Final Scientific/Technical Report – DE-EE0005520
Novel Coupled Thermochronometric and Geochemical Investigation of Blind Geothermal Resources in Fault-Controlled Dilational Corners
Awardee: University of Texas as Austin

1. **Project Title: Novel Coupled Thermochronometric and Geochemical Investigation of Blind Geothermal Resources in Fault-Controlled Dilational Corners (DE-EE0005520)**

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- Subcontractors and Participating Organizations: None

2. **Distribution Limitation**

3. **Executive Summary**

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.

Our new geological mapping and fault kinematic analysis derived a structural 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).

More importantly, this study provides the first constraints on transient fluid flow through the novel application of apatite (U-Th)/He (AHe) and $^{4}He/^{3}He$ thermochronometry in the geothermally active Dixie Valley area in Nevada. Structural mapping and fault kinematic analysis show that the valley is bound to the west by a high angle normal fault along which the adjacent Stillwater Range has been recently exhumed in the footwall. Zones of elevated shallow geothermal gradients (geothermal anomalies) occur in dilational corners along the range front and

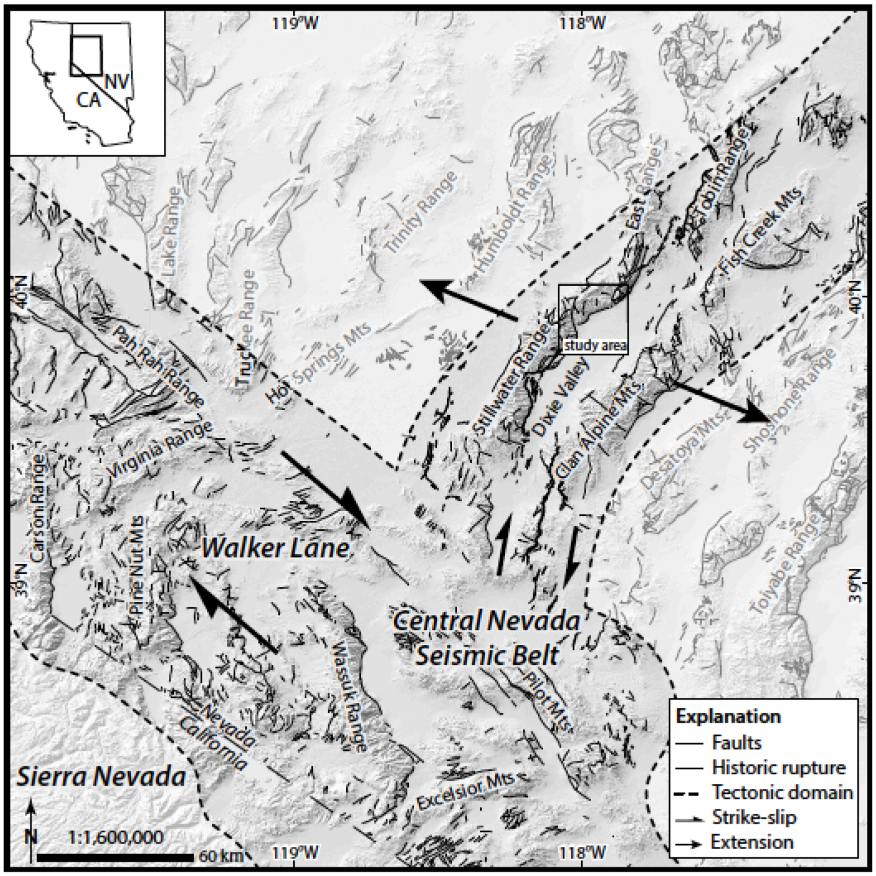

Figure 1: Hillshade of a digital elevation model and major faults show the location and structural setting of the Stillwater Range at the junction of the Walker Lane and Central Nevada Seismic Belts (Stewart Carlson, 1976; Wallace, 1984; Fosdick Colgan, 2008)

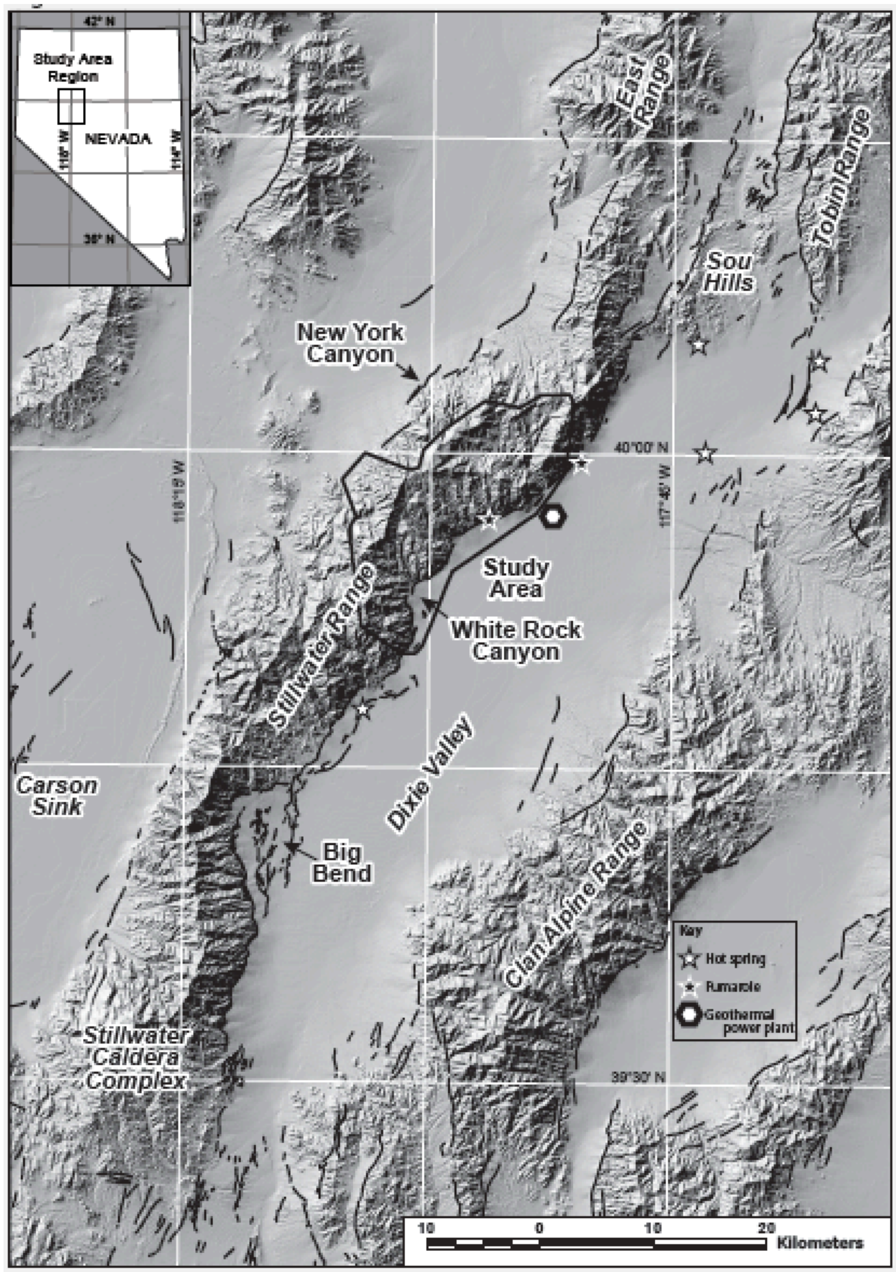

Figure 2. Map of the study area region showing shaded relief, geothermal features (Garside, 1994) and Quaternary fault scarps (Machette et al., 2004). Inset map shows location of the regional figure in Nevada.

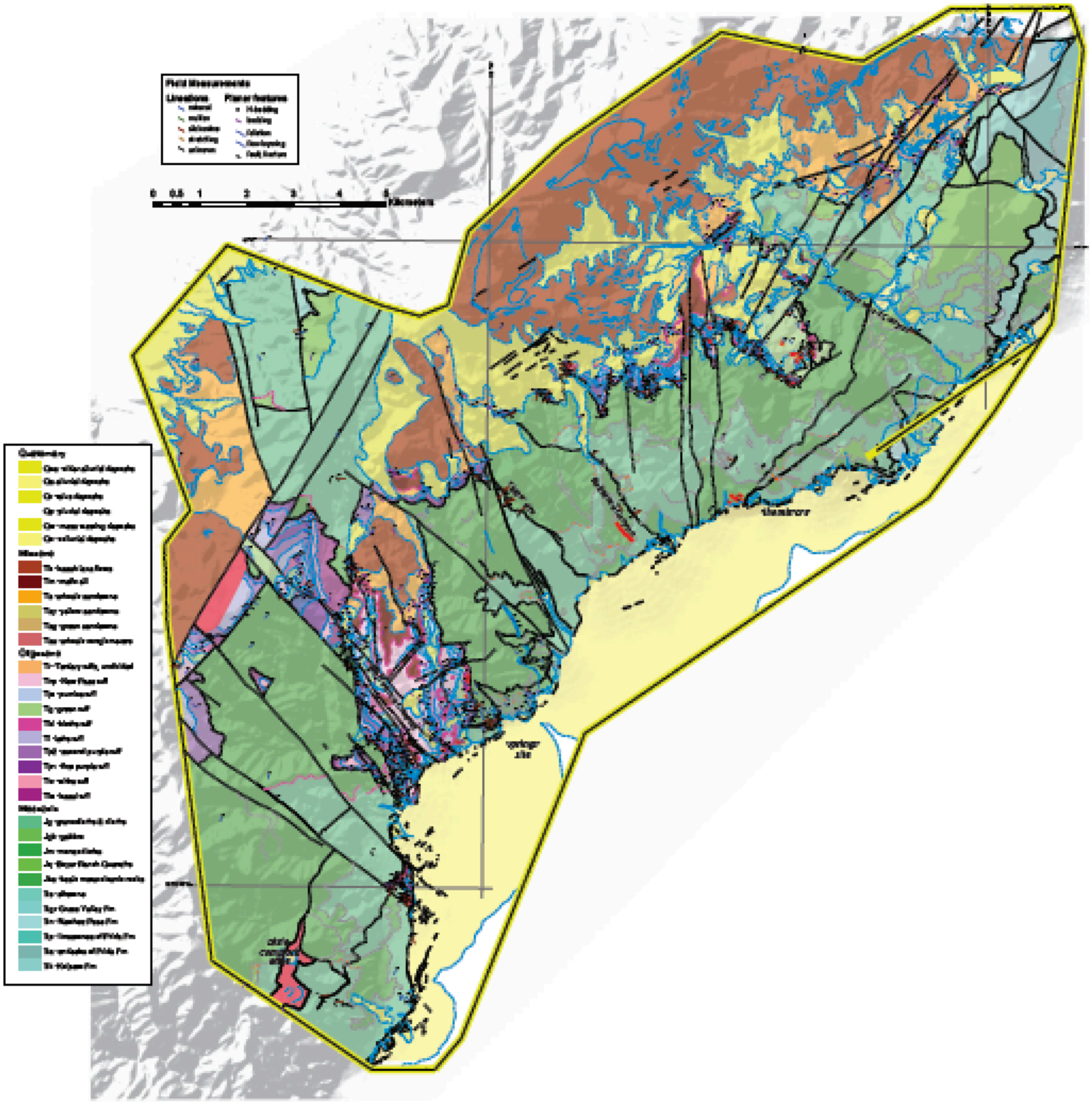

Figure 3. New GIS-based geologic map of the study area.

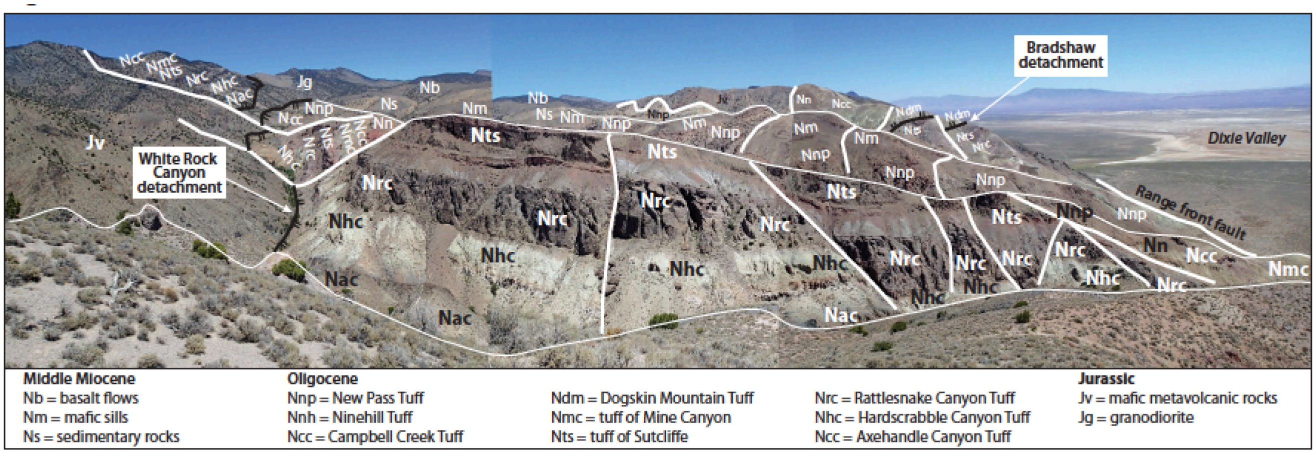

Figure 4. Annotated image of White Rock Canyon detachment fault that juxtaposes the Oligocene and Miocene rocks over Jurassic metavolcanic and plutonic rocks. Note the hanging wall horst and graben complex.

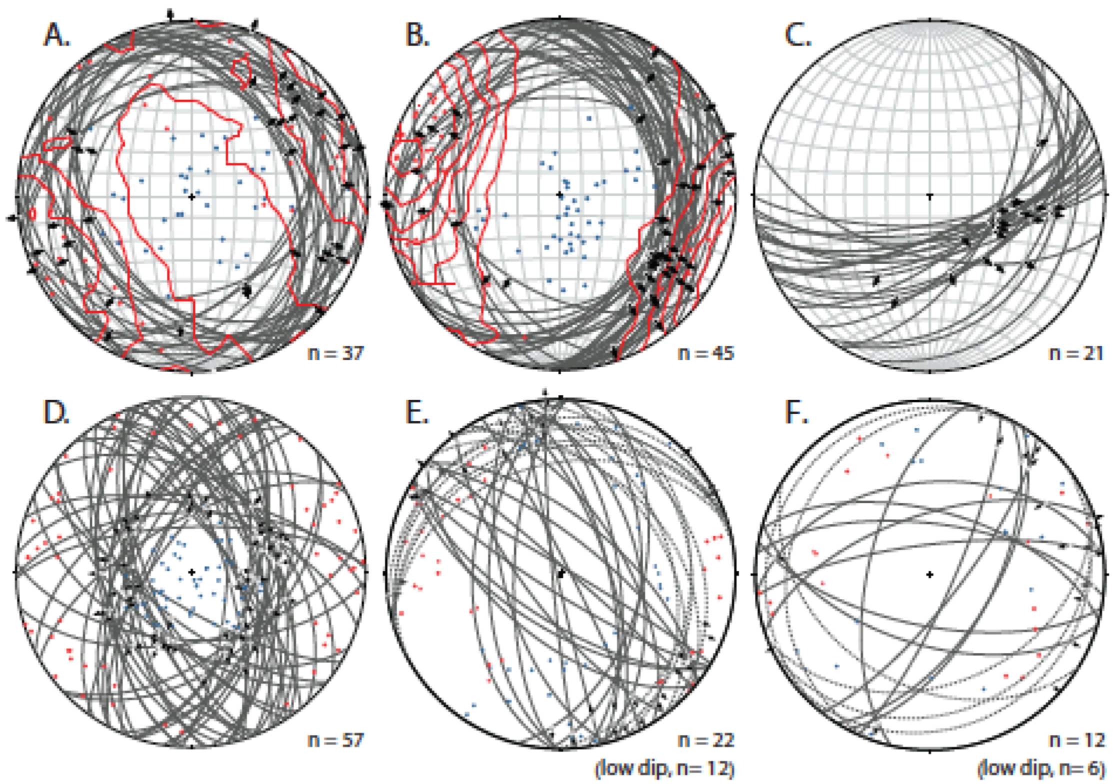

Figure 5: Kinematic data from fault planes in the northern Stillwater Range. Gray great circles are fault planes, dashed great circles are low angle strike-slip fault planes, blue points are poles to planes, red dots are slickenlines, and black arrows are slip vectors. (A) Low to moderate angle faults and associated slip vectors at the base of Neogene tufs over Jurassic metamorphic rocks show extension oriented _NE-SW. (B) Low to moderate angle faults and associated slip vectors at the base of Neogene tuffs over Jurassic metamorphic rocks in White Rock Canyon show extension oriented NW-SE. (C) Slip surfaces and corresponding slip vectors trending southeast from "the mirrors"- a broad zone of slickensides occurring along the range front. Data from (Caine et al., 2010). (D) Faults with a 45-75_dip and high rake from throughout the map area in the Stillwater Range show the two major fault orientations to the NW and to the NE with some accompanying conjugate faults. (E) Relatively high angle right-lateral faults strike north to northwest along with some low angle faults with right-lateral slip and hanging wall motion to the northeast. (F) Conjugate left-lateral faults strike approximately northeast or east.

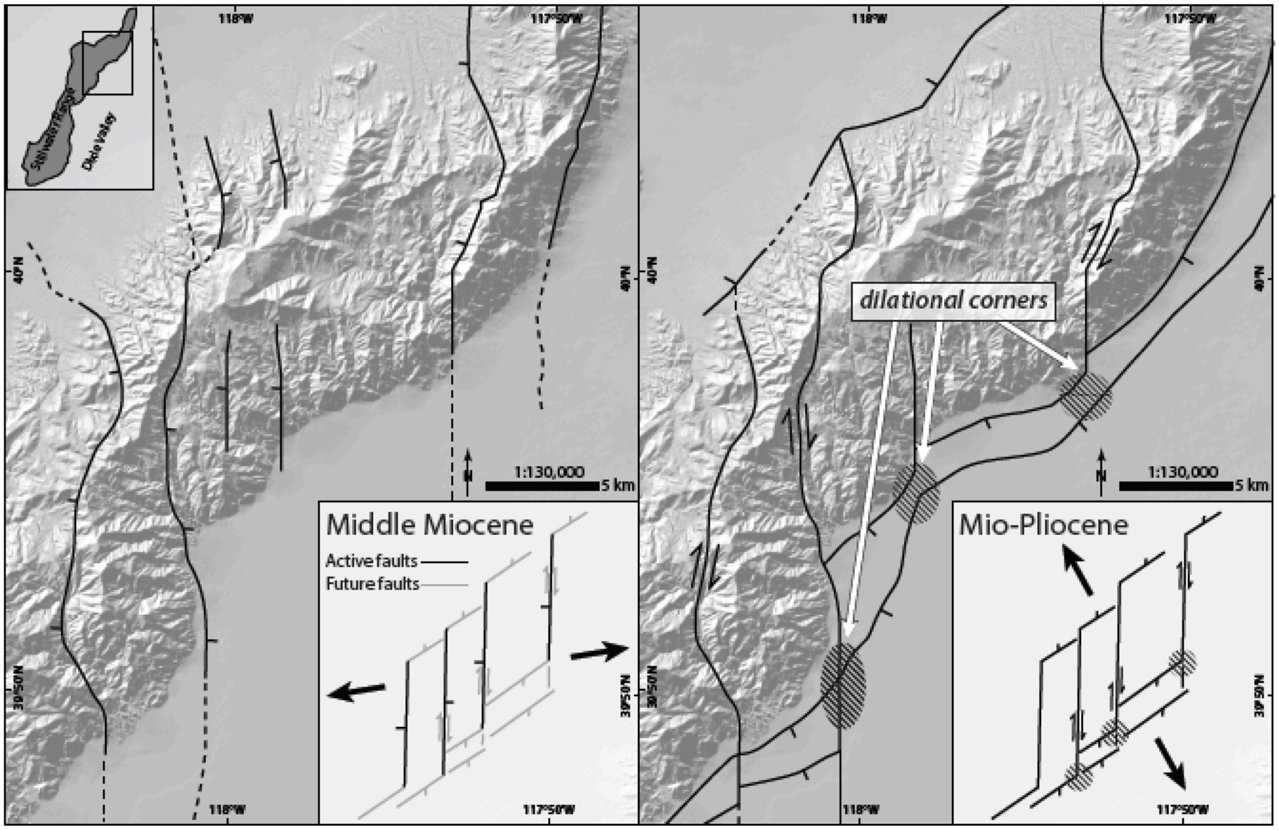

Figure 6. A multiple phase model of the structural evolution of the northern Stillwater Range. During the Middle Miocene the range is cut by _N-S normal faults to accommodate approximate E-W extension as part of the formation of the Basin and Range. Oligo-Miocene volcano-sedimentary strata were displaced and tilted in fault-bound half grabens. In the Mio-Pliocene deformation is dominated by NW directed Walker Lane-related transtension. The deformation is expressed as the right-lateral reactivation of middle Miocene normal faults and the initiation of the range front normal fault if slip to the SE.

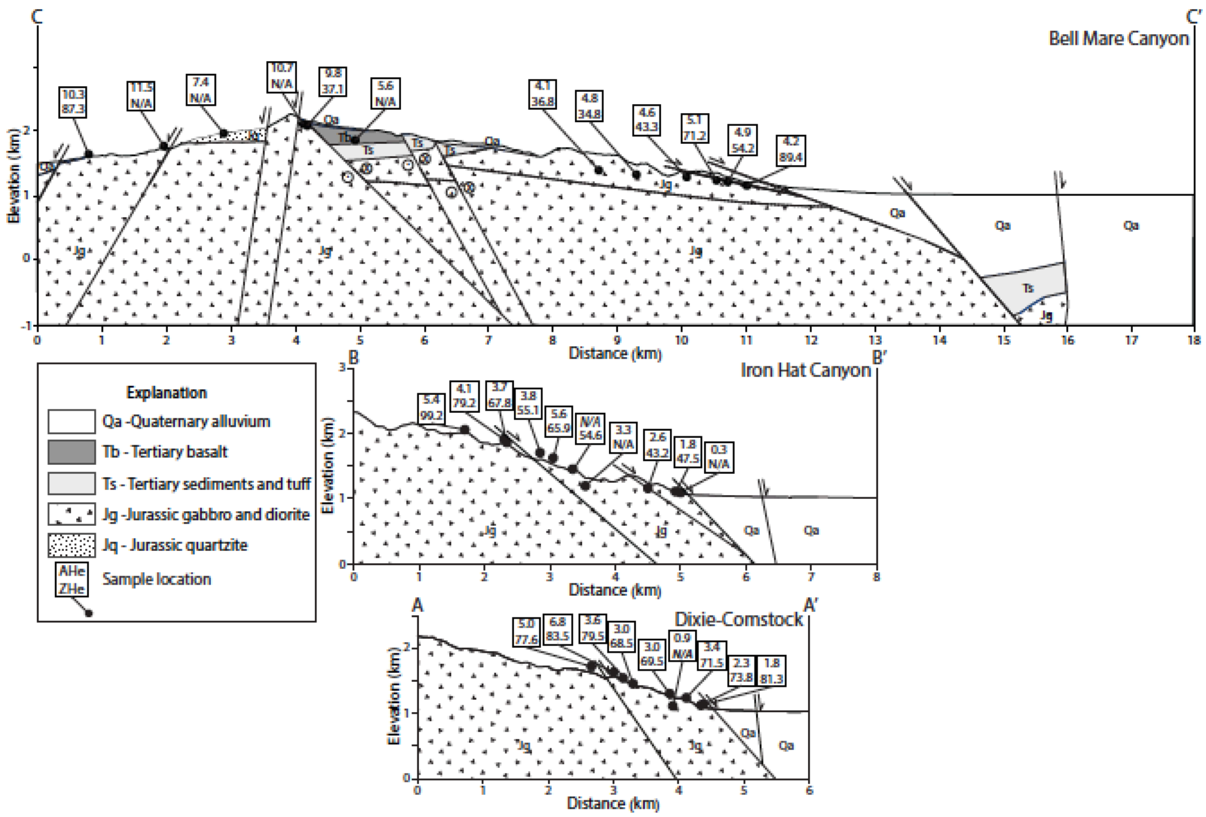

Figure 7: Cross sections for the Dixie-Comstock, Iron Hat Canyon, and Bell Mare Canyon sample transects.

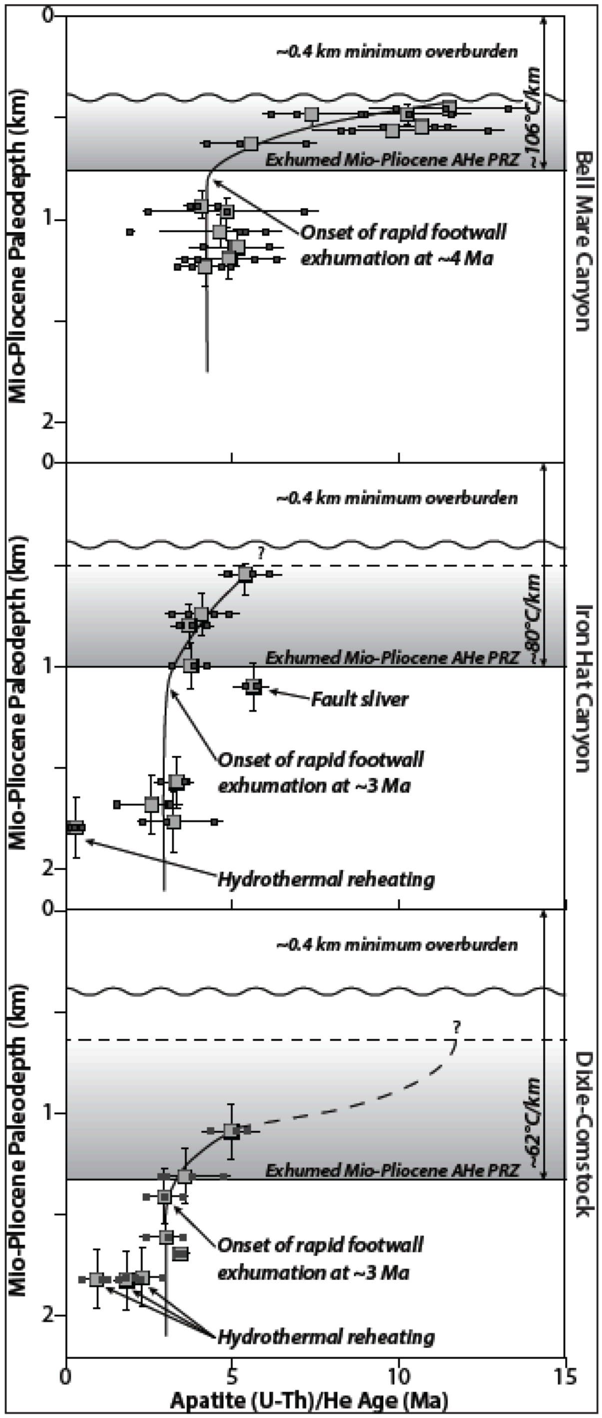

Figure 8: Apatite (U-Th)/He thermochronometric data plotted against pre- extensional Mio-Pliocene paleodepth for the Stillwater Range footwall. Small black squares represent ages for individual aliquots and associated 6% error bars. Large grey squares show the arithmetic mean age of aliquots for each sample with 1_ error bars and paleodepth error based on _2_ dip. In points in the data trends reveal fast cooling from _4 Ma. Exhumed Mio- Pliocene AHe PRZ lower boundaries are marked and yield estimates of the pre-extensional geothermal gradient. The potential upper boundary of the PRZ (dashed line) is projected from this calculation.

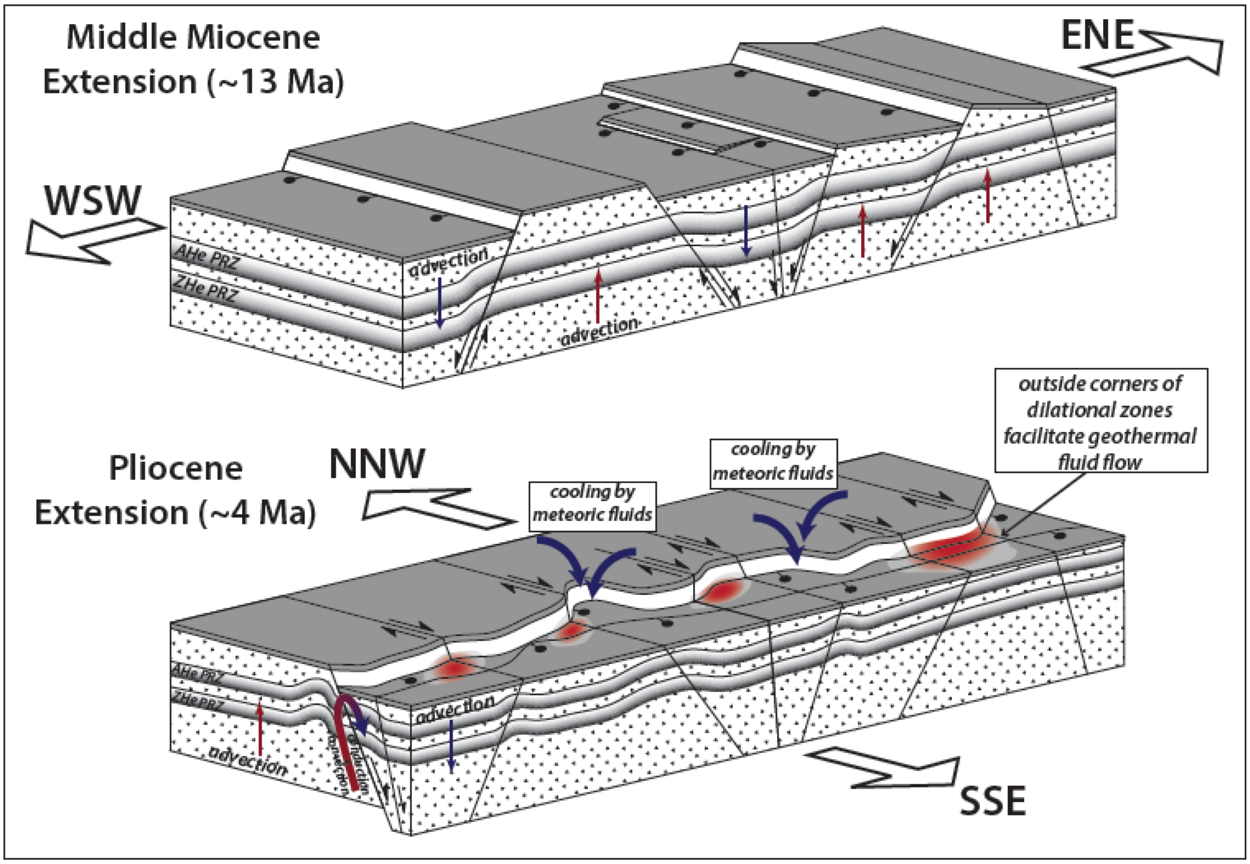

Figure 9: Model block diagram showing the multiple-stage evolution of the Stillwater Range. Middle Miocene approximately E-W Basin and Range extension creates moderately exhumed fault-bound half grabens. Subsequently, Pliocene NW-directed Walker Lane transtension reactivates Middle Miocene faults and initiates exhumation along the DVF. The intersection of these faults creates dilational corners where increased fracture permeability enables the flow of hot hydrothermal fluids from the circulating in the upper crust.

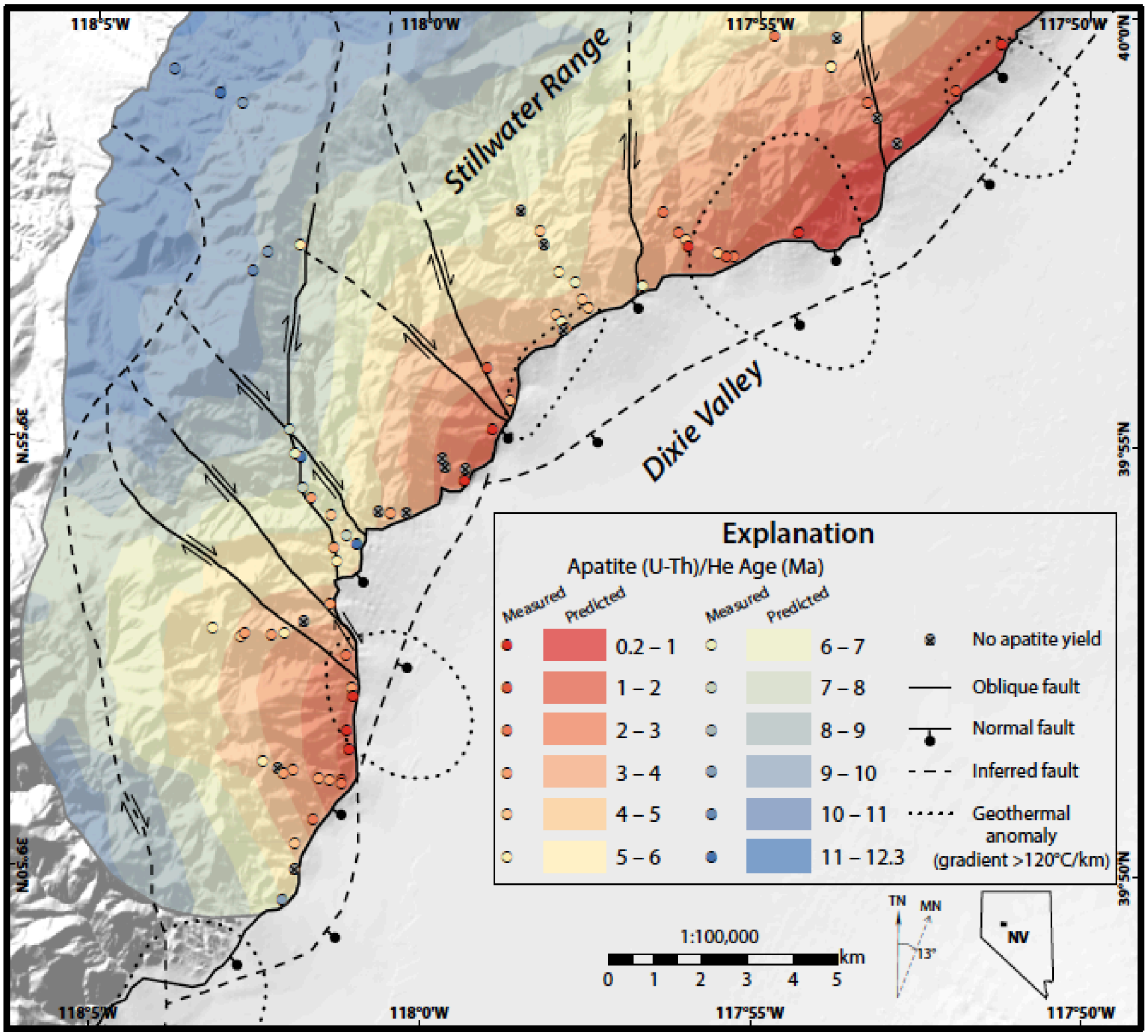

Figure 10: AHe ages interpolated in the northern Stillwater Range using ordinary kriging methods. The youngest AHe ages are co-located with dilational corners and mapped blind, shallow geothermal anomalies (Iovenitti et al., 2012).

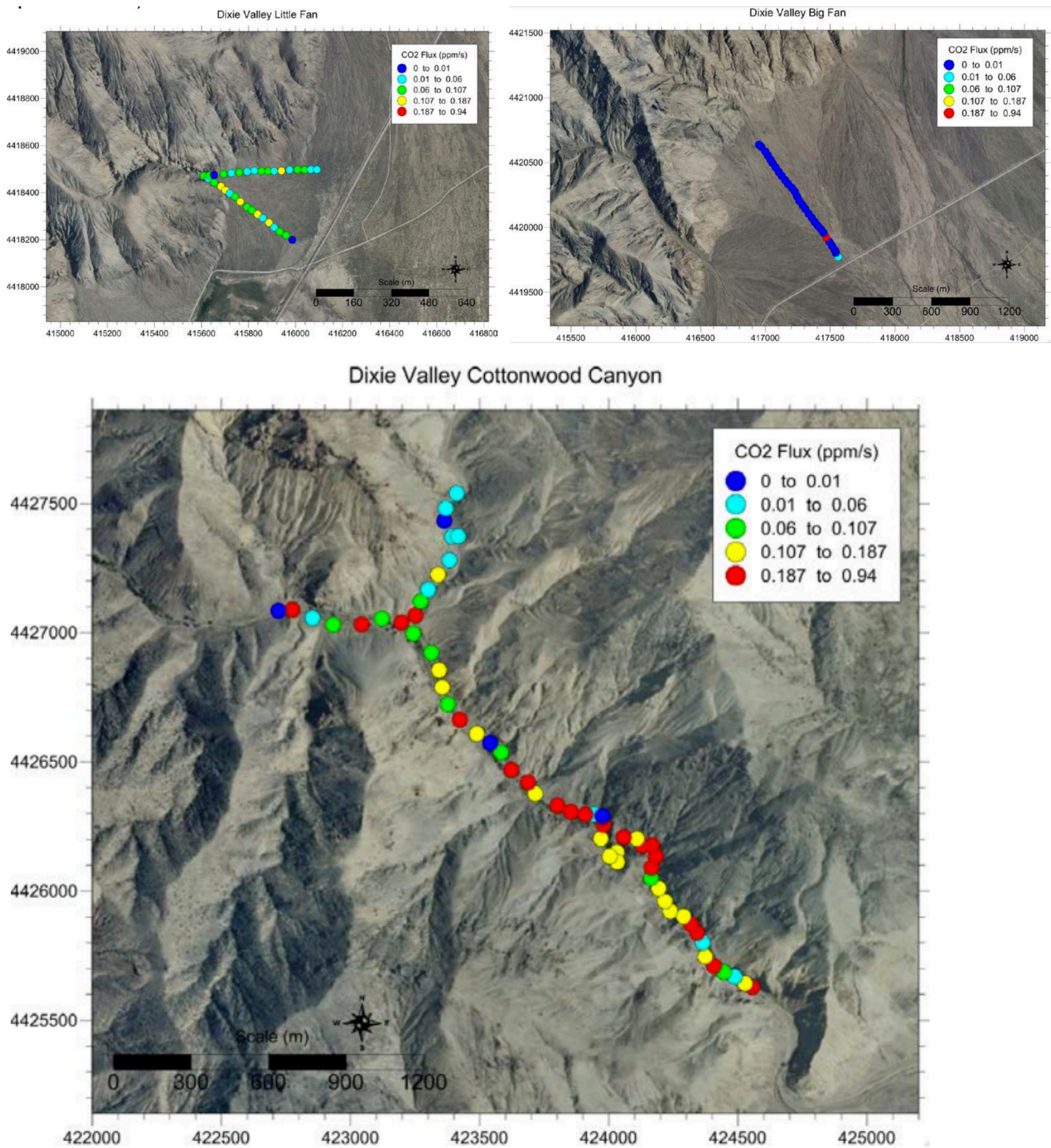

Figure 11: CO_2 soil gas survey results from alluvial fans and from Cottonwood Canyon within the northern Sillwater Range. Note the absence of any discernible CO_2 soil gas signal from alluvial fans. In contrast, elevated CO_2 signals were detected near faults with the range.

therefore make Dixie Valley an ideal site to test the sensitivity of the AHe thermochonometer to fluid flow in the shallow crust. Apatites yield (U-Th)/He ages ca. 0.2-16 Ma and three elevation transects record advective cooling of the footwall due to exhumation onset at ~4 Ma. Many younger AHe ages (<4 Ma) are significantly younger and do not overlap tectonic exhumation related cooling ages. Because of this disparity the younger AHe ages are distinguishable as hydrothermally reset and demonstrate the ability of this method to resolve conductive cooling ages from overprinted, fluid-reheated ages. Interpolation of AHe ages shows that the youngest ages correspond with remarkable accuracy to the spatial extents of previously mapped geothermal anomalies. This proof-of concept study illustrated the tremendous potential of AHe thermochronometry to constrain the timing and location of paleofluid flow and that it can be used as a powerful, cost-effective tool in geothermal exploration. These young ages are corroborated by selected $^4He/^3He$ thermochronometric analyses that show reheating due to geothermal fluids <200 ka. While the analytically more involved and more expensive $^4He/^3He$ thermochronometric analyses can be used to more precisely recover the thermal history from a single sample, they are not a viable means to map out and locate the long-term thermal anomalies. In contrast to the success of the structurally integrated thermochrometric survey, CO_2 soil gas surveys across the alluvial fans show no discernable soil gas anomaly associated with degasing of upwelling geothermal fluids – likely due to soil gas scrubbing by hydrological and pedogenic processes.

In summary, this proof-of-concept study successfully demonstrated that this novel approach integrating approach combining structural geology and (U-Th)/He and $^4He/^3He$ thermochronometry can help minimize ambiguities, reduce the geothermal exploration risks, and improve the feasibility evaluation of blind geothermal exploration.

4. Comparison of Planned Activities and Actual Accomplishments

Planned Objectives and Accomplishments

The following section lists the primary objectives and purposes of the project:

- Complete a multifaceted proof-of-concept program in Dixie Valley to identify blind geothermal resources using a combination of structural geology, (U-Th)/He and $^3He/^4He$ thermochronometry, and CO_2 soil gas surveys in order simultaneous address fault-related dilation, long-term heat advection, and geothermal fluid flow. *Accomplished*
- Demonstrate that this multi-faceted, innovative and integrated approach presents geothermal operators with a ***cost-effective approach*** to identify the location of blind geothermal resources. *Accomplished, although there has not been any independent verification by exploration*
- Evaluate the importance of ***fault interactions*** of multiple sets of Miocene and Pliocene high-angle normal faults creating fault intersection dilational corners that promote geothermal fluid circulation and creating and maintenance (i.e., rejuvenation) of fracture permeability. The identification and characterization of bedrock faulting lead to an extensive structural remapping of the N Stillwater Range. *Accomplished.*
- Characterize the long-term structural and thermal evolution of the area and ***identify long-term thermal anomalies*** by novel low-temperature thermochronometry in combination with detailed structural geology. This turned into one of the most impressive demonstration of the technique and very positive test result of the main component of this proof-of-concept study. *Accomplished*
- Identification of long-term "hot spots" – interpreted as bling geothermal resources – by conventional apatite (U-Th)/He and $^4He/^3He$ thermochronometry. "Hot spot" anomalies defined by anomalously young He ages that are in stark deviation from the background thermal field of the Stillwater Range. *Accomplished*

- Carry out CO_2 soil surveys across possible blind geothermal resources to identify fluid flow zones around fault-controlled dilation zones. *Accomplished, but no positive results likely due groundwater scrubbing. Accomplished, but negative test.*
- Besides the exploration and scientific benefits, educate several graduate (1) and undergraduate (2) students, and help ***train a new generation*** in renewable energy exploration, as well as temporary employment for researchers and students (2 postdoctoral scholars, 2 graduate and 2 undergraduate students) and collaborators. *Accomplished.*
- Demonstrate the power of low- and intermediate-temperature ***thermochronometry as a novel, powerful, and very cost-effective geothermal exploration tool*** (locating long-live and blind geothermal anomalies). *Accomplished.*
- ***Identify of a viable geothermal resource*** that could be explored by drilling in the future and possibly leading to increased geothermal production and impacting to local/regional economy through long-term employment. *Accomplished.*

5. Project Activities for the Entire Project

5.1 Project Activities

- **Geology and Structural Geology.** Geological and structural mapping and related subtasks were one of three major foci during this project. Stockli, Andrew (KU postdoctoral researcher), and MacNamee (UT graduate student) spent nearly 100 combined days (all FTEs combined) in the field completing all geological and structural mapping, collecting structural field measurements, measuring stratigraphic sections, and collecting a systematic array of samples for geo- and thermochronometry. The team completed geological mapping focused in the northern Stillwater Range. KU postdoctoral researcher Dr. Joe Andrew and UT graduate student Alison MacNamee (M.S.) completed geological and structural mapping critical to key areas in the northern Stillwater Range. The KU/UT team finished compilation of existing mapping and new geological and structural data and completed a structural and fault kinematic model for the northern Stillwater Range and its interface (range front) with Dixie Valley. Alison MacNamee completed her M.S. thesis at UT in 2015. The team completed all map compilations and delivered a structural model for the area. This represented a major effort of the project and was necessary to provide the proper and detailed structural framework for the integration and interpretation of the thermochronometry and soil gas portions of this project. Dr. Andrew fine-tuned his GIS-based, publication-ready integration of all geologic mapping of the study area in the north-central Stillwater Range, including seven digital cross sections from the 1:20,000 geologic map with all new fault kinematic data. He also completed a manuscript (in preparation) describing the team's new structural and fault kinematic data and integrating these data into a complete Miocene and Pliocene structural evolution model for publication. The structural model pays special attention to the implications of the findings for Dixie Valley sub-surface geothermal resources.

  The main focus of this period of work was completion of geological and structural fieldwork and compilation of all mapping. Dr. Andrew completed all geologic mapping and sample collection in the northern Stillwater Range. The major activity during the fourth quarter was finishing the geologic map created from the fieldwork done in the previous quarters. An analysis of fault measurement data was accomplished to quantify the structural configuration of the various major fault sets. Comparison of this data with the geologic map observations allowed examination of changes in faulting through time. These data were inverted to calculate the stress fields to create such orientations and kinematics of faults. The major finding was that there was a change in the stress field from the least compressive stress direction oriented NE-SW to a NW-SE orientation. The NE-SW orientated stress field creates faults that cut units as young as 24 Ma and is overlain by ~14 Ma basalts (age from correlation to other basalts in the region). A low-angle detachment fault is associated with the NE-SW stress field. The younger NW-SE oriented least compressive stress direction is still active in the Holocene and Pleistocene as the Dixie Valley fault. The major embayment in the range front along Dixie Valley at White Rock Canyon is a location where the earlier low-angle detachment fault was cut by conjugate strike slip faults formed in the younger stress regime and then both the detachment fault and strike-slip faults were reactivated by fault slip during the most recent time. The White Rock embayment is thus a location of weakness where the range front fault has progressively cut downwards into the footwall to create the embayment. The map, structural data and these interpretations were presented at the annual meeting of the Geological Society of America on October 27th. Further refinements to the map and its digital database were made after presenting this research.

Thermochronology. Analytical efforts started immediately after samples were collected during the earliest phases of the project. For these efforts, we added two undergraduate research assistants to the team to help with mineral separation and analytical work. During structural fieldwork, we completed collection of all samples for geochronology and thermochronology. By Q3 FY13, all collected samples were completely separated and we commenced isotopic analyses of thermochronometric and geochronologic samples. By the end of Q3 FY13, the team had completed ~70% of all isotopic analyses. Lack of apatite or poor apatite quality in some samples (~30%) required extensive re-sampling in the summer of 2013 and additional analytical efforts. During Q4 2013, the KU team basically completed the additional thermochronometric analytical efforts, also some re-analysis of samples were pending due to the relocation of the laboratory to the University of Texas at Austin (UTA), the continued troubles with poor apatite quality in some samples. All completed analytical data (ages) were compiled in map form and contoured the long-term thermal evolution.

This major initial “grid-sampling” phase during FY13 clearly demonstrated the enormous potential of apatite (U-Th)/He thermochronometric in identifying long-term thermal anomalies by exhibiting clear “hot-spot” patterns deviating from the range-wide background exhumational/thermal evolution of the N Stillwater Range and identifying geothermal hotspots that are structurally controlled at dilational corners (fault intersections). During this phase, a ~50 samples were collected and a major push of mineral separation efforts was carried out by MacNamee, after she was fully trained in mineral separation and all analytical aspects of conventional (U-Th)/He dating methods. During Q1 FY14, Stockli and MacNamee collected addition samples both from transects across the range and along the range front, with special focus on the dilational corners (fault intersections). She completed an additional 10 samples for conventional apatite (U-Th)/He analysis. During Q2 FY14, Stockli and MacNamee collected addition samples both from transects across the range and along the range front, with special focus on the dilational corners (fault intersections). A total of ~85 samples were dated for this project, far exceeding the promised number of samples. All samples were dated by both apatite and zircon (U-Th)/He and are contained in MacNamee’s UT M.S. thesis. In addition to the apatite (U-Th)/he thermochronometric data, we also carried out zircon U-Pb dating to constrain the eruption ages of volcanic rocks in the Stillwater Range.

In addition, apatite and zircon (U-Th)/He data were integrated with structural data to (1) test the structural models and more importantly (2) to start shedding light on and identify possible thermal anomalies related to blind geothermal resources along the Stillwater Range frontal fault system. The data from within the range clearly demonstrate middle Miocene cooling related to E-W extensional along both low-angle and high-angle normal faults. Most importantly, however, from a geothermal standpoint, was the fact that the data clearly show that the range underwent conductive cooling as a result of normal faulting, while samples from inside and outside corners deviate from the expected conductive cooling trend. Ages become systematically younger towards the fault apices deviating from the 4 Ma age trend and are as young at 0.5 Ma. This clear indication of age rejuvenation in a predicable structural fashion is a major funding and validates the original conventional thermochronology hypothesis. This represents a major success of the main component of our proof-of-concept study at the heart of this project.

In terms of $^{4}He/^{3}He$ dating, we conducted a limited number (6 sample) of $^{4}He/^{3}He$ thermochronometric analysis to corroborate the conventional (U-Th)/He study and to illustrate its potential. For this purpose, the addition of Dr. Patterson in July 2013 turned out to be a major break-through as he enabled us to complete the technical aspects of this portion of the study. He completed the first calibration $^{3}He/^{4}He$ experiments and benchmarked the methodology applied to our samples. MacNamee has worked with Dr. Farley at Caltech in preparing her selected samples for $^{4}He/^{3}He$ proton irradiation at Harvard Medical School and samples will be irradiated in early Dec. 2013, meaning that will be ready for analysis in early Spring 2014. Samples were analyzed for 4He/3He in Q1 of FY15 and modeled to determine continuous thermal histories from both dilational corners and linear range front. The results clearly demonstrate the difference in thermal histories from single samples. The approach, however, also shows that a conventional (U-Th)/He data grid is better at identifying and locating the long-term thermal anomalies, but that the $^{4}He/^{3}He$ data yield excellent results from the anomalies once located – advocating for a two-pronged approach and suggesting that a clear need for conventional (U-Th)/He.

MacNamee and Stockli, with the help of Andrew Smye (UT postdoctoral scholar) and Nicole Hart (UT M.S. graduate student) also spent significant time and energy completing and fine-tuning all thermochronometric inverse modeling of apatite and zircon (U-Th)/He vertical-transect and range-front data as well as $^{4}He/^{3}He$ data modeling (inversion) and interpreting and integrating all the results. As aforementioned, these efforts were part of MacNamee's M.S. thesis at UT under the supervision of Stockli. During Q2 FY15, MacNamee and Stockli completed two publication-style manuscripts that represent the bulk of MacNamee UT M.S. thesis. She completed and successful defended her thesis and recently started a position in the oil & gas industry in Houston, TX (Hess). The thesis was fully approved and submitted to the University of Texas. The two manuscripts focus on (1) the structural interpretations, thermochronometric results, discussion of the tectonic and thermal evolution of the Stillwater Range as well interpretations and ramifications for geothermal heating and on (2) the application of low-temperature thermochronometry on geothermal exploration in extensional structural settings.

- **CO_2 Surveys**.

During Q4 FY12, the sample gas survey planning and sampling strategy was fine-tuned and finalized between Kennedy and Stockli and gas sample collection occurred early in Q1 FY13. The sampling was carried out successfully and data were analyzed and interpreted. All planning and staging activities occurred in close collaboration between Kennedy and Stockli and proved to be very effective. A total of >120 soil gas survey stations were collected: 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 anomalies, but a second occupation is planned for Q4 FY 13 and the expansion of targeted areas in concert with structural and thermochronometric findings. Unfortunately, the flux signals were very small and no clear patter emerged either due to the lack of anomalies, interaction with vegetation, or soil scrubbing. While preliminary data did not reveal and major anomalies, a second occupation is planned for Q4 FY 13 and the expansion of targeted areas in concert with structural and thermochronometric findings. Few activities were planned for Q3 with respect to soil gas survey work. Drs. Kennedy and Stockli completed data integration of soil gas data with structural models and presented those findings at the DoE Peer Review Meeting in Denver. In addition, Kennedy and Stockli started planning the second occupation is planned for Q4 FY 13 and the expansion of targeted areas in concert with structural and thermochronometric findings. As no major anomalies were found, we also attempted to refine/revamp the deployment strategy for late Q4 FY13 or early Q1 FY14. After finalizing the deployment plans between Kennedy and Stockli. The BNL team completed the second data collection campaign late in Q4 FY13. At this point the data are not yet available to the PI as the BNL team is still compiling all the new results and completing the initial data interpretation. We remain hopeful that the change in strategy, accommodating the new structural model and taking into account the novel thermochronometry results, that the new campaign data will yield more promising results. Interpretation for data collected during the second deployment was planned for early FY14.

The BNL team completed the second data collection campaign late in Q4 FY13. During Q1 FY14, Kennedy and his team compiled all soil gas data in map format and started analyzing the soil gas data. There appears to be more signal, but also more noise in the data compared to the Q1 FY13 data. This is likely due to the change in strategy in terms of sampling location focus. While data was collected mostly on alluvial fans with little success in FY13, FY14 soil gas collection focused on canyons within the Stillwater Range to evaluate the influence of faults.

In summary, we completed 15 CO_2 soil gas transects along a total of ~20 km stretch along the Stillwater Range Front fault system. Of these, 10 transects were conducted within outwash fans of the Stillwater Range and the remainder were conducted in canyons cutting into the Stillwater Range. None of the 10 transects conducted on the outwash fans showed any anomalous CO_2 flux, with values ranging from 0-2 gm/m^2-day. Although one of the fan transects did indicate an apparent increase in flux (from ~2 to ~4 gm/m^2-day) upon entering the mouth of the outwash canyon. For two of the canyon transects fluxes were consistently <1 gm/m^2-day. The other three all showed anomalous fluxes ranging as high as 12-14 gm/m^2-day. In one of these, the high flux values were spatially associated with localized areas with a large number of trees (cottonwoods), suggesting that the anomalous fluxes were related to biologic activity. However, in the remaining two canyons the areas of anomalous flux were highly localized and spatially correlated with mapped north trending faults that appear to traverse Dixie Valley from the south and cutting through the Stillwater Range. The flux for these two canyons is shown below. Several of these anomalous sites will be revisited during the upcoming summer field work, to include collection of soil gas samples for isotopic analysis. Also, we will attempt to conduct additional flux transects, but originating from the NW side of the Stillwater Range.

In conclusion, it is not clear why the fans consistently show little or no CO_2 flux, despite evidence for sub-surface structures consistent with zones of dilation. Either these zones are not fluid pathways or in transit to the surface heterogeneous distribution of inter-bedded clay layers are deflecting or masking the upward gas flux through the fan deposits. Assuming the latter, we have been assembling a field deployable system for acquiring high density SP (self-potential) data. This will be used to interrogate the fans for deeper zones of upwelling fluids. Similar to the CO_2 flux measurements, we will be able to acquire the SP data over large distances in attempts to capture the occurrence of deep anomalies.

5.2 Technical Barriers and Difficulties

- Technical challenges and barriers during the project were minimal. There were no delays in geological and structural work. There were no delay in geochemical data collection for conventional (U-Th)/He or CO2 soil gas analysis
- Only delay pertained to the ^{3}He/^{4}He analysis as novel methodological approaches had to be developed for the split-flight tube mass-spectrometer. These analytical complications were initially underestimated and lead to delays, but were resolved through the addition of Dr. Desmond Patterson to the UTChron noble gas laboratory.
- While not per-se a technical barrier or difficulty, the outcome of the CO_2 soil gas surveys was disappointing and ultimately a scientific failure. However, all analytical procedures and measurement devices worked flawless.
- The chief technical barrier for thermochronometry turned out to be the lack of zircon and apatite or good-quality apatite in some of the mafic lithologies as expected and as recognized by the

review of the original proposal. However, enough good data and a sufficiently high-resolution data density were collected for a robust dataset and a very exciting outcome.

5.3 Project Targets and Timeline

- Project funds conditionally released in Q2 FY12 and DoE-UT contract signed.
- Fall 2013: Start of structural and thermochronometric field program
- Fall 2013: Installation of ESI autosampler for HR-ICP-MS instrument
- Fall 2013: Structural mapping, fault kinematic analysis, and thermochronology sample collection
- Fall 2013: Acquisition of phase I CO_2 soil gas data
- Spring 2014: Completion of phase I thermochronometry sample collection & processing. Completion of phase I of isotopic analyses and interpretation
- Summer 2014: Completion of phase II thermochronometry sample collection & processing. Completion of phase II of isotopic analyses and interpretation
- Fall 2014: Acquisition of phase II CO_2 soil gas data
- Fall 2014: Completion of $^4He/^3He$ thermochronometry
- Fall 2014-Spring 2015: Completion of thermochronometric modeling and quantitative data interpretation, as well as integration with all new structural data and models
- Spring 2015: Completion of 3 manuscript drafts and submission of UT M.S. thesis (MacNamee)

5.4 Project Challenges and Difficulties

- Project challenges were very limited (esp. compared to past projects, such as Pearl Hot Springs). There were no logistical problems or difficulties that pertained to field work, sample collection, or soil gas surveys
- Only project challenges pertained to the scientific/technical difficulties: (1) apatite and zircon quality, requiring collection of a far greater number of samples than anticipated and/or budgeted, (2) lack of signal in soil gas surveys on the alluvial fans, and (3) analytical delays and methodological complexities in $^4He/^3He$ analysis. However, all these issues were readily overcome and did not delay or jeopardize the overall progress and success of the project.

5.5 Conclusions and Prospects for the Future

- The project set out to investigate the structural, thermal, and fluid flow evolution of blind geothermal resources controlled by dilational fault corners or fault interaction zones. We believe that the project was extremely successful as it validated (1) our novel (U-Th)/He and $^4He/^3He$ exploration methodologies with a well-established and studied structural context, (2) demonstrating the cost-effectiveness and low environmental impact of our integrated approach chosen (now drilling), (3) the identification of multiple long-term thermal analomalies with the potential of being geothermal anomalies and presenting very promising exploration targets.
- The proof-of-concept project aimed to demonstrate that the employed innovative geothermal exploration strategy presents geothermal explorationists and operators with a sound and cost-effective approach to locate utility-grade geothermal resources, minimizing exploration risks and uncertainties and optimizing exploration success in terms of locating exploration and ultimately utility-grade geothermal production wells.

- Our results suggest that there is a significant and potentially viable blind resource present along the range front of the northern Stillwater Range in structurally controlled dilational fault corners.
- The grid like approach of conventional apatite and zircon (U-Th)/He dating in combination with detailed structural work illustrated the potential of mapping out the long term thermal history of the range as a function of its tectonic history and the presence and longevity of thermal anomalies with no surficial expression.
- $^{4}He/^{3}He$ dating of apatite showed the potential to reconstruct the thermal histories of thermal anomalies in greater detail, but only after the identification of the anomalies through grid-style sampling of conventional apatite and zircon (U-Th)/He thermochronometry.
- CO_2 sampling showed potential in canyons within the range, but showed essentially no useful signal on the alluvial fan transects. Despite extensive sampling on the alluvial fans and CO_2 degassing due to geothermal fluid upwelling and degassing is either not present or more likely scrubbed or obscured by surficial and/or near-surface hydrological processes.

6. Identify products developed under the award and technology transfer activities

- Andrew, J., and Stockli, D., 2013, Neogene Polyphase Extension in the Northern Basin and Range, Stillwater Range, Nevada. Geological Society of America *Abstracts with Programs.* Vol. 45
- MacNamee, A., and Stockli, D., 2013, Thermochronometric and structural Evaluation of Blind Geothermal Prospects in Fault Inside Corners. Geological Society of America *Abstracts with Programs.* Vol. 45
- MacNamee, A. and Stockli, D.F., 2014, Thermochronometric Investigation of Fluid Flow and Geothermal Systems in Extensional Settings, Dixie Valley, Nevada. AGU Fall Meetings, San Francisco, EP21A-3522.
- Stockli, D.F., Arnost, D., and MacNamee, A., 2016, Constrains on the Magnitude and Longevity of Geothermal and Meteoric Fluid Flow from (U-Th)/He Thermochronometry. 2016 International Thermochronometry Conference, Maresias, Brazil.
- Alison MacNamee, M.S, 2015, Thermochronometric investigation of structural evolution and geothermal systems in extensional settings, Dixie Valley, Nevada. University of Texas MS Thesis, Austin, Texas, 145 p.
- Types of data generated (Phase I) and dissemination/archival:
- Geochronology data (isotopic) - http://geochron.org (NSF supported site)
- Geological Mapping - Publication and on-line availability (KU digital thesis repository)
- Data, metadata, and interpretations will also be published in peer-reviewed journals and publications (3 manuscripts currently in final preparation, review, or revision)
- M.S. thesis by MacNamee (UT) available online through UT or by request from PI (to be shared with NGDS)