PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Slim Hole Reservoir Characterization for Risk Reduction

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Keywords: learning curve, play fairway analysis, drilling costs, drilling risk, resource risk, sustainability risk, conceptual models

ABSTRACT

High initial capital requirements and subsurface risk are commonly cited as significant impediments to more widespread development of hydrothermal resources. However, expensive production wells are often drilled at the early stages of development when risk is high. By drilling and testing slim holes at early stages, a developer can realize a significant reduction in risk at reasonable cost. In this paper, we will review different drilling approaches, their costs and impact on risk reduction. Slim holes have been promoted for reservoir characterization because of lower cost. However, they are also conducive to enhanced data collection that is critical for establishing conceptual models. Properly conducted injection tests provide reservoir engineering information that is equivalent to data collected from large well tests. When utilized in the reservoir testing phase, slim holes can provide greater volumetric sampling of a prospect than production-size wells at an equivalent cost. Therefore, significant risk reduction can be realized before the initiation of high-cost field development. Exploration is a knowledge-based activity and data collection and application to conceptual reservoir models is a requirement. We briefly discuss the data framework of the Play Fairway approach to demonstrate risk reduction.

1. INTRODUCTION

Subsurface risk is commonly cited as an impediment to geothermal energy development. This risk has three manifestations: resource risk or uncertainty concerning the size and quality of a reservoir; drilling risk or the successful completion of and fluid production from a well; and, sustainability risk or the capacity of a reservoir to sustain production through the life of a project. There are a number of different approaches to managing subsurface risk, and perhaps a re-definition of drilling success and approach to evaluating geothermal resources is necessary.

This paper will focus on slim-hole drilling as a means of reducing uncertainty associated with geothermal development. 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; 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.

Enhanced Geothermal System (EGS) reservoir development would require greater subsurface knowledge than a naturally producing hydrothermal system. This is because of the requirement to generate new fractures or enhance permeability along existing fractures. Therefore, EGS development costs are expected to be higher and the risks greater than those associated with production from natural hydrothermal convection systems. For EGS systems reducing the cost of drilling is important for the technology to move forward (DOE, 2008). The JASON (2014) report has extensive discussions of the benefits of "microholes" (<5" diameter) for the evaluation of EGS prospects.

2. SLIM HOLE DRILLING TECHNOLOGY

2.1 Drilling Equipment

Slim holes can be drilled using different techniques: rotary, diamond coring or mud motors. Rotary drilling uses high weight on bit and low rpm to crush rock, and the only recovered samples are rock fragments (cuttings). Once major fluid loss zones are encountered, it may be impossible to recover cuttings and the well is drilled without geologic control. Diamond coring uses high rpm and low weight on bit to cut rock and produce a core sample. Lost circulation generally does not impact core collection. Rotary drilling is normally faster whereas diamond coring produces a straighter hole, superior lithologic samples and less thermal and chemical disturbance.

Slim hole drilling has been applied directly from the mining industry, and there has been little effort to optimize the technology for geothermal applications. Many coring rigs drill to depths of 1000 m. Rigs that will core to 2000 m or more are not as common, but they are available and can be adapted to geothermal service. Hybrid drilling systems that install a high-speed top drive on a standard rotary rig have also been used to collect core during geothermal exploration (Nielson, 2001). Several rig manufactures offer multipurpose rigs that can drill the upper part of the hole with air hammers or mud rotary, and following emplacement of casing, complete the hole using core drilling. Rig optimization could significantly improve the efficiency of drilling geothermal assessment holes.

Since most geothermal fluid production is found in steeply inclined faults and fractures, it is often advantageous to drill holes perpendicular to the trend of the fractures. Core rigs commonly drill angle holes by tilting the derrick. Mud motors can also be used in slim holes and can directionally drill from a vertical casing or perform multilateral completions.

A significant advantage of slim hole drilling equipment over production well drilling is its smaller size and greater mobility. This translates into smaller well pads and less environmental disturbance. For remote locations, the savings in road construction and transportation costs can be significant.

2.2 Fluid Circulation

The fluid circulation system pumps drilling fluid (mud) down the hole through the center of the drill pipe or rod, past the cutting surface of the bit and returns the mud and entrained cuttings to the surface. The purpose is to cool and lubricate the bit, remove cuttings and stabilize the hole. The cost of mud can be a significant component of the overall drilling costs (Silverman et al., 2014). Diamond coring typically circulates at a rate of about 10 gallons per minute. This contrasts with production well (rotary) methods that circulate hundreds of gallons per minute.

Recent technology developments include centrifuge systems that effectively clean mud for recirculation. This decreases mud cost and may be advantageous in many parts of the world because it also decreases the consumption of water. The oil & gas industry has pioneered underbalanced drilling methods that control well pressure to less than the hydrostatic pressure. This reduces the likelihood of lost circulation and formation damage. Injection of air into high temperature environments can result in corrosion, so other gases such as nitrogen can be used at relatively low cost.

To-date, geothermal mud-loss data have not been employed to make quantitative determinations of the permeability of natural fractures encountered during drilling. In petroleum drilling, mud losses as small as 0.5 bbl have been measured and used as permeability indicators (Dyke *et al*., 1995). Also, petroleum industry has developed mathematical models (Huang *et al*., 2011; Akin, 2013) for computing permeability of natural fractures using mud-loss data. We have proposed using this approach to quantify permeability in real time as the drill penetrates a target reservoir

2.3 Tubulars

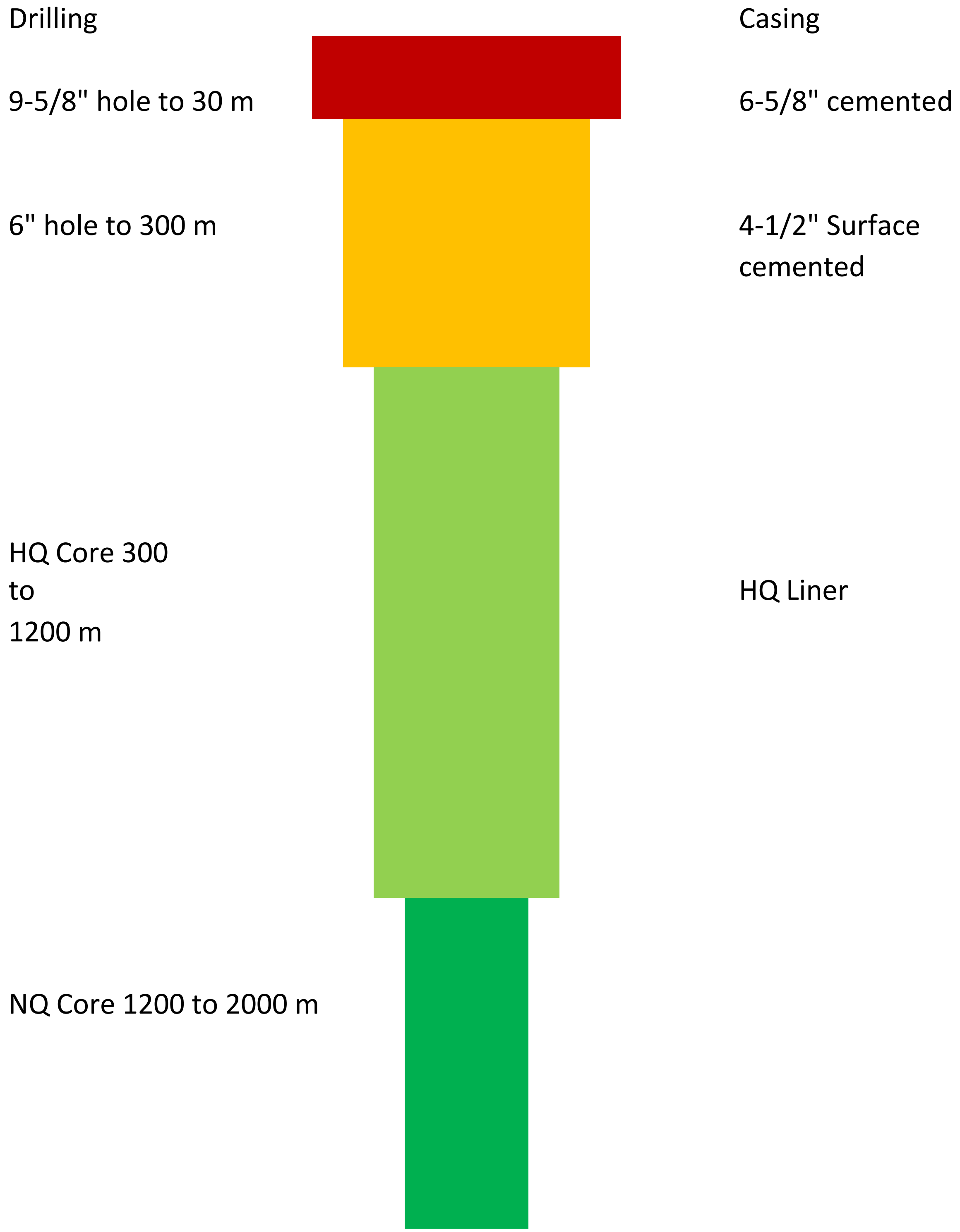
Drilling rod has flush joints in contrast to the large tool joints on drill pipe used for production drilling. Standard rod sizes are P (4.5" x 4"), H (3.5" x 3.063") and N (2.75"x 2.375"). In the event of hole problems, drill rod can be left in the hole as casing and the next smaller drill string can be used to continue drilling. The annular space between the rod and the hole is small, typically 0.25 to 0.5 inches. The inner diameter is also flush and the bits are open at the end. This allows the driller to use a larger size as casing and drill out the end of the assembly without pulling it back to the surface and setting a separate casing string.

Slim holes are not intended for geothermal production, and reservoir engineering tests in slim holes are usually conducted through injection. Therefore, casing strings can be smaller than those used in wells that are intended for fluid production.

2.4 Hole Design

Slim holes should be designed differently than production wells. We often see "slim hole" drilling plans that are similar to production wells, except that they use casing strings that are one or two sizes smaller. These designs still require large drilling rigs and multiple casing strings that eliminate cost advantages, and rotary techniques reduce sample quality.

A reference design for a 2000 m slim hole is shown in Figure 1. A 9-5/8 inch diameter hole is drilled to a depth of 30 m and a 6-5/8 inch conductor is cemented in place. Following that, a 6-inch hole is drilled to 300 m and a 4-1/2 inch surface casing is cemented in place and pressure tested. Alternatively, the hole may be cored PQ if lithologic samples are required in the upper part of the section. Regulatory agencies typically require the surface casing to be 10% of the total depth of the hole. An annular blowout preventer, in contrast to a full BOP stack, is often acceptable. From that point, HQ core can be collected to a depth of 1200 m, and NQ can be collected from 1200 to 2000 m. Delahunty et al. (2012) describe drilling experience using this general hole design. Our reference 2000 m slim hole has a cost of about $1.2 million.



3. GEOLOGIC CHARACTERIZATION

In contrast to the focus on production well drilling, geologic data collection is a key factor in prospect assessment. White et al. (2010) present several brief case studies documenting the advantages of slim hole drilling, particularly for the construction of a conceptual model of a geothermal reservoir. They state that the primary reason for drilling slim holes is to improve the chance of success in siting and drilling production wells.

Geologic characterization should focus on developing and updating a conceptual model of the geothermal system. We use the term conceptual model throughout this paper, and it is a significant component of the Play Fairway analysis (Nielson et al., 2015). A conceptual model represents the three-dimensional model of a reservoir that incorporates the significant geological aspects of the resource as well as associated physical properties. A viable model should show the following.

- Distribution of lithologic units (porosity, permeability, density, electrical resistivity, magnetic susceptibility)
- Hydrothermal alteration (mineralogy, electrical resistivity, associated fluid inclusions)
- Fluid Chemistry
- Faults, their geometry, distribution, orientation and relationship to fluid flow
- Dikes and sills, orientation, composition and age
- Stress orientation
- Temperature gradients

The principal goals of the conceptual model are to provide a context for locating and drilling successful production wells, to describe the distribution of physical properties that provide ground truth for the interpretation of geophysical methods, and to provide a basis for the interpretation of reservoir monitoring information.

4. RESERVOIR ENGINEERING

In order to establish the utility of slim holes for definitive reservoir assessment, it is necessary to be able to predict the discharge characteristics of large-diameter wells based on discharge and/or injection tests on small-diameter boreholes. To compute the probable discharge characteristics of a large-diameter well, a relationship between the injectivity and/or productivity of slim holes and large-diameter production and/or injection wells is required. Garg and Combs (1997) examined production and injection data from slim holes and large-diameter wells at five geothermal fields (Oguni, Sumikawa, Takigami, and Kirishima, Japan; Steamboat Hills, U.S.A.) in order to establish relationships (1) between productivity and injectivity indices, and (2) between discharge capacity of slim holes and large diameter wells. For boreholes with liquid feed zones, the productivity and injectivity indices are more or less equal, and the productivity (or injectivity) index is independent of borehole diameter. It therefore follows that the productivity index of large-diameter production wells can be estimated based on injection tests on slim holes. If the productivity index is sufficiently large, the discharge rate of the well will not be limited by the formation; in this case, a wellbore simulator can be employed to investigate the production characteristics of a well regardless of the borehole diameter. To summarize, discharge rate of large-diameter wells with liquid feed zones can be predicted using either production or injection test data from slim holes. It may also be feasible to predict the performance of wells with two-phase feed zones (Garg and Combs, 2000). Garg et al. (2016) indicates the importance of data collection for thermal modeling associated with early stages of exploration.

5. GEOTHERMAL DEVELOPMENT RISK

5.1 Risk

The exploration and development of a natural resource is a speculative risk that a developer undertakes because it offers 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. With its high degree of front-end risk, geothermal energy requires a high return on investment. However, the cost of electricity is generally regulated by governments 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 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 addresses 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 2 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) and Deloitte (2008) with anticipated costs.

			Project Costs		
	TASK		**ESMAP**	**Deloitte**	**This Paper**
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 Developmment**		$ 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

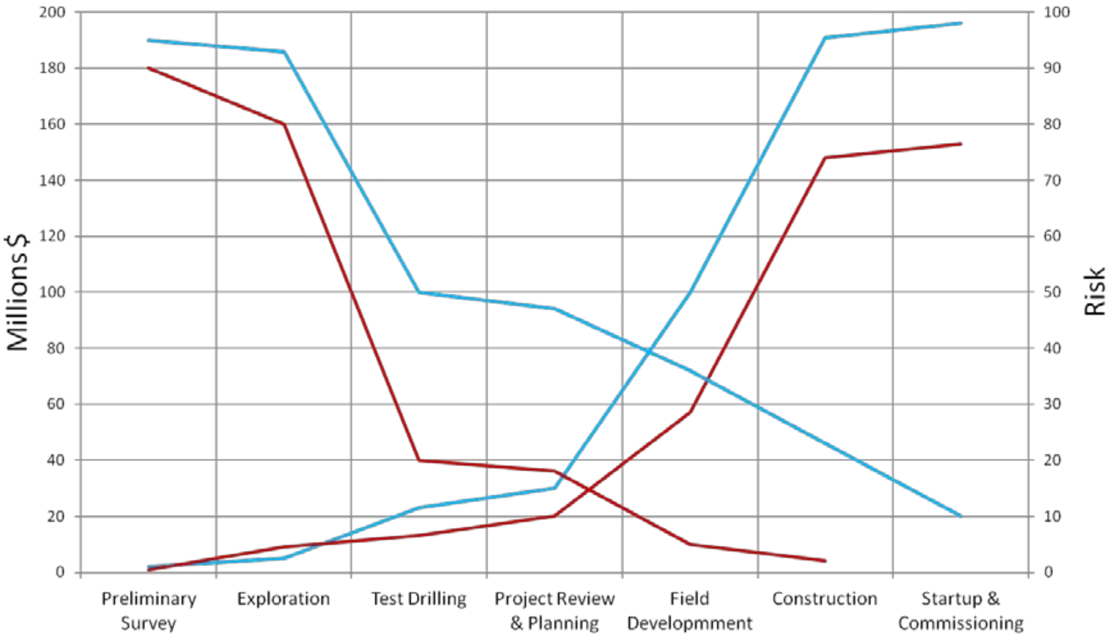


Figure 2 Risk versus investment for a typical 50 MWe geothermal development project. Blue curves are from ESMAP (2012) and red curves are from Deloitte (2008).

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 Play Fairway project that is investigating the geothermal potential of the Snake River Plain, is currently at the Task 1 level (Shervais *et al.*, 2015). Subsequent work will be data collection and model refinement (Task 2: Exploration). We believe that one of the clear advantages of the Play Fairway technique is that it defines the data that should be collected to support the conceptual model of the system.

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) has 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.

5.2 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, we present the following pro forma evaluation of a similar resource. We estimate 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. We assume a 2000 m drilling depth with costs of $1.2M (Delahunty et al., 2012) Our 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. We also assume each production well can 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 production wells would be required to yield the 10 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 medium 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 managing production and injection.

We have only briefly addressed EGS in this paper. However, we believe that the development of an EGS reservoir is going to present higher costs and risks than a typical hydrothermal reservoir. Slim holes can again provide better spatial coverage as well as the information required to plan and implement stimulation activities.

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 is the only means 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.

7. CONCLUSIONS

Geothermal exploration and development risk may be mitigated through the systematic application of methods that address conceptual models of the system. Slim holes can be drilled at lower cost than production wells and offer equivalent, and at times, better opportunities for the collection of geologic and reservoir engineering data. The Play Fairway approach provides a good framework for the organization of data applicable to conceptual system models. A pro forma analysis shows how a comprehensive slim hole reservoir characterization program results in better volumetric coverage at equivalent cost to production well drilling.

Acknowledgements- We have benefitted from reviews by Benjamin Matek, Philippe Wyffels, Blaise Stephanus and John Shervais. This paper was supported in part by the U. S. Department of Energy, Geothermal Technologies Office through award DE-EE0006733 to Utah State University.

REFERENCES

Akin, S.: Estimating natural fracture permeability from mud-loss data: *Proceedings,* 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2013).

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.

Dyke, C.G., Wu, B., and Milton-Tayler, D.: Advances in characterizing natural-fracture permeability from mud-log data: SPE Formation Evaluation, **10**, (1995) 160-166.

Department of Energy (DOE): An evaluation of Enhanced Geothermal Systems technology: (2008) 37 p.

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., 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).

Garg, S. K., Pritchett, J. W. and Alexander, J. H.: A new liquid hold-up correlation for geothermal wells, *Geothermics*, **33**, (2004) 795-817.

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

Huang, J., Griffiths, D.V, and Wong, S.-W.: Characterizing natural-fracture permeability from mud-loss data: SPE Journal,**16**, (2011) 111-114.

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

JASON: Enhanced geothermal systems: The MITRE Corporation, McLean, VA, (2013) 147 p.

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.: Deep wireline coring in geothermal reservoirs, *Transactions,* GRC, **25**, (2001) 115-118.

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., 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, p. 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, Stanford, CA (2015) 159-167.

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.

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.

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.

White, P., MacKenzie, K., Verghese, K. and Hickson, C.: Deep slimhole drilling for geothermal exploration: *Transactions*, GRC, **34**, (2010) 269-272.