

THE GEOSCIENTIFIC UNDERSTANDING OF THE UTAH FORGE EGS SITE

Stuart F. Simmons^{1,2}, Stefan Kirby³, Rick Allis³, John Bartley⁴, John Miller⁵, Christian Hardwick³, Clay Jones¹, Phil Wannamaker¹, Rob Podgorney⁶, and Joseph Moore¹

¹EGI, University of Utah, 423 Wakara Way, suite 300, Salt Lake City, UT

²Department of Chemical Engineering, University of Utah, 50 S. Central Campus Dr., Salt Lake City, UT 84112

³Utah Geological Survey, 1594 W. North Temple St., Salt Lake City, UT 84114

⁴Department of Geology & Geophysics, University of Utah, 115 South 1460 East, Salt Lake City, Utah 84112

⁵Consulting Geophysicist, Golden, CO 80401

⁶Idaho National Lab, Idaho Falls, Idaho

ssimmons@egi.utah.edu

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ABSTRACT

The current geoscientific understanding of the Utah FORGE site has been obtained from synthesis of numerous independent datasets, including new geological, geophysical, and geochemical surveys, plus drilling and logging of three new wells, the deepest being 58-32 which penetrates to 7536 ft (2248 m) depth.

The stratigraphy consists of two broad rock types, comprising basin fill sediments and crystalline basement rocks mostly made of Miocene granitoids. The contact between these rock types forms an inclined plane, which dips ~20° west and which likely represents a large-scale normal fault that has been rotated during extension. Anomalous heat flow comprises localized hydrothermal convection east of the Opal Mound fault and regional conduction (~70°C/km, well 58-32) west of the Opal Mound fault. The modern stress regime is extensional, characterized by normal faulting and a maximum horizontal compressive stress oriented approximately N25°E.

Well 58-32 penetrated the basement at 3176 ft (968 m), which consists of granitic rock containing plagioclase, K-feldspar, and quartz. Between 1700 and 7536 ft (518-2248 m), the temperature profile increases linearly with a maximum bottom hole temperature of 197°C. The FMI log imaged ~2000 natural fractures, with predominant north-south, east-west, and northeast-southwest orientations that strongly resemble fracture patterns exposed in the Mineral Mountains.

Analysis of about 100 thermal gradient and deep exploration holes show how convective and conductive heat transfer are partitioned. Convective heat transfer is a small-scale feature restricted to Roosevelt Hot Springs, whereas conductive heat transfer is a large-scale feature that is regionally developed in the crystalline basement rocks in and around the EGS reservoir. The groundwater hydrology and chemistry reflect the thermal structure with hydrothermal upflow being confined to east of the Opal Mound fault. Where the rising hot water gets to shallow level, it forms a westward outflow zone that disperses down the hydraulic gradient through shallow alluvium.

1. INTRODUCTION

The Utah FORGE site is an underground test facility for advancing EGS technologies. It is located 350 km south of Salt Lake City and 16 km north northeast of Milford, Utah.

The site covers 5 km², and it is situated on a west sloping alluvial fan in north Milford valley, roughly halfway between the crest of the Mineral Mountains to the east and the Beaver River to the west. The EGS reservoir, which is to be developed, is entirely hosted by fractured Tertiary granitoid rocks that form the basement unit to the north Milford valley and that is also exposed throughout the core of the nearby Mineral Mountains.

The Utah FORGE site and nearby Roosevelt Hot Springs have been subject to a number of geoscientific investigations since the late 1970s, and a new phase of study commenced in 2015 as part of the process for site selection for the FORGE laboratory. In 2017, well 58-32 was drilled to 7536 ft depth to prove temperature and lithology, and to characterize fracture patterns and stress regime. In 2019, two additional shallow vertical wells were drilled close to 58-32 in order to deploy downhole seismometers for stimulation testing; 68-32 was drilled to 1000 ft depth and 78-32 was drilled to 3280 ft depth. The current state of knowledge is now underpinned by a wide range of geological, geophysical, and geochemical data derived from surface and well measurements (Moore et al., 2018; Allis and Moore, 2019).

2. GEOLOGIC SETTING

The Utah FORGE is part of a broad zone of elevated heat flow that lies inside the southeast margin of the Great Basin. The regional stratigraphy is made of folded and imbricated Paleozoic-Mesozoic strata that has been overprinted by widespread Basin and Range style extension and eruption of Tertiary-Recent mafic-felsic magmatic centers (e.g. Nielson et al., 1986; Coleman et al., 2001; Kirby, 2019). Near the Utah FORGE site, Paleozoic-Mesozoic strata are absent, and consequently the stratigraphy is divided into two broadly defined units, comprising crystalline plutonic rocks that form the basement and younger overlying bedded alluvium and volcanic deposits that fill the basin (Fig. 1). The processing of 3D seismic reflection highlights the westward dipping surface that separates these two units, which forms the basement contact (Fig. 2).

The basement rocks are made of granitoids, which were emplaced between 26 and 8 Ma (Aleinikoff et al., 1987; Coleman and Walker, 1992; Coleman et al., 2001). They represent products of magmatic processes, which most recently resulted in the eruption of young rhyolite centers (0.5-0.8 Ma) in the Mineral Mountains (Lipman et al., 1978). The granitoid plutons intruded tightly folded Precambrian gneiss (~1720 Ma), but only rafts of this older lithology are preserved, as seen in the western foothills of the Mineral Mountains and as intersected in wells 9-1, 52-21, and 14-2

(Glenn and Hulen, 1979; Glenn et al., 1980; Nielson et al., 1986).

The basin fill consists of a layered sequence of sedimentary and volcanic deposits (>3000 m), which range from Tertiary to Recent in age. The strata from youngest to oldest consist of calcareous lacustrine siltstones and sandstones, volcaniclastic sandstones and gravels, tuffaceous deposits, and localized flows of andesitic lavas. On the surface, the youngest deposits in the vicinity of well Acord 1 are composed of fine sediments and reworked alluvium that were deposited in Lake Bonneville, whose shoreline is marked by wave cut escarpments and westward extending point bars. To the east including the area surrounding the FORGE site, late Pleistocene alluvial fans are mainly composed of pea-sized gruss, and scattered fragments of obsidian, derived from the Mineral Mountains. Across the Opal Mound fault, around the area of Roosevelt Hot Springs, the alluvium deposits are older, more than 0.8 Ma, as constrained by dates on overlying flows of rhyolite (Lipman et al., 1978); the oldest alluvium likely dates back several million years, and it is restricted to a few isolated exposures (Kirby, 2019; Knudsen et al., 2019).

All of the faults in the vicinity of the Utah FORGE site are products of Basin and Range extension, mostly occurring in late Miocene time well after the main phase of plutonic intrusion (Coleman et al., 2001; Bartley, 2019). Four major faults and fault systems are known, based on field observations, seismic reflection, and correlation of drill logs (Kirby, 2019; Knudsen et al., 2019; Simmons et al., 2019).

The Opal Mound fault extends for ~5 km in a NNE direction, branching in the northernmost part, with an inferred steep eastward dip (e.g. Nielson et al., 1986). It marks the western boundary of the Roosevelt Hot Springs hydrothermal system and importantly forms a hydrological barrier to westward hydrothermal flow as revealed by pressure profiles from wells either side of the fault (Allis and Larsen, 2012; Allis et al., 2016). In the past, springs discharged from the southern and northern ends of the Opal Mound fault, but today surface activity is limited to steaming ground with acidic steam-heated water at its northern end. Approximately 1600-1900 years ago, the discharge of nearly neutral pH thermal water was localized around the south end of the fault, depositing a thick sheet of silica sinter that marks the Opal Mound (Lynne et al., 2005).

The Negro Mag fault is an east-west striking structure that extends several kilometers eastward from intersection with the Opal Mound fault. This relatively short fault can be traced on the surface over a distance of ~1 km where it offsets an old alluvial fan deposit, creating an east-west ridge in the middle of Negro Mag wash. Judging from the orientations of numerous east-west trending joints and fractures in the Mineral Mountains, the fault is probably vertical, with an offset of <10 m downward on the north side (Kirby, 2019; Knudsen et al., 2019).

The Mineral Mountains West fault system represents a corridor of north-south trending fault scarps that are mappable on fan deposits south of the FORGE site. The system is up to 3 km wide, and it runs for at least 40 km, west of and parallel to the range front along the southern part of the Mineral Mountains. Individual strands form scarps, generally having heights <5m that form coherent traces up to 3 km long.

The most significant fault in the vicinity of the FORGE site is marked by the contact between overlying basin fill and the underlying crystalline basement rock. It forms an inclined undulating ramp that dips 20-35° west and intersects the surface near the Opal Mound fault (Figs. 1 and 2). This structure and related subparallel structures in the basement are believed to have accommodated large-scale down-dip displacement of >10 km (Bartley, 2019). The evidence that supports such interpretation includes seismic reflection data, regional outcrop patterns, the uniform eastward dip of stratified rocks in the Mineral Mountains, the uniform westward dip of late Miocene dikes in the Mineral Mountains, paleomagnetic data, and cooling patterns interpreted from thermochronology (Smith and Bruhn, 1984; Nielson et al., 1986; Smith et al., 1989; Coleman and Walker, 1992, 1994; Coleman et al., 2001). Thin section of analysis of 58-32 and 78-32 drill cuttings shows clear evidence of intense shearing, brecciation, and cataclasis in the footwall directly beneath the basement contact (Jones et al., 2019). Most of the extension accommodated along this and related structures occurred during a short period of accelerated displacement in the late Miocene (10-8 Ma), which resulted in uplift, exhumation, and tilting (Nielson et al., 1986; Coleman and Walker, 1994; Coleman et al., 2001). What is now a shallow dipping fault surface probably initiated as a moderate to steeply dipping plane (Wernicke and Axen, 1988; Buck, 1988; Coleman and Walker, 1994; Bartley, 2019). Once the surface and related subparallel structures acquired shallow dips, the propensity for new fault slips greatly diminished because of cohesion. Erosion derived sediments probably started covering this surface shortly after movement ceased.

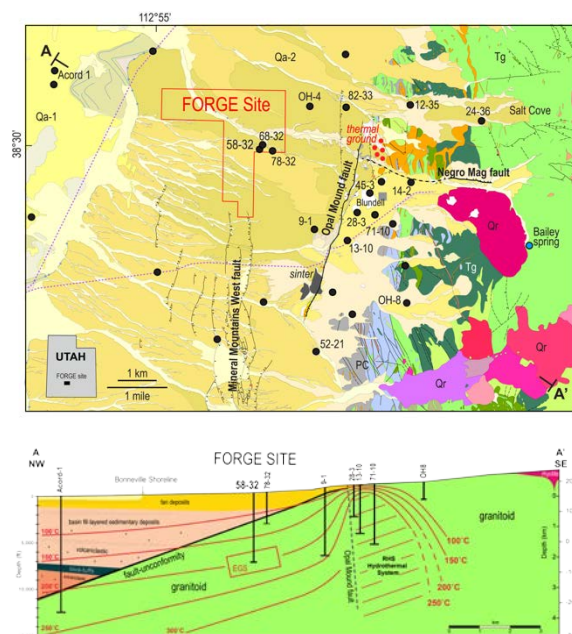


Figure 1. Geological map and cross section for the Utah FORGE site based on the integration of legacy reports, new field observations, seismic reflection profiles, temperature surveys and gravity data interpretation (Allis et al., 2019; Kirby, 2019; Knudsen et al., 2019; Simmons et al., 2019).

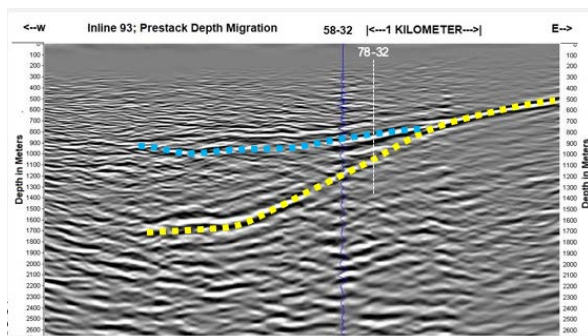


Figure 2. West-East seismic reflection profile through wells 58-32 and 78-32, showing the major reflectors that represent the west-dipping contact with the basement granitoid (yellow dashed line) and the subhorizontal bedding in the basin fill alluvium.

The crystalline plutonic rocks that are exposed in the Mineral Mountains are directly analogous to the rocks penetrated by well 58-32, and they were used to validate fracture characteristics in the proposed EGS reservoir (Bartley, 2019). Fracture lengths range from 20 to 200 m, and fracture spacings range from 5-15 m. Fracture azimuths range widely, with about half the population being randomly oriented. The remaining fracture azimuths fall into two predominant populations of 90 to 120° and 0 to 30°. The E-W trending population dips steeply to the north, whereas the NNE-SSW population dips steeply and gently west to form a conjugate set. The fracture patterns, combined with the independent evidence of eastward tilting, strongly suggests that the low-angle normal faults are high-angle normal faults, which after displacement were tilted to low angle subhorizontal dips.

3. 58-32 TEST WELL

Well 58-32 was drilled vertically to 7536 ft (2298 m) depth, penetrating layered alluvium deposits down to 3176 ft (968 m), where it crossed the contact with underlying crystalline basement rocks, which make up the rest of the stratigraphy to the bottom of the hole. Drill cuttings were collected every 10 ft and samples of core were collected from two intervals at 6800-6810.25 ft (2073-2076 m) and 7440-7452.15 ft (2268-2272 m). The FMI log provides a continuous image of sedimentary and igneous rock textures.

The upper interval of layered alluvium (0-3176 ft; 0-968 m) consists of poorly sorted and poorly lithified sands and gravels made of quartz and feldspar eroded from the plutonic rocks exposed in the Mineral Mountains. The upper two-thirds probably resembles sediments exposed on the surface making up fan deposits. The lower interval (3176-7536 ft; 968-2298 m) consists of plutonic igneous rocks, very similar to those exposed in the Mineral Mountains. Based on thin section and X-ray diffraction analyses of cuttings and cores, plagioclase, K-feldspar, and quartz are the dominant minerals, with minor amounts of biotite, hornblende, clinopyroxene, apatite, titanite, zircon, and magnetite-illmenite. Clay minerals generally constitute <5% of the rock, and these mainly consist of illite and chlorite. Other secondary minerals include carbonate and anhydrite, and fractures in the cored intervals are locally lined with chlorite or epidote.

A wireline temperature survey was run 37 days after the completion of all well testing. The maximum temperature of 197°C was measured at the bottom of the hole, and the linear

profile (below 1700 ft, 518 m depth) indicates a conductive gradient of 73°C/km.

Approximately 2000 natural fractures were identified in the FMI image log. The fracture spacing (<1 to 20 per 10 ft interval) and orientation range widely, but there is a predominance of north-south, east-west, and northeast-southwest fracture orientations. The patterns strongly resemble the spacings and orientations of fractures in granitic rocks exposed in the Mineral Mountains, particularly those occurring east of Roosevelt Hot Springs. They are also different from the fractures and joint patterns occurring in young rhyolite flows, and this suggests that most of the fractures in granitic rocks formed before 0.5-0.8 Ma. For comparison, induced fractures produced during drilling show a narrow range of orientations, predominantly northeast-southwest with near vertical dips. This direction represents σ_{Hmax} and is consistent with the orientation of σ_{Hmax} determined from geological observations to the east. Well testing shows that the EGS reservoir has very low natural permeability (<30 microdarcies).

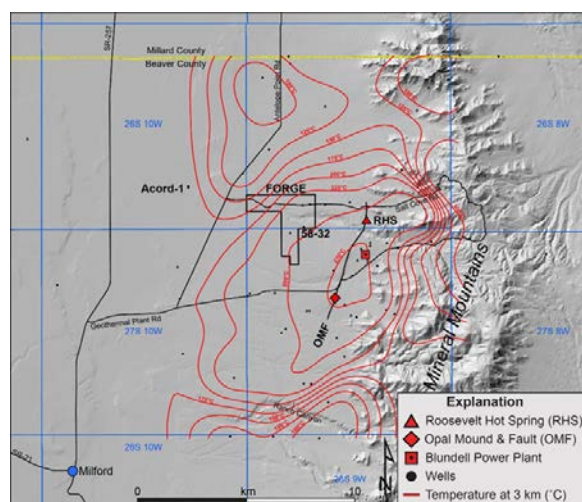
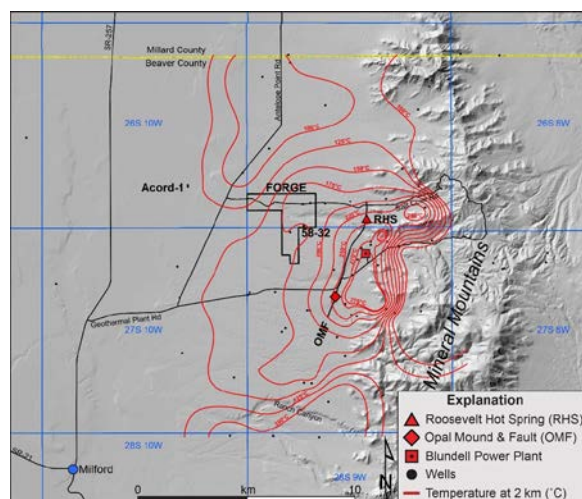


Figure 3. Isotherm maps at 2 and 3 km depth based on analysis of temperature gradients in wells (Allis et al., 2019). The area at a temperature of more than 200°C in these maps increases from about 25 km² at 2 km depth to 70 km² at 3 km depth.

4. REGIONAL THERMAL STRUCTURE

Analysis of about 100 thermal gradient and deep exploration holes, combined with thermal conductivity measurements, provides the basis for calculating regional heat flow and defining the thermal structure within and surrounding the EGS reservoir (Allis et al., 2015, 2019). These results show the partitioning of convective and conductive heat transfer, which are the products of regionally anomalous heat flow (Fig. 3).

Convective heat transfer is a small-scale feature restricted to hydrothermal upflow east of the Opal Mound fault, which forms Roosevelt Hot Springs and the geothermal reservoir supplying the Blundell power plant. Close to the surface, hot water from Roosevelt Hot Springs leaks out around the tips of the Opal Mound fault through shallow aquifers to form an outflow structure that follows the downward sloping hydraulic gradient into the valley. Conductive heat transfer by contrast is a large-scale feature that is regionally developed in the crystalline basement rocks, and this controls the temperature gradient in and around the EGS reservoir. The overall heat flow is ~50 MWth, and the thermal anomaly covers a large area of ~100 km² (Allis et al., 2019).

5. GROUNDWATER HYDROLOGY

The shallow unconsolidated basin fill forms the primary aquifer, ranging in thickness from 100 to >500 feet. Two distinct pressure regimes exist separated by the north-northeast trending Opal Mound fault. Pre-production pressure profiles for deep geothermal wells are uniform indicating a hydrostatic pressure head that is 3 MPa higher than those measured in exploration/monitoring wells on the west side of the Opal Mound fault. The potentiometric surface slopes steeply to the west away from the Opal Mound fault from 5800 to 4900 feet in elevation over approximately 8 km. Beneath the FORGE deep drill site, the groundwater elevation is approximately 5100 feet and the depth to water is between 200 and 500 feet.

The compositions of the groundwaters vary systematically according to location and geologic setting (Fig. 4). The Mineral Mountains cold springs discharge fresh groundwaters representative of modern meteoric waters. Roosevelt Hot Springs consist of boiled neutral pH chloride waters that formed from deep circulation of paleo-meteoric water followed by high temperature water-rock interaction with fractured granitoid, and then boiling before dispersing laterally near the surface through shallow aquifers (Simmons et al., 2018). Beneath the vicinity of the Utah FORGE site, warm neutral pH chloride groundwaters represent the dispersion and northwesterly outflow from Roosevelt Hot Springs. In the North Milford valley, groundwaters reflect distal outflow from Roosevelt Hot Springs that have been modified by varying amounts of dilution and mineral dissolution that have elevated aqueous concentrations of bicarbonate.

6. SUMMARY

A large multidisciplinary geoscientific dataset has been acquired at the Utah FORGE site, including the drilling, logging, and testing of a deep vertical test well to 7536 ft (2298 m) depth, plus drilling and stratigraphic logging of two shallower vertical holes used for seismic monitoring. The proposed reservoir occurs between 2 and 3 km (6560 and 9840 ft), and it is composed of hot (175-225 °C) granitic rock that is laterally extensive (~100 km³). The reservoir rocks are

also fractured, but they lack connectivity to support natural flow of water. The geological record indicates that the Utah FORGE site is located in a part of the Basin and Range that is tectonically quiet, consistent with long term monitoring of seismic activity (e.g., Pankow et al. 2019).

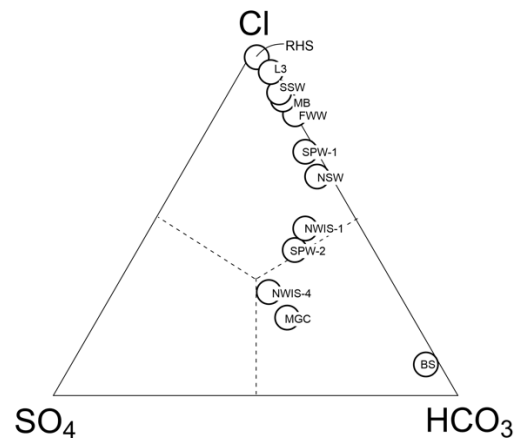
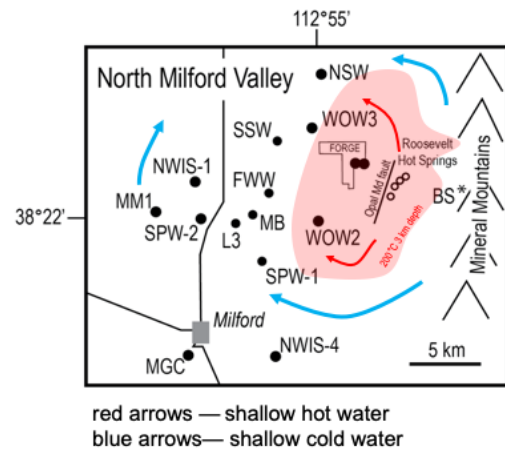


Figure 4. Map of the geohydrology in the north Milford valley, showing shallow wells and groundwater flow paths. Triangular plot showing the variation in groundwater compositions in the vicinity of the Utah FORGE site.

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REFERENCES

- Allis R. G. and Larsen, G.: Roosevelt Hot Springs Geothermal field, Utah – reservoir response after more than 25 years of power production. *Proceedings. 37th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA. (2012).
- Allis, R. G. and Moore, J.N.: Geothermal Characteristics of the Roosevelt Hot Springs System and Adjacent FORGE EGS Site, Milford, Utah. Miscellaneous Publication 169-C Utah Geological Survey. (2019).

- Allis, R.G., Gwynn, M., Hardwick, C., Kirby, S., Moore, J., and Chapman, D.: Re-evaluation of the pre-development thermal regime of Roosevelt Hot Springs geothermal system, Utah. *Proceedings, 40th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA. (2015).
- Allis, R.G., Moore, J.N., Davatzes, N., Gwynn, M., Hardwick, C., Kirby, S., Pankow, K., Potter, S., and Simmons, S.F.: EGS Concept Testing and Development at the Milford, Utah FORGE Site. *Proceedings, 41st Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA. (2016).
- Allis, R.G., Gwynn, M., Hardwick, C., Hurlbut, W., Kirby, S., and Moore, J.: Thermal characteristics of the Roosevelt Hot Springs system, with focus on the FORGE EGS site, Milford, Utah. *Utah Geological Survey Miscellaneous Publication*, 169-D. (2019).
- Alienikoff, J.N., Nielson, D.L., Hedge, C.E., and Evans, S.H.: Geochronology of Precambrian and Tertiary rocks in the Mineral Mountains, south-central Utah. *US Geological Survey Bulletin*, 1622, 1-12. (1987).
- Bartley, J.M.: Joint patterns in the Mineral Mountains intrusive complex and their roles in subsequent deformation and magmatism. *Utah Geological Survey Miscellaneous Publication* 169-C, (2019).
- Buck, W.R.: Flexural rotation of normal faults. *Tectonics*, 7, 959-973. (1989).
- Coleman, D.S., and Walker, J.D.: Evidence for the generation of juvenile granitic crust during continental extension, Mineral Mountains batholith, Utah. *Journal of Geophysical Research*, 97, 11011-11024. (1992).
- Coleman, D.S., and Walker, J.D.: Modes of tilting during extensional core complex development. *Science*, 26, 215-218. (1994).
- Coleman, D.S., Walker, J.D., Bartley, J. M., and Hodges, K.V.: Thermochronologic evidence of footwall deformation during extensional core complex development, Mineral Mountains, Utah. *The Geologic Transition, High Plateaus to Great Basin-A symposium and field guide, AAPG Pacific Section Guidebook*, 78, 155-168. (2001).
- Glenn, W.E., and Hulen, J. B.: Interpretation of well log data from four drill holes at Roosevelt Hot Springs KGRA. DOE Earth Science Laboratory Report, University of Utah, pp. 74. (1979).
- Glenn, W.E., Hulen, J. B., and Nielson, D.L.: A comprehensive study of LASL well C/T-2 Roosevelt Hot Springs KGRA, Utah, and applications to geothermal well logging. Los Alamos Scientific Laboratory Report, LA-8686-MS, pp 175. (1980).
- Jones, C.G., Moore, J.N., and Simmons, S.: Petrography of the Utah FORGE site and environs, Beaver County, Utah, in Allis, R., and Moore, J.N., editors, Geothermal characteristics of the Roosevelt Hot Springs system and adjacent FORGE EGS site, Milford, Utah. *Utah Geological Survey Miscellaneous Publication* 169-K. (2019)
- Kirby, S.M.: Revised mapping of bedrock geology adjoining the Utah FORGE site. *Utah Geological Survey Miscellaneous Publication*, 169-A. (2019).
- Knudsen, T., Kleber, E., Hiscock, A., and Kirby, S.: Quaternary geology of the Utah FORGE site and vicinity, Millard and Beaver Counties, Utah. *Utah Geological Survey Miscellaneous Publication*, 169-B. (2019).
- Lipman, P.W., Rowley, P.D., Mehnert, H.H., Evans, S.H., Jr., Nash, W.P., and Brown, F.H.: Pleistocene Rhyolite of the Mineral Mountains, Utah: Geothermal and Archeological Significance. *US Geological Survey Journal of Research*, 6, 133-147. (1978).
- Lynne, B.Y., Campbell, K.A., Moore, J.N., and Browne, P.R.L.: Diagenesis of 1900 year-old siliceous sinter (opal-A to quartz) at Opal Mound, Roosevelt Hot Springs, Utah. *Sedimentary Geology*, 179, 249-278. (2005).
- Moore, J.N., McLennan, J., Allis, R., Pankow, K., Simmons, S.F., Podgorney, R., Wannamaker, P. E., and Rickard, W., The Utah Frontier Observatory for Geothermal Research (FORGE), the results of recent drilling and geoscientific surveys. *Proceedings Geothermal Resources Council*, 42. (2018).
- Nielson, D. L., Evans, S.H., and Sibbett, B.S.: Magmatic, structural, and hydrothermal evolution of the Mineral Mountains intrusive complex, Utah, *Geological Society of America Bulletin*, 97, 765-777. (1986).
- Pankow, K.L., Potter, S., Zhang, H., Trow, A.J. and Record, A.S.: Micro-seismic characterization of the Utah FORGE site. *Utah Geological Survey Miscellaneous Publication*, 169-G. (2019).
- Simmons, S.F., Kirby, S., Allis, R., Moore, J.N., and Fischer, T.: Update on the production chemistry of Roosevelt Hot Springs reservoir. *Proceedings 43rd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA. (2018).
- Simmons, S.F., Kirby, S., Bartley, J., Allis, R., Kleber, E., Knudsen, T., Miller, J., Hardwick, C., Rahilly, K., Fischer, T., Jones, C., and Moore, J.N.: Update on the geoscientific understanding of the Utah FORGE site. *Proceedings, 44th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA. (2019).
- Smith, R.B., and Bruhn, R. L.: Intraplate extensional tectonics of the eastern Basin-Range: Inferences of structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation. *Journal of Geophysical Research*, 89, B7, (1984). 5733-5762.
- Smith, R.B., Nagy, W.C., Julander, K.A., Viveiros, J.J., Barker, C.A., and Gants, D.G.: Geophysical and tectonic framework of the eastern Basin and Range-Colorado Plateau-Rocky Mountain transition. *Geological Society of America Memoir* 172 (1989). 205-233.
- Wernicke, B.P., and Axen, G.J.: On the role of isostasy in the evolution of normal fault systems. *Geology*, 16, 848-851. (1988)