Final Scientific/Technical Report – DE-EE0002960
Recovery Act: Detachment faulting and Geothermal Resources - An Innovative Integrated Geological and Geophysical Investigation of Pearl Hot Spring, Nevada
Awardee: University of Texas as Austin

1. Detachment faulting and Geothermal Resources – An Innovative Integrated Geological and Geophysical Investigation of Pearl Hot Spring, Nevada (DE-EE0002960)

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- Project team: Josh Burrus (MS student), Nikki Seymour (MS Student), Michael Prior (PhD student) (all University of Texas), J. Douglas Walker (University of Kansas), John Deymonaz (Fish Lake Valley)
- Subcontractors and Participating Organizations: Dr. Katie Kerenan (left OU for Cornell 6/2013), Dr. Keller, Matthew McGuire (MS student) (University of Oklahoma) and various industry partners (initially Sierra and subsequently Ram Power and temporarily with Rockwood Lithium)

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3. Executive Summary

The Pearl Host Spring Geothermal Project funded by the DoE Geothermal Program was a joint academic (KU/UT & OU) and industry collaboration (Sierra and Ram Power) to investigate structural controls and the importance of low-angle normal faults on geothermal fluid flow through a multifaceted geological, geophysical, and geochemical investigation in west-central Nevada. The study clearly showed that the geothermal resources in Clayton Valley are controlled by the interplay between low-angle normal faults and active deformation related to the Walker Lane. The study not only identified potentially feasible blind geothermal resource plays in eastern Clayton Valley, but also provide a transportable template for exploration in the area of west-central Nevada and other regional and actively-deforming releasing fault bends. The study showed that deep-seated low-angle normal faults likely act as crustal scale permeability boundaries and could play an important role in geothermal circulation and funneling geothermal fluid into active fault zones. Not unique to this study, active deformation is viewed as an important gradient to rejuvenated fracture permeability aiding the long-term viability of blind geothermal resources. The technical approach for Phase I included the following components, (1) Structural and geological analysis of Pearl Hot Spring Resource, (2) (U-Th)/He thermochronometry and geothermometry, (3) detailed gravity data and modeling (plus some magnetic and resistivity), (4) Reflection and Refraction Seismic (Active Source), (5) Integration with existing and new geological/geophysical data, and (6) 3-D Earth Model, combining all data in an nnovative approach combining classic work with new geochemical and geophysical methodology to detect blind geothermal resources in a cost-effective fashion.

The projects technical effectiveness and economic feasibility of methodology is clearly a major upside to the project. The projected show showed the thermochronometry is a powerful and low-cost tool to delineate economic blind geothermal resources by identifying non-conductive long-term thermal anomalies. This was in part validated by a 2m shallow-gradient survey, but can ultimately only be tested

by actually exploration drilling. On the active reflection seismic data front there are two notable achievements to report. One: the successful use of low-cost auger drilling for shot hole drilling, two: the successful deployment of "disposable" temperature probes attached to explosive charges in seismic shot boreholes for dual use as shallow thermal gradient holes.

Project was of limited economic benefit to the public due to the project conclusion after completion of Phase I. During Phase I, the project employed a local auger drilling company, funded an archeological survey, and modest expenditures during field campaigns. Long-term impact given the possible economic feasibility of the identified and delineated geothermal resources could be significant, but require a stable and significant private industry investments that are currently unlikely.

4. Comparison of Planned Activities and Actual Accomplishments

The project successfully accomplished all Phase I objectives. The Pearl Hot Spring Project was conducted by UT/KU/OU researchers to minimize 2d to 3D structural/thermal uncertainties and elucidate the 4-D thermal evolution of the geothermal resource with the aim to optimize drill location siting and exploration success (Phase I) in a structurally complex and actively-deforming blind geothermal play in the Basin and Range Province. Despite successful completion of all geological and geophysical objectives, the project was fraught with difficulties with respect to changing industry partners from the moment it was awarded. Hence the project initially shifted from Northern Fish Lake Valley to adjacent Clayton Valley and subsequently was characterized by changing industry partners (Sierra, Ram and temporarily with Rockwood Lithium). Due the lack of continuing industry support, the project was terminated with at the end of Phase I despite very positive findings that should have rendered Phase II feasible and desirable.

Planned Objectives and Accomplishments

The following lists the primary objectives and purposes of the project

- Complete a 3-phased program on geothermal leases in Clayton Valley (Pearl Hot Spring and/or adjacent leases) along the northern and eastern edge of the Clayton Valley pull-apart basin near Silver Peak, NV in west-central Nevada. *Halted after Phase I completion due to lack of industry partner.*
- Demonstrate that our innovative and integrated approach presents geothermal operators with a very ***cost-effective approach*** to help plan the location of exploration and ultimately production of utility-grade geothermal wells. *Accomplished, although ultimate testing by drilling in Phase II not completed.*
- Evaluate the importance of ***fault interactions*** of NW-trending strike-slip faults with high-angle normal faults, and low-angle detachment faults for both fluid circulation and creating and maintenance (i.e., rejuvenation) of upper- or lower-plate fracture permeability. *Accomplished.*
- Characterize the long-term structural and thermal evolution of the area and ***identify long-term thermal anomalies*** by novel low-temperature thermochronometry that deviate from structurally controlled conductive cooling due to geothermal fluid flow. *Accomplished.*
- ***Acquisition and installation of a inductively-couple plasma mass-spectrometer (ICP-MS)*** for low-temperature and geochemical analysis. *Accomplished.*
- Carry out a 2D reflection and refraction seismic survey and potential fields study in combination with surface geology to **characterize the structural setting**. *Accomplished.*
- Test ***instrumenting active source shot holes for shallow gradient measurements*** as a cost-effective dual-purpose approach to characterize the shallow thermal field along the reflection seismic survey line. *Accomplished.*
- Besides the exploration and scientific benefits, educate several graduate (3) and undergraduate (3) students, and help ***train a new generation*** in renewable energy exploration, as well as temporary employment for students (4 graduate and 3 undergraduate students), collaborators, and contractors (e.g., drillers). *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) (e.g., Gorynski et al., 2010, 13a, 13b). *Accomplished.*
- ***Identify of a viable geothermal resource*** that could be explored by drilling during phases II and III and eventually leading to geothermal production and impacting to local/regional economy through long-term employment. *Accomplished.*
- ***Drilling and test of two geothermal exploration wells*** (cored) after ongoing careful evaluation of our recommendation at the end of Phase I and a go/no-go decision (Phases II & III). *Not completed.*

5. Project Activities for the Entire Project (by year)

5.1 Project Activities

- **Geology and related subtasks.** Geological and structural mapping and related subtasks were one of three major foci during 2010-15. Stockli, graduate students, and/or research associates spent nearly 200 combined days (all FTEs combined) in the field completing all geological and structural mapping, measuring stratigraphic sections, and collecting samples for geo- and thermochronometry. We completed geological mapping focused on the northern and eastern margins of Clayton Valley and finalized the mapping of the southern portion of the valley, containing the consolidated Ram Power Pearl Hot Spring Leases. UT graduate students Josh Burrus (M.S.) and Michael Prior (Ph.D.) completed geological and structural mapping critical to key areas in the Weepah Hills, Clayton Ridge, and Montezuma Range. Mapping and all geological efforts continued to be closely coordinated with Ram Power staff geologist, Caleb Stroub, and mapping and field efforts by the PI (Dr. Stockli) and his post-doctoral scholar, Dr. Charlie Verdel. The KU/UT team finished compilation of existing mapping and geochemical data has completed a preliminary structural and fault kinematic model for eastern Clayton Valley (before integration of geophysical data). Burrus completed his M.S. thesis at UT in 2013. He completed all map compilations and delivered a structural model for the area.
- **Geochronology, thermochronology, and geochemistry**. Analytical efforts started as soon as samples were collected during the earliest phase of Q1 FY11 and added two undergraduate research assistants to the team to help with analytical work. During Q2 FY11, we completed collection of all samples for geochronology and thermochronology. By Q3 FY11, all collected samples were completely separated and we commenced isotopic analyses of thermochronometric and geochronologic samples and by the end of Q3 FY11, 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 2011 or additional analytical efforts. During Q4 2011, 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) have been compiled in map form and contoured the long-term thermal evolution and commenced comparing those results with the modern thermal anomaly as outlined by the 2m survey. Burrus completed his M.S. thesis in 2013. Nikki Seymour (M.S. student) was hired in 2013 with the anticipated move to Rockwood Lithium lease holdings and the incorporation of additional geo- and thermochronometric data to connect the Ram, former Sierra, and Rockwood lease holdings. She completed most of this task in 2013. During 2014, additional zircon U-Pb work was conducted in collaboration with KU and the University of Alaska on tuffs recovered from boreholes (Rockwood) and surface outcrops to improve understanding of basin stratigraphy. In to thermo- and geochronometric analysis in and around the horseshoe surrounding eastern Clayton Valley, we conducted extensive research of the exposed portion of the Weepah Hills detachment fault in the Weepah Hills on the north side of Clayton Valley. The structural and stratigraphic work as well as the zircon U-Pb and apatite and zircon (U-Th)/He data greatly aided our understanding of the temporal evolution and the subsurface

geometries of the Weepah detachment fault beneath Clayton Valley (see Burrus KU M.S. thesis for maps and data.

- **Acquisition of Inductively Coupled Plasma Mass-Spectrometer (ICP-MS)**. For extensive geo-thermochronometric and geochemical research for this project and development of novel tools for geothermal research, we acquired a Thermo Element2 HR-ICP-MS partially funded by this grant and $100k contribution from the University of Kansas. Stockli's 2011 move to UT also involved the Thermo Element2 HR-ICP-MS acquired under Phase I after formal transfer to UTA (UT reimbursing KU for the $100k matching funds). The HR-ICP-MS instrument is now housed in a completely renovated state-of-the art laboratory space. UTA completed laboratory renovations for Stockli's entire new laboratory (incl. new state-of-the-art space and infrastructure for the Element2 HR-ICP-MS) for a total of $1.2M! UTA also covered the professional move by Thermo Fisher technical staff and a 3-year service contract for the instrument. The infrastructure support will ensure long-term use of the instrument and application in geothermal research. The service contract was renewed for another 3 years in 2014. The instrument was also heavily used for a DoE Geothermal Project in Dixie Valley (DE-EE0005520) and it is currently also directly contributes analytical data to a collaborative UT-lead DoE project (DE-SC0001114) investigating CO2 sequestration at Bravo Dome. The instrument currently also supports 3 NSF projects with Stockli as PI and co-PI and contributes data and analytical services for a plethora of projects of UT and external scientists with federal research support. We fully anticipate that this kind of support and collaborations will continue and that this now 6-year old instrument will continue to play a very important role in this research.
- **Reflection and refraction seismic survey**. Slow processing and approval of the NOI for the reflection seismic line by the BLM delayed initiation of the planning and execution, but we completed all final detailed planning and organizational work necessary to conduct the planned seismic survey in 2009. The active seismic survey instrument deployment and data acquisition were carried out in the second week of January (Jan 10-16, 2010). Drs. Keranen and Stockli executed all portions of Task 2 with the help of a large group of students and volunteers from KU, OU, UTEP (Dr. Harder) and staff from IRIS (PASCAL). 800 seismometers (Texans) from the PASCAL pool were reserved for the full-scale seismic experiment and delivered and staged in Tonopah, Nevada. For the major 15 km long 2D reflection and refraction seismic line, 13 shot holes were drilled with the help of UTEP and PASCAL seismic explosives expert Dr. Harder. Each drilled shot hole was loaded with ~20-70 kg of special explosives and wired for detonation. In addition, each shot hole was not only used for the active seismic survey, but also instrumented with RTD temperature devices for up to three days before detonation. A total of 800 geophones and Texans (recorders) were deployed along the 15 km long seismic line in a single day. Geophone spacing varied from 10-20 m with shot point being 1 km apart in most cases. A second shorter (1 km) high-resolution seismic reflection and refraction survey was acquired during the same time, along the southern portion of the trace of the long (15 km) line, but with smaller charges (1/3 lbs 2 m deep) and with a shot and geophone spacing of only 5 m. The main target of the shorter line was the Paymaster Fault, marking the southern boundary of the basin. Data processing was completed by McGuire as part of his M.S. thesis at OU in the winter 2011/12. McGuire completed his M.S. thesis in 2013. The data were professionally reprocessed in 2013 and the refined interpretations integrated into the structural and geothermal model. Preparation of manuscripts based on McGuire's data and interpretations is in process.
- In addition to the ***RTD instrumentation of the seismic shot holes***, we also carried out in collaboration with Ram Power a detailed ***2m geothermal gradient survey*** in a swath parallel to the seismic line and off to the east. in Jan 2011; spearheaded by Ram Power staff geologist Stroub in collaboration with Deymonaz (co-PI). The 2m gradient survey and the 50-100 ft RTD shot hole thermal gradient measurements have proven very informative in refining the very promising geothermal anomalies below the consolidated Peal Hot Spring leases. The 2m gradient raw data are property of Ram Power, but the data map and data derivatives were given to our team for dissemination without any restrictions.
- In 2011-2012, the UT/OU/KU team also carried out detailed ***gravity and magnetic surveys*** to further supplement the geophysical datasets and test. In total data from over 1200 (!) gravity stations were

collected in January and March 2011. Gravity data was acquired along linear transect in a NW-SW direction with a s pacing 50 m along three lines parallel to seismic survey and spacing ranging from 100-500 m along-line along additional cross-valley lines are from 500-m to 2-km apart. Despite delays in geophysical data processing and data integration due to grant transfer to UT and personnel issues, we completed (1) final processing of the short reflection line, (2) interpretation of the refraction data and construction of velocity model based on the 15 km seismic line, and (3) combined all new gravity data (>1000 gravity data points), (4) final processing of 15 km reflection line, (5) integration of seismic and gravity data, and (6) completion of preliminary 3D Earth Model for siting of slimhole locations.

- ***Structural geometry of the basin***, suggests the presence of high-angle dilational faults, transferring slip from NW-trending strike-slip faults across these dilational steps eastward, before intersecting the Paymaster Fault zone. These step-overs are along the northern edge of the Valley and in my opinion control the thermal anomaly (as found in the 2m survey). The dilation step-overs likely create significant fracture permeability in the upper plate of the older detachment (in Pz carbonates). This fault geometry is also confirmed by our detailed gravity. It's not a single and simple E-W fault, but rather a series of E-stepping relays. Professional reprocessing of reflection seismic data and integration of borehole data from Rockwood Lithium helped refine the structural model and address issues of fracture permeability and fault sealing (mineralization). To improve our temporal basin model, we also collaborated with Rockwood and with researchers from the University of Alaska and University of Kansas, dating ash samples from borehole samples.
- ***Velocity model integrating reflection, refraction, and gravity data*** clearly show the basin-bounding fault, and antithetic faults within the basin and the north of the basin. We see at least 4 antithetic faults, along with probably a synthetic fault (not modeled here). In 3-D, these antithetic faults accommodate E-stepping slip transfer from NW-trending transcurrent faults. There is a major horst behind the main fault to the south. This model has a very good fit to the data. We interpret that the high-angle fault is cutting the Weepah Hills detachment (~5-6 km/sec boundary).
- The seismic data show that both the Paymaster Fault (south side of Valley and Pearl "bath house" area) is very reflective. The high-amplitude reflectivity suggests to us that the fault is heavily mineralized - a clear indication for geothermal fluid flow along the fault. There is also good ***geophysical evidence for geothermal fluid flow*** along faults. Velocities are slow along the faults, indicating (most likely) geothermal fluids moving along them.
- The ***geochemical and thermochronometric data*** are somewhat spotty due to the lithologies encountered, but the youngest ages in comparison to background samples from around the basin are centered along the north side of the valley (thermochronometric anomaly) and spatially coincides with the thermal anomaly mapped out by the 2m survey shallow gradient survey. The collocation of the anomaly with a mineralized outflow sheet and our discovery of actual steam exhalations (fumaroles) suggest that there is a surface manifestation of the hydrothermal plume.

5.2 Technical Barriers and Difficulties

- Technical challenges and barriers during the project were minimal. Geological and geochemical work was slightly delayed due to the lead PI Stockli's move from the University of Kansas (KU) to the University of Texas (UT) in 2011. As part of this move, the acquired ICP-MS was also moved to UT with professional moving costs covered by UT. The ICP-MS is housed in a custom-designed and climate-controlled facility entirely paid for by start-up funds to Stockli through UT – a major investment into the long-term success and operation of the instrument partially funded by the DoE grant. The move delayed final analytical work by (only) several months.
- Reflection and refraction active seismic work initially experience minor delays with permitting of the BLM-required archeological survey need for permission to drill active-source shot holes.
- Due to limited budget for active-source shot holes, the project turned to inexpensive auger drilling for seismic shot holes. This turned out to be challenging on coarse-grained and boulder-littered alluvial fans,

given required penetration depth resulting in smaller shots and loss of auger steel. However, it is worth stressing that auger drilling ultimately did do the job and in fact was very successful in the playa of Clayton Valley, ultimately making the reflection seismic very survey cost-effective.

- Experimentation with disposable RTD thermal probe instrumentation of shot holes together with explosive charges for seismic survey turned out to be successful and a cost-effective pay of accomplishing two tasks simultaneously, namely acquiring shallow gradient information (beyond 2m) and drilling shot holes.
- The chief technical barrier for thermochronometry turned out to be the lack of apatite or good-quality apatite in some of the Paleozoic lithologies surrounding eastern Clayton Valley; this could be remedied by novel 4He/3He thermochronometry (as successfully shown in another DoE project in Dixie Valley). Despite this, results of apatite and zircon (U-Th)/He thermochronometric analyses clearly demonstrated the power of low-temperature thermochronometry and the spatial agreement with the 2m shallow geothermal gradient survey.

5.3 Project Targets and Timeline

- Project funds conditionally released in May 2010, BLM permission granted in Oct 2010, and DoE-KU contract signed in Nov 2010.
- July 2010: Start of structural and thermochronometric field program and installation of HR-ICP-MS instrument
- Fall 2010: Structural mapping and thermochronlogy sample collection
- Jan 2011: Acquisition of seismic and gravity data
- January 2011: Completion of thermochronometry sample collection & processing. Completion of isotopic analyses and interpretation (numerical modeling) anticipated by July 2011
- January 2011: Thermal gradient holes through both (1) instrumented seismic shot holes and (2) 2m survey (conducted by Ram Power). Legacy data and new data set (1 and 2) clearly outline thermal anomalies in E Clayton Valley. During survey several travertine deposits and active fumaroles were discovered and mapped.
- The bulk of the early 2011 effort was devoted to the acquisition of the Reflection/Refraction Seismic Survey (after BLM and EA permitting) - Data acquisition (Jan 2011) was extremely successful and early processed data appears to be of very high quality. Two lines were shot along the permitted transect. (1) Line A: 15 km long 2D line with 13 shot points (~20-70 kg shots) and a 10-20m geophone (with Texan) spacing. (2) Line B: 2 km high-resolution seismic line across the Paymaster Fault (southern portion) with 5m shot (1/3 lbs) and geophone spacing.
- March 2011: Completion of Gravity surveys (plus Magnetics/Resistivity data collection), resulting in collection of >1000 gravity stations (spacing 50 m along three lines parallel to seismic survey and spacing ranging from 100-500 m along-line along additional cross-valley lines are from 500-m to 2-km apart).
- Fall 2011: Move of Stockli and research team to Univ of Texas at Austin and pending novation since 8/11
- 2013: Completion of novation process (!) and temporary new partnership with Rockwood Lithium (to replace Ram Power)
- 2013: Integration of new data from Rockwood and other adjacent former Sierra/Ram properties (Silver Peak) into a self-consistent model.
- 2013: Collection of additional thermochronometric data in Rockwood area and collection of zircon U-Pb data from borehole samples provided by Rockwood in collaboration with the University of Alaska.
- 2013: Completion of all analytical work and geophysical data processing and data compilation and integration into 3-D Earth Model.
- 2013-2014: Tremendous efforts were spent trying to salvage the project and come to terms with a new industry partner after Ram Power abandoned the project. Stockli had secured a preliminary agreement and e-mail commitment from Rockwood Lithium, but upper management eventually withdrew that commitment.

- 2014: Decision to forgo Go/No-go decision on drilling and to complete final report at the end of 2015. After Rockwood Lithium's withdrawal, the decision was made to abandon efforts to find reliable industry partner to drill required Phase II drill holes.

5.4 Project Challenges and Difficulties

- The Pearl Hot Spring DoE award was conditionally awarded in April 2010 pending approval of the Notification of Intent (NOI) by the Tonopah BLM office for the Phase I (task 2) reflection and refraction seismic survey to be carried out by the University of Oklahoma (subcontract). The BLM Tonopah office approved and signed the NOI for the phase I seismic work (ref N-88945; DOI-BLM-NV-B020-20 10-0141 -CX) on Sept. 16, 2010, after review of our filed NOI and archeological reports. The award was formally awarded to KU in late Sept, 2010 (releasing all phase I funds for the project), but not finalized between DoE and KU (incl. OU subcontract) until early Dec, 2010 due to contract legal language pertaining to indemnity issues.
- The project was marked by a number of changes and circumstances that have delayed or hampered our FY11-12 efforts. Despite these difficulties, we feel that we have accomplished the major tasks and goals set and needed for our end-of-phase-I go/no-go stage gate. These changes include: (i) internal turmoil of our industry partner Ram Power, leading to dramatic reduction in logistical and scientific support and exchange and personnel restructuring. (ii) Stockli and his research team's move to the University of Texas at Austin with all analytical facilities in the early Fall 2011 (incl. transfer of the HR-ICP-MS). (iii) An summer internship by OU graduate student, Matt McGuire, delayed completion of the seismic processing and interpretation. Stockli's relocation and pending novation/transfer of the award to UTA meant that Phase I funds became unavailable during Q4 of FY11.
- In 2012, Ram Power essential withdrew from the involvement as the industry partner of Phases II and III. The company has canceled their power-sharing agreement for the Paymaster/Clayton Valley area and notified us of their intent to abandon their United States operation.
- As a consequence, we evaluated alternative avenues for the completion of the project in 2013. This effort absorbed a major portion of Stockli's involvement during 2012-2014. Encouraged by DoE, we explored a collaboration with DoD's GPO (China Lake) – an effort that was suspended in light of insurmountable legal barriers related to ARRA funding. Subsequently, we linked up with Rockwood Lithium and their geothermal exploration efforts to continue phase II and III in Clayton Valley. UT and Rockwood Lithium had tentatively agreed to this effort and worked out the legal details with the blessing of DoE. As part of this process, we commenced integrating Pearl data with Rockwood Lithium and SGP/RAM (Silver Peak) data to accommodate the new partnership and move forward.
- Late 2013, Rockwood Lithium upper management, coming off a disappointing geothermal collaboration on a power plant project on their property, decided to reverse is commitment decision and withdrew it commitment for Phase II and III in the middle of renewed and retooled Phase I efforts by UT/KU, incorporating Rockwood property data and collecting selected additional data.
- Rockwood's decision has been discussed with DoE Geothermal Staff and Management and it appears this decision will result in completion of Phase I, preparation of a final report, and abandonment of Phases II and III.

5.5 Conclusions and Prospects for the Future

- Despite initial delays due to permitting and finalization of the grant and release of funding, we believe that the project has been extremely successful in (1) helping to validate our novel exploration methodologies, (2) demonstrating the cost-effectiveness of the integrated approach chose, (3) the initial identification of multiple geothermal anomalies and one very promising exploration target. The project has experienced a switch in industry partnership to Ram Power Inc. after acquisition of Sierra.

- The 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 viable utility-grade blind resource present along the northern edge of the central portion of the Pearl Hot Spring lease with a temperature of >180F at 100m. A deep exploration core or thermal gradient hole would be the best and safest way to proceed to evaluate the real potential of this resource. In addition, as secondary resources were identified along the Paymaster Fault in SE Pearl Hot Spring (near old Hot Spring baths). We worked extensively with with Ram Power to develop a plan for phase II and once a contract with UT was signed and once novation was finalized, but internal Ram Power turmoil and economic reasons lead to Ram Power abandoning the project and withdrawing their staff and any commitments to the project.
- In 2013, we teamed up with Rockwood Lithium. The project team recommended to our industry partner to drill an initial slimhole (cored) in N Clayton Valley based our integrated geological and geophysical study. Rockwood Lithium evaluated our reports and initially recommended independent evaluation of our recommendation by a third party after positive in-house evaluation. However, all efforts were abandoned when Rockwood Lithium, the last feasible partner, pulled out of the project prior to any independent evaluation or formal commitment to DoE and UT.

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

- As part of the outreach and education portion of the project during Q1 of FY 11, Stockli spearheaded, organized and chaired a session on innovative geothermal exploration at the AGU 2010 Fall Meeting in San Francisco in Dec 2010.
- The Pearl Hot Spring Team presented an abstract at the GRC meeting in Sacramento, CA in 2011.
- The Pearl Hot Spring Team presented an abstract at the GRC meeting in Sacramento, CA in 2012.
- Joshua Burrus, M.S, 2013, Integrated footwall and hanging wall tectonics and stratigraphic evolution of the Weepah Metamorphic Core Complex, NV. University of Texas MS Thesis, Austin, Texas, 104 p.
- Matthew McGuire, 2012, Geophysical characterization of transtensional fault systmes in the Eastern California Shear Zone – Walker Lane Belt, Univ. of Oklahoma M.S. thesis, Norman, Oklahoma, 49 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)
- - Gravity and Magnetic Data - UT El Paso Nation Gravity and Mag Database
- - Seismic raw data - IRIS/PASCAL repository and UTIG (although mostly marine)
- - Data, metadata, and interpretations will also be published in peer-reviewed journals and publications
- - M.S. thesis by Burrus (KU) and McGwire (OU) available online or by request from PI (to be shared with NGDS)

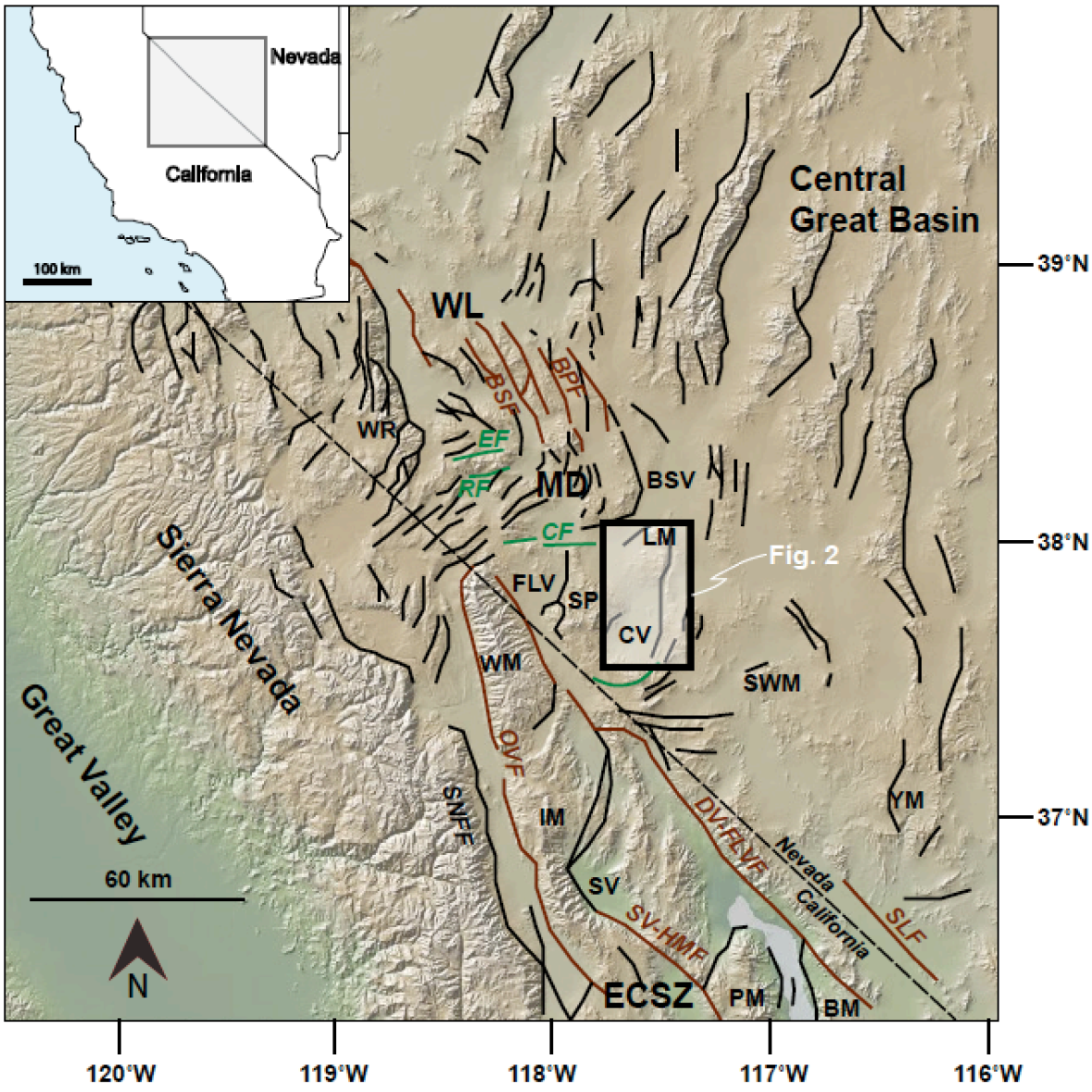

Figure 1: Tectonic overview of the Walker Lane and Eastern California Shear Zone in west-central Nevada and eastern California, showing major late Cenozoic faults of the western Great Basin and Sierra Nevada. Normal faults-black; dextral strike-slip faults-orange; sinistral strike-slip faults-green. Image is Global Multi-Resolution Topography (http://www.geomapapp.org). Cenozoic faults after Oldow et al., (2009). BM-Bare Mt.; BPF-Bettles Well-Petrified Springs fault; BSF-Benton Springs fault; BSV-Big Smokey Valley; CF-Coaldale fault; CGB-Central Great Basin; CV-Clayton Valley; DV-FLVF-Death Valley-Fish Lake Valley fault; ECSZ-eastern California shear zone; EF- Excelsior Mts. fault; FLV-Fish Lake Valley; LM-Lone Mt.; IM-Inoyo Mts.; MD-Mina Deflection; OVF-Owens Valley fault; PM-Panamint Mts.; RF-Rattlesnake Flat fault; SLF-Stateline fault; SNB-Sierra Nevada batholith; SNFF-Sierra Nevada Frontal fault; SP-Silver Peak Range; SVHMF-Saline Valley-Hunter Mt. fault; SV-Saline Valley; SWM-Stonewall Mt.; WL-Walker Lane structural belt; WM-White Mts.; WR-Wassuk Range; YM-Yucca Mt.

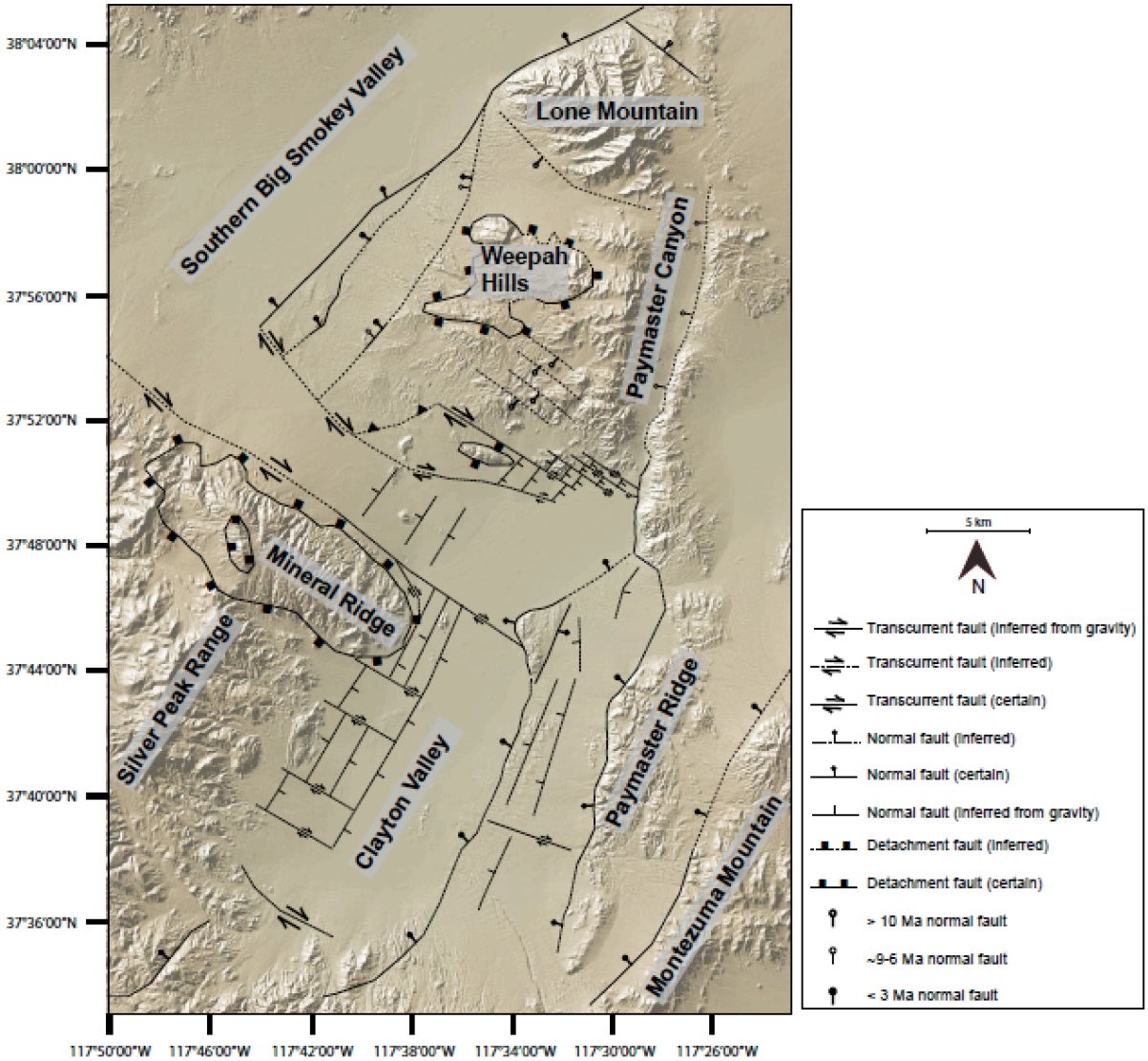

Figure 2: Global Multi-Resolution Topography image of Clayton Valley and Southern Big Smokey Valley area. High-angle normal faults are differentiated based on timing of activity. The major Mio-Pliocene high-angle normal faults and transcurrent faults produce a structural stepover that kinematically links the Eastern California shear zone and the Walker Lane structural belt through a complex network of faults that tranfers strain across the Silver Peak-Lone Mountain extensional domain. Faulting prior to 10 Ma accommodated extension during early Miocene Basin and Range style extension. Imagery from http://www.geomapapp.org; Ryan et al., (2009).

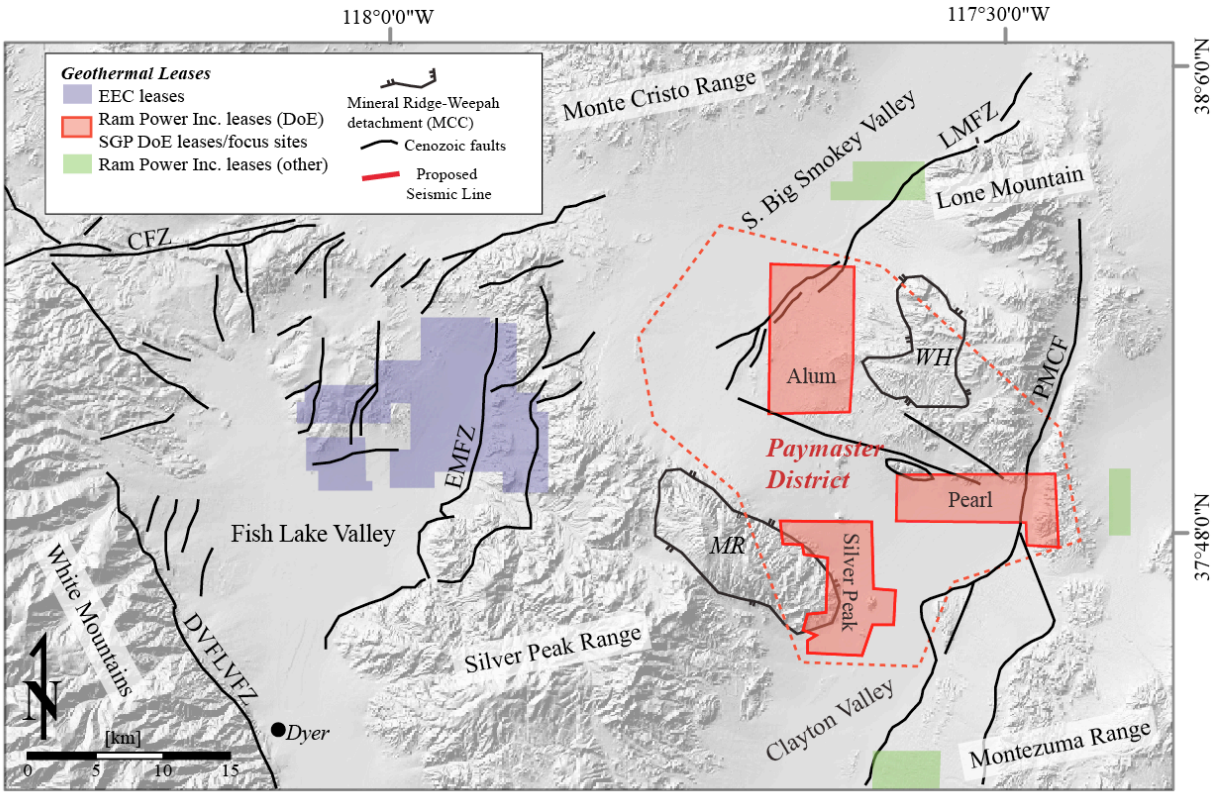

Figure 3: Shaded relief map of the Silver Peak-Lone Mountain area in west-central Nevada showing the Geothermal Lease holdings in 2010 at the beginning of the project.

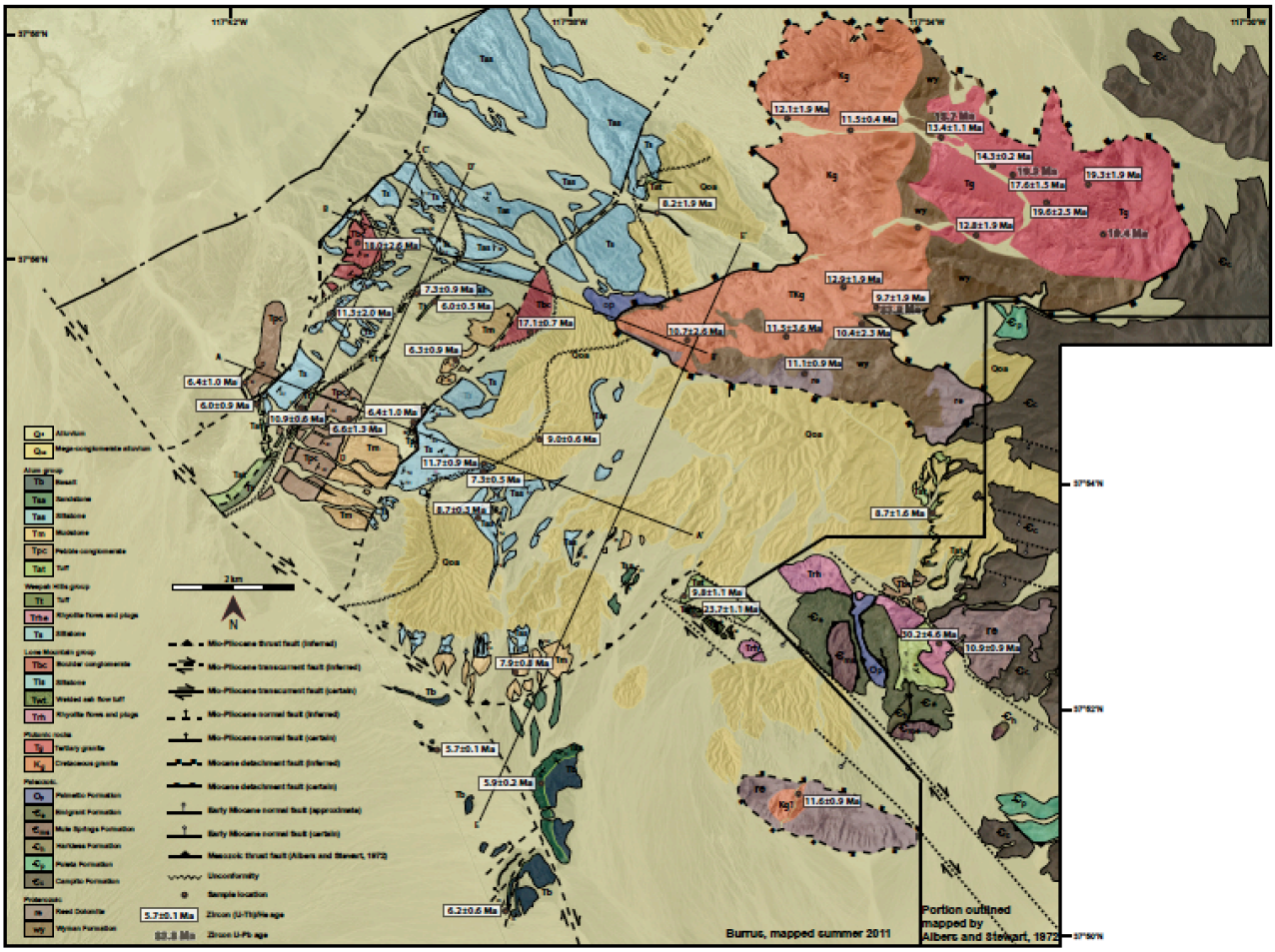

Figure 4: Detailed geological and structural map of the Weepah Hills on the north side of Clayton Valley, where the corrugated Weepah Detachment fault is exposed and was able to be sampled. Boxes show geo- and thermochronometric sample locations used to determine the background exhumation cooling and timing of fault slip. Map from MS thesis of Joshua Burrus (2013).

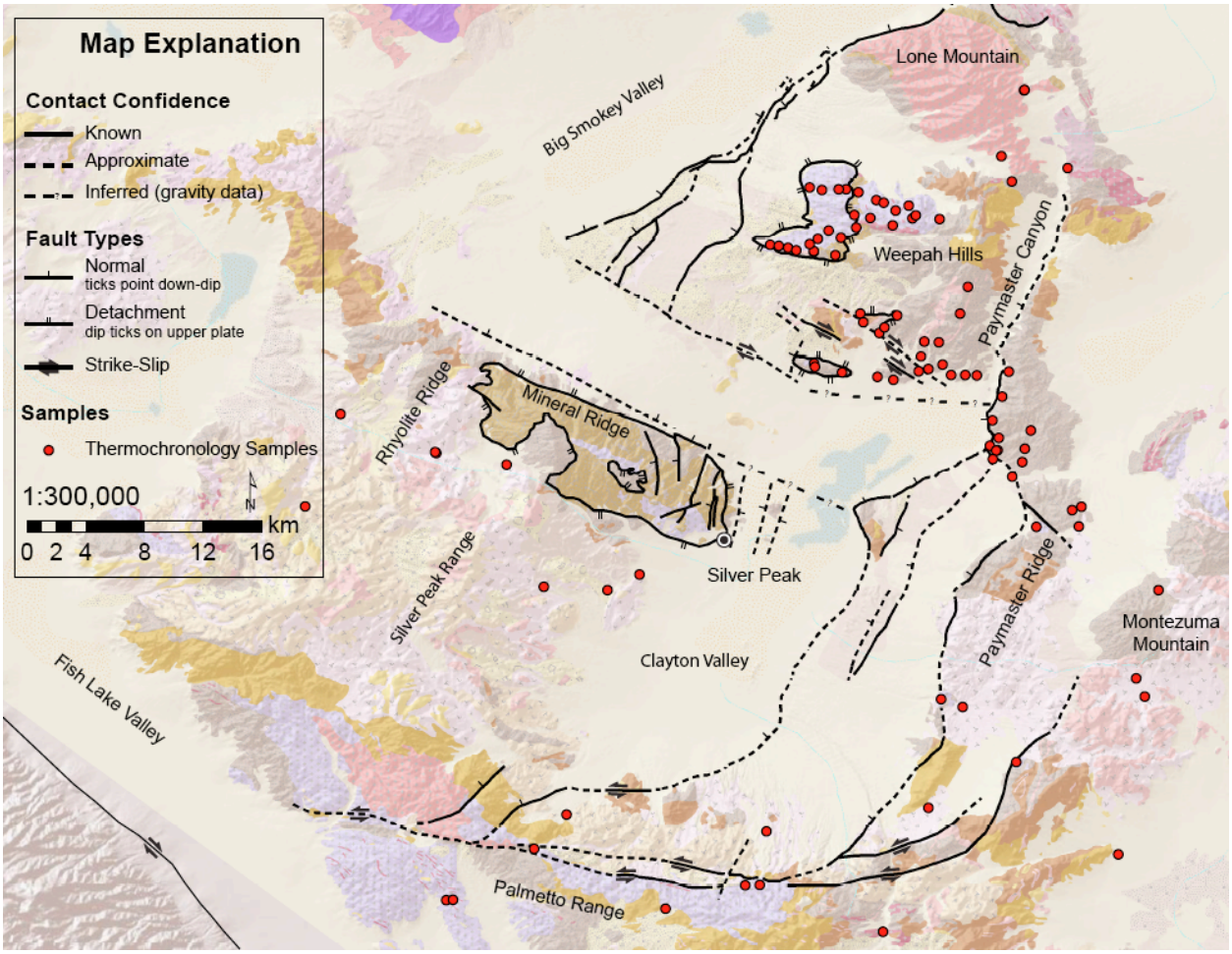

Figure 5: Geological and structural map of the Silver Peak – Lone Mountain area showing all thermochronometric sample locations. Most data are reported in Burrus (2013) or are available through geochron.org.

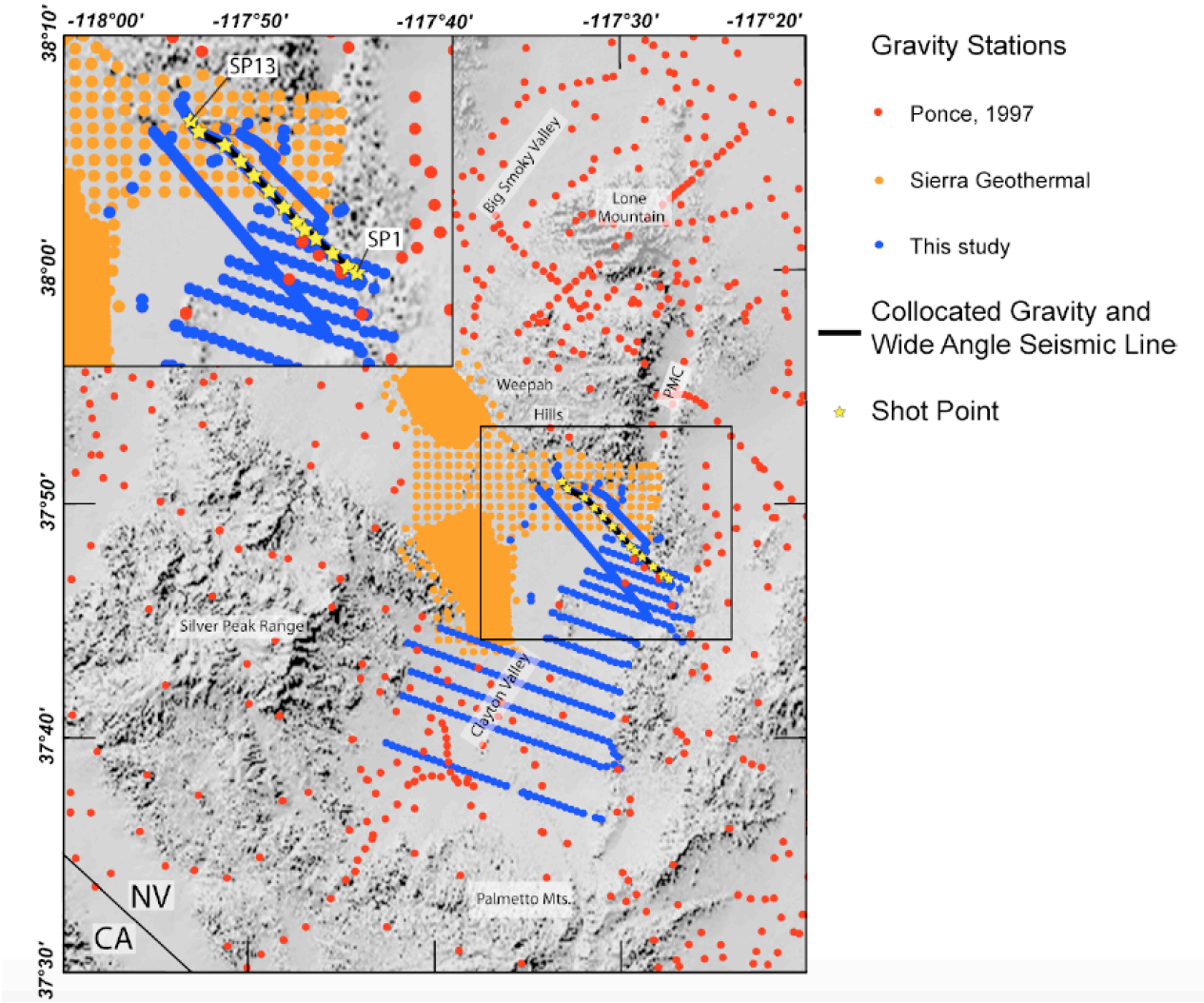

Figure 6: Shaded relief map of gravity data collected (blue) and compiled for this study. Orange data are Sierra Geothermal data transferred to our team. All blue stations (>1200) were collected as part of this project. Raw data are in McGuire MS thesis (2012). Box shows insert in upper-left hand. Insert also shows location of reflection and refraction active source wide-angle seismic line and shot holes.

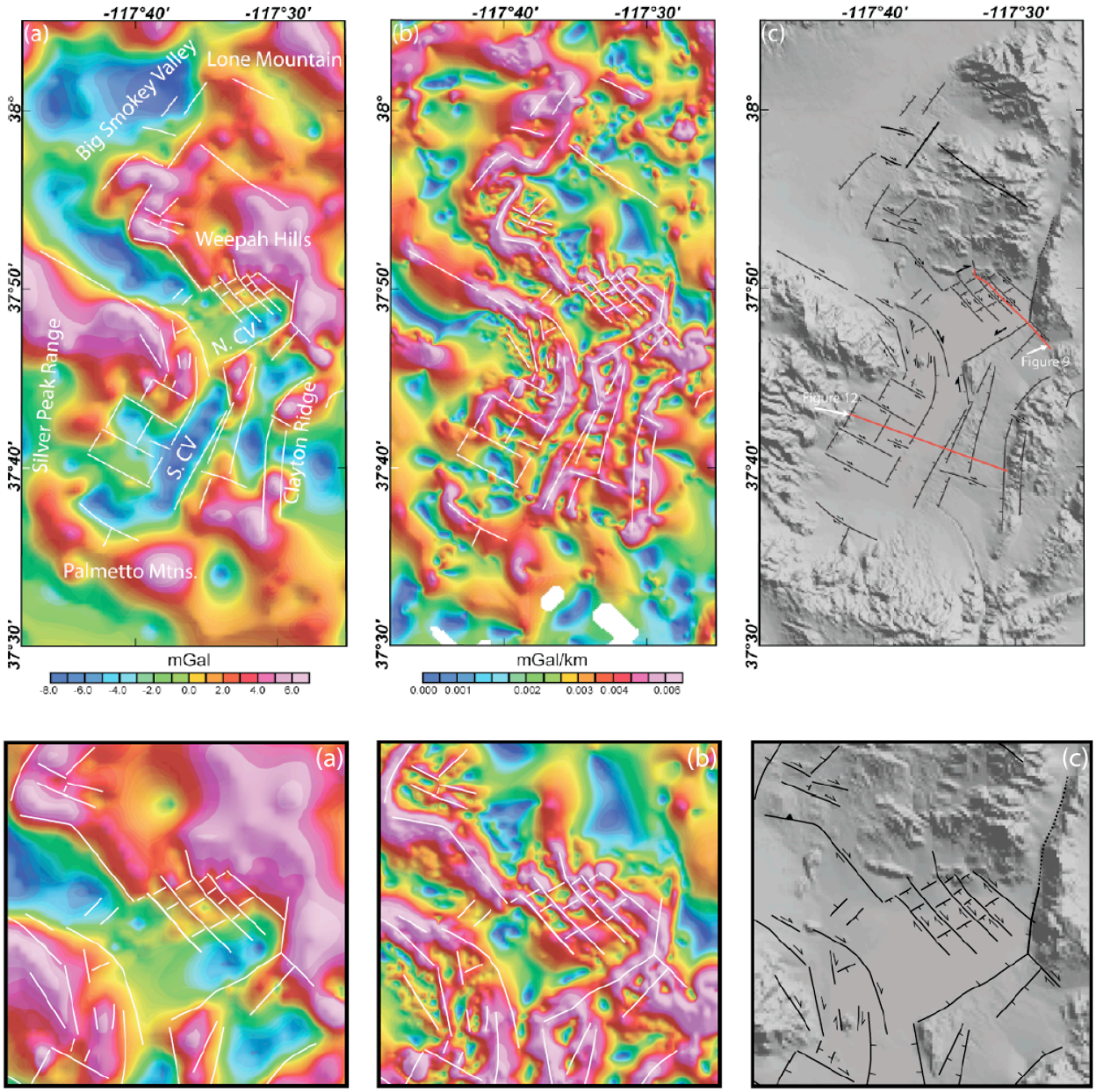

Figure 7: Regional residual simple Bouguer anomaly (a), Bouguer gradient anomaly (b), and structural fault (c) maps for study area from new, Sierra, and other published gravity data. Data in McGuire (2012).

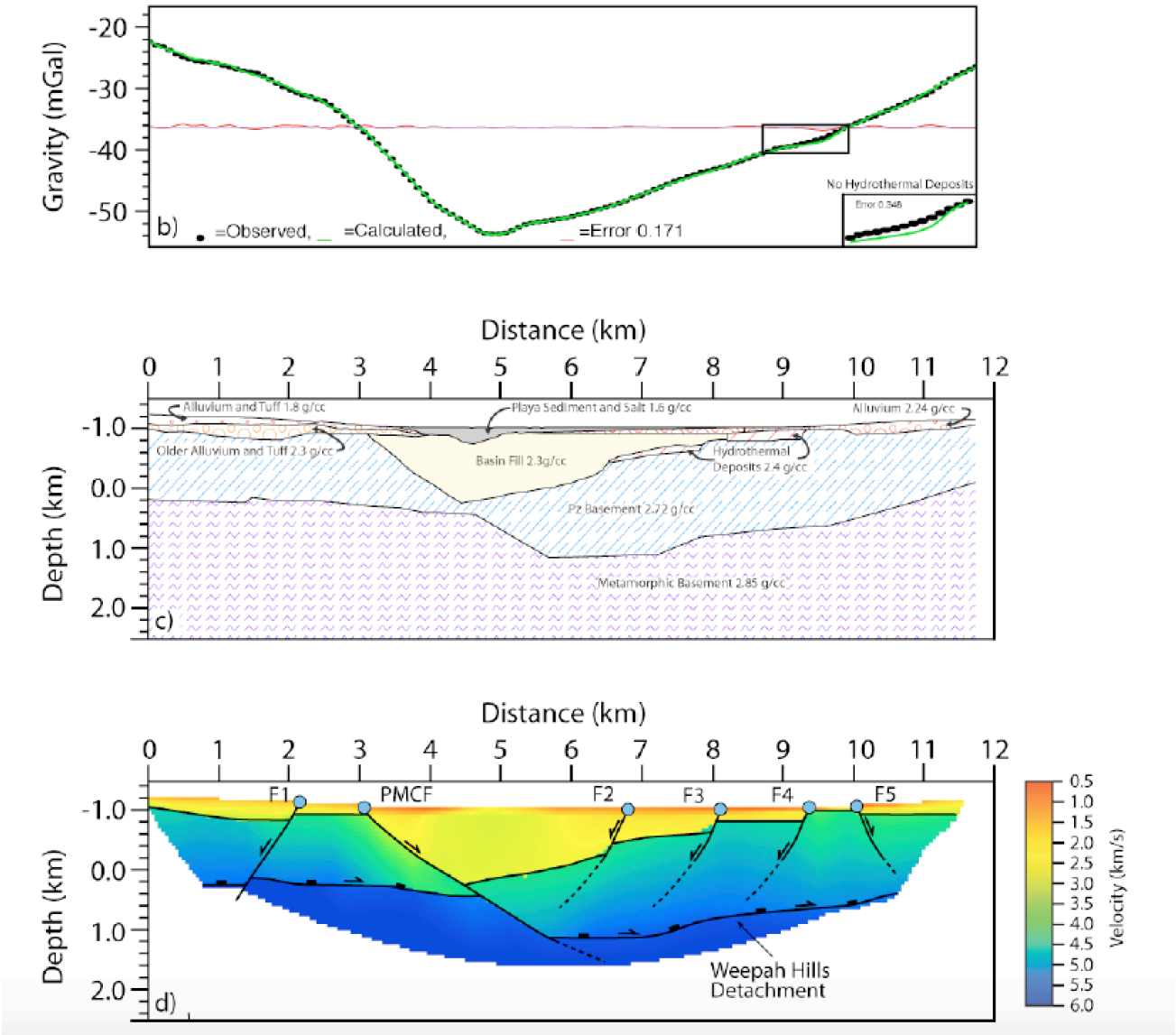

Figure 8: Seismic, gravity, and structural model along the wide-angle seismic line in eastern Clayton Valley. (A) Observed and modeled gravity data. (B) Density model for gravity modeling with input from reflection seismic data. (3) Structural model for the interaction between Weepah Hills Detachment and Paymaster Canyon Fault (PMCF). Gravity data and modeling in McGuire (2012).

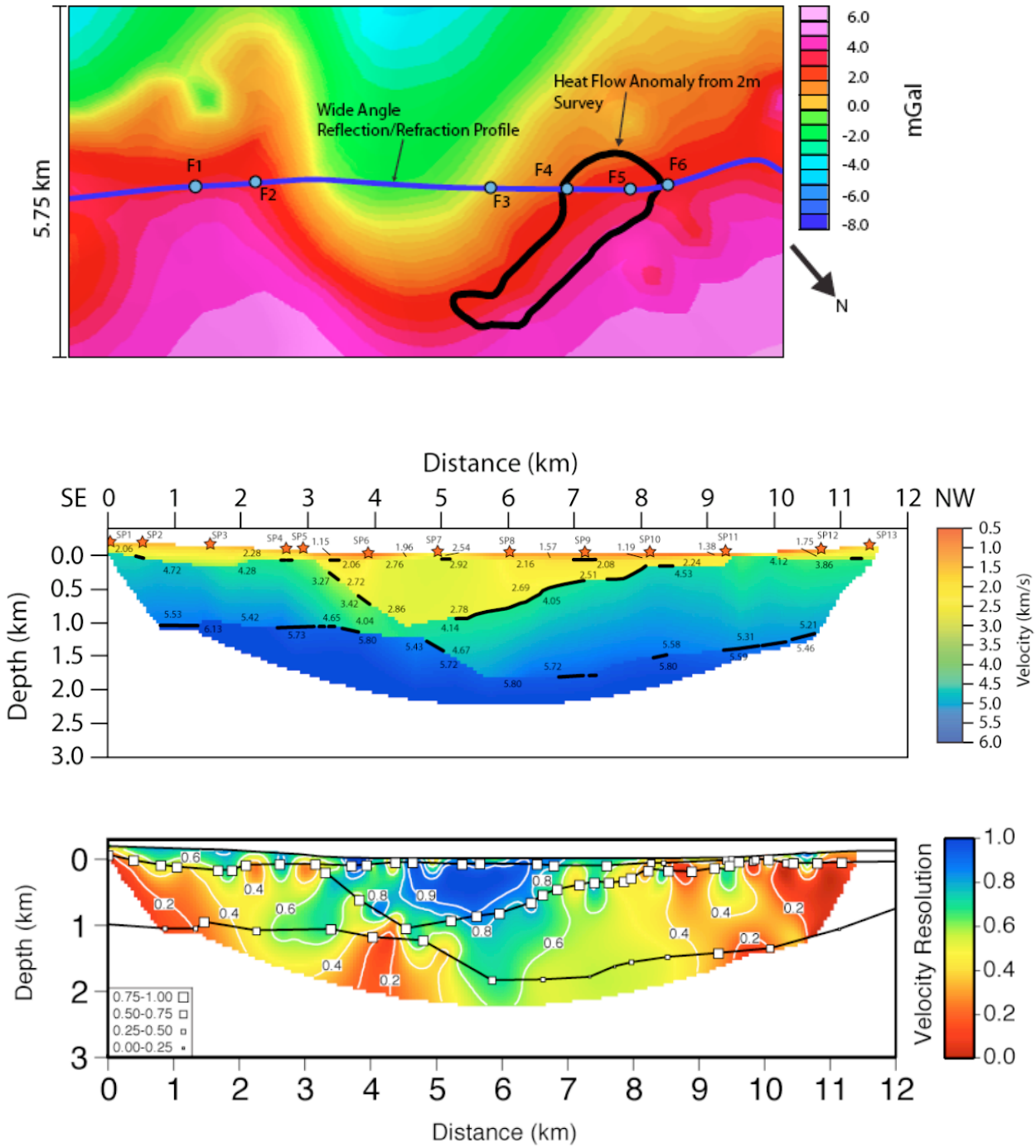

Figure 9: (A) Gravity map of eastern Clayton Valley, showing wide-angle active seismic line acquired for this study, and structural model along the wide-angle seismic line in eastern Clayton Valley. (B) Velocity from reflection seismic data. (3) Resolution map for velocity model. Velocity data and modeling in McGuire (2012).

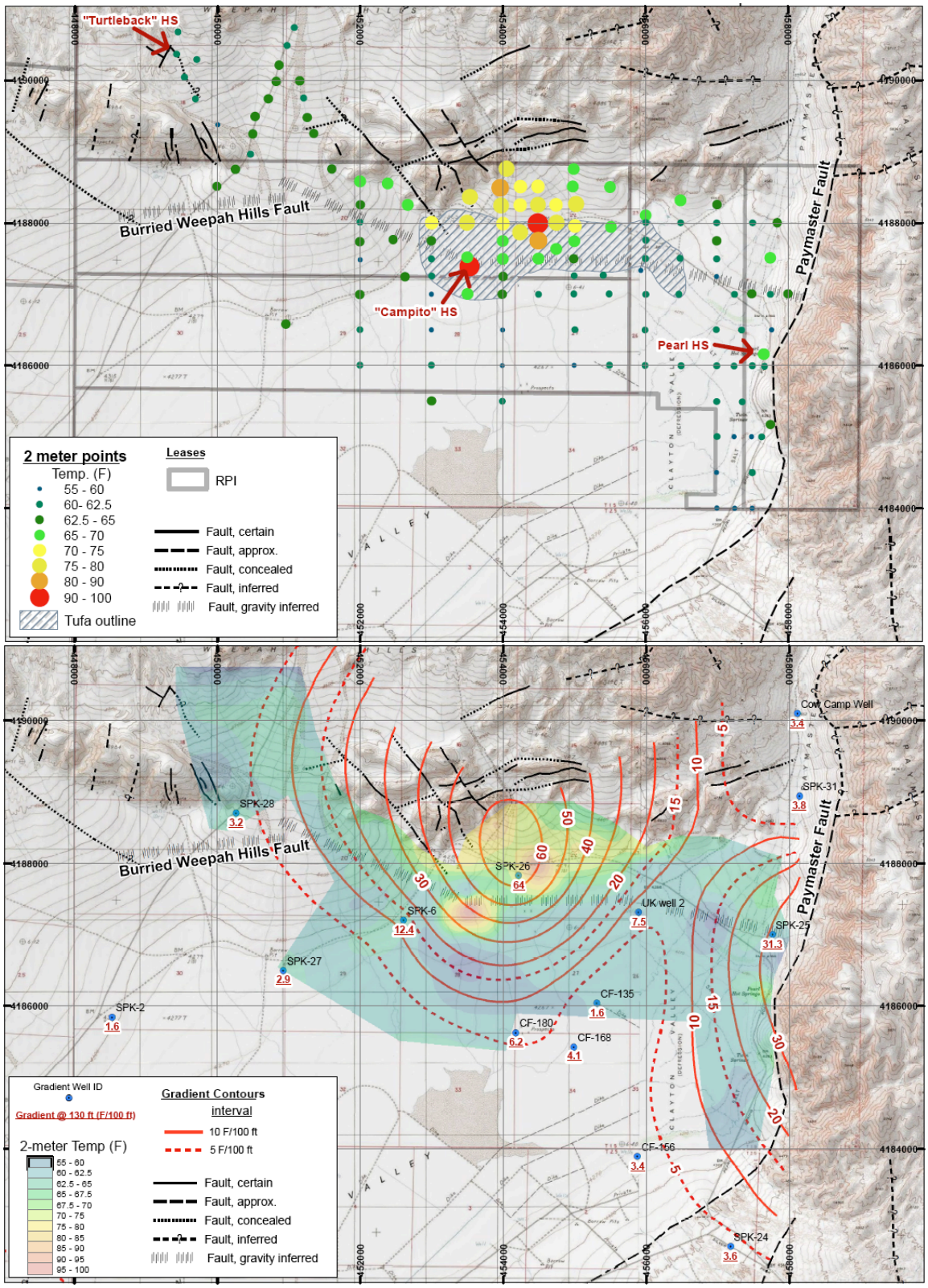

Figure 10: Shallow gradient temperature maps of eastern Clayton Valley from both 2m survey (top map) and contour map (lower map) of shallow thermal gradient from both 2m survey and instrumented active shot holes. Raw data for 2m survey with Ram Power.

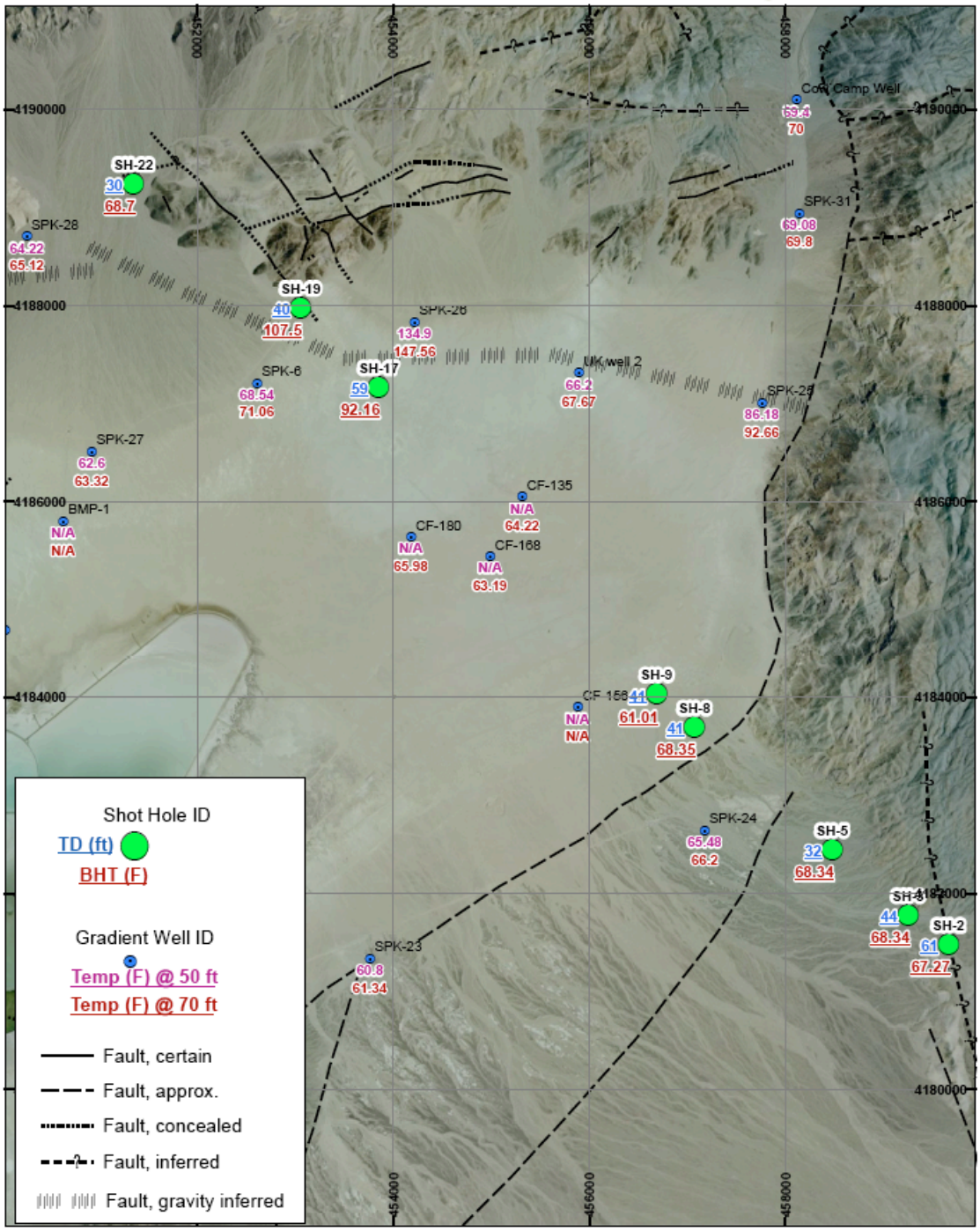

Figure 11: Satellite image of eastern Clayton Valley and Paymaster Canyon showing shallow thermal gradients from instrumented seismic survey shot holes and surveyed Rockwood and legacy boreholes.

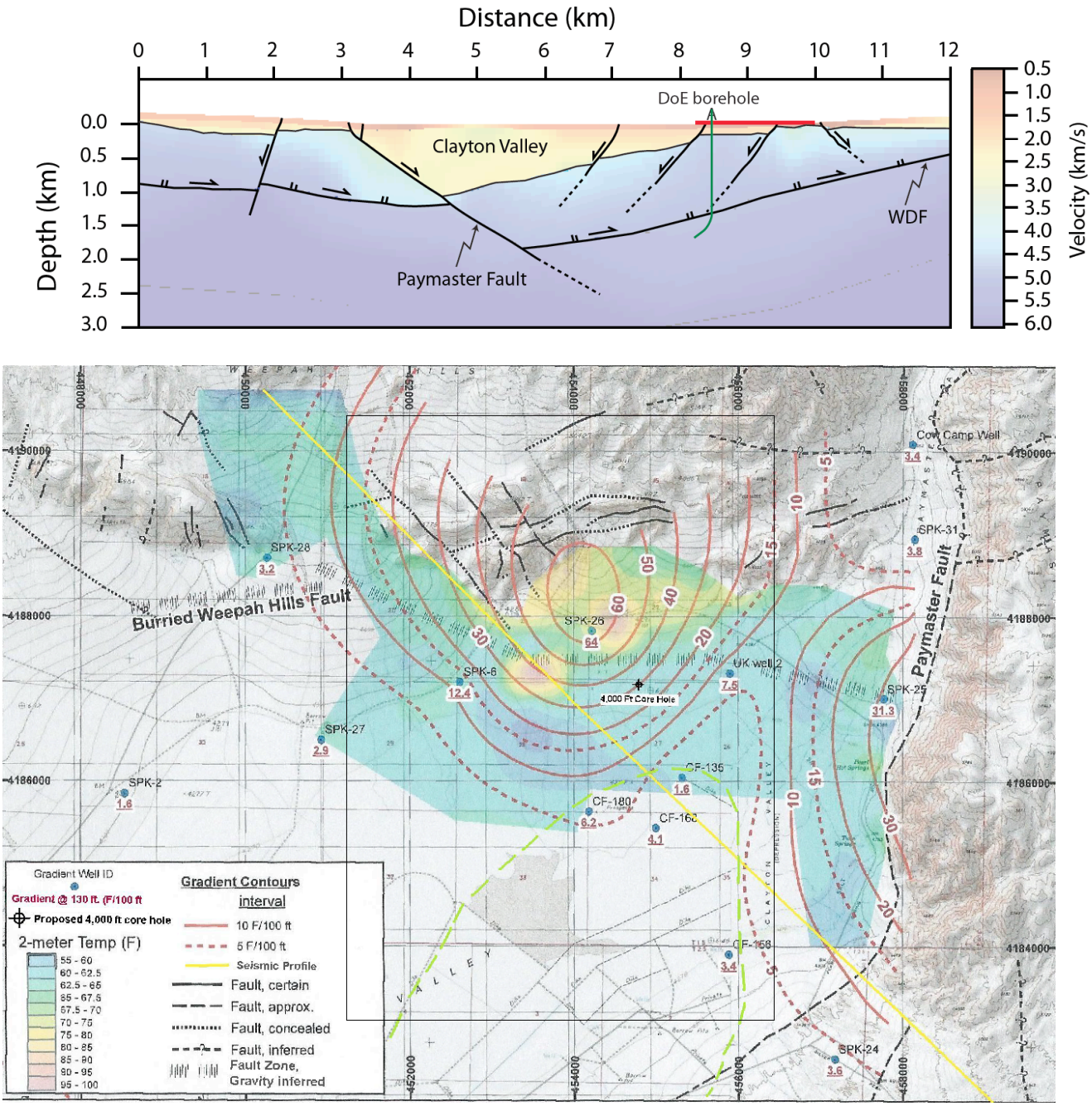

Figure 12: Shallow gradient temperature contour map of eastern Clayton Valley from both 2m survey and instrumented active shot holes showing clear thermal anomaly in NE Clayton Valley. Cross Section (yellow trace) shows structural model for E Clayton Valley based on structural mapping, active seismic survey, and potential fields data, showing proposed Phase II exploration borehole.