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Phase II Activities in Play Fairway Analysis for Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah

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ABSTRACT

Our research team is carrying out a play fairway analysis (PFA) for geothermal resources in the Eastern Great Basin extensional tectonic regime of western Utah. Here, active Basin and Range (B&R) extension with volcanism having a N-S strike is superimposed upon pre-existing E-W belts of plutonic rocks and large-scale structural lineaments. The PFA aims to illuminate the potential sources of heat and permeability in the region, which are the two principal criteria for establishing a geothermal resource. Initial (Phase I) play fairway analysis (PFA) integrated several favorability indicators to define focus areas for Phase II followup that is intended to develop thermal gradient drilling targets. Criteria selected for establishing heat potential include direct heat flow measurements, MT low resistivity, seismicity swarms, fluid geochemistry, and proximity to recent volcanism. In particular, high-temperature systems commonly appear to connect via steep, low-resistivity crustal fault systems to deeper magmatic sources.

Under Phase II support, new MT surveying is concentrated around Crater Knoll and Twin Peaks, and provides near continuous denser coverage westward from Cove Fort. Coarse MT site coverage extended south past the Roosevelt Hot Springs producing area. A geothermal fluid origin for low resistivity MT upwelling structures is being tested using Nodal passive seismic surveying that seeks presence of seismic swarms. New structural analysis in the area will exploit Google high-resolution DEM data that has become available for the state of Utah. Gravity fill-in is being accomplished to improve resolution of possible cryptic subsurface structures. Approximately 160 thermal gradient wells, 8 deep wells and 20 water wells with thermal information are being analysed and show a cumulative heat loss west and north of Cove Fort exceeding 100 MW, approximately twice that of the Roosevelt Hot Springs producing system. Promising geophysical and geological structures will be profiled for magmatic source input using new passive ^{3}He detectors developed at the University of Utah.

1. INTRODUCTION

Play Fairway Analysis (PFA) in the geothermal context combines regional geological/geophysical understanding with knowledge of prospect control elements (e.g., origin of heat, pathways to heat up and concentrate fluids) to produce an inventory of prospect leads (see Fraser, 2010, for an oil and gas analog). The potential for new discoveries should be increased dramatically in regions where active magmatism creating a large heat endowment occurs in conjunction with diverse structural trends some of which may be well oriented to create reservoir space. Thus we have been drawn to examine the active eastern Great Basin of western Utah. Here, active N-S striking extension with high-temperature, bimodal volcanism (Tingey et al., 1997; Bendersky et al., 2012) cross-cuts E-W trending plutonic belts of mid-Cenozoic age including including large transverse structures of this age or greater (Wannamaker et al., 2008) (Figure 1).

Our approach to reassessing geothermal resource potential in this region has been described in detail in Wannamaker et al. (2016). It emphasizes application of MT geophysics, seismic swarms, fluid and isotope geochemistry, structural geology, volcanic distributions, and globally-contexted geothermal system modeling to resolve heat source and permeability. It draws upon experience elsewhere in the extensional Great Basin and worldwide where producing geothermal systems are characterized by crustal-scale, low electrical resistivity roots resolved from MT surveying that connect to deep magmatic activity. Such systems lie also in favorably dilatent structural settings and appear to have isotopic compositions (He, O, C) indicative of deep high-T input. In this PFA project, we seek to identify areas in the eastern Great Basin containing systems with such characteristics as priority areas for followup.

2. BACKGROUND AND ASSUMPTIONS

In extensional (rift) systems, exhumation of the crust elevates the geotherm and creates fracture permeability (e.g., Henley and Ellis, 1983). Induced circulating fluids tend to be neutral pH and Cl bearing with modest salinity (1-2 wt %). A common model for geothermal systems here involves deep circulation of waters driven by topographic flow to depths potentially of 10 km near the brittle-ductile lithologic transition (Wisian and Blackwell, 2004). Other high temperature extensional systems clearly have magmatic affinities given nearby volcanism and other evidence such as He isotopes (e.g., Simmons et al., 2015).

GPS-based geodesy shows that present-day extension rates at the surface are ~4 mm/yr cumulative from the Wasatch Front to the Nevada border (Kreemer, 2012). Western Utah contains the most pronounced seismic tomography anomalies in its upper-most mantle of the entire U.S. apart possibly from the eastern Snake River Plain (Schmandt and Lin, 2014) signifying strong degrees of melting. A pronounced N-S trend of Quaternary basaltic and bimodal magmatism runs the length of the state of Utah, extending into the Grand Canyon of Arizona and to the Snake River Plain of Idaho (Nelson and Tingey, 1997) (Figure 1). The basaltic magmatism feeding into the crust is interpreted to be the hottest of the Great Basin (Bendersky et al., 2012). The thermal processes of extension under the eastern Great Basin are responsible for cumulative heat flow along the N-S strike of the state totalling approximately 5 GW above background stable interior (Edwards and Chapman, 2013).

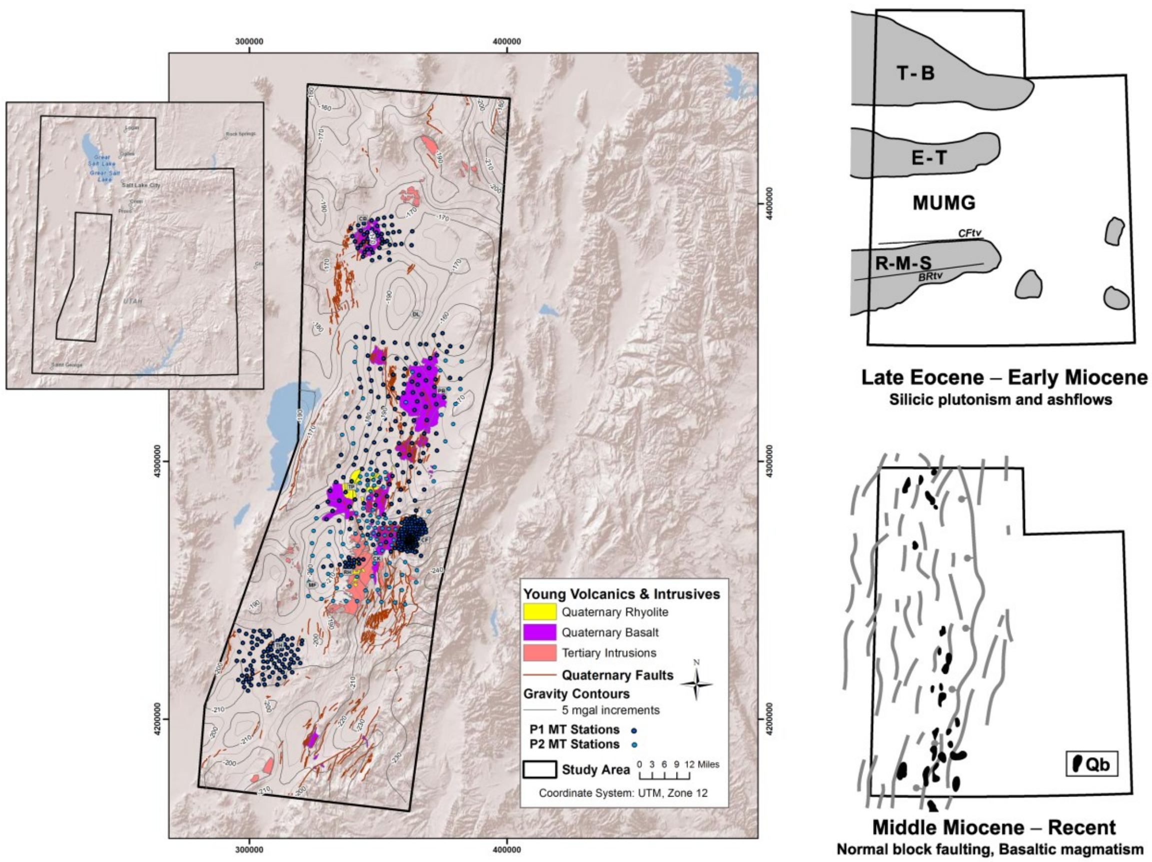


Figure 1: Left: DEM map of western Utah showing extension-dominated physiography. Black polygon represents play fairway of our project with 5 mgal gravity contours. Producing geothermal systems include Roosevelt Hot Springs (RHS), Cove Fort (CF) and Thermo (TH). Important Q volcanic extrusives are Crater Bench (CB), Pavant Butte (PB), Twin Peaks (TP) and Crater Knoll-Red Knoll (CK). Urban centers are Delta (DL) and Milford (MF). Phase I (P1) and Phase II (P2) MT stations coverage represented with dark and light blue dots respectively. Upper right: Middle Cenozoic tectonism in Utah is dominated by voluminous plutonism in E-W belts: Tuscarora-Bingham (T-B), Eureka-Tintic (E-T) and Reno-Pioche-Marysvale-San Juan (R-M-S) separated by mid-Utah magmatic gap (MUMG). Prominent structural lineaments along the R-M-S belt are the Cove Fort transverse zone (CFtv) and the Blue Ribbon transverse zone (BRtv). Lower right: Mid-Miocene to present Basin and Range extension overprints previous tectonic and plutonic episodes creating numerous intersecting trends and magmatic heat sources. Quaternary basalts (Qb) of abnormally high potential temperatures are erupted in a N-S trend the length of the state.

We are modernizing understanding of geothermal prospectivity of the eastern Great Basin by emphasizing a combination of magnetotellurics (MT), structural geology, and fluid chemistry integrated in a context of heat flow, seismicity and volcanology. High-temperature geothermal systems elsewhere in the Great Basin and other parts of the world show MT low-resistivity roots connecting to probable magmatic underplating and fluid release in the deep crust (Wannamaker et al., 2007, 2011; Siler et al., 2014; Bertrand et al. 2012, 2015) (Figure 2). Such roots represent large-scale permeability and potential heat upwelling. Thus we acquire and examine available MT data in the extensional eastern Great Basin in a fully 3D fashion for such roots as evidence toward the existence of previously blind geothermal systems. Dense arrays of modern seismic instrumentation are intended to confirm deep fluid upwellings by advanced detection of seismicity swarms in proximity to conductive MT structures.

The Great Basin studies above also showed that high-temperature systems lie in structural geological settings favorable for dilatency. The generally N-S striking rift faults are obvious on geological maps. However, our PFA area is noteworthy for the existence of fundamental E-W structural lineaments associated with emplacement of major belts of plutonic rocks in the middle Cenozoic prior to rifting (Neilson et al., 1986; Rowley et al., 1998a,b, 2001). Intersection of faults of diverse trends under a deformational regime is a prescription for dilatency and the creation of space and permeability for geothermal fluids (e.g. Faulds et al., 2013). The Dixie Valley and McGinness Hills systems also exhibited elevated ^{3}He content in sampled fluids confirming mantle magmatic geochemical contributions suggested by the MT resistivity structure. Thus the three methods of MT, structural geology, and fluid geochemistry will be combined with other techniques in our study to infer the likeliest zones of high-temperature upwelling into favorable structural situations.

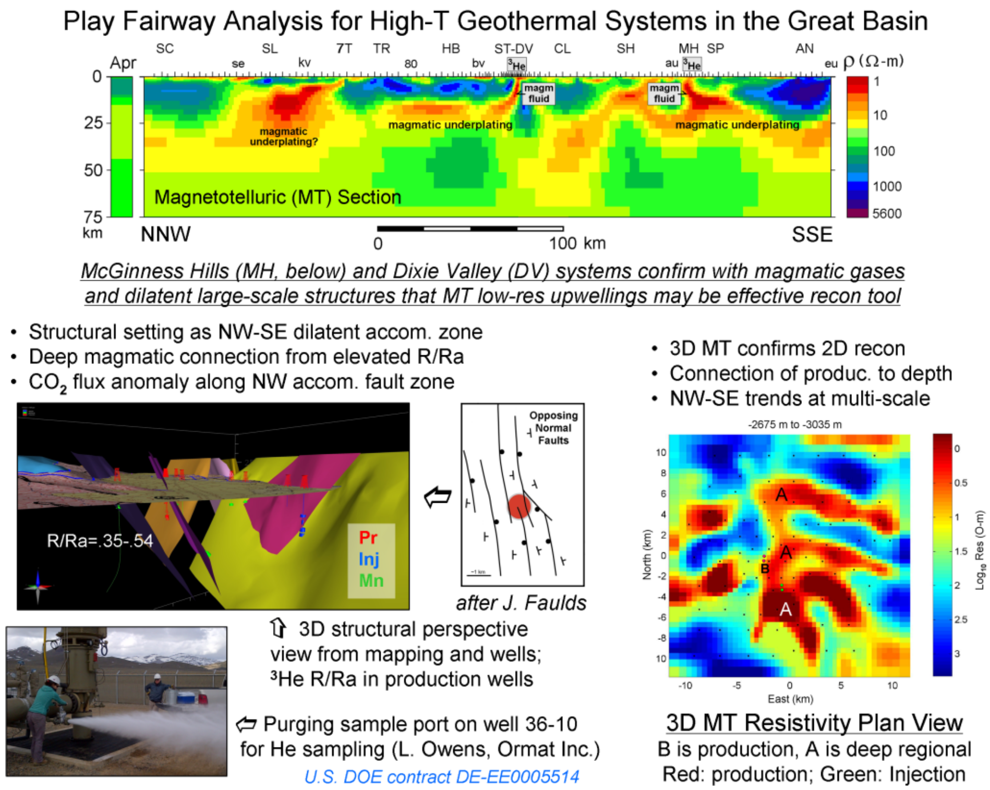


Figure 2: Illustration of integrative interpretation of the McGinness Hills NV moderate temperature geothermal system. Regional MT transect studies (top) uncovered several low-resistivity bodies in the deep crust ascribed to magmatic underplating and hydrothermal fluid release. Such systems in turn lie in 3D structural zones promoting dilatency. Sampled fluids show isotopic compositions confirming magmatic input. Study by Wannamaker et al. (2013b).

The relative abundance of data in our PFA area allows useful common risk segment (CRS) maps of heat source and permeability to be derived (Wannamaker et al., 2016). Ideally, risk distributions would be computed from a family of spatially continuous inputs represented in the depicted flow diagram. Most of the inputs at hand are sufficiently sampled to derive a probability function which, together with meta-rankings of inputs, provide quantitative CRS distributions.

3. WORKFLOW AND RESULTS

In Phase I, pertinent data to conduct PFA were assembled for the eastern Great Basin region (Wannamaker et al., 2016). These included: 1), a large number of MT site response functions; 2), earthquakes from the Utah Seismic Network for clustering analysis; 3), fault locations and orientations from the USGS and Utah Geological Survey (UGS) active fault databases and the literature; 4), major element and isotopic compositions of spring fluids from the USGS and UGS databases and published/unpublished literature; 5), heat flow from the SMU database greatly augmented by temperature gradient holes culled from industry records; and 6), volcanic distributions from the Utah Geological Survey database. Subsequently, data were processed using state-of-the-art modeling approaches to obtain modern 3D geophysical images, an updated active fault database, identification of critically stressed zones from potential fields and aerial photography, updated heat flow from numerous industry thermal gradient wells, a re-evaluation of chemical geothermometry, and conceptual models of geothermal resources in this region. From this analysis using kriged probabilities, common risk segment maps for heat, permeability and prospectivity in the eastern Great Basin were derived to define followup investigations aimed at determining drilling targets (Wannamaker et al., 2016). Areas of particular interest that emerged were the northern Cinder Knoll areas on the northeast flank of the Mineral Mountain, Twin Peaks rhyolitic volcanic center, and a northward extension of the Cove Fort field.

On this basis, the main workflow for Phase II is as follows. Just over 100 new MT soundings were acquired via contractor principally as fill-in around the Twin Peaks area and from northern Crater Knoll eastward to adjoin the Cove Fort system. We also extended coarse swath coverage southward past the Roosevelt Hot Springs system to near the south end of the Mineral Mountains. As concept test of fluid significance of deep MT structure, a detailed passive seismic array using three-component Nodal seismometers was deployed over the northern Cinder Knoll MT structure discovered in Phase I to search for accompanying seismic swarms. Gravity infill measurements were taken to help ensure hidden basement structures could be characterized. Extensive thermal gradient well data underwent quality control and were placed in a GIS framework for heat flow and thermal power analysis. Recently mapped siliceous sinter at Twin Peaks is undergoing age analysis and Google Earth high resolution DEM imagery is being compiled.

3.1 Magnetotelluric Resistivity Structure

The new MT data were integrated with existing soundings (Wannamaker et al., 2016) to undergo 3D inversion. The 3D resistivity images are produced using a recent edge finite element algorithm also developed under DOE/GTP support described in detail by Kordy et al (2016a,b). This algorithm simulates topography precisely using deformable hexahedral elements and uses the entire MT tensor set of 12 quantities (four complex impedance elements and two complex tipper elements) per frequency per site. Images are stabilized (regularized) by damping model slope in the three local x-y-z directions at a mesh cell. The solution of all system matrices is direct (non iterative), making use of the Intel MKL matrix packages PARDISO for the sparse finite element system and PLASMA for the full parameter step matrix. The latter matrix is formulated in data space for compactness.

The central portion of the finite element mesh appears in Figure 3. There are 294 stations over the study area and the period range used is 0.01 through 320 s. Cell widths among the sites typically are 600 m and the total finite element mesh is 214 (N) x 132 (E) x 46 (Z) cells with the upper 13 element layers devoted to the air. A narrow rim of finite elements around the mesh sides and bottom is kept fixed so the inversion domain is 212 x 130 x 31 = 854,360 parameters. Error floors were 5% of max{ $|Z_{ij}|$; $|Z_{xy}-Z_{yx}|/2$ } and 0.04 tipper for tipper. The starting model was 40 ohm-m and a final nRMS of 1.1 was achieved monotonically in 25 iterations. Run times were ~22 hours/iteration.

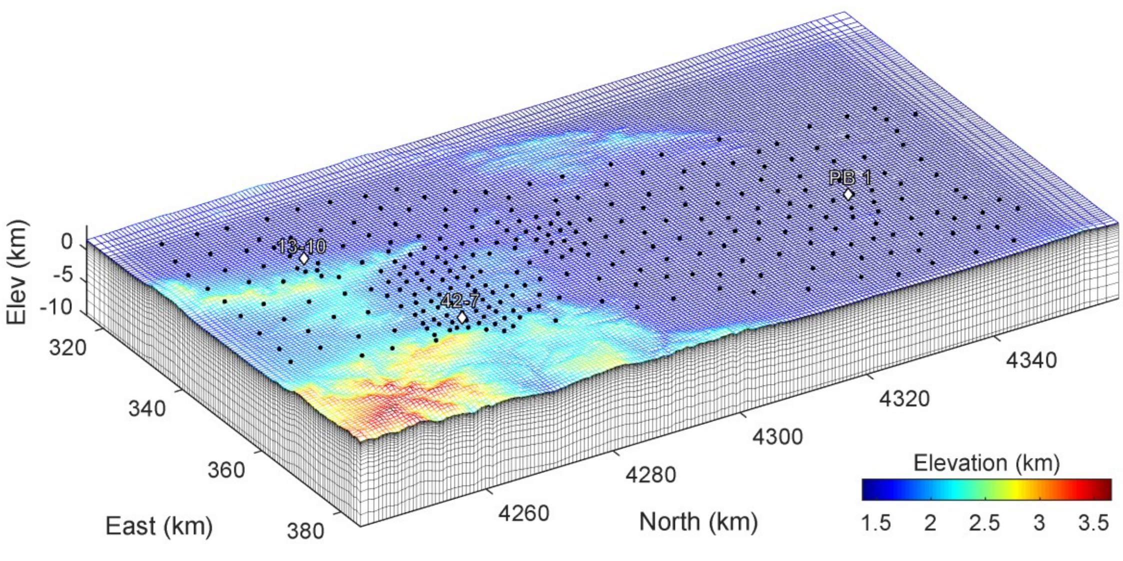


Figure 3: Central section of finite element model inversion mesh for the Sevier Desert MT data set. Topography is represented through gradual distortion of the hexahedral elements and color coded for elevation. Wells from Cove Fort (42-7) and Pavant Butte (PB-1) thermal areas noted.

Plan views at four depth levels appear in Figure 4 for a portion of the mesh focusing upon the transition from the southern Sevier Desert and onto the Pioche-Marysvale plutonic belt. This model volume was computed with a regularization (smoothing factor) more conservative (stronger versus depth) than that of Wannamaker et al. (2016). At the shallowest levels (2.5 and 5.7 km), the Crater Knoll (CK) anomaly is more focused in spatial extent compared to Wannamaker et al. (2016) and lies somewhat west of the earlier, coarser depiction. In this general area, the conductors reside in what should be predominantly mid-Tertiary granodioritic basement of the RMS belt. Deeper in the model (12 and 21 km) of Figure 4, the (northern) Cove Fort (NCF) and Crater Knoll conductors persist and align E-W with a possible additional conductor just west of the MT site coverage along the Cove Fort structural trend (Rowley et al., 1998a,b; Rowley and Dixon, 2001; Wannamaker et al., 2016). Under a regime of E-W extension, these auxiliary structures may suffer dilatency and provide conduits for upward geothermal fluid flow. Only a rather subtle low-resistivity structure appears in the model in the 2.5 km depth slice near the Roosevelt Hot Springs system (Allis et al., 2015), and specifically underlies the Quaternary Bailey Ridge (BR) rhyolite dome and flow (Figure 4). However, sampling here is coarse and further data collection is needed to clarify possible sources to the Roosevelt system as reflected in electrical resistivity structure.

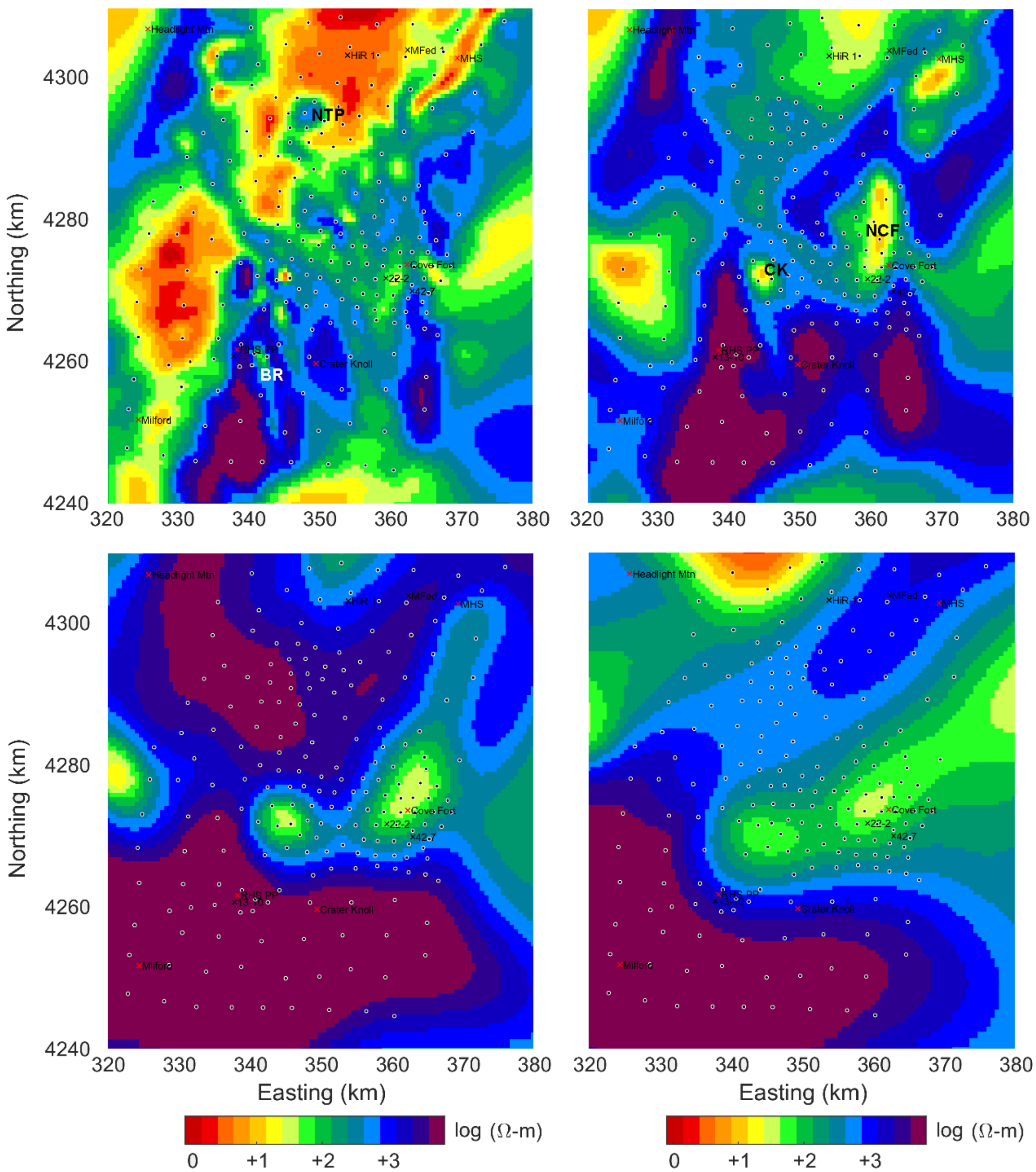


Figure 4: Plan views at four depths of preliminary MT resistivity inversion. Wells from Roosevelt Hot Springs (13-10), Cove Fort (42-7) and Pavant Butte (PB-1) thermal areas noted. Structural features discussed in text include northern Twin Peaks (NTP), Bailey Ridge (BR), Crater Knoll MT anomaly (CK), and northern Cove Fort MT anomaly (NCF). A number of deep geothermal or oil wells (Allis et al., 2015b) are marked by X.

3.2 Seismic Swarm Analysis

Phase I efforts saw a redoing of earthquake clustering of earthquakes using the Utah Seismic Network catalog (Wannamaker et al., 2016). It was pointed out that swarm clusters and non-swarm clusters occur in the same areas. Unfortunately, the Utah Seismic Network lies mainly to the east and is sparse in the geothermal areas, so double-difference relocation showed little improvement. Despite these limitations, swarms are identified with the Cove Fort geothermal system, and with the newly found MT conductor named the Crater Knoll (CK) conductor, suggesting that seismic swarms may be fluid-related. Curiously, natural seismicity clustering behavior was not obvious over the Roosevelt Hot Springs producing area per se, but we hope to examine the possibility of much lower detection limits there in future surveying.

Under Phase II we emplaced an array of 45 Nodal three-component passive seismometers over the northern Crater Knoll conductor as imaged with the Phase I MT data (Wannamaker et al., 2016) (Figure 5). These recorded events for 30 days spanning the month of July, 2016. Analysis is still in progress but good horizontal locations for 16 events have been obtained through a frequency domain analysis in an energy passband of 1-20 Hz. We have not yet determined event depths. However, the correlation in horizontal location of the group of seismic events with the MT conductor is striking. In detail, the shallowest conductor lies toward the western subevents in the seismic group. The seismicity also hints at an E-W alignment. The 16 events occurred periodically throughout the time of the experiment. There were no swarms detected within the time frame of the Nodal experiment. If a swarm nature to at least some quakes is confirmed, it strengths the concept that both MT upwelling anomalies and seismic swarms in this extensional environment may be fluid related.

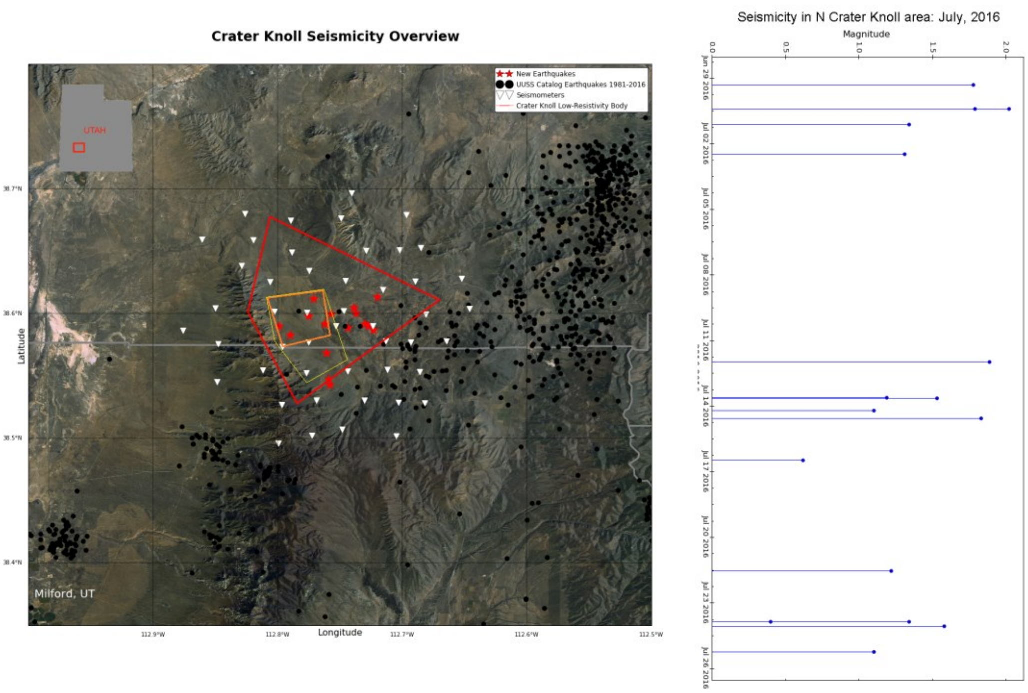


Figure 5: Left: Seismicity cluster resolved off the northeast flank of the Mineral Mountains approximately coincident with Crater Knoll MT low resistivity upwelling structure. Individual seismic events are red diamonds and Nodal site locations are white triangles. Domain of MT upwelling structure based on Phase I site distribution and inversion is bounded by red polygon while that based on finer Phase II site distribution and inversion is bounded by orange and yellow (deeper) quadrilaterals. Right: "Popsicle" diagram of the 16 earthquake events within the Nodal experiment area showing non-swarm behavior.

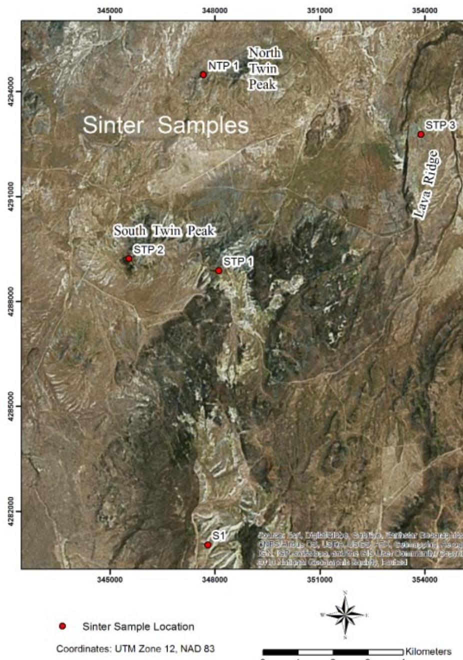
Plans are to apply advanced subspace detection, using the 16 events identified with the Nodal experiment as templates. Subsequently we will look for more events within the 30 day Nodal time frame, and then look for swarms over a longer time period using the regional catalog. We then will use relative relocation to focus event positions. Events will be separated into swarm and non swarm earthquakes and checked for diffusive movement that would be additional evidence of fluid involvement.

3.3 Structural Geology

As reported in Wannamaker et al. (2016), the northern Cinder Knoll and Cove Fort MT structures lie within the E-W oriented Cove Fort structural transverse zone. The Cinder Knoll sub-region is dominated by a NNW striking-NE dipping, Quaternary normal fault system with intersections, fault tips, and an accommodation zone bounding its southern extent. Google Earth imagery at 6 inch (15 cm) scale has recently become available for the entire state of Utah, and project Co-I Greg Nash has been named the EGI contact for these data. These fine-scale results will be highly valuable for remote structural assessment of geophysically promising areas.

Exposed siliceous sinter samples from the Twin Peaks area were submitted to the X-ray diffraction lab at EGI for analysis to yield relative age progressions. Results are compiled in Figure 6. The opal CT + low quartz from Twin Peaks is similar to that found in the 1,900 year old Opal Mound opal at Roosevelt. A study on sinters in New Zealand states that it took ~40k years for a complete transition to quartz (Lynne and Campbell, 2003). Potentially, all may be younger than Lake Bonneville (<~11 ka) although this warrants closer examination. Geomorphology indicates that some of the deposits formed along faults that appear to have developed after Lake Bonneville receded.

Going forward, new digital imagery will be analysed in an attempt to pinpoint active and potentially dilatant structures extending near-surface which could connect into deep fluids perhaps represented by the northern Crater Knoll MT and seismicity anomalies. A more precise establishment of fault ages associated with Twin Peaks sinter will be carried out.



XRD results on Twin Peaks area opal.

Sample #	Quartz	Opal-CT	Calcite	Hematite	Goethite
NTP 1	8	92			
STP 1	6	75		1	17
STP 2	78	14	8		
STP 3	3	97			
S1	8	92			

Figure 6: Left: Location map of siliceous sinter samples acquired in the Twin Peaks Quaternary rhyolite field. Right: Table of sinter phase state for Twin Peaks siliceous samples. Table entries represent percentage of each mineral a sample.

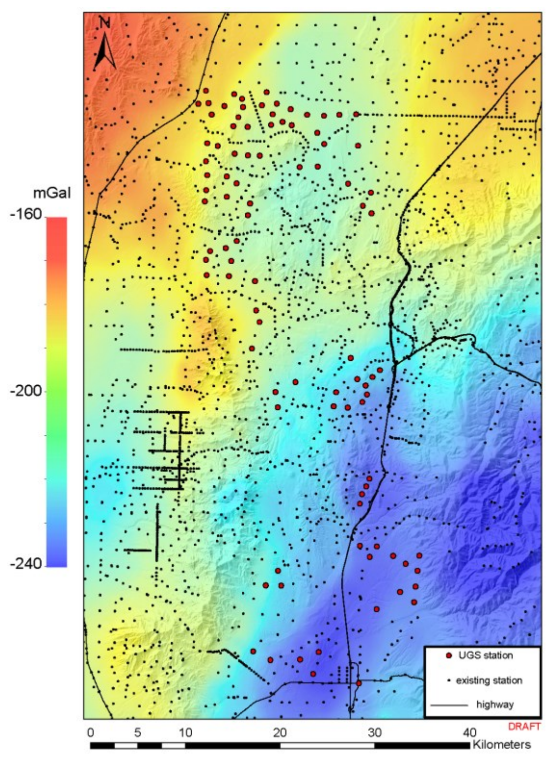


Figure 7: Gravity station coverage in PFA project area showing new sites (filled red circles) acquired by the UGS in Phase II of this PFA.

A total of 95 new gravity stations were established in this field area (Figure 7). Processing of gravity data for Cove Creek/Beaver Utah area is nearing completion. GPS data collected are high quality (vertical control is at 10 cm or better) and gravity station data have very low noise (errors at 1 microGal level). Terrain corrections for all stations are nearly complete which will give way to more confident Complete Bouguer Gravity Anomaly values. Additional gravity coverage and 2D gravity modeling will continue in 2017.

3.4 Thermal Gradient and Heat Flow Data

Analysis of ~170 thermal gradient measurements released from industry archives, including 8 wells between 500 and 2300 m depth, is described in detail by Allis et al. (2017, this conference). Contouring shows an area of ~500 km^2 having anomalously high temperatures (20-50 C) at 100 m depth extending north-northeast and northwest from the Cove Fort geothermal power plant (Figure 8a). Cumulative anomalous heat flux from this area exceeds 100 MW (Figure 8b), more than twice that of the Roosevelt Hot Springs system. Most of the anomalous area is underlain by fractured carbonates of high permeability. Because the highest recorded temperatures as measured in deeper wells are near the Cove Fort producing area, the carbonates are suggested to host a large outflow zone fed from an upflow zone, possibly near to the south or southeast of Sulphurdale. Curiously, deep oil wells within a 30 km radius of Cove Fort show rather low heat flow of ~60 mWm^{-2}, well under the Basin and Range average of 85 mWm^{-2}, suggesting possible regional hydrological disturbance (Allis et al., 2017, this conference). We plan further examination of pressure trends in the region, highlighting the differences between the local aquifer in the alluvium and volcanics near Cove Fort and the regional aquifer in the Paleozoic section. Distribution of high heat flow subregions in the study area will be compared to confluences of MT low-resistivity upwellings, structural dilatency and isotopic evidence of deep sources.

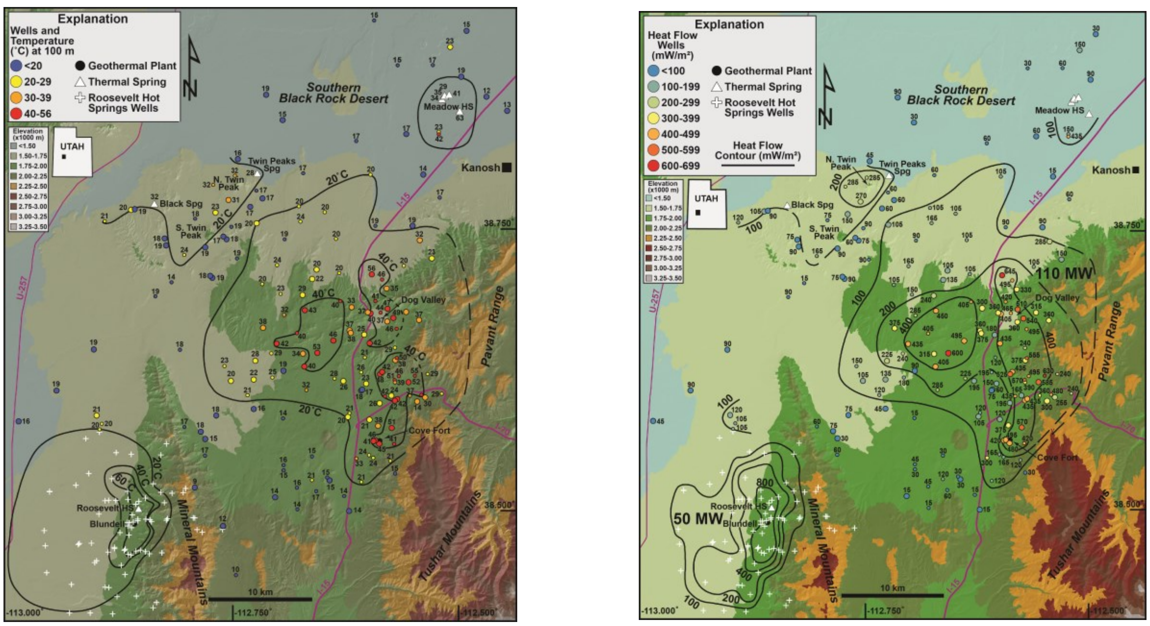


Figure 8: Left (a): Temperature at 100 m depth in the central portion of the PFA study area based on ~170 thermal gradient measurements from released industry sources (Allis et al., 2017, this conference). Right (b): Heat flow over same area.

3.5 Geochemistry and System Modeling

Geochemistry is the third initial leg of the platform from which the search for hidden geothermal systems proceeds, together with MT low resistivity and structural geology. As reviewerd by Wannamaker et al. (2016), geochemistry of produced fluids in western Utah systems show that the rock volumes through which these fluids move are much greater than those represented by the reservoir rocks themselves. Na/K geothermometry values suggest temperatures higher than those of produced fluids exist at some depth below the recognized systems. A heuristic composite model for geothermal systems in the eastern Great Basin involves deep circulation of meteoric waters subsequently modified by hot water-rock interaction (Simmons et al., 2015). Geological evidence suggests that the main deep lithology is made up of crystalline basement rocks (i.e., gneiss, granite). The precise source of aqueous Cl, SO_4, and HCO_3 are unclear, but the occurrence of young volcanic centers along with anomalous helium isotope ratios open the possibility that some portion comes from intruding magmas similar to geothermal fluids in volcanic regions. Presence of ^{3}He suggests that the regional Sevier thermal anomaly owes its origin to deep intrusion of magma(s). The large regional endowment of thermal energy associated with hot basement rocks suggests there is considerable potential for finding blind resources including those occurring in deep sedimentary aquifers and EGS reservoirs (Allis et al., 2015a,b).

Specific activity in geochemistry for Phase II of this PFA largely awaits further refinement of geophysical and structural models as described previously. In an attempt to identify localization of deep magmatic activity that could heat rocks for hidden geothermal systems, ^{3}He sampling will be carried out across promising MT and seismicity geophysical anomalies that appear to be intersected by young faulting. New sensor designs that do not require acquisition of fluids from either springs or wells will be deployed for this purpose early in 2017 across structures intersecting promising geophysical anomalies (Dame et al., 2015) (Figure 7). This is early research as we need to ascertain spatial scales and amplitudes of ^{3}He occurences relative to potential geothermal systems.

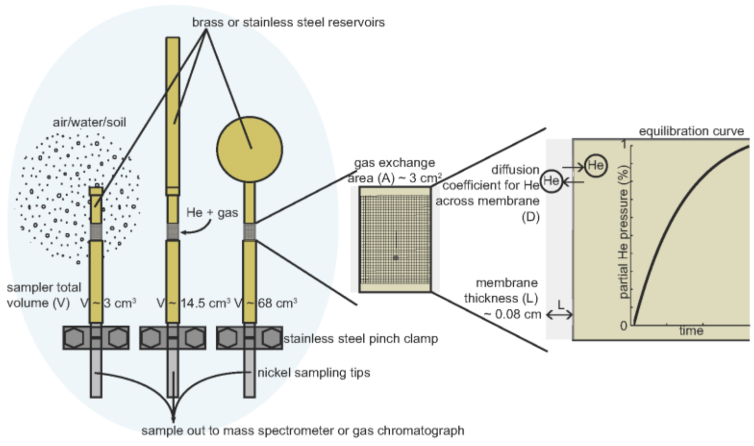


Figure 9: Sampler suite schematic for acquiring noble gas concentrations including ^{3}He from soils. Device is buried on the order of two feet and left for approximately one week to equilibrate. Figure from Dame et al. (2015).

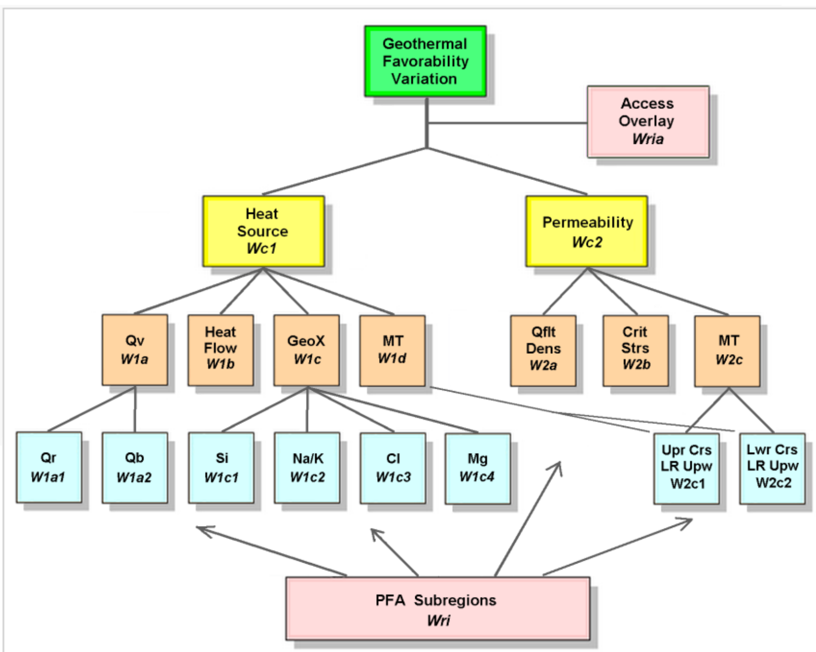


Figure 10: Idealized flow chart in a Multi-Criteria Decision Making (MCDM) framework illustrating factors or criteria considered for prioritizing subregions of the Eastern Great Basin PFA area (Wannamaker et al., 2016). If all criteria data were sufficient to be represented in a fully rasterized form, higher level criteria weights such as for heat or permeability result from multiply-sum operations on sub rows. Weights Wijk may be derived from e.g. analytic hierarchy processing (AHP) or directly user specified.

4. CONCLUSIONS AND PLANS

New efforts in the central-eastern Great Basin PFA have generally confirmed, but also modified, understanding of possible geothermal resource controls in this region. Use of upper-middle crustal MT resistivity, dilatent structural potential, and isotope geochemistry in our view remain pathfinder techniques for identifying blind and possibly high-temperature systems. Preliminary 3D MT inversion of the newly sampled site coverage confirms and narrows resistivity upwellings associated with Crater Knoll and Cove Fort prospect areas. Of these, Cove Fort remains the most pronounced extending well to the north of the producing area similar to the heat flow distribution. Preliminary results from a Nodal passive seismic array survey over the Crater Knoll area reveal a compact distribution of seismicity closely associated with the MT structure. Young siliceous sinter has been identified in the Twin Peaks area.

In Phase I of this PFA study, Wannamaker et al. (2016) derived common risk segment maps of geothermal indicators for use in estimating total resource prospectivity in a statistical fashion. This approach made use of probability kriging in the ArcGIS statistical toolbox in order to translate diverse data types into unity ranges of probability of an indicator exceeding a favorable threshold. We quantified prospective subareas through a probabilistic multi-criteria decision making (MCDM) approaches (Figure 9). We will pursue a similar MCDM approach that will be more focused in scale given the new data coverage being analyzed in Phase II. Additional data such as major element fluid chemistry and thermal gradient (heat flow) anomalies will be integrated more formally at this stage. We hope to replace the current PFA analysis goal of geothermal favorability variation with an analysis goal of that approaches probable drilling success.

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REFERENCES

Allis, R. G., M. Gwynn, C. Hardwick, S. Kirby, J. Moore, and D. Chapman, Re-evaluation of the pre-development thermal regime of Roosevelt Hot Springs geothermal system, Utah: Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, **204**, 12 pp., 2015a.

Allis, R. G., C. Hardwick, M. Gwynn, and S. Johnson, Pavant Butte geothermal prospect revisited: Geothermal Resources Council Transactions, **39**, 2015b.

Allis, R., M. Gwynn, C. Hardwick, S. Kirby, J. Moore, S. Simmons, and P. Wannamaker, Characteristics of the Cove Fort - Dog Valley - Twin Peaks Thermal Anomaly, Utah: Proc. 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, **212**, this conference, 2017.

Bendersky, C., T. Plank, D. W. Forsyth, E. H. Hauri, C-T. Lee, and D. Forsyth, Magmatism and lithospheric destruction along the Colorado Plateau margin: EOS, Transactions AGU, Fall Meeting, San Francisco, California, 2012.

Bertrand, E., T. Caldwell, G. Hill, E. Wallin, S. Bennie, N. Cozens, S. Onacha, G. Ryan, C. Walter, A. Zaino and P. Wameyo, Magnetotelluric imaging of upper-crustal convection plumes beneath the Taupo volcanic zone, New Zealand: Geophysical Research Letters, **39**, 6 pp., 2012.

Bertrand, E., T. Caldwell, S. Bannister, S. Soengkono, S. Bennie, G. Hill, and W. Heise, Using array MT data to image the crustal resistivity structure of the southeastern Taupo volcanic zone, New Zealand: Journal of Volcanology and Geothermal Research, **305**, 63-75, 2015.

Blackett, R. E., Review of selected geothermal areas in southwestern Utah: Geothermal Resources Council Transactions, **31**, 111-116, 2007.

Blackett, R. E., and S. I. Wakefield, Geothermal resources of Utah, a digital atlas of Utah's geothermal resources: Utah Geological Survey, **OFR-397**, CD-ROM, 2002.

Dame, B. E., D. K. Solomon, W. C. Evans, and S. E. Ingebritsen, Developing a new, passive diffusion sampler suite to detect helium anomalies associated with volcanic unrest: Bulletin of Volcanology, **77**, 17 pp, 2015.

Edwards, M. C.., and D. S. Chapman, A geothermal assessment of the Basin and Range province in western Utah: Report to Utah Geological Survey, UGS award 120000, 114 pp., 2013.

Faulds, J. E., N. H. Hinz, G. M. Dering, and D. L. Siler, The hybrid model – the most accommodating structural setting for geothermal power generation in the Great Basin, western USA: Geothermal Resources Council Transactions, **37**, 3-10, 2013.

Fraser, A. J., A regional overview of the exploration potential of the Middle East: a case study in the application of play fairway risk mapping techniques: in Vining, B. A., and S. C. Pickering, eds., Petroleum geology: from mature basins to new frontiers, Proc. 7th Petroleum Geology Conference, Geological Society of London, 791-800, 2010.

Henley, R. W., and A. J. Ellis, Geothermal systems ancient and modern: A geochemical review: Earth-Science Reviews, 19, 1-50, 1983.

Hintze, L. F, and B. Kowallis, Geologic History of Utah, Brigham Young University Press, 202 pp, 2009.

Kennedy, B. M., and van Soest, M. C., 2007, Flow of mantle fluids through the ductile lower crust: helium isotope trends: Science, **318**, p. 1433-1436.

King, D., and E. Metcalfe, Rift zones as a case for advancing geothermal occurrence models: Proc. 38th Workshop on Geothermal Reservoir Engineering, Stanford, CA, SGP-TR-198, 1578-1588, 2013.

Kordy, M. A., P. E. Wannamaker, V. Maris, E. Cherkaev, and G. J. Hill, 3-D magnetotelluric inversion using deformed hexahedral edge finite elements and direct solvers parallelized on SMP computers, Part I: forward problem and parameter jacobians: Geophysical Journal International, **204**, 74-93, 2016a.

Kordy, M. A., P. E. Wannamaker, V. Maris, E. Cherkaev, and G. J. Hill, 3-D magnetotelluric inversion using deformed hexahedral edge finite elements and direct solvers parallelized on SMP computers, Part II: direct data-space inverse solution: Geophysical Journal International, **204**, 94-110, 2016b.

Kreemer, C. W. C. Hammond, G. Blewitt, A. A. Holland and R. A. Bennett, A geodetic strain rate model for the Pacific-North American plate boundary, western United States: Nevada Bureau of Mines and Geology, Map 178, scale 1:1,500,000, 2012.

Lynne, B. Y., and K. A. Campbell, Diagenetic transformations (opal-A to quartz) of low- and mid-temperature microbial textures in siliceous hot-spring deposits, Taupo Volcanic Zone, New Zealand: Canadian Journal of Earth Sciences, 40, 1679-1696, 2003.

Nelson, S. T., and D. G. Tingey, Time-transgressive and extension-related basaltic volcanism in southwest Utah and vicinity: Geological Society of America Bulletin, **109**, 1249-1265, 1997.

Nielson, S. H. Evans and B. S. Sibbett, Magmatic, structural and hydrothermal evolution of the Mineral Mountains intrusive complex, Utah: Geological Society of America Bulletin, **97**, 765-777, 1986.

Rowley, P. D., Cenozoic transverse zones and igneous belts in the Great Basin, western United States: their tectonic and economic implications: in Faulds, J. E., and J. H. Sterart, eds., Accommodation zones and transfer zones: the regional segmentation of the Basin and Range province, Geological Society of America, Special Paper **323**, 195-228, 1998.

Rowley, P. D., C. G. Cunningham, T. A. Steven, H. H. Mehnert, and C. W. Naeser, Cenozoic Igneous and Tectonic Setting of the Marysvale Volcanic Field and Its Relation to Other Igneous Centers in Utah and Nevada: in, Friedman, J. D., and Huffman, A.C., Jr., ed., Laccolith Complexes of Southeastern Utah: Tectonic Control and Time of Emplacement -Workshop Proceedings: U.S. Geological Survey Bulletin **2158**, 167-201, 1998.

Rowley, P. D., and G. L. Dixon, The Cenozoic evolution of the Great Basin area, U.S.A. - new interpretations based on regional geologic modeling: in, The Geological Transition: Colorado Plateau to Basin and Range, Proc. J. Hoover Mackin Symposium, ed. by M. C. Erskine, J. E. Faulds, J. M. Bartley and P. Rowley, UGA/AAPG Guidebook **30/GB78**, Cedar City, Utah, September 20-23, 1-38, 2001.

Schmandt, B., and F.-C Lin, P and S wave tomography of the mantle beneath the United States: Geophysical Research Letters, **41**, 6342-6349, 2014.

Simmons, S., S. Kirby, J. Moore, P. Wannamaker, and R. Allis, Comparative analysis of fluid chemistry from Cove Fort, Roosevelt and Thermo: implications for geothermal resources and hydrothermal systems on the east edge of the Great Basin: Geothermal Resources Council Transactions, **39**, 2015.

Siler, D. L., B. M. Kennedy, P. E. Wannamaker, Regional lithospheric discontinuities as guides for geothermal exploration: Geothermal Resources Council Transactions, **38**, 39-47, 2014.

Wannamaker, P. E., W. M. Doerner, and D. P. Hasterok, Integrated dense array and transect MT surveying at Dixie Valley geothermal area, Nevada; structural controls, hydrothermal alteration and deep fluid sources, Proc. 32nd Workshop on Geothermal Reservoir Engineering, Stanford, CA, **SGP-TR-183**, 6 pp, 2007.

Wannamaker, P. E., D. P. Hasterok, J. M. Johnston, J. A. Stodt, D. B. Hall, T. L. Sodergren, L. Pellerin, V. Maris, W. M. Doerner, and M. J. Unsworth, Lithospheric dismemberment and magmatic processes of the Great Basin-Colorado Plateau transition, Utah, implied from magnetotellurics: Geochemistry, Geophysics, Geosystems, **9**, Q05019, doi:10.1029/ 2007GC001886, 36 pp, 2008.

Wannamaker, P. E., V. Maris, D. Hasterok, and W. Doerner, Crustal Scale Resistivity Structure, Magmatic-Hydrothermal Connections, and Thermal Regionalization of the Great Basin: Geothermal Resources Council Transactions, **35**, 1787-1790, 2011.

Wannamaker, P. E., V. Maris, J. Sainsbury, and J. Iovenitti, Intersecting fault trends and crustal-scale fluid pathways below the Dixie Valley geothermal area, Nevada, inferred from 3D magnetotelluric surveying, Proc. 38th Workshop on Geothermal Reservoir Engineering, Stanford, CA, **SGP-TR-198**, 9 pp, 2013a.

Wannamaker, P. E., J. Faulds and B. M. Kennedy, Integrating magnetotellurics, soil gas geochemistry and structural analysis to identify hidden, high enthalpy, extensional geothermal systems, Annual Report to the U.S. DOE/GTP, Contract DE-EE0005514, 13 pp., 2013b.

Wannamaker, P. E., V. Maris, and C. Hardwick, Basin and rift structure of the central Black Rock Desert, Utah, and initial thermal implications, from 3D magnetotellurics: Geothermal Resources Council Transactions, **37**, 41-44, 2013c.

Wannamaker P. E., K. L. Pankow, J. N. Moore, G. D. Nash, V. Maris, S. F. Simmons and C. L. Hardwick, Play Fairway Analysis for Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah: Proc. 41st Workshop Geothermal Reservoir Engineering, Stanford University, Stanford, CA, **209**, 17 pp., 2016.

Wisian, K. W., and D. D. Blackwell, Numerical modeling of Basin and Range geothermal systems: Geothermics, **33**, 713-741, 2004.