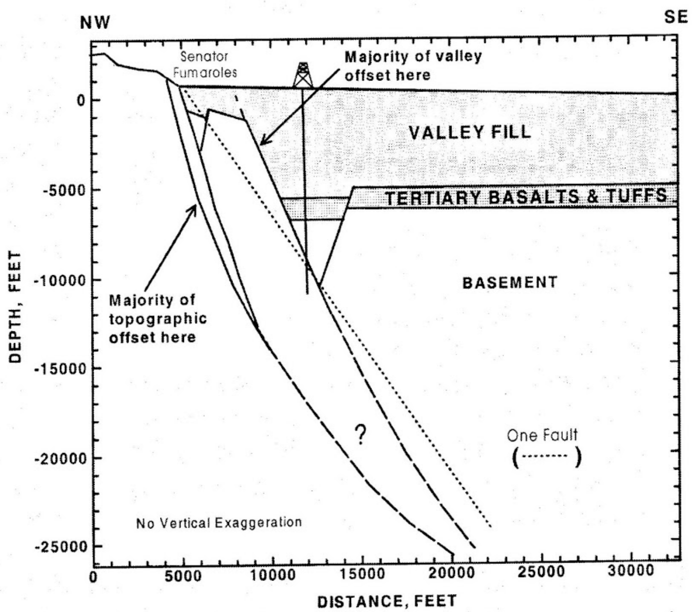
(4) Alteration chemistry of dilational fault corners

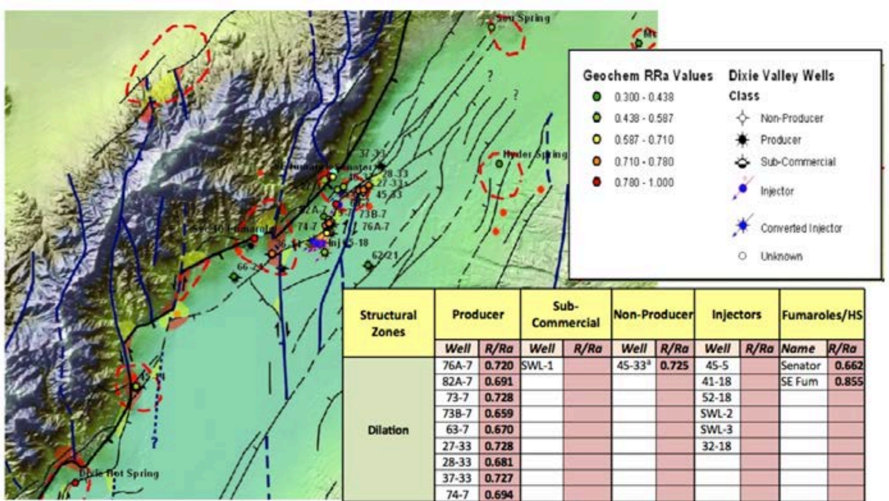
(5) Soil gas Surveys in basin fill and range drainages

(6) Structural and geochemical data integration and model

Innovative approach combining structural work with alteration and novel noble gas geochemical methodology

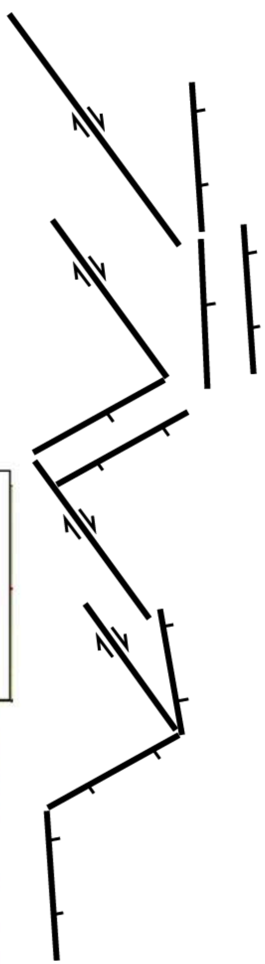
This Proof of Concept study will make use of relatively new techniques and for the first time employ **(U-Th)/He and $^4He/^3He$ thermochronometry** and **soil-gas geochemistry** together in an integrated fashion to establish **the temperature and fluid evolution of dilational fault corners and relay structures**, using Dixie Valley as our natural laboratory. The combination of thermochronometry and soil gas work in a detailed structural context presents a new, unique, and innovative approach to geothermal exploration.





Structural Zones	Producer		Sub-Commercial		Non-Producer		Injectors		Fumaroles/HS	
	Well	R/Ra	Well	R/Ra	Well	R/Ra	Well	R/Ra	Name	R/Ra
Dilation	76A-7	**0.720**	SWL-1		45-33*	**0.725**	45-5		Senator	**0.662**
	82A-7	**0.691**					41-18		SE Fum	**0.855**
	73-7	**0.728**					52-18			
	73B-7	**0.659**					SWL-2			
	63-7	**0.670**					SWL-3			
	27-33	**0.728**					32-18			
	28-33	**0.681**								
	37-33	**0.727**								
	74-7	**0.694**								
Compression			36-14	**0.770**	62-23A				Dixie	**0.845**
			45-14	0.587	82-5					
Other			38-32		66-21	0.306	65-18	0.560	Sou	0.528
					62-21		27-32	0.583	Hyder	0.438
					76-28				McCoy	0.345
					53-15				Jersey	0.495

*Well data available to AltaRock is limited. It is unknown why this well is a non-producer.

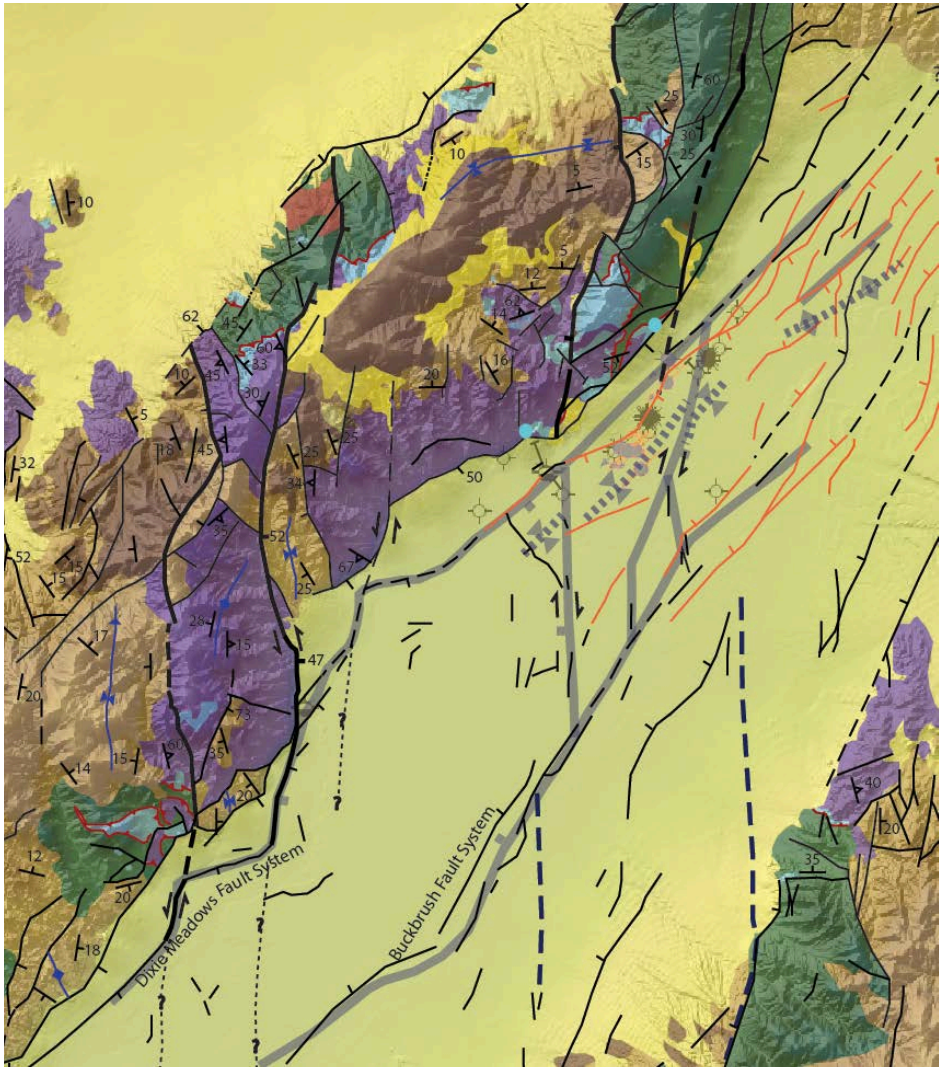


Existing structural models can be divided into **2 main contrasting models**:

(1) Pre-existing range-front fault that is offset by faults cross cutting the range in a left-lateral fashion. Corners are passively offset segements of a range-bounding normal fault.

(2) Range-front normal faults that are kinematically linked to right -lateral strike-slip faults cross-cutting the range.

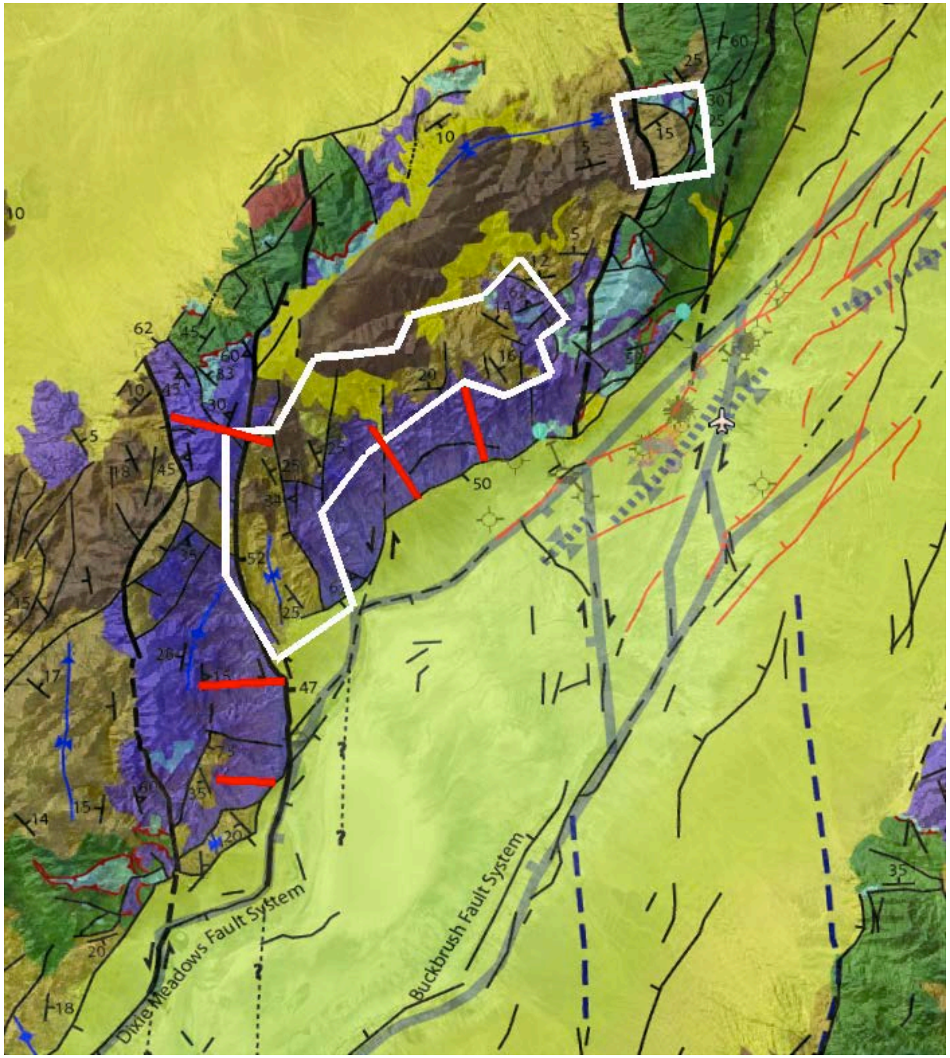
However, our new structural model based on new mapping and fault-kinematic data suggests that model (1) is incompatible with fault kinematic data: both initial normal displacement, (2) overprinting right-lateral fault motion, and (3) regional fault kinematic frame-work (Walker Lane Belt)

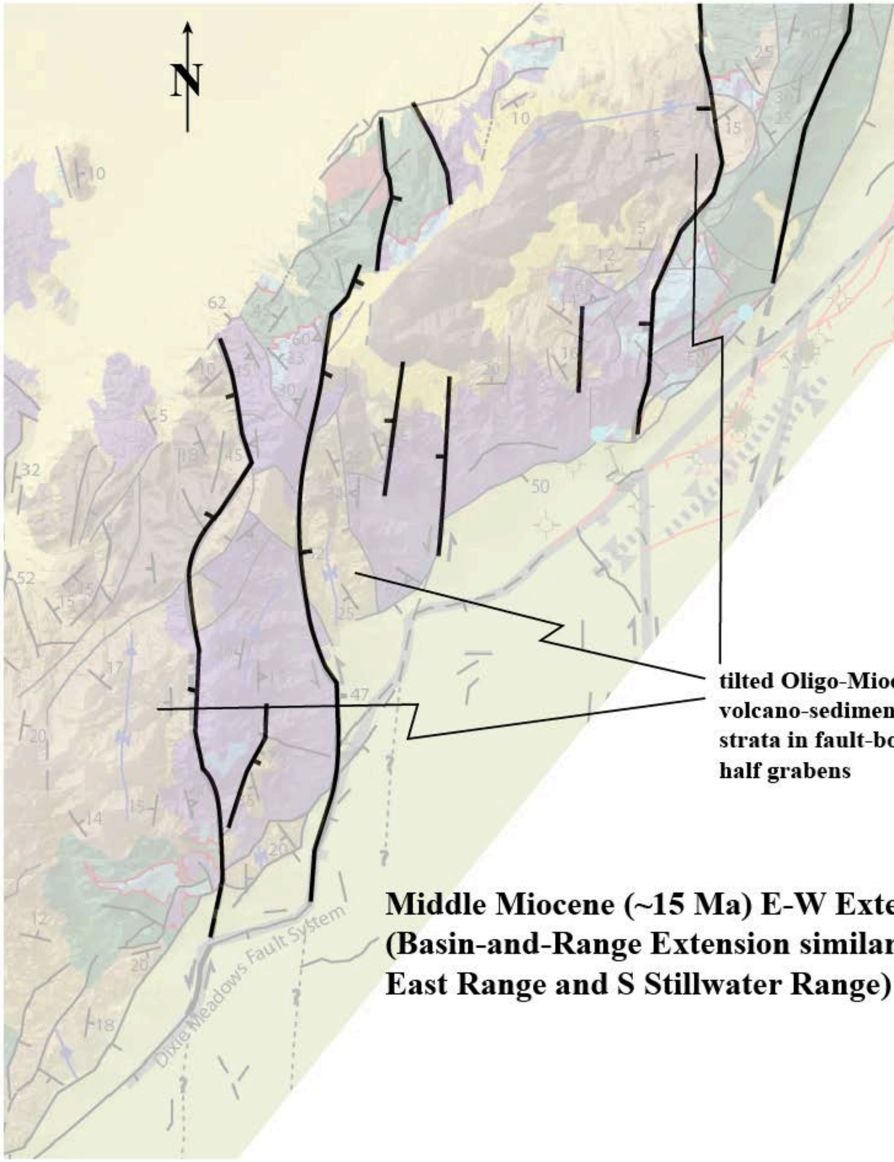


Courtesy of Dr. Iovenitti(AltaRock)

Our new model suggest a **two-stage structural evolution** with (a) **middle Miocene N-S trending normal faults** (faults cutting across the modern range), - and tiling Olio-Miocene volcanic and sedimentary sequences (similar in style to East Range and S Stillwater Range). **NE-trending range-front normal faulting initiated during the Pliocene** and are both truncating N-S trending normal faults and reactivating some former normal faults in a right-lateral fashion.

Thus the two main fundamental differences to previous structural models are (1) **N-S trending faults are pre-existing middle Miocene normal faults** and (2) these faults are **reactivated in a right-later fashion** (*NOT* left-lateral) and kinematically linked to the **younger NE-trending range-bounding normal faults (Pliocene in age)**.



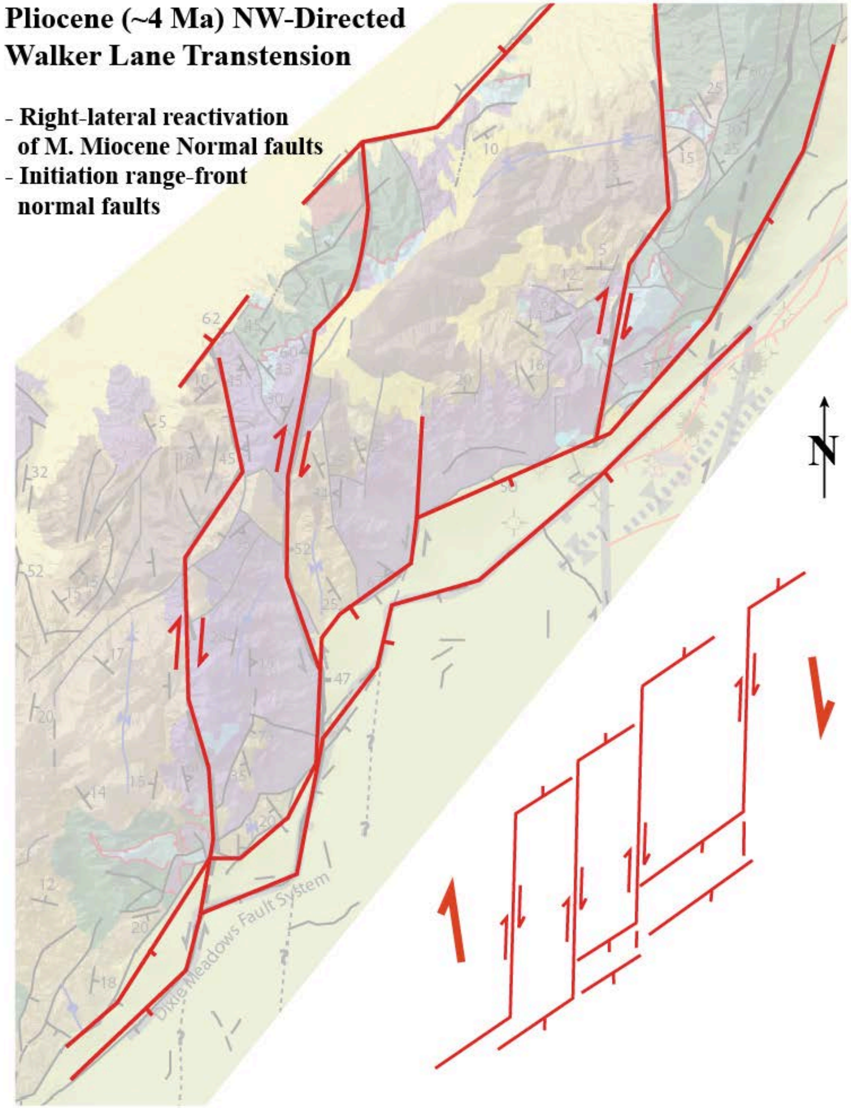


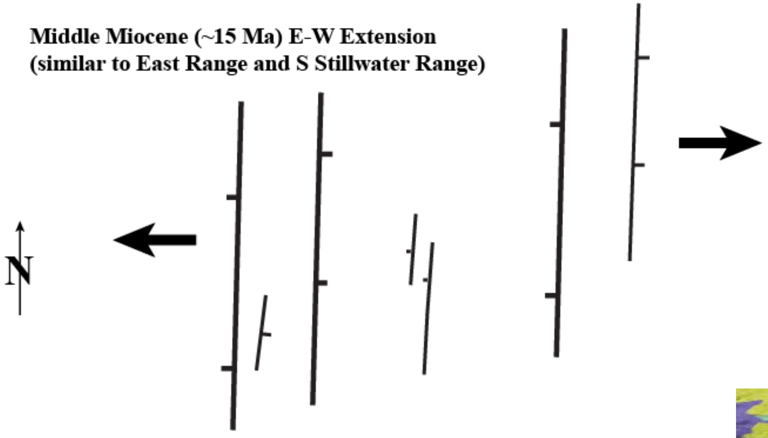
tilted Oligo-Miocene volcano-sedimentary strata in fault-bound half grabens

Middle Miocene (~15 Ma) E-W Extension (Basin-and-Range Extension similar to East Range and S Stillwater Range)

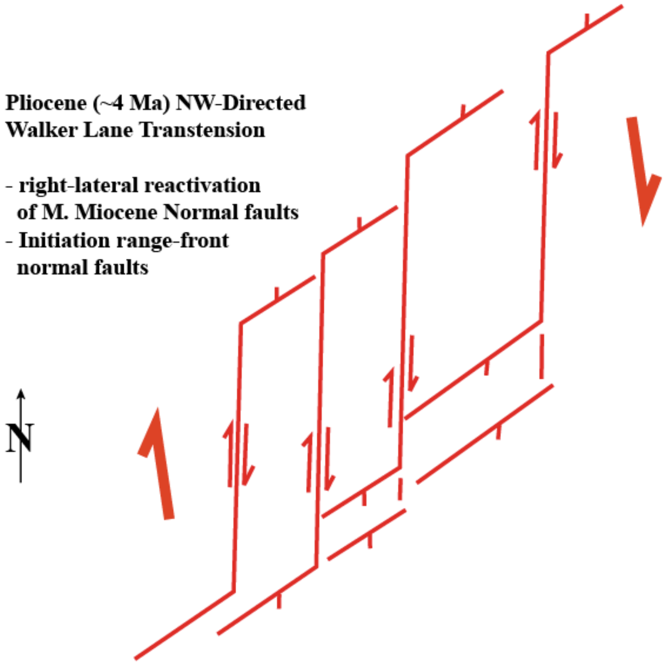
Pliocene (~4 Ma) NW-Directed Walker Lane Transtension

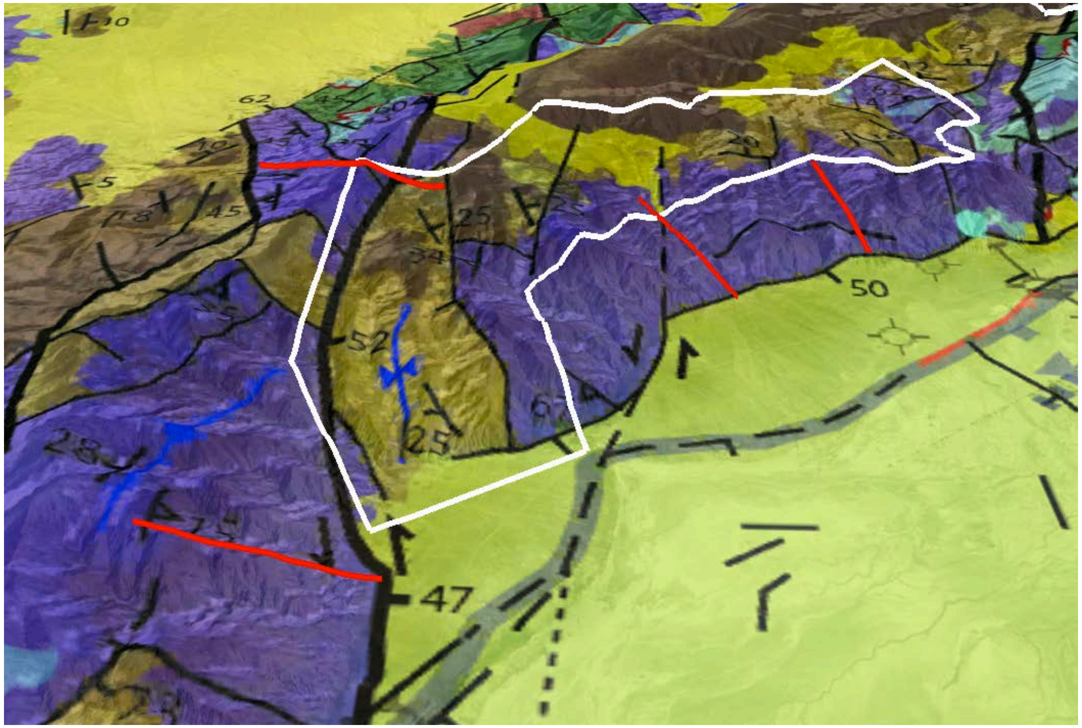
- **Right-lateral reactivation of M. Miocene Normal faults**
- **Initiation range-front normal faults**





Detailed structural mapping and fault kinematic analysis & integrated “conventional” Zr and Ap (U-Th)/He thermochronometry





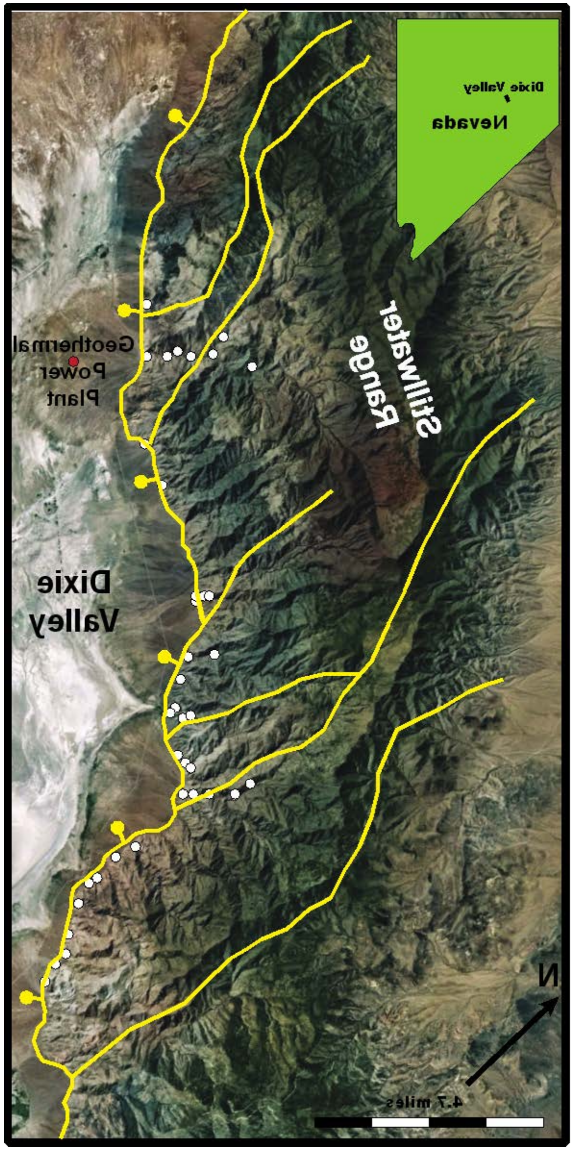
ŅConventionalÓ Geo- and Thermochronometry

>50 samples collected from the range front, fault corners, and vertical transects in order to constrain the thermal evolution of the Stillwater Range and the superimposed geothermal imprint. 15 conventional zircon and apatite He ages show a clear pattern:

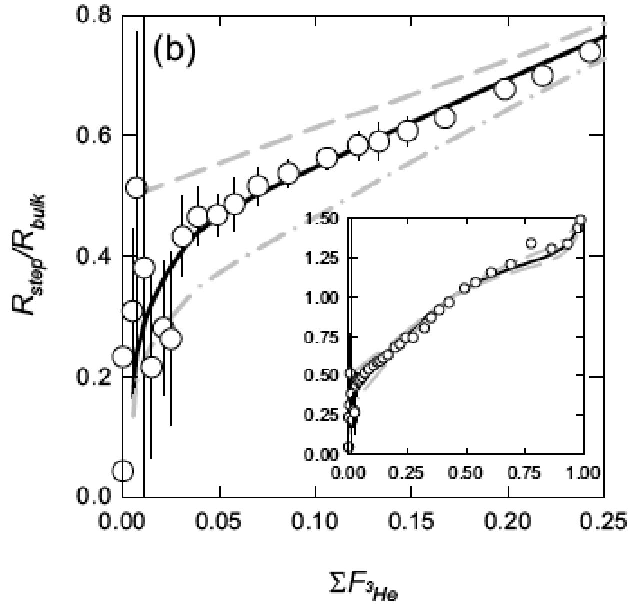
Zircon He ages record major middle Miocene (~15 Ma) normal faulting and exhumation (see structural model below).

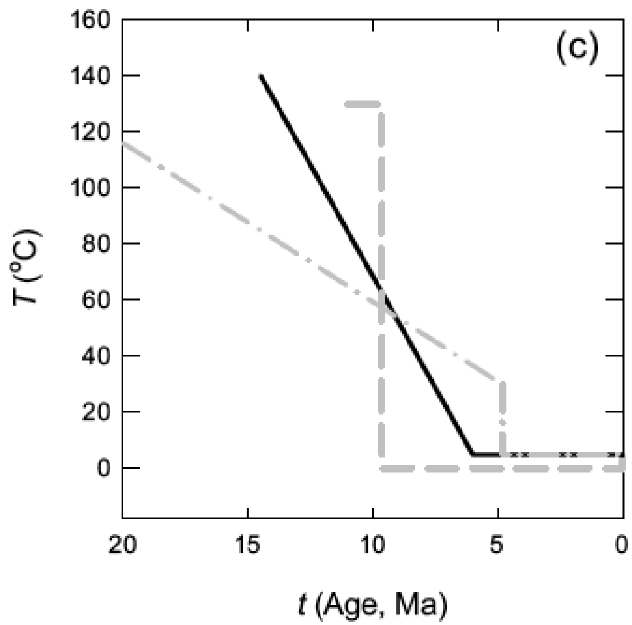
Apatite He ages from the range front cluster around 4 Ma, suggesting a Pliocene initiation age for range-front faulting. Samples from inside- and outside dilational corners are currently the focus of intense additional analytical work.

In addition, **LA-ICP-MS zircon U-Pb dating** of eruption ages of Oligo-Miocene volcanic rocks (29-6 Ma) to further constrain the structural evolution and models.

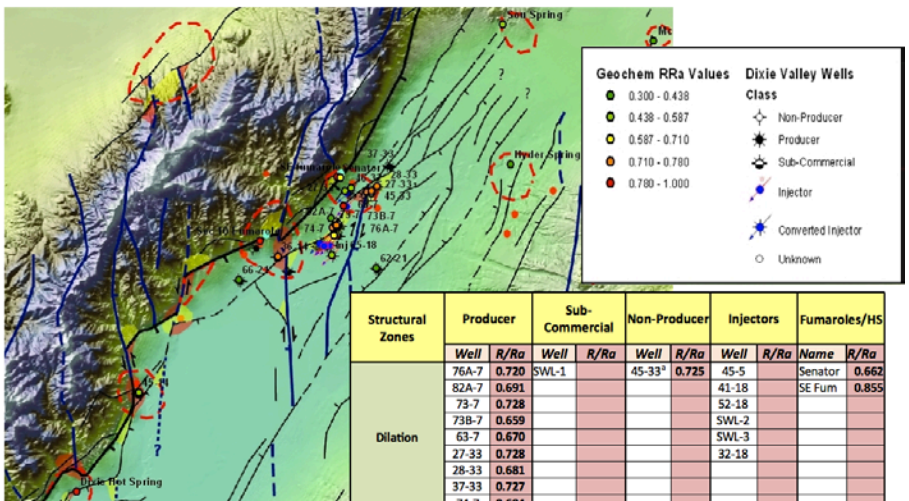


Apatite ***^{4}He/^{3}He thermochronometry*** provides a novel approach to provide quantitative constraints on the continuous time-temperature history of apatite grains from very low temperatures, covering a thermal sensitivity window from ~80-20 °C (Shuster and Farley, 2004). While thermal history reconstruction extraction from conventional (UŠTh)/He data relies on multiple thermochronometers, spatial distribution of multiple samples, or kinetic variations in multiple aliquots in single samples, ^{4}He/^{3}He thermochronometry constrains the ***continuous low-temperature cooling history data from a single sample*** based on the spatial concentration profile of ^{4}He within an apatite grain.





The objective of the **soil gas** CO_2 flux study is to search for zones of anomalous surface CO_2 flux in the Stillwater Range and Dixie Valley that may be related to upwelling deep geothermal fluids at dilational fault intersections. In regions where there are no obvious surface manifestations of deep advecting hydrothermal systems (e.g., springs, fumaroles, etc.), **soil gas studies may provide the only direct surface clues for the presence of a geothermal resource.** Although the technique is relatively new, CO_2 soil flux studies have been widely used for volcano monitoring and delineation of fault and fracture zones where volatiles from deeper hydrothermal fluids emerge.



Structural Zones	Producer		Sub-Commercial		Non-Producer		Injectors		Fumaroles/HS	
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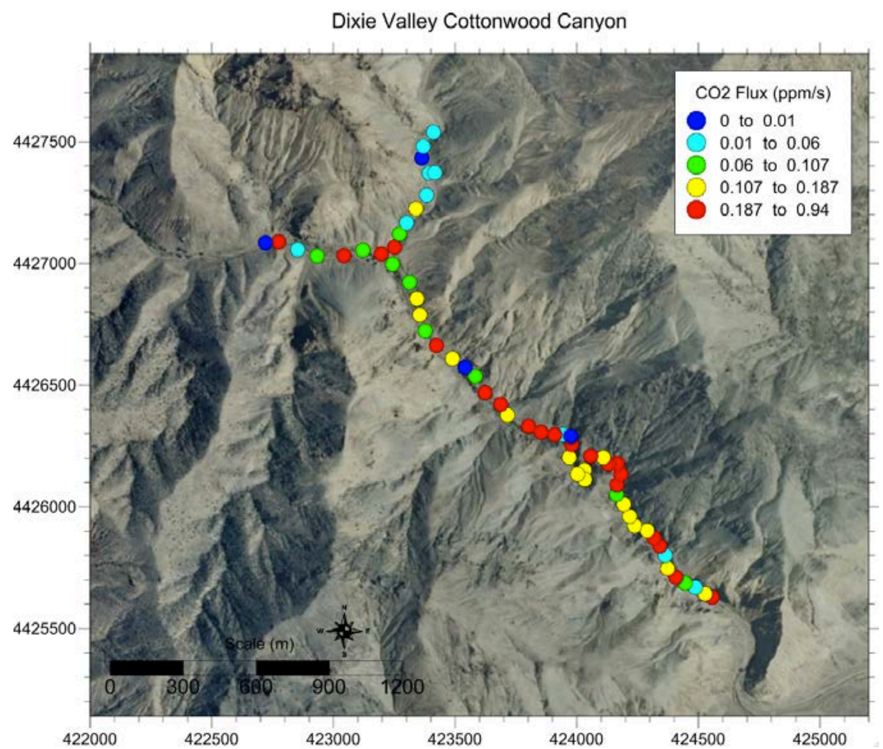
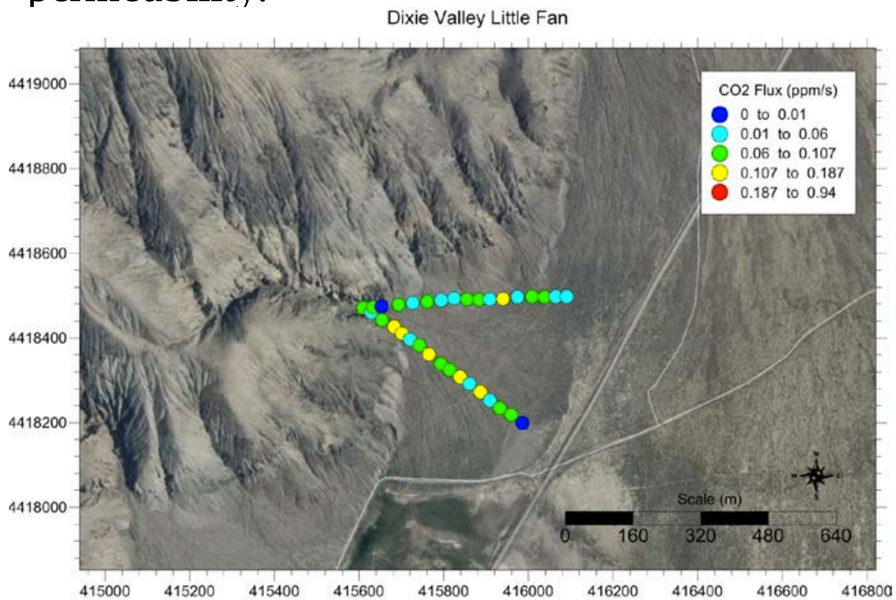
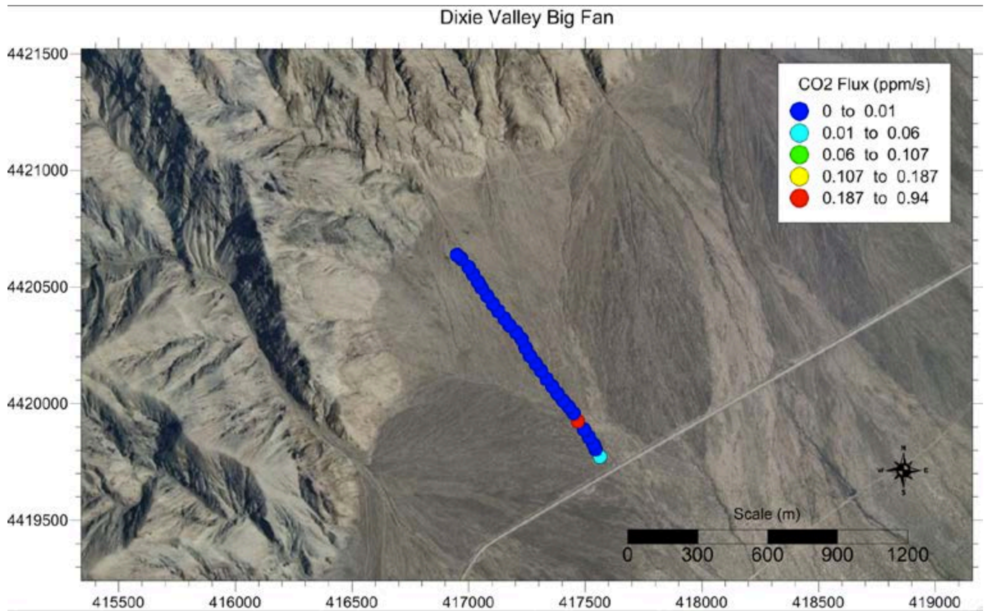


Dr. Kennedy and his team from LBNL (subcontract) collected soil gas analyses at a total of >120 survey stations: 33 soil gas survey stations (Dixie Valley Little Fan), 30 soil gas survey stations (Dixie Valley Little Fan), 60 soil gas survey stations (Cottonwood Canyon). Preliminary data analysis shows **no major CO2 anomalies**, but a second occupation is planned for Q4 FY 13 and the expansion of targeted areas in concert with structural and thermochronometric findings. In light of the new structural model, however, the soil gas survey targets will likely be modified. While range-front fault segments and out-side corners (normal and strike-slip fault intersections protruding out into the valley) were the focus so far, in-side corners (range re-entrants where normal and strike-slip fault intersect) will be emphasized a foci of dilational fault-induced permeability.





Planned milestones for FY12 and FY13

Milestones:

- Geological Mapping and Structural Analyses by Summer 13
- "Conventional" He Thermochronometry by Summer 13
- Novel $^{4}He/^{3}He$ Thermochronometry by Fall 13
- Alteration chemistry analysis by Fall 13
- Soil Gas Surveys by Oct 12/Oct 13
- 3-D Earth Model Integration and Evaluation Fall 13

- Phase I project only (no go-/no-go decision)

Accomplishments, Expected Outcomes and Progress

Progress to date and/or planned accomplishments/outcomes:

-Team in place (UT, KU, and LBNL) incl. students and postdoc and all efforts are well under way (all tasks and subtasks)

- Structural and fault kinematic field campaign started in Fall 2012 (suspended during winter) and will be completed in April/May of 2013, followed by integration into self-consistent model. Preliminary new model has yielded major insights into the tectonic history of the range

-"Conventional" geo- and thermochronometry sample collection (>50) and analysis (>15) has has shed light on the thermal evolution of the range and coupled with the structural and fault kinematic data led to a dramatically revised two-stage Miocene and Pliocene model

-Soil gas survey was carried out by Dr. Kennedey and his team, collecting soil gas results from 120 soil gas survey stations from Dixie Valley Little Fan, Dixie Valley Little Fan, and Cottonwood Canyon. However, preliminary data analysis shows **no major CO2 anomalies.**

Summary of immediate plan:

Spring/Summer 2013: Completion of structural field work and compilation of data

Summer 2013: Completion of geo- & thermochronometry, interpretation, and intergration

Fall 2013: Expansion and completion of Soil Gas Work (2nd dry seasons)

End of 2013: Data compilation/integration into comprehensive model

Future Directions

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We hope to demonstrate that our work presents geothermal operators with a holistic, but **cost-effective approach** to help plan the location of exploration and ultimately production of utility-grade geothermal wells.

Besides the exploration and scientific benefits, the project will result in the **education** of several graduate and undergraduate students, helping train a new generation in renewable energy exploration, as well as temporary employment for students, and collaborators.

If the exploration work identifies a viable resource, then the economic impact will include long-term employment and significant development potential for the local region.

Mandatory Summary Slide

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- Geothermal plays are largely controlled by three ingredients: heat, fluid, and permeability and their temporal evolution. This Proof of Concept study will characterize all three in a holistic and integrated geochemical fashion in a sound structural context.
- While the individual techniques themselves are still quite novel, the exciting combination of the two techniques holds tremendous promise as it addresses two crucial ingredients for a exploitable geothermal resources, the **thermal history** (heat) and **fluid flow** and chemistry in an unprecedented fashion. $^{4}He/^{3}He$ dating, an exciting new technique to recovering thermal histories from a single sample, will be applied for the first time in geothermal exploration. The combination of conventional (U-Th)/He and $^{4}He/^{3}He$ dating in conjunction with soil-gas surveys is a exciting new approach in the exploration of blind geothermal resources.

Data Sharing

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DOE's GTP requires that all projects provide data to the DOE Geothermal Data Repository for linking to the National Geothermal Data System.

- Types of data generated (Phase I) and dissemination/archival:
- - Geochronology data (isotopic) - http://matisse.kgs.ku.edu/geochron/ (NSF supported site)
- - Geological Mapping - Publication and on-line availability (KU digital thesis rep and NBMG on-line maps)
- - Soil-gas and alteration geochemistry data will be sent to the DoE GDR in spreadsheet format with sample locations (Lat, Long, elev)
- Data, metadata, and interpretations will also be published in peer-reviewed journals and publications
- All data above will also be made available as data or served through the above portals to the nascent "DOE Geothermal Data Repository" - currently under development by Boise State University. The DOE Geothermal Data Repository will be made public through the National Geothermal Data System, or retained in the DOE Geothermal Data Repository as business confidential, where applicable.

Mandatory Summary Slide

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- **Phase I**: This study combines traditional (but critical) field structural and fault kinematic analysis, with "conventional" and 4/3He thermochronometry and soil gas analysis to more holistically investigate both the thermal and fluid flow evolution in a detailed structural context (dilational fault corners). The project's preliminary results have already shed important new insights into the tectonic evolution of the Stillwater Range - results that will be critical for the evaluation the geothermal controls in this well-studied setting.
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	FY2012	**FY2013**
Target/Milestone	Field campaign I Soil Gas Survey I (U-Th)/He I Prelim 3D Model Data compilation	Field campaign II Soil Gas Survey II (U-Th)/He II 4He/3He Finalized 3D Model
Results	Completed 2012 All subtasks are on track	To be completed Fall 2013 No delays expected