Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Slim Hole Assessment and Geothermal Business Model

Dennis L. Nielson, Sabodh K. Garg and John Shervais

Geoscience, Technology & Engineering, Salt Lake City, Utah USA
Geologica, San Diego, California USA
Utah State University, Logan, Utah USA

dnielson@dosecc.com
sgarg@geologica.net
john.shervais@usu.edu

Keywords: Basaltic magmatism, sills, normal faults, hydrothermal breccias, clay alteration, gravity, learning curve, play fairway analysis, drilling costs, drilling risk, resource risk, conceptual models

ABSTRACT

Drilling costs and risk are major issues influencing the development of geothermal resources. While assessment of competing renewable energy sources (wind and solar) is relatively straight forward and inexpensive, the assessment of geothermal reservoirs (drilling and testing) is expensive and the results are not predictable. Geothermal has the advantage of base-load generation, but this does not command a premium in the market. We have advocated for some time that front-end costs and risk can be reduced through the use of slim hole drilling and testing. Slim hole testing involves a spectrum of options that can extend from measurement of temperatures and analysis of geologic conditions to full flow and injection testing. Although echoed by others, this approach has not been widely adapted. We describe the slim hole assessment of a hidden system at Mountain Home Air Force Base in Idaho, USA to illustrate an intermediate option between temperature gradient and full reservoir testing. Our analysis suggests that subsidies in the form of government or scientific investigations are necessary to mitigate front-end risk, particularly in exploration for buried systems.

1. INTRODUCTION

Subsurface risk is commonly cited as an impediment to geothermal energy development. This risk has two manifestations: resource risk or uncertainty concerning the size, quality and sustainability of a reservoir, and drilling risk or the successful completion of and fluid production from a well. There are a number of different approaches to managing subsurface risk, that range from the technical (slim hole drilling during high-risk phases) to government or scientifically sponsored exploration and drilling.

This paper will discuss business models that incorporate slim hole drilling as a means of reducing uncertainty associated with geothermal development (Nielson and Garg, 2016). Most of the discussion of slim hole drilling has focused on reducing the cost of drilling; however, a compelling benefit of slim hole drilling is overall risk reduction through subsurface data collection. As an example, the mining industry uses core drilling to collect high-quality samples that are subjected to laboratory analysis, in order to characterize the commodity that will be produced. Core samples are also used to construct three dimensional models of deposits, define metallurgical extraction modes, and understand the engineering requirements of mine development. Mineral prospects are delineated using slim hole drilling to support the engineering and financial decisions required to move forward with mine development. Data are collected that are analogous to reservoir engineering analysis of a geothermal system. Slim-hole coring has been applied to assessment of hydrothermal systems for some time (Olson and Demonaz, 1995; Garg and Combs, 1997, 2000; Garg *et al*., 1998). An exploration hole drilled using slim-hole coring costs 25% to 35% of the cost of a large-diameter well drilled to an equivalent depth. Therefore, an operator can drill three or four holes for the same cost as one production well, providing better spatial coverage of a reservoir.

Geothermal exploration often involves drilling production wells immediately following surface geophysics and temperature gradient drilling. In other words, very expensive wells are drilled when reservoir knowledge is low and the risk of economic viability is still high. One reason for this is the belief that large-diameter wells are required to collect reservoir engineering information. Another reason often heard is that the operator does not want to invest money in a slim hole that, if successful, will not contribute to production. A third reason is that this is the method that has been traditionally employed in geothermal development. A paradigm shift is needed to reduce the risk in the development of geothermal resources.

Competing renewable energy resources (wind, solar, hydropower) have assessment methodologies that are less expensive and lower risk than geothermal. In addition, wind and solar resources are ubiquitous; although of variable quality, in contrast to the localized occurrence of electrical-grade geothermal systems. Technology improvements have brought down the cost of solar and wind conversion equipment. Although their deliverability is much lower than a base-load geothermal system, the difference is made up by extensive arrays and natural gas backup.

Internationally, there are a number of different business models that strive to increase the viability of geothermal power generation. In a number of geothermal countries, the resource is government owned and national companies undertake the exploration and delineation drilling. Once the resource has been identified, private firms are brought in to build the power plants and deliver power to the grid.

2. GEOTHERMAL DEVELOPMENT RISK

The exploration and development of a natural resource is a speculative risk that a developer undertakes because it should offer a high rate of return on investment, and the developer has sufficient knowledge to address the risk by understanding a resource through acquisition and processing of data. However, the cost of electricity is generally regulated by markets and geothermal must be competitive with other means of electrical generation. For this reason, exploration activities are often supported by governments or international funding organizations to one degree or another until the risk has been reduced to an acceptable level for private investment (Barnett et al., 2003). Indeed, many of the geothermal systems in production today in the US involved exploration that was underwritten by the US Department of Energy's Industry Coupled Program. This initiative also provided data collection to improve interpretation and develop exploration strategies (Ward et al., 1981). Information is a key element in the development of a geothermal project (ESMAP, 2012). Front-end risk is mitigated through diversified project portfolios and incremental development of individual projects to address sustainability risks.

There are different types of risk in a geothermal project. Matek (2014) describes resource risk as the uncertainty concerning the size and quality of a geothermal reservoir. This risk remains high until a sufficient number of wells have been drilled into the reservoir. He also describes drilling risk since the cost of drilling is typically 35% to 40% of the total capital cost of the project. High upfront costs are associated with drilling and many projects require 10 years or more to realize revenue. The high risk at early stages of a project requires equity funding and financial returns of up to 40%. Matek also discusses sustainability risk that requires a monitoring program to assure that the resource will be sustainable for the 30 year life of the power plant.

Several exploration and development approaches discuss risk explicitly. ESMAP (2012) presents a comprehensive seven-step approach for the development of a geothermal resource of approximately 50 MWe (Table 1), and we will use this approach as a reference. This study addressed project risk at each phase of the development process from preliminary surveys to startup and commissioning, and the approximate cost of each phase. Projects start with a high risk that is lowered with an increase in knowledge through each stage of the development process (ESMAP, 2012; Figure 0.1). The ESMAP development scenario applies gradient and slim hole drilling in Task 2: Exploration, slim holes and full size wells in Task 3: Test Drilling, and production and reinjection wells in Task 5: Field Development. Deloitte (2008) considers a similar approach for a 50 MWe development with different terminology. Figure 1 compares these studies, and although the costs and risks have different values, the curves are similar. ESMAP has a reduction in project risk from about 93% to 50% in the Test Drilling phase. Whereas, Deloitte has a risk reduction from 80% to 20% in a similar phase. An interesting aspect of both of the curves is that the most dramatic risk reduction takes place in the initial test drilling phase before the largest expenditure of project costs. Clearly, the initial drilling into the reservoir has the largest influence on risk reduction.

Table 1 - Project development approach for a 50 Mwe geothermal resource after ESMAP (2012), Deloitte (2008) and Nielson and Garg (2016).

TASK	ESMAP	Deloitte	Nielson & Garg
1. Preliminary Survey	$ 2,000,000	$ 1,000,000	$ 2,000,000
2. Exploration	$ 3,000,000	$ 8,000,000	$ 3,000,000
3. Test Drilling	$ 18,000,000	$ 4,000,000	$ 23,200,000
4. Project Review & Planning	$ 7,000,000	$ 7,000,000	$ 7,000,000
5. Field Development	$ 70,000,000	$ 37,000,000	$ 61,750,000
6. Construction	$ 91,000,000	$ 91,000,000	$ 91,000,000
7. Startup & Commissioning	$ 5,000,000	$ 5,000,000	$ 5,000,000
	$ 196,000,000	$ 153,000,000	$ 192,950,000

With the systematic approaches of ESMAP and Deloitte, a developer buys down the risk at each stage. Although there are significant go/no-go decision points (Table 1, Task 4), a project could presumably be abandoned at any time in the process, either because the reservoir was inadequate or because efforts were shifted to a project of lower risk. We would maintain that the project costs up to the point of abandonment would still have value if the data collected is applied to the conceptual system model, and used to contrast productive versus non-productive projects.

An exploration approach that seeks to quantify risk is the Play Fairway analysis. This is a mature practice in the petroleum industry and has been recently evaluated for geothermal applications (Nielson et al., 2015; Shervais et al., 2015). The basis of the analysis is a risk matrix that assigns risk through confidence in the conceptual model of the resource (Nielson and Shervais, 2014) and the data that support the model. In our Play Fairway approach (Nielson et al., 2015), the critical components of a geothermal reservoir model are heat source, reservoir volume, recharge and seal. As an example, data that supports the presence of a heat source are heat flow, volcanic vents, ages of volcanic an intrusive rocks, and chemistry of igneous rocks.

Within a fairway, there may be several plays available that have high probabilities for success. In the terminology of ESMAP, our project has identified a fairway in the vicinity of Mountain Home Air Force Base (MHAFB); although the boundaries of the fairway have not been determined. In the context of ESMAP, this area is at the Task 3 level where some drilling has taken place,

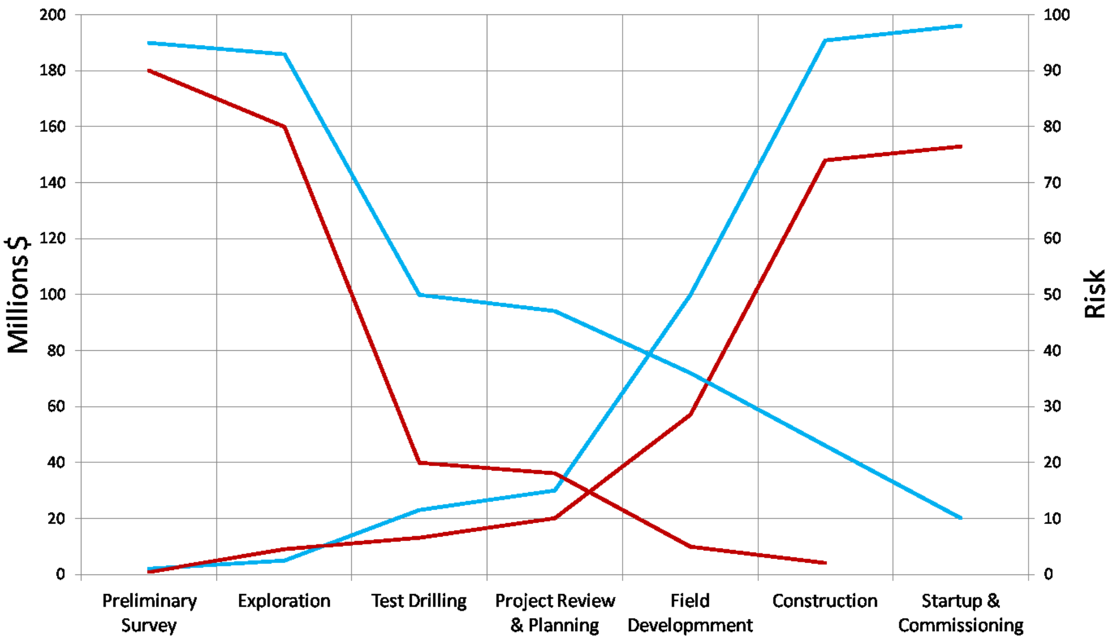

Figure 1 Risk versus investment for a typical 50 MWe geothermal development project. Blue curves are from ESMAP (2012) and red curves are from Deloitte (2008).

and a preliminary conceptual model has been formulated. The drilling has utilized slim holes and the funding has been provided by the US government and the International Continental Scientific Drilling Program (ICDP).

There is a great deal of discussion in the literature about success rates of production well drilling and its impact on the overall project success. The International Finance Corporation (IFC, 2013) studied the success of geothermal wells worldwide and points out that there is no consensus on what constitutes a successful well, but it defines a successful well as one that will produce a minimum of 3 MWe. IFC classifies the first five wells in a field as Exploration wells and finds that the first well drilled has a success rate of 50%, but overall, the success rate of the first 5 wells is 59%. The next stage is Development where the success rate is 74%. During the Operational stage, the success rate is 83%. Thus there is a strong learning curve effect where experience and reservoir knowledge contributes to risk reduction. Hance and Gawell (2005) also discuss the learning effects on drilling success rates and state that drilling success increases from 25% in the exploration phase to 60% in confirmation to 80% during development drilling. Sanyal and Morrow (2011) evaluated the Kammojang field in Indonesia, and documented a success rate of about 25% in the exploration phase and about 55% in the development phase, and 75% in the operational phase.

Thus, there is a learning curve that results in an increase in drilling success rate over time. This is ideally the case as long as geoscience and engineering data from individual wells are being correctly analyzed. There are notable exceptions to the learning curve; although, failures are not normally reported in the literature. The Baca project in New Mexico experienced a success rate of 45% for the initial 11 wells, followed by a success rate of only 15% for the subsequent 13 wells (Molloy, 1982). The principal reason given for this failure was the lack of a conceptual model that could reliably define drilling targets. A second issue that led to project failure was the large number of mechanical problems associated with drilling production wells.

Geothermal exploration is a knowledge-based enterprise. Characterization of wells as successful or not successful is not appropriate until development drilling. Each data component should reduce risk either by leading to a positive outcome or abandoning a project. So, it is equally important to abandon a project that will not be successful as it is to move ahead with one that will be financially viable.

3. DEVELOPMENT APPROACH

The preceding discussion shows that the greatest reduction in project risk is associated with test or delineation drilling accompanied by reservoir engineering testing (Task 3 of ESMAP). The most efficient way of accomplishing Task 3 is by undertaking a slim hole exploration program that has the following objectives.

- Measure the distribution of temperature and permeability.
- Identify system boundaries and their character.
- Identify upflow, outflow (plumes, temperature reversals) and recharge for planning production and injection well locations and design.
- Collect rock samples and measure physical properties, alteration and fluid inclusions
- Analyze data from down hole logs to help refine surface geophysics
- Collect fluid samples for chemical analysis
- Define controlling structures (faults)

Since both the ESMAP and Deloitte studies consider a 50 MWe project, Nielson and Garg (2016) presented a pro forma evaluation of a similar resource. They estimated that a 50 MWe prospect has a volume of about 32 km^3, and the surface area of a candidate field is about 16 km^2 with a reservoir located between 1000 and 3000 m depth. They also assumed a 2000 m drilling depth with costs of $1.2M (Delahunty et al., 2012). These slim hole costs are compared to $4.5M for drilling a 2000 m production well (Mansure and Blankenship, 2011; Silverman et al., 2014). Reservoir testing costs are estimated to be about $250K per well, and it was assumed that each production well could produce 5 MWe.

We propose a slim hole characterization program with a spacing of one hole per square kilometer. For our hypothetical 50 MWe reservoir, 16 slim holes will be drilled for an estimated $19.2M plus $4M for well testing. However, through the knowledge gained on the slim hole program, we are proposing that 1) this reservoir can be accurately compared to other exploration areas in the portfolio, and 2) the success rate for production well drilling is ~80% or equivalent to that achieved in the operational stage (IFC, 2013; Hance and Gawell, 2005; Sanyal and Morrow, 2011). Therefore, 13 wells would be required to yield the 10 successful production wells necessary to satisfy our 50 MWe objective. The production wells would cost $58.5M plus an additional $3.25M for testing for a total cost of $61.75M.

Table 1 compares these project costs with the median costs presented in ESMAP, and we can see that they are essentially the same. If the $23.2M we allocated for the slim hole program was used to drill and test production-size wells, a developer could only drill about five wells. Clearly 16 slim holes to characterize a 32 km^3 volume will produce a better result than five holes.

There is always the risk of failure of a well because of mechanical issues. Slim holes can provide information for the construction of production wells and can improve purchasing efficiency.

We also advocate the completion of slim holes either for long-term monitoring or even as injection wells (Nielson et al., 2001). Field-wide monitoring is an important process to mitigate sustainability risks. Initial well testing can only approximate the response of a reservoir under long-term production conditions. The broad spatial coverage of slim holes will provide a comprehensive array for monitoring response of the reservoir to production and injection.

In a Play Fairway approach, exploration is guided by specific geophysical anomalies or high-confidence areas defined by Common Risk Segment maps. The method is most useful in outlining prospects for buried geothermal systems, those without surface manifestations. In our Snake River Plain project, one of the most significant issues is the presence of high-level cold water aquifers that mask the presence of higher temperature fluids (Nielson et al. 2012). In this environment, slim hole drilling makes business sense for comparing individual prospects.

Slim hole drilling should have a data collection strategy that focuses on critical aspects of the reservoir model. It is important that the testing and data collection strategy be defined prior to drilling since it is necessary to budget for these activities as well as to have appropriate equipment on site.

4. MOUNTAIN HOME GEOTHERMAL SYSTEM

The geothermal system at the MHAFB (Figure 2) represents a blind high-temperature geothermal system that is not associated with any mapped faults or surface geothermal manifestations. Initial investigations of the resource were prompted by elevated geothermal gradient estimates (65ºC/km) determined from a wildcat oil well (Bostic 1A, 2949 m) drilled in 1973 at a location 20 km southeast of the town of Mountain Home (Figure 2). A 1342 m exploratory slim hole (MH-1) was drilled in 1986 (Lewis and Stone, 1988) as part of an effort to assess resources at MHAFB. A temperature of 93ºC logged at a depth of 1207 m, and a thermal gradient of 69ºC/km suggested that temperatures at depths of 1500–1800 m are high enough to support binary cycle power generation.

MH-2 was cored to a depth of 1821 m 4.7 km away from MH-1 (Delahunty et al., 2012; Nielson et al., 2012) as part of the Hotspot Scientific Drilling Program. The hole was drilled through basalt flows to a depth of 200 m where it encountered lacustrine sediments that were present to a depth of 740 m. The top of the sediments were 76 m deeper than the equivalent horizon encountered in MH-1. The bottom of these sediments showed indications of hydrothermal alteration that led us to postulate that relatively impermeable lake beds form the caprock for the hydrothermal system (Nielson et al., 2015). Below the lake section, MH-2 encountered sediments, basaltic flows and hyaloclastites before it intersected hydrothermal fluids at a depth of 1745 m. The fluids were contained by a fault zone, and core shows the presence of hydrothermal brecciation with associated calcite and minor amounts of quartz, pyrite and chalcopyrite (Nielson et al., 2012; Nielson and Shervais, 2014). More detailed analysis of fluid inclusions (Atkinson, 2015) demonstrated past boiling conditions with maximum temperatures of 340ºC.

The sequence of low-permeability lake sediments that overlie the geothermal system at Mountain Home likely helped to maintain the resource by insulating the reservoir, preventing upward migration of the thermal fluids, and inhibiting mixing with cold meteoric water that could degrade the resource (Shervais et al., 2016).

Kessler et al. (2017) conducted a comprehensive structural analysis of the lower part of MH-2 that included the fault zone that hosts the hydrothermal fluids. They concluded that the zone hosting the hydrothermal fluid has normal offset, a strike of 300º and a dip of approximately 80º to the NE (Nielson et al., 2018). Walker and Wheeler (2016) have studied clay mineralogy in MH-2 below the lake beds. Smectite is pervasive in the core indicating hydrothermal alteration; however, in a zone from 1708 to 1793 m, corrensite is present consistent with prograde alteration. However, smectite again is the dominant clay mineral from 1793 m to TD. The significance of the return to smectite below 1793 m is that the borehole penetrated a cooler regime that we interpret as the footwall of the fault zone that controls hydrothermal fluid flow. From the structural and alteration evidence, we postulate that the geothermal system is hosted by a graben structure and MH-2 intersected a bounding fault of that structure and then continued into a lower thermal regime to the southwest.

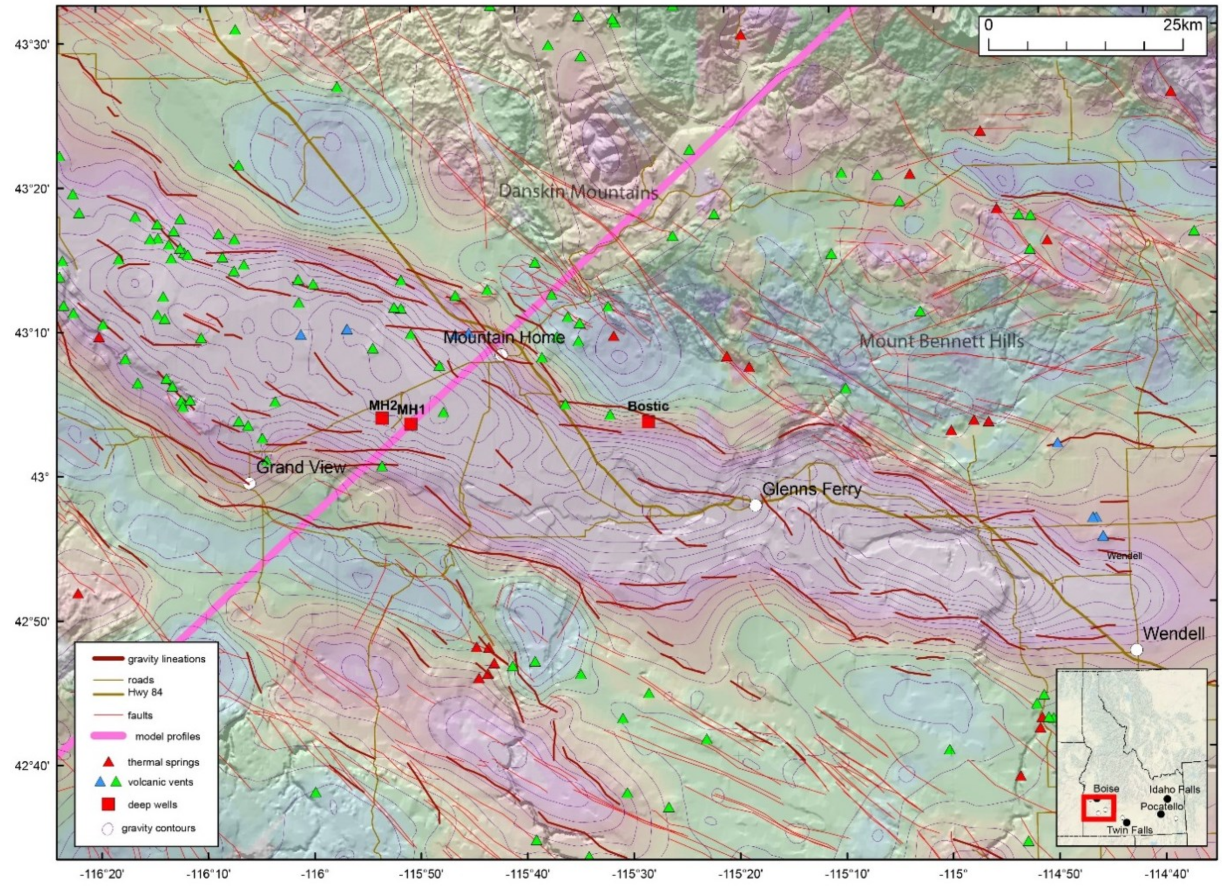

Figure 2. Colored residual isostatic gravity and shaded topographic relief map of the western SRP showing volcanic vents, thermal springs, and deep drill holes. Also shown are geophysically-inferred structural features (gravity lineations) based on maximum horizontal gradients of residual isostatic gravity. Geophysical grids are superimposed on a topographic base map (after Glen et al., 2017, Fig. 3).

Explored geothermal systems in basaltic terrains are associated with areas having a high magma budget (Nielson et al., 2017; Karson et al, 2015). There have been limited observations of the heat sources for basalt-related systems, but we believe that they are either sheeted dike complexes or sills. The hydrothermal brecciation in MH-2 leads us to postulate the proximity of intrusive rocks, and we set up a tentative model based on the volume and geometry of a high-level sill exposed at the western margin of the SRP (Graveyard Point). This sill had original dimensions that we estimate as 5 km x 3 km and a thickness of 200 m. Numerical models of thermal evolution during sill injection show that a single sill emplaced at a depth of about 2 km will result in heating of the surrounding rocks to over 300ºC after 20,000 years (Nielson and Shervais 2014; Nielson et al., 2017); multiple sill injections will result in the continuous accumulation of heat as the ambient temperature of the host rocks is raised with each injection.

A regional potential field model was developed for the western SRP based on high-resolution gravity data collected across the plain (Glen et al., 2017). The dominant feature along the profile is a prominent gravity high that extends nearly the full length of the western SRP (Figure 2). This high is primarily modeled as a dense mafic root and sill complex intruded into the lower and middle crust and a high-density block in the upper crust consisting largely of a thick section of mafic lavas and sills. Both wells (MH-1 and MH-2) drilled at the MHAFB are located over the gravity high (Figure 2) and extend into basalts interpreted to mark the top of the high-density block. However, neither of these holes intersected dikes or sills.

Due to the large density contrast of the mafic intrusive complex with respect to surrounding silicic volcanic and granitic basement rocks, gravity offers a particularly well-suited method for characterizing the sill and aiding with the interpretation of the subsurface. Figure 3 is an interpreted cross section along the profile line shown in Figure 2. Note that this line passes through MH-1, but MH-2, Anschutz Federal #1 and Bostic 1A are projected onto the section to provide geologic control. As shown in Figure 3, the geothermal system is interpreted to be located in a thick section of basalt flows that are underlain by sills. The sills are inferred from the high fluid inclusion temperatures and presence of hydrothermal breccias; although they are not present in core from MH-1 or MH-2. The permeability is controlled by faults that appear to represent a graben with steep dips to the NE as evidenced by the geologic relationships in MH-1 and MH-2.

Drilling and temperature data from MH-1 and MH-2 together with high resolution gravity, ground magnetic, magnetotelluric (MT), and seismic reflection surveys were used to define key structural features responsible for promoting permeability and fluid flow. A 3-D numerical natural state model was developed using the latter dataset (Garg et al., 2017). The model volume is 2750 cubic kilometers (25 km in the east-west direction, 20 km in the north-south direction, and 5.5 km in the vertical direction). Available temperature profiles from wells MH-1 and MH-2 display good agreement with the computed results. The natural state model provides a point of departure for additional exploration and development of the geothermal resource in the Mountain Home area.

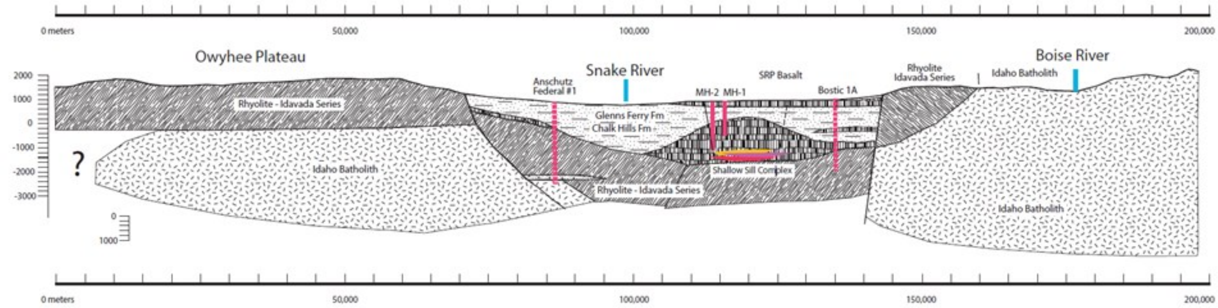

Figure 3. Conceptual model along NE-SW profile across the SRP extending through the MHAFB. Profile location is shown as the pink line on Figure 2 (Nielson et al. 2019).

4. CONCLUSIONS

The most recent magmatic activity in the Snake River Plain is basaltic and related to post-caldera forming stages associated with the Yellowstone mantle plume. In areas of high magma budget where the volume of magma generation exceeds the tectonic accommodation space, sill complexes can form and serve as the heat source for geothermal circulation. Although the SRP is not presently magmatically active, voluminous flows younger than 200 ka have been documented.

Our conceptual model involves the high heat flow of the SRP that is produced by lower- and mid-crustal sill complexes, and associated with this regional foundation, are areas of high-level (~2 km) intrusive bodies that generate hydrothermal circulation at depths that can be exploited. The primary heat source for the drillable resource has been modeled as a sill complex (Nielson et al., 2017). We believe that exploitable geothermal resources in the overall high heat flow province are associated with shallow sill complexes that occasionally erupted to feed recent flows, but principally served as high-level magma reservoirs that power hydrothermal circulation.

The fairway associated with the MHAFB system is defined by the gravity high that we believe represents the high-level injection of basaltic magma. However, there are no surface manifestations of the hydrothermal system. In addition, cultural disruption has eliminated any evidence of recent faulting and inhibits the application of electrical geophysical methods. Therefore, within our fairway, drilling is the primary exploration tool. Significantly, this drilling would not have been possible without the financial interest of scientific funding organizations.

Acknowledgements-This paper was supported in part by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) through award DE-EE0006733 to Utah State University and with support from the U. S. Geological Survey's Energy Program. Slim hole drilling at MHAFB was supported by the US Air Force and the International Continental Scientific Drilling Program.

REFERENCES

Atkinson, T. A., Geochemical characterization of the Mountain Home geothermal system: All graduate theses and dissertations, Paper 4599. (2015).

Barnett, P., Randle, J. B., Fikre-Mariam, A.: Risk and risk management in geothermal exploration and development: *Transactions*, GRC, **27**, (2003) 209-212.

Delahunty, C., Nielson, D. L. and Shervais, J. W.: Deep core drilling of three slim geothermal holes, Snake River Plain, Idaho: *Transactions,* GRC, **36**, (2012) 641-648.

Deloitte Development LLC: Geothermal risk mitigation strategies report, Department of Energy - Office of Energy Efficiency and Renewable Energy Geothermal Program, (2008), 44p.

ESMAP (Energy Sector Management Assistance Program): Geothermal handbook: planning and financing power generation, World Bank Group, Washington, DC, (2012) 164 p.

Garg, S. K. and Combs, J.: Use of slim holes with liquid feed zones for geothermal reservoir assessment: *Geothermics,* **26**, (1997) 153-178.

Garg, S.K. and Combs, J.: Geothermal reservoir assessment using data from slim holes, *Transactions* GRC, 24, (2000) 581-587.

Garg, S. K., Combs, J., Kodama, M. and Gokou, K.: Analysis of production/injection data from slim holes and large-diameter wells at the Kirishima geothermal field, Japan, *Proceedings,* 23rd Workshop on Geothermal Reservoir Engineering, Stanford, (1998) 64-76.

Garg, S.K., Gasperikova, E., Shervais, J., and Nielson, D.: Mountain Home geothermal area: Natural state model, *Transactions* GRC, 41, (2017), 13 pp.

Garg, S. K., Nielson, D. L., Shervais, J. W. and Sonnenthal, E.: Thermal modeling of the Mountain Home geothermal area, *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford, (2016).

Glen, J., Liberty, L, Gasperikova, E, Siler, D, Shervais, JW, Ritzinger, B, Athens, N, Earney, T,: Geophysical Investigations and Structural Framework of Geothermal Systems in west and southcentral Idaho; Camas Prairie to Mountain Home. *Proceedings,* 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, (2017).

Hance, C. N. and Gawell, K.: Factors affecting cost of geothermal power development and production: *Transactions,* GRC, **29**, (2005) 449-454.

International Finance Corporation (IFC): Success of geothermal wells: a global study: International Finance Corporation, Washington DC, (2013) 80 p.

Karson, J. A., Kelley, D. S., Fornari, D. J. Perfit, M. R. and Shank, T. M.: Discovering the deep A photographic atlas of the seafloor and ocean crust, Cambridge University Press, (2015) 414 p.

Kessler, J.A., Bradburry, K.K., Evans, J.P., Pulsipher, M.A., Schmitt, D.R., Shervais, J.W., Rowe, F.E. and Varriale, J., Geology and in situ stress of the MH-2 borehole, Idaho, USA: insights into western Snake River Plain structure from geothermal exploration drilling: *Lithosphere,* GSA data repository item 2017171, (2017).

Lewis, R.E. and Stone, M.A.J., Geohydrologic data from, a 4,403-foot geothermal test hole, Mountain Home Air Force Base, Elmore County, Idaho: USGS Open-file report 88-166, 30 p. (1988).

Mansure, A. J. and Blankenship, D. A.: Geothermal well cost update 2011, *Transactions,* GRC, **35**, (2011) 189-192.

Matek, B.: The manageable risks of conventional hydrothermal geothermal power systems, Geothermal Energy Association, (2014) 34p.

Molloy, M. W.: Baca geothermal demonstration project-reservoir definition review: *Transactions*, GRC, **6**, (1982), 301-303.

Nielson, D. L., Delahunty, C. and Shervais, J. W.: Geothermal systems in the Snake River Plain, Idaho, characterized by the Hotspot project, *Transactions*, GRC, **36**, (2012) 727-730.

Nielson, D. L. and Garg, S. K.: Slim hole reservoir characterization for risk reduction: *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford University, (2016) 113-120.

Nielson, D. L., Garg, S., Koenig, B. Truesdall, A., Walters, M. A., Stark, M., Box, W. T. and Beall, J. J.: Concept for an Enhanced Geothermal Reservoir at The Geysers, *Transactions,* GRC., **25**, (2001) 191-194.

Nielson, D. L. and Shervais, J. W., 2014, Conceptual model of Snake River Plain geothermal systems: *Proceedings*, 39th Workshop Geothermal Reservoir Engineering, Stanford University, (2014) 1010-1016.

Nielson, D. L., Shervais, J., Evans, J., Liberty, L., Garg, S. K., Glen, J., Visser, C., Dobson, P. Gasperokova, E., and Sonnenthal, E.: Geothermal play fairway analysis of the Snake River Plain, Idaho, *Proceedings,* 40th Workshop on Geothermal Reservoir Engineering, Stanford University, (2015) 159-167.

Nielson, D.L., Sonnenthal, E., Shervais J.W., Garg, S.K., Mafic Heat Sources for Snake River Plain Geothermal Systems. *Proceedings*, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2017) 1205-1212.

Nielson, D. L., Atkinson, T. A. and Shervais, J. W., Evaluation of the Mountain Home AFB geothermal system for the Play Fairway project. *Proceedings,* 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2018) 1442-1448.

Nielson, D. L., Shervais, J. W. and Glenn, J., Conceptual model for a basalt-related geothermal system, Mountain Home AFB, Idaho: *Proceedings*, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, (2019) 852-855.

Sanyal, S. K. and Morrow, J. W.: An investigation of drilling success in geothermal exploration, development and operation, *Transactions,* GRC, **35**, (2011) 233-238.

Shervais, J. W. Glen, J. M., Liberty, L. M., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Nielson, D. L., Garg, S., Evans, J.P., Siler, D., DeAngelo, J., Athens, N. and Burns, E.: Snake River Plain play fairway analysis-Phase 1 report: *Transactions,* GRC, **39**, (2015) 761-769.

Shervais, J. W., Glenn, J. M., Nielson, D. L., Garg, S., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Liberty, L. M. Deangelo, J., Siler, D. and Evans, J. P.: Geothermal play Fairway analysis of the Snake River Plain: Phase 1: *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford University, (2016) 1997-2003.

Silverman, R. L., Lukawski, M. J. and Tester, J. W.: Uncertainty analysis of geothermal well drilling and completion costs: *Transactions,* GRC, **38**, (2014) 419-422.

Olson, H. and Demonaz, J. E.: The use of slim hole technology in the Hawaii Scientific Observation Hole (SOH) Program, *Proceedings,* World Geothermal Congress, (1995) 1467-1472.

Walker, J. and Wheeler, J., The smectite to corrensite transition: X-ray diffraction results from the MH-2B core, western Snake River Plain, Idaho: *Clay Minerals*, **51**, (2016) 691-696.

Ward, S. H., Ross, H. P., and Nielson, D. L.: Exploration strategy for high-temperature hydrothermal systems in the Basin and Range Province, Am. Assoc. Petroleum Geologists Bull., **65/1** (1981) p.86-102.