USE OF DEEP SLIMHOLE DRILLING FOR GEOTHERMAL EXPLORATION

K.M. Mackenzie, G.N.H. Ussher, R.B. Libbey, P.F. Quinlivan, J.U. Dacanay and I. Bogie

Jacobs (formerly SKM)

e-mail: ken.mackenzie@jacobs.com; gregory.ussher@jacobs.com; ryan.libbey@jacobs.com; paul.quinlivan@jacobs.com; julius.dacanay@jacobs.com; ian.bogie@jacobs.com

ABSTRACT

Deep slimholes were used very effectively in Indonesia in the 1990's for geothermal resource delineation and potentially again have a major role in assisting early exploration of geothermal prospects that are increasingly challenging because of ambiguous surface indications and more remote and difficult terrain.

The capital expenditure required to drill deep geothermal exploration wells to prove any geothermal system can be substantial particularly if a project is remotely located and requires large infrastructure work to facilitate the exploration and resource proving process. In the absence of tariffs commensurate with the risks in exploration drilling, developers are cautious to embark on high cost drilling, particularly where the probability of successfully finding a resource with the first few wells may be low because of resource uncertainties.

Deep slimhole drilling using equipment that is smaller and requires less road and water supply infrastructure can achieve exploration outcomes at lower cost. However, successful application of this technology requires a solid foundation comprising five elements: an appropriate well design; a simple and clear strategy covering major drilling decision points; a robust procurement and implementation plan; a suitably experienced and equipped drilling contractor; and experienced technical supervision of the operation. Following this approach it is possible to obtain exploration and resource characterisation equal to that provided by full sized exploration wells.

The use of deep slimholes can improve the success rate of subsequent appraisal drilling using conventional or large diameter wells and so it can provide cost savings on the total project cost. The use of deep slimholes for exploration reduces the early capital spend on a project, and therefore improves the success-weighted Net Present Value (NPV) of a project, particularly where there is a reduced probability of successfully finding a resource. In combination, the reduced capital and improved scheduling of expenditure plus reduced cost of failure for a project (or for a portfolio of projects), has the ability to reduce the tariff required for geothermal projects in Indonesia.

Small diameter wells can potentially produce geothermal fluids sufficient for several hundreds of kW of electricity, raising the possibility of a group of such wells supplying electricity economically in areas where demand is low such as small, remote or isolated grids. The feasibility of doing this in Eastern Indonesia is currently being considered.

Keywords: geothermal exploration, resource uncertainty, financial risk, conceptual model, deep slimhole drilling

INTRODUCTION

There is a range of drilling alternatives that can be considered for purposes of geothermal exploration and assessment of resource potential. The applicability of one or more of these alternatives is ultimately dependent on key project considerations such as schedule, cost and risk management, and is usually evaluated on a case by case basis depending on the objectives for a particular project and the extent of existing resource knowledge.

This has become increasingly important as the "low hanging fruit" exploration projects in which pre-drilling exploration results were sufficiently good that initially successful drilling could be conducted with full size wells have already been exploited.

With the high cost of drilling, it is becoming increasingly important to optimise well targeting, particularly for the first wells in a geothermal system. Where there is uncertainty as to the resource potential, location and extent; or in the location, nature and orientation of permeability, there can be good reasons to use slimholes initially. The primary reason for drilling slimholes is twofold:

- to reduce the overall risk (cost) of failure in exploration drilling
- to improve the probability of success of appraisal, delineation and production wells.

The significant lower upfront capital expenditure and reduced financial risk makes this approach particularly attractive for the early part of the drilling phase where the level of risk is normally the highest (Figure 1).

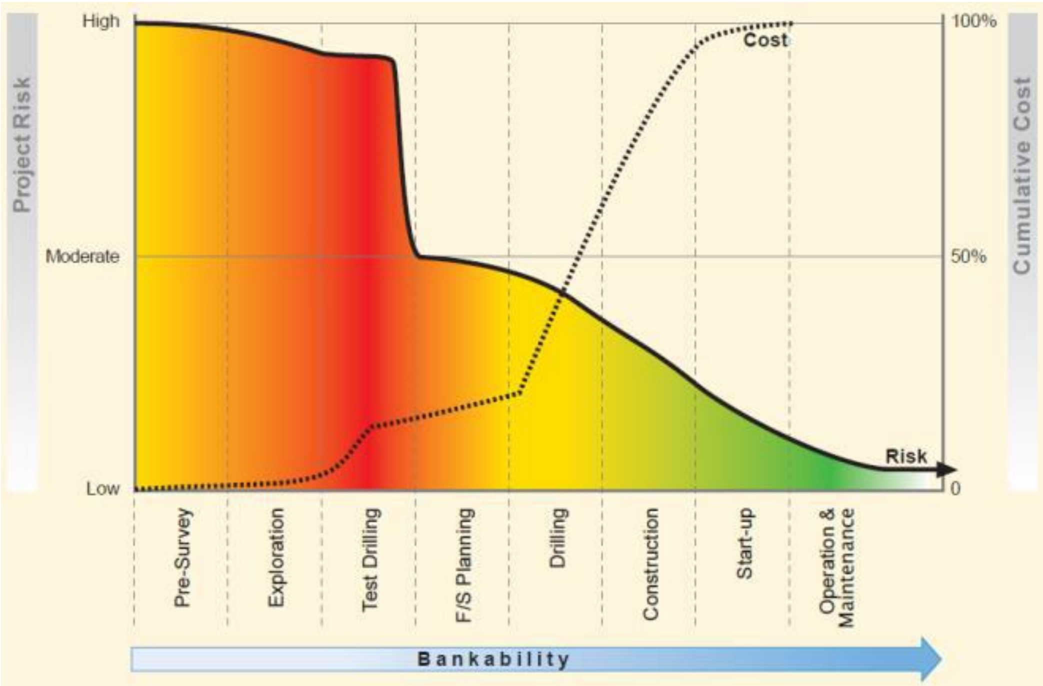

Figure 1: Bankability versus risk for a geothermal project, note the strong drop in risk engendered by successful test drilling. From: Gehringer and Loksha (2012).

Deep slimhole drilling was used effectively for geothermal exploration in Indonesia in the 1990's notably at Wayang Windu, Darajat (Riza and Berry, 1998), and Sarulla (Gunderson et al, 2000). Over the past 25 years, slimhole drilling has become increasingly utilized for geothermal resource exploration and delineation in other regions notably in the USA, Japan, New Zealand, the Caribbean, Central America and Chile, and even recently in Malaysia (see for example White et al., 2012; Garg and Combs, 1993; Nielson and Garg, 2016; Nielson and Garg, 2017; Libby et al., 2017).

This paper summarises the relative advantages and disadvantages of slimhole drilling, and describes the typical equipment and infrastructure requirements for this approach. It also provides some examples of where deep slimhole drilling has been successfully implemented on geothermal projects to address different project objectives with focus on application in Indonesia.

TERMINOLOGY AND ASSUMPTIONS

Within the geothermal industry there are two generic well types normally considered for exploration drilling; these are slimhole wells and what are typically referred to as 'conventional' sized wells. Each generic well type has two variants that are normally selected according to the objectives of a particular drilling program and other factors such as cost. These generic well types are summarised in Table 1 and depicted schematically in Figure 2.

Table 1: Generic Well Definitions and Applications

Type	Variant	Description
Slimhole Well	Temperature Gradient	Well completed above the level of the productive reservoir to establish presence of clay conductor, confirm temperature, and validate conceptual model. ~200 – 800 mVD.
	Deep Slimhole (2 3/4" – 7" PC)	Drilled into the reservoir to confirm commercial temperature (primary objective) and can test productivity (secondary objective). ~500 – 2,000 mVD.
Conventional Well	Standard (9 5/8" PC)	Wells that penetrate substantial thickness of the reservoir, enable comprehensive testing of resource productivity, and may be used for production or injection in a development. ~2,000 – 3,000 mVD.
	Large (13 3/8" PC)	

Notes: PC = production casing, VD = vertical depth

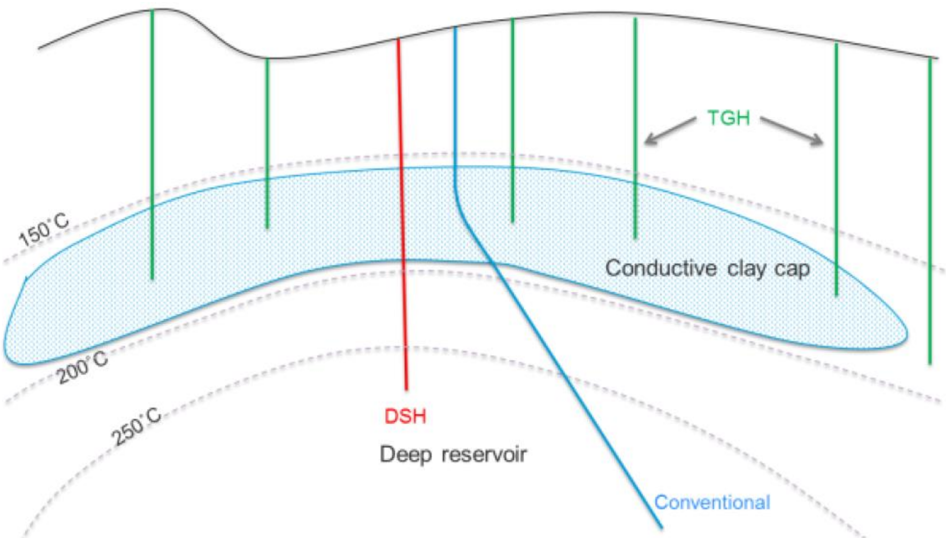

Figure 2: Generic drilling options (TGH = temperature gradient hole, DSH = deep slimhole)

A deep geothermal slimhole is defined as a well that is drilled with a continuous wireline core rig or a small rotary drilling rig with the specific aim of drilling into the geothermal reservoir. Note that a "reservoir" is simply defined as a permeable hot aquifer, which is commonly, but not always situated beneath a hydrothermal clay cap. The target reservoir is most often linked to a zone of deep upflow, however, some smaller projects target shallow permeable zones that reside within the clay cap and/or along shallow outflow paths.

Slimholes have been designed and constructed to safely core or drill into hot formations up to 275˚C. Generally the finished hole size ranges from NQ size (75.7 mm diameter) to 6-1/4" (normally using rotary drilling techniques and tricone bits).

Slimhole depths are mostly limited by the rig capacity and well designs prepared by Jacobs have mostly targeted maximum depths of 2,000 m. Most wells are continuously cored for their full depth or rotary drilled in the shallow sections using a tricone bit, then cored in the main interval of interest through the hydrothermal clay cap and underlying reservoir rock. Slimholes are usually drilled straight, either vertically or at an angle to the horizontal (slant) depending on exploration targeting requirements. There is also the technology to drill directional holes, most particularly using coiled tubing with a mud motor, but so far the use of this technology appears to be restricted to the oil and gas exploration industry.

Temperature gradient holes are a shallow type of slimhole aimed at helping to define the upper part of the geothermal system and which are terminated above the level of the productive reservoir, primarily due to rig and well control (blow out prevention) restrictions, and most particularly depth limitations on setting the final cemented casing. Such holes are normally used to help define the shallow geological environment, in particular the extent of the geothermal clay cap and to confirm whether it has associated shallow heat flow or is a relict feature. Collectively this information can be used to validate and refine the conceptual model. It can be used to estimate what the deep reservoir temperatures might be, although care needs to be exercised when extrapolating shallow temperature information. This is most particularly the case in andesitic volcanic piles where perched groundwater aquifers are common and can severely reduce temperature gradients.

Temperature gradient hole drilling uses the same type of equipment and associated infrastructure required for deep slimhole drilling, including all of the necessary precautions required for well control and overall site safety.

INFORMATION SECURED FROM SLIMHOLES

In general, slimholes obtain very similar information regarding the geothermal reservoir to that obtained with conventional larger diameter holes, but with some important differences.

Geology:

Continuous coring means that an almost complete geological section is obtained compared with only cuttings in most geothermal wells, possibly supplemented by a short length of "spot" core. Within conventional rotary drilled holes there is also the likelihood of obtaining no cuttings below any major loss zones, unless drilling with aerated fluids is successful in maintaining circulation. Coring enables much greater confidence in identifying the lithologies, alteration and veining, and the relationships between different units or events. In addition, potential problem units (e.g., smectite-rich lithologies within the reservoir) may be identified at an early stage before they cause potentially costly drilling problems in larger diameter production wells. For example, it was only through data from cored slimholes at Wayang Windu in the 1990's that our geologists were able to understand the rather thin formations that were causing major problems in drilling conventional production wells and eventually saved a large amount of drilling time.

The availability of continuous core samples also provides an opportunity for detailed profiling of rock properties, including porosity, permeability, resistivity and density. This can be useful for helping to validate the conceptual geothermal model and geophysics profiling, and for constraining numerical models of the reservoir that will be used throughout the project life. Oriented cores can also be obtained (at some extra cost) to help characterise geological structure within the reservoir. Where there are concerns over subsidence, obtaining a good core record will be an advantage for determining geotechnical properties of formations.

Temperature:

Slimholes are ideally suited for collecting temperature measurements. Temperature measurements that approximate undisturbed reservoir temperatures can be made during drilling, using small temperature logging tools easily run during short operational pauses. Simple maximum registering thermometers (MRT) can provide temperature data in excess of 250°C, and where a wireline coring rig is used, can provide a temperature for each interval drilled. Small electronic temperature data loggers (e.g., the HOBO® U12-015) are available to log temperatures at all depths and at temperatures up to 150°C.

The reason that these measurements when drilling are so viable is that very little drilling fluid is circulated during slimhole drilling in comparison to a full size operation, thus a 2-3 hour heat-up can be sufficient to give a temperature that is nearly representative of natural state conditions (especially near the bottomhole). Evidence for this is provided by a comparison between MRT/HOBO® data collected during drilling and temperature logs made after months of heating in Libbey et al (2017). Conventional pressure-temperature-spinner logs using standard geothermal industry wireline tools (e.g., 1.75" Kuster K10 PTS tool) can also be run in slimholes following well completion to characterise the conditions over the full length of the well.

The early collection of temperature data is useful for two reasons. Firstly, if there are major drilling difficulties that lead to premature abandonment of the well there will still be some temperature data available. Secondly, if low temperatures are found down to reservoir depths the well can be terminated early thereby saving on additional drilling cost while other well targets can be reviewed.

Permeability:

Permeability will be noticed when found with slimholes, just as with larger diameter wells (e.g., drilling breaks, fluid losses, kicks, etc.). Completion tests can measure injectivity indices, and provide general guidelines for whether good permeability has been found. A normal type of completion test is run in slimholes, measuring water loss, injectivity and pressure fall off.

Productivity:

Provided that slimholes are properly designed (see the section on well design in this paper), slimholes can be flowed if they encounter suitable temperature, pressure and permeability. Our research indicated over 16 projects where slimholes have been flowed. Garg and Coombs (1993) report several wells at Oguni in Japan that flowed with about 6-8 tph of steam or close to 1 MWe. Jacobs has tested wells at the Mita project in Guatemala with a reservoir temperature of only 205 °C, but with good permeability. In this example the 4" diameter wells provided flows equivalent to over 1 MWe (Figure 3).

Figure 3: A flow test of 1,300 m deep angled slimhole in Mita, Guatemala. Final hole size was HQ (100 mm). Production was about 1 MWe.

Chemistry:

Provided a slimhole encounters suitable permeability and temperature (or artesian pressure), it will be possible to discharge the well and obtain samples of hot water and separated steam for analysis. In this way, the chemistry and enthalpy of the deep reservoir fluid may be characterised prior to the first production well being drilled. This can be a useful risk reduction approach, particularly in areas where there may be indications of acid magmatic chemistry or secondary bicarbonate fluids prone to scaling. Information related to fluid chemistry (past and/or present) is also provided by the hydrothermal mineralogy observed in the core and cuttings.

SLIMHOLE DESIGN AND DRILLING

Slimhole well design follows the same process as for conventional wells. It is a step by step process that requires consideration of the anticipated conditions of the particular geothermal resource to be drilled, followed by the design of appropriate pressure containment and casing loading limitations. The recommended well design process is defined by the New Zealand Standard Code of Practice for the Drilling of Deep Geothermal Wells (NZS2403:2015).

However, there are special or unique design issues related specifically to slimholes that need to be considered and managed in the design process. In particular the small annular spaces for cementing, type of slurry design required, methods for centralising casing, and choice of the smaller tubing connections (or core rod connections) are important considerations. It has to be noted that slimholes can reach the same very high temperatures that conventional drilling encounters, and although well control is generally easier than with larger diameter wells, the casings are put under similar stresses and cementing integrity is just as essential for safe well completion. An example well design outline for a 1,000 m deep slimhole is provided in Figure 4.

Casing Details	Hole Size	Casing Shoe Vertical Depth (meters)	Casing Shoe Temperature	Remarks
9-5/8" OD Grade K55 43.5 or 36 ppf	12-1/4"	6	Ambient near surface	Conductor - drilled and set with rig
6-5/8" OD, Grade K-55 20 ppf R3 Seamless	PQ core, open out to 8-1/2"	100	< 100 °C	Cement casing back to surface. Set-up 7-1/16" BOP equipment on 6-5/8" casing
4-1/2" OD Schedule 40 pipe welded connections	PQ core, hole size open out to 5-3/4"	400	210 °C	Cement casing back to surface. Set up 7-1/16" (or 4-1/16") BOP equipment on 4-1/2" casing
3-1/2" OD Schedule 40 flush joint connection perforated	HQ	1000	250 °C	Squat on bottom (can core NQ and leave NQ rod perforated if encounter HQ coring difficulties. Uncemented liner

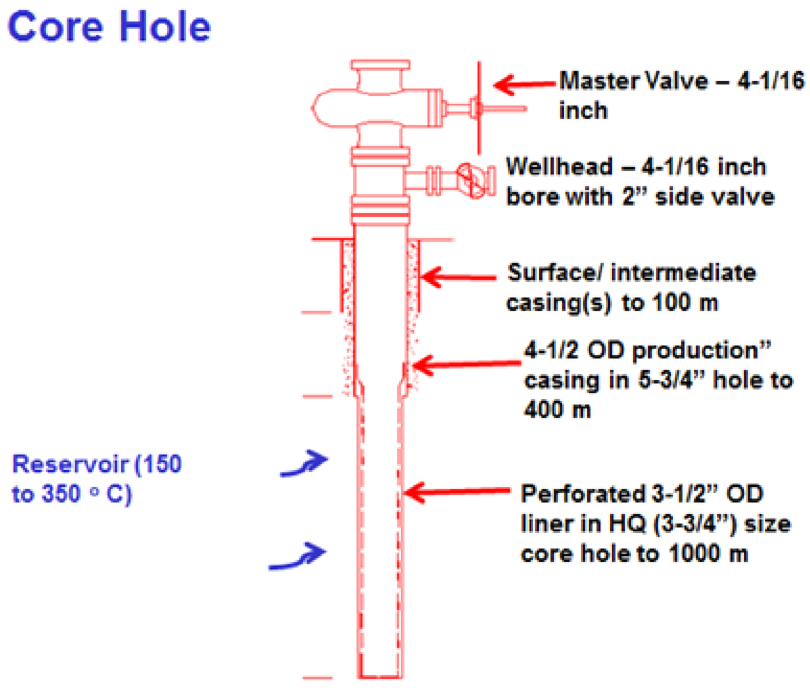

Figure 4: Typical well construction details for a 1,000 m cored slimhole

Compared to large rigs used for production drilling the rigs used for slimhole drilling are relatively small, often self- propelled and have to be jacked up above the ground to accommodate the Blowout Prevention Equipment (BOPE) needed to maintain a safe drilling operation for any geothermal well. For coring rigs without any pony sub or any headroom below the rotary table, the vertical clearance required to accommodate the BOPE is provided by constructing a shallow cellar.

Depending on site accessibility and well targeting objectives a slimhole can be drilled vertically or slant. For a slant hole, the mast can be tilted to allow for the drilling of a straight slant hole at any angle ranging from vertical to 45 degrees from vertical. A typical core rig uses high rotational speeds to cut the rock with relatively light core rods. Generally these rigs provide their own cementing equipment, mud services and directional instrumentation.

For the production casing string, the flush jointed connections of core rods are not designed to withstand compressive loadings during thermal cycling in a well. On the first heat up of the well there is a high risk of failure if threaded connections are used in the production casing string. It is for this reason the production casing used for slimhole wells is recommended to be installed using welded casing connections.

Figure 5 shows a typical slimhole coring rig while Figure 6 shows a typical wellhead set up with the BOPE installed on a slant hole – this was drilled at the Mita project in Guatemala (White et al., 2010).

In addition to the pure technical requirements of a slimhole rig there is also a need that operators and crew have a sufficient level of previous geothermal slimhole experience as indicated by a track record of recent successfully drilled wells. Careful contracting is also required with clear evidence for the drilling contractor's financial robustness such that unexpected requirements for additional consumables and spare parts can be immediately met.

Figure 5: Typical slimhole coring rig

Figure 6: Blowout Preventer for slanted slimhole drilling

The water supply requirements for slimholes can vary greatly depending on the type of slimhole drilling. When drilling with smaller diameter rotary drilling, the water requirements tend to scale down from conventional well drilling in proportion to hole area – so may be of the order of 50% of that for conventional wells. Continuous coring systems however require very small maximum flowrates (~40 lpm, compared to 2,000-3,000 lpm for conventional wells) and can readily be supplied by water carried by small tanker. The challenges with available water supplies may dictate the type of drilling that can be achieved initially. In very challenging locations, slimholes may give the confidence necessary to invest in water supply infrastructure to provide the necessary requirements for larger and deeper wells.

One of the differences with conventional drilling is that slimhole drilling operations are more commonly undertaken by a single contractor who is typically the rig owner. This contractor will provide all of the services and materials on site under one umbrella contract.

Such contracts are still best delivered using an independent engineer that provides well design, drilling plans and supervision so as to look after the Owner's interests in the operation. While a fixed price per metre (as sometimes used in the minerals industry) may provide some protection for the Owner, the drilling company will want to complete the well but may not do everything necessary to have a sound and stable geothermal well that provides the necessary data and long-term mechanical integrity for the Owner. If the contractor comes from a minerals background and proves to be "out of their depth" in geothermal drilling, then it is possible that without good supervision the wells will take unduly long or not reach their targets, which is not in the Owner's interest. Table 2 provides a summary of the technical aspects of slimhole and conventional wells.

Table 2: Comparison between common slimhole and conventional drilling approaches

Item	**Slimhole Drilling**	**Conventional Drilling**
Rig size for at least 1,000 m deep well	Small truck mounted	Large (more horsepower)
Number of truckloads for moving rig/ consumables	6 to 10	40 to 80
Production hole diameter	2.98" (NQ) to 3.78" (HQ)	8-1/2" (standard), or 9 5/8" (large)
Approximate time to complete 1,000 m	40 days (24 hours per day, 7 days per week)	20 days (25 days for 1,500 m), (24 hours/ day, 7 days/week)
Approximate rig pad size	40 m x 40 m	100 m x 70 m
Storage area	40 m x 40 m	200 m x 200 m
Access road	Single lane track or helicopter	2 lane with no steep grades
Highest structure	Mast up to 15 m above ground	Mast up to 45 m above ground
Waste sump volume	250 cu m approximately.	1, 000 cu m approximately, maybe larger.
Noise	Not a significant issue.	Significant in close proximity to site.
Peak water supply requirements	2,000 cu m per day for small rotary holes, 60 cu m per day for coring HQ holes.	3,500 cu m per day.

PROJECT DEVELOPMENT IMPLICATIONS

The following are some of the characteristics of slimholes that will have an impact of project risk, cost and schedule.

Early Infrastructure:

With many projects now being explored in remote and challenging terrain, the scale of access roads and water supplies required can have costs greater than the actual well drilling process. Conventional drilling with many personnel and services and large volumes of consumables and materials requires good all weather access for the high volume of traffic and large truck loads. The very high day cost of conventional drilling drives a high quality of infrastructure to avoid any costly down time on drilling operations. Typically this infrastructure is built to a semi-permanent standard on the assumption that when the resource is discovered drilling operations will continue past the exploration stage.

The smaller scale of equipment, materials, water supply and services needed for slimhole drilling may enable the use of smaller and lower standard access infrastructure. Roads may be of a quality typical to those used for mineral exploration drilling and only upgraded later if the resource is discovered. In some settings a helicopter supported operation might be a preferred option for accessing a remote exploration location in difficult terrain. This approach has been successfully applied for several slimhole drilling campaigns in Chile (e.g., Laguna del Maule, Tolhuaca). The water supply needed for cored type slimholes is less than 10% of that for conventional drilling and is thus easier to source locally near the drilling operation (e.g., with a temporary stream catchment).

Drilling and Infrastructure Cost:

Depending on the location and rig availability, a 1,500 m deep slimhole (with HQ bottomhole dimensions) may cost approximately US$1.3-1.8 million. A standard 8-1/2 inch diameter geothermal production well to this depth would typically cost 3-4 times as much. This means that an operator can theoretically drill several slimholes for the same cost of one standard diameter well, and achieve exploration coverage of a wider area.

In addition to the actual cost of drilling, the construction of roads, well pads, and water supply (see above) should all have lower cost (typically ~50 % or less) for a slimhole rig where the supporting infrastructure requirements are substantially less than those needed for a normal rotary drilling approach.

Permits and Land Access:

Conventional exploration wells are expected to be retained as a productive asset for any subsequent project development and so the land for exploration needs to be secured (through ownership or suitable lease) for the expected life of the project. This process can take considerable time and may mean early relocation of existing occupants, which may not be necessary if the project does not proceed. If slimholes are not intended to be permanent assets (possibly being abandoned after testing) then land acquisition may be avoided by more temporary lease arrangements that suit all parties.

Environmental permitting will typically also be quicker and cheaper in some jurisdictions due to the smaller environmental footprint, lower site impacts and temporary nature of the exploration drilling and testing activities.

Schedule:

The time for construction of roads, well pads, water supply and rig mobilisation can be very much less for a slimhole rig campaign compared to one using large rotary drilling rigs. The smaller footprint for well pads can mean they are constructed faster and may be located in more ideal locations possibly even closer to populations.

Typically slimhole drilling with a coring rig will involve a single contractor for materials and services and so procurement may be simpler and faster than a multi-package drilling program. However, an initial shortage of experienced slimhole drilling contractors in Indonesia may require mobilisation of an international contractor.

Where time is critical to achieve exploration outcomes (e.g. to meet regulatory or financial deadlines or limited budget), slimholes may be the only realistic option.

A deep slimhole approach, when used to deliver exploration outcomes (primarily being the proving of the presence of a useful reservoir, and possibly extending to define the areal extent of such a reservoir) should not extend a development schedule because it is not inserting an additional drilling stage. Instead it is achieving the exploration/discovery stage with a different method, with subsequent delineation and appraisal drilling still being achieved with conventional wells. A good exploration drilling program with several deep slimholes should be able to drive increased rates of success in the subsequent drilling phases.

In some projects, slimhole drilling has been done in parallel with conventional exploration drilling to help accelerate the schedule for resource delineation (proving that sufficient reservoir exists to support long term production). An example of this was at Wayang Windu where 4 x 1,500 m deep vertical slimholes were drilled to help confirm reservoir extent while production drilling focused on the central resource area. This not only saved on drilling costs, but helped accelerate the time needed to meet the lender’s requirements for proving resource bankability.

Perhaps the biggest impact that using slimholes can make on schedule is when the cost or difficulty of conventional drilling means that this exploration phase of drilling does not start until a range of other factors (such as risk equity funding and a high tariff) are in place. In these cases, the projects can be stalled for decades following the surface exploration activities.

PROJECT FINANCIAL IMPACTS

Return on Investment - Internal Rate of Return (IRR):
Where projects are developed on an Independent Power Producer (IPP) basis they are oftentimes owned by a Special Purpose Company (SPC) and developed on a Non-Recourse Finance basis. In this situation Developer equity is usually required to fund the SPC activities up to the Financial Investment Decision (FID) gate. Greenfield geothermal projects usually take at least 4 years from concession capture to FID, and frequently longer. During this period exploration, delineation and finally appraisal wells are progressively drilled to respectively prove the resource, then delineate the resource and finally get to the proven MWe under wellhead that the lenders require at FID. Where the exploration and delineation drilling involves full size wells rather than slimhole wells, the Developer equity is larger and has to wait longer for its return. This means the tariff required must be higher.

An argument often made in favour of full size exploration wells is that since slimholes produce very little if any MWe (megawatt electrical equivalent), then more appraisal wells will be required and all the slimholes are doing is adding more total cost to the project. But actual analysis shows that the increased success rates of conventional drilling due to earlier slimholes more than offsets the cost of the slimhole drilling.

This is demonstrated in Figure 7 showing reduced capital over a similar timeframe is required to reach Commercial Operation Date (COD) using deep slimholes. The reduced capital cost has the opportunity to allow a reduced tariff for a given Internal Rate of Return (IRR), or increased IRR for a given tariff.

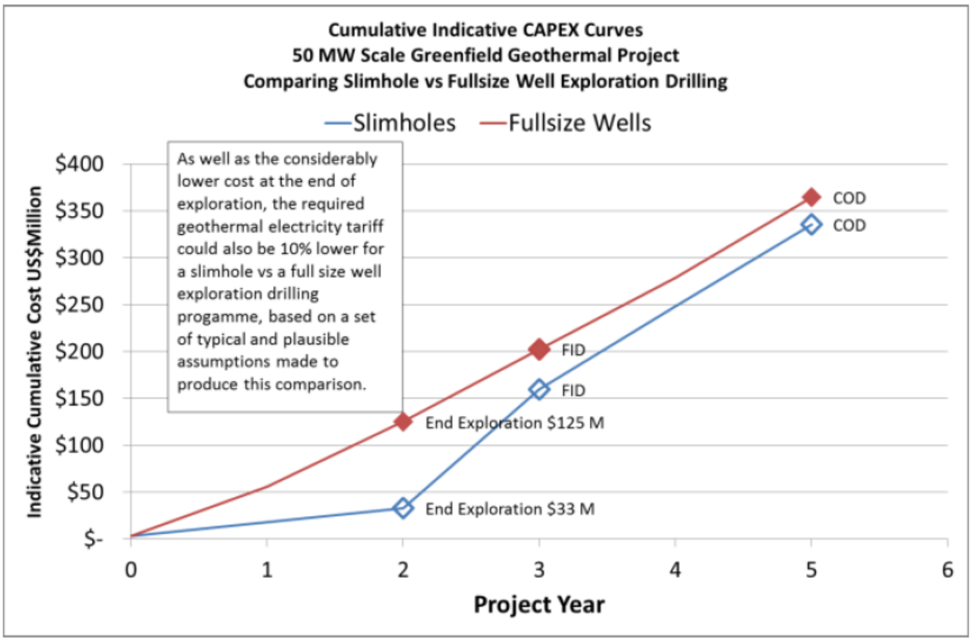

Figure 7: Indicative CAPEX for a 50 MWe project with and without use of deep slimholes. Red curve is using only conventional drilling, blue curve is using deep slimholes for the exploration phase. FID = Financial Investment Decision, COD = Commercial Operation Date.

Cost of Failure:

Throughout the exploration and delineation drilling phases of a greenfield geothermal project there is a risk that there is no resource, or that the resource will be too costly to develop, or that the project may not proceed to FID. Developers will commonly apply a decision tree process to assess the probability that they will exit the project at each of the main decision gates. At exit, some or all of the cost expended to that point will be lost for no return.

Geoscientific data collected may indicate a significant chance that exploration drilling may not find a useful resource. For example, this may be because there are few, if any, strong thermal features, and much of the evidence for a system rests on geochemistry from weakly flowing springs and positive geological and geophysical indications. We see some projects at this stage where the probability of discovering a useful resource may be much less than 50%. Under these circumstances there is a considerable chance that equity invested in exploration and delineation drilling may be lost. If the decision is made to abandon the project based on the results of the first wells, then the best result for the Developer would be to have spent the smallest amount of equity on the drilling campaign. This concept emphasises the utility of a slimhole exploration and delineation program for high risk projects, and is demonstrated in Figure 8.

[Note that Probability of Discovery is now officially defined for geothermal in the UNFC 2009 resource classification system which is endorsed by the International Geothermal Association (IGA): “Specifications for the application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to Geothermal Energy Resources”].

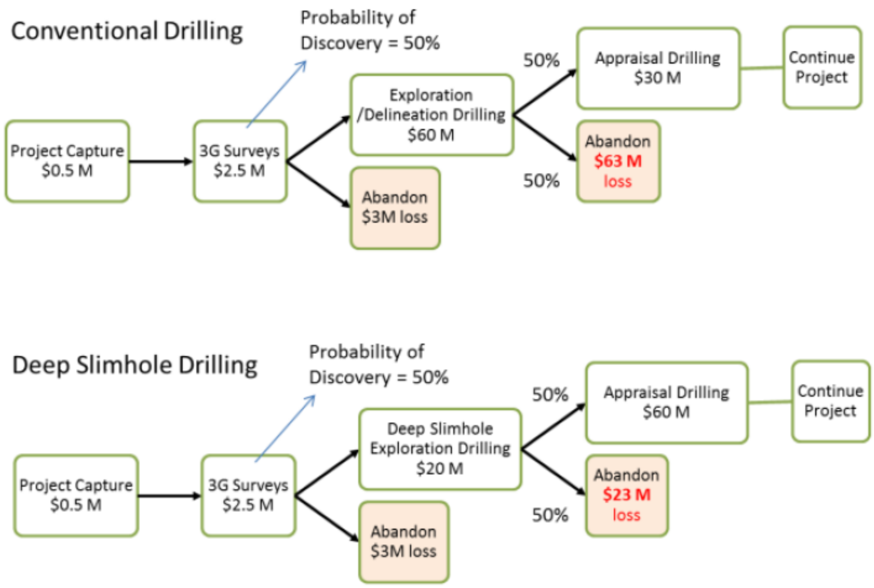

Figure 8: There is potential to exit a project at each major phase if the project does not prove viable. If Probability of Discovery from exploration drilling is low, then the use of deep slimholes puts less capital at risk than when using conventional wells for the exploration phase.

Risk Adjusted Net Present Worth (rNPV):

This burden of the cost of failure has to be evaluated and can be estimated using probability weighting of the NPV stream for the project.

The highest risk adjusted net present value (rNPV) for the project may be achieved by a slimhole exploration and delineation program, particularly where the Probability Of Discovery (POD) of actually finding a resource is low.

As one of our very experienced geothermal development clients recently noted "We try and prove that the resource DOES NOT EXIST as cheaply as possible".

A big reason for following this approach is that for a geothermal developer with a portfolio of projects, they have to carry the cost of failures across the business. It is not enough to just do the economics for the success case: a competent and responsible developer has to account for the "failures" as well.

Any tariff structure for geothermal should consider this, but equally in a fixed tariff environment, reducing failure cost will improve the viability of projects.

CASE STUDY EXAMPLES

We have compiled a dataset of 45 geothermal fields from 14 countries where slimholes have been utilized (Figure 10 and Table A1). Slimholes have been flowed at 28 of these projects (62%), and slimholes at 33 of these projects (73%) have successfully intersected the target reservoir. Below are some specific examples of projects included in this database.

Wayang Windu, Indonesia

The first exploratory slimhole was drilled at the Wayang Windu field in 1993-1994 by Pertamina. Another four slimholes were drilled in 1996 by Mandala Nusantara Limited, the initial developers of the field. This later slimhole drilling was undertaken in parallel with the drilling of initial deep production wells in the central part of the field, as part of an accelerated exploration and development drilling program. The objective of slimholes was to delineate the geothermal reservoir to help accelerate financial closure (Figure 9). The slimholes were rotary drilled in the upper section and then continuously cored to a total depth of 1,500 m and constructed as permanent monitoring wells.

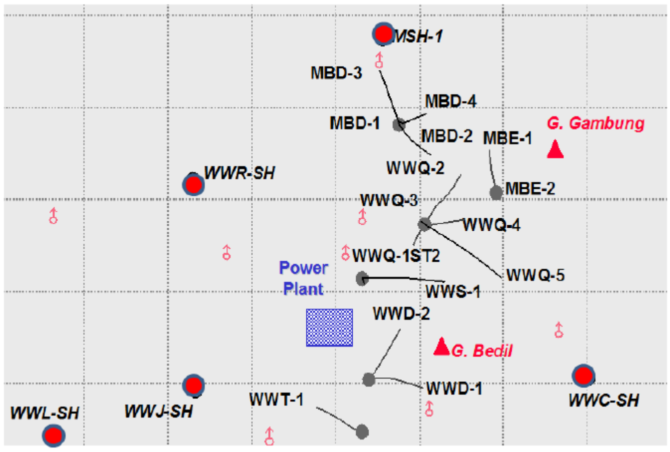

Figure 9: Wayang Windu early well field layout. Delineation slimhole locations shown as red circles and denoted by –SH suffix

In addition to helping prove the extent of the resource and validating the field concept model, the slimholes were a key component in the development of a four facies volcanic model of the field (Bogie and MacKenzie, 1998). The continuous core samples were valuable in supplementing the geological and formation imaging information obtained from the larger production wells. The lithostratigraphic information was particularly important in helping to understand the distribution and physical characteristics of clay-rich tuffaceous siltstone beds which are widespread across the Wayang Windu area (Bogie et al., 2008). These beds were responsible for significant formation related drilling difficulties during the early stages of the deep production well drilling campaign. They were difficult to delineate from cuttings generated by conventional rotary drilling due to their geomechanical instability when hydrated by drilling fluids and propensity to contaminate cuttings derived from the underlying strata. The continuous core samples obtained from the slimholes proved highly valuable in this regard.

The slimholes were all constructed with continuously grouted casing and a perforated liner within the deeper sections of the wells. This enabled temperature and pressure measurements to be made to total depth. One of the slimholes, WWR, also sustained discharge of low pressure steam for several days.

The four deep slimholes drilled in 1996 were all completed close to their design depth without any major technical difficulties. The drilling process was completed efficiently and, in addition to achieving the desired technical outcomes, the drilling budget and program objectives were successfully met. A key reason for this successful outcome was the use of suitably specified and well maintained drilling equipment that was procured from the USA. This equipment was provided by Tonto Drilling Inc. and comprised a truck-mounted Universal Drill Rig Model 1500 (Figure 11). The use of a drilling contractor with substantial experience in geothermal drilling conditions was also important for completing a successful drilling campaign and for the wells achieving their intended objective.

Figure 11: Combined slimhole (orange rig in foreground) and conventional well drilling (white rigs in background) approach used at Wayang Windu, Indonesia in 1996.

APAS KIRI, MALAYSIA

A recent slimhole has been drilled at the Apas Kiri project in Sabah, Malaysia in the NE of the island of Borneo (Libbey et al., 2017). The field is associated with the Pleistocene-aged Mt. Maria volcano, the westernmost of a chain of volcanic features that are situated along the Semporna Peninsula. The result of initial surface geoscientific exploration provided indications of a medium to high temperature resource (Siong et al., 1991; Barnett et al., 2015), however, there was considerable uncertainty owing to the nature of the surface manifestations (the hottest features are 75°C effervescent springs) and ambiguity in the resistivity model of the system.

To further assess the economic potential of the Apas Kiri prospect, slimhole AK-1D was drilled vertically to a depth of 1,449 m from a pad on the SE flank of Mt. Maria. The upper 310 m of the well was drilled using percussion-air and tricone methods and the remainder was drilled using a diamond core bit. The bottomhole diameter is NQ, with an HQ production casing cemented at 1,359 mMD.

Core samples from AK-1D revealed a subsurface stratigraphy dominated by massive and brecciated dacite and andesite flows, with intercalated volcaniclastic units. The rocks are highly fractured, faulted, and veined and display a prograde hydrothermal alteration sequence typical to geothermal systems situated in volcanic terranes.
Initial temperature runs were conducted during drilling pauses using a HOBO® U12-015 data logger and maximum registering thermometers (the latter which were useful for providing measurements beyond the data logger's limit of ~150°C). Data provided by these preliminary measurements correspond quite closely with more detailed temperature logs that were collected after the completion of the well (Libbey et al., 2017). Measured temperature profiles display a transition from conductive to more convective gradients at a depth of ~1,100 m, where a temperature of 180°C is reached. Maximum temperatures in the well are exhibited at the bottom of the hole and reach ~200°C. A small temperature inversion near the top of the profile reflects a shallow warm water (likely mixed steam-heated) aquifer. Multiple cement plugs were required to seal off this zone.

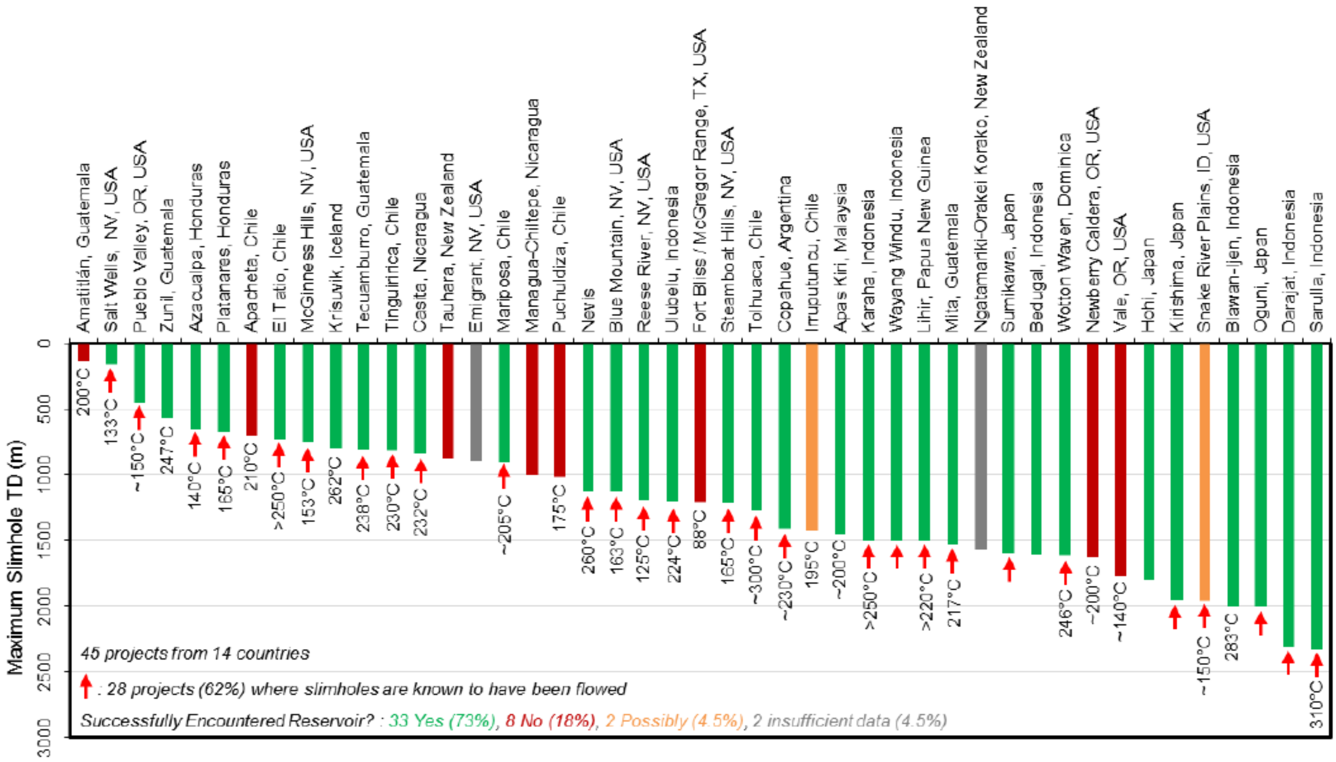

Figure 10: Maximum depth of slimholes utilised at geothermal projects. Maximum temperatures intersected also shown. Red arrows delineate projects where slimholes are known to have been flowed. See Table A1 for more detailed information.

The measured temperatures, rapid heat-up times, and largely convective temperature gradient at the base of the well were all considered successful outcomes of AK-1D. A related success for the project was the observed correlation between the downhole alteration zonation and measured temperature profiles with the conductor in the 3D MT inversion model.

The correlation between the surface and downhole geological, geophysical, and P-T datasets has proven highly valuable for confirming the presence of a medium to high temperature, neutral pH geothermal resource at Apas Kiri. Data made available from the slimhole has greatly assisted with refining the conceptual model of the geothermal resource and defining future well targets. Additionally, the identification of clay-rich volcaniclastic units and shallow warm-water aquifers has provided vital information about "problem formations" that will assist with the planning, design and successful completion of future wells.

Casita

The Casita geothermal project is located in the NW of the Cordillera de los Marrabios of Nicaragua that constitutes part of the volcanic arc that runs through the country (White et al., 2012).

A MT survey and gas chemistry from a single fumarole provided positive results indicative of a steam cap that may be sitting upon a wider liquid resource. Risks from terrain constraints, poor slope stability and the limited occurrence of thermal features that could provide valid geothermometry was addressed by drilling the CSS-1 slimhole in 2011.

Figure 12: Slimhole drilling with a very small well pad enabled well CSS-01 at Casita to be drilled on very steep slopes. Water was carried by water tanker to the site.

It was planned to drill the hole vertically to 1,000 m and to set a production casing at 600 m. Drilling difficulties lead to a reduction of these depths to 842 m and 495 m, respectively. The hole penetrated intercalated andesitic lavas and pyroclastics as had been expected. Several large losses in drilling circulation were associated with many of the fractured lava flows that were encountered and this required the placement of numerous cement plugs. Weak argillic alteration was found above the reservoir and much stronger alteration deeper in the well. This deeper alteration did not match with current conditions and appears to have formed during an earlier liquid alteration event where temperatures were lower.

The well produced dry steam (Figure 13) confirming the presence of a steam cap, but it failed to reach its full programmed depth and the occurrence of an underlying liquid reservoir was not fully tested. Nevertheless, the gas geochemistry indicated that this was most likely the case.

Figure 13: Slimhole well CSS-01 on discharge; note that the water vapour is coming out the silencer with none coming from the weir box indicative of a dry discharge.

The CSS-1 slim hole reduced the risk of constructing full size roads, pads and wells in in areas indicated by the MT survey to establish that the MT survey is indicative of the resource. It is anticipated that a full sized drilling program will take place in the near future.

Darajat, Indonesia

Three deep production wells were drilled at Darajat by Pertamina in the late 1970s, and a further 14 by Amoseas Indonesia between 1986 and 1994, when the 55 MWe Darajat Unit I was commissioned. Further exploration between 1996 and 1998 included geophysical and geochemical surveys, and 12 new production wells. Also at this time, 6 deep slimholes were drilled toward the field margins with the purpose of helping to confirm the extent of the steam zone and to develop updated resource capacity estimates. The detailed geological information from these slimholes, together with data from production and reinjection wells, meant that a detailed three dimensional volcanic facies based geological model of the Darajat geothermal reservoir could be constructed (Rejeki et al, 2010). This three dimensional geological model was then used as the basis of a numerical simulation model that Chevron used for making reservoir predictions and informing further field development and operational strategies.

One of the key reasons for using slimhole drilling at Darajat was because it provided a lower cost approach for resource delineation. Providing a reduced environmental impact in challenging terrain due to the smaller equipment and drilling infrastructure requirements was also an important driver for the slimhole drilling approach.

A detailed review of the Darajat slimhole drilling experience is provided by Riza and Berry (1998). The equipment used was the same Tonto Universal Drilling rig set-up used at Wayang Windu. The slimholes were successfully completed and met their objectives at a daily rate of about 40% of the daily cost that was applicable at the time for a large rig drilling approach. Riza and Berry (1998) describe some important learnings from the slimhole drilling campaign including:

- the use of a rotary drilling approach for hole sections which prove difficult for coring or with persistently low drilling penetration rates.
- options for retrieving any stuck pipe or 'fish' left in hole due to drilling difficulties are limited compared to a conventional large rig approach. This required needing to drill a sidetrack leg in some wells.
- some issues with increased torque when coring deeper sections successfully alleviated through the use of lubricant additives to the drilling fluid system.
- formation related drilling difficulties in friable red clay-rich units could be stabilised by cementing though did prove time consuming to deal with and drill out.

Riza and Berry (1998) tabulated the depth of the wells drilled, and we have calculated the days per 1,000 m drilled for these (Table 3). Two wells (S-3 and S4) were deepened using a larger coring rig, and eventually the reservoir was encountered with all but one well. The deepening of S-4A encountered many problems, but the average drilling rate for all other drilling was about 39 days per 1,000 m of depth.

Table 3: Depth vs drilling duration for Darajat slimhole drilling. Based on data provided by Riza and Berry (1998).

Well	TD (m)	Days / 1,000m	Entered Reservoir
S-1	1,356	38	Yes
S-2	1,449	59	Yes
S-3	1,567	41	No
S-4	1,602	32	No
S-5	2,300	24	Yes
S-6	1,932	30	No
S-3A	2,337	45	Yes
S-4A	2,213	152	Yes

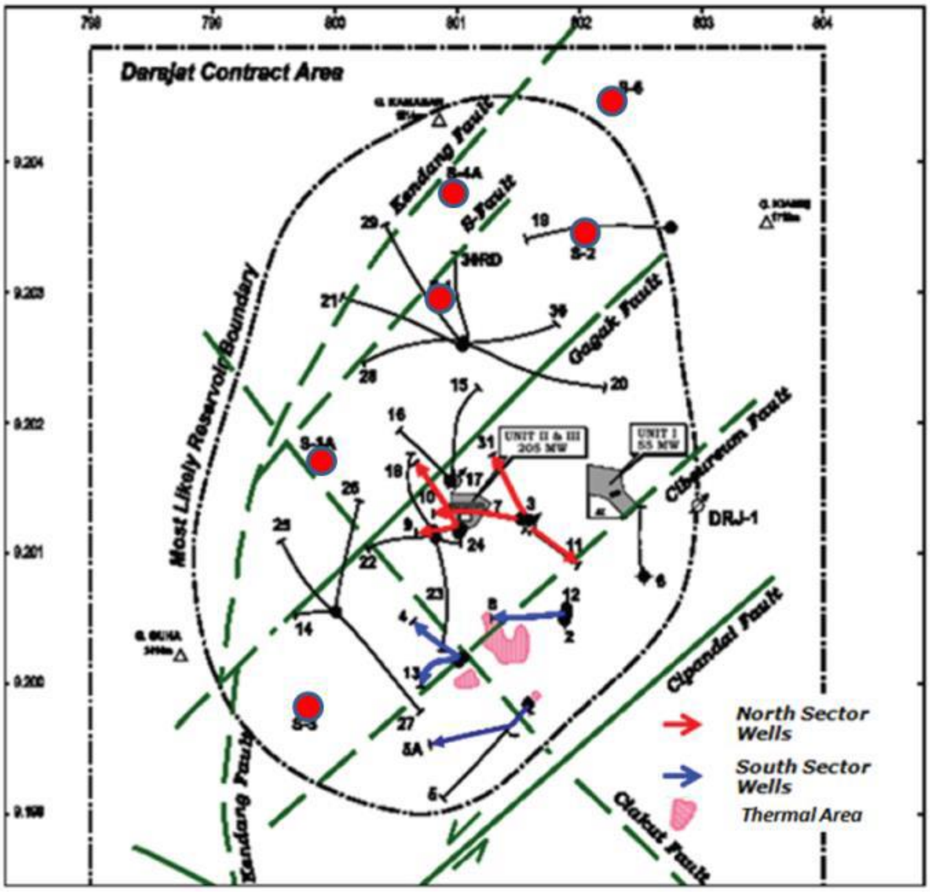

Figure 14: Darajat steamfield, with the slimholes drilled in 1996-98 circled in red. The coverage of these wells gave confidence in the extent of reservoir, particularly in the north, and deep deviated wells have not been drilled in that area.

Mita, Guatemala

The Mita geothermal system is located at Cerro Blanco in southern Guatemala and hosts a high grade epithermal gold deposit. While initially identified as a highly prospective mining project, early exploration drilling indicated a large volume of hot water in close proximity to the ore deposit. Environmental permitting requirements meant that any mining would need to be undertaken by underground methods, so a significant early challenge was to dewater and cool the rocks before mining could safely proceed. At the same time that the mine dewatering requirements were being defined it was identified that exploitation of the associated geothermal resource was an option for providing power generation to the project.

Field geology, geochemistry and geophysical surveys to investigate the geothermal resource were completed in 2007 and 2008, but there was still considerable uncertainty as to the location and conceptual understanding of the geothermal system. Because of this uncertainty, the next stage of investigation comprised four inclined (at up to 30° from vertical) slimholes drilled to depths of 1,200-1,530 m. The first of these holes targeted the interpreted upflow zone, but was not particularly hot, and had very low permeability. The core from this hole indicated that interpretation of the MT data was complicated by fossil hydrothermal alteration, including alteration associated with the epithermal mineralisation, and a thick sequence of clay-rich sedimentary rocks, overlain by young lava flows. The second and third slimholes were also not very permeable, but they were hotter and did discharge, and it was not until the fourth hole that good permeability was encountered. Long term production testing of the last well enabled detailed characterisation of the reservoir production testing and enabled the discharge chemistry to be evaluated (Figure 3).

For the Mita project, slimhole drilling was used to test the initial conceptual model, which was poorly constrained after surface exploration so was considered to have a low probability of drilling success. It enabled the resource to be outlined (to a degree) for a much lower cost than would have been the case with production wells, and helped inform a strategy for drilling production and injection wells for a potential power generation development.

Lihir, Papua New Guinea

The Lihir geothermal field is unusual in many ways, not least of which is that the first deep geothermal wells were drilled after hundreds of shallow holes, which delineate the superimposed gold deposit. To assess a proposed 40 MWe expansion to the geothermal power plant developed to supply electricity to the mining operation, four step-out deep exploration slimholes were drilled between 2007 and 2008. These wells were deviated at 30° from vertical and drilled to a total depth of 1,500 m to evaluate the extent of geothermal resource to the northeast and northwest of the existing production sector. Core samples from these slimholes provided significant new information, particularly in characterising the monzonitic intrusive complex in the reservoir, since although there are many standard geothermal wells in this area, no cores were taken during geothermal drilling, and no drill cuttings were collected after total losses were encountered, typically at about 600 m.

Drilling and testing of two slimhole wells (GW47 and GW52) confirmed zones of fracture permeability and significant temperatures (> 220°C). The slimholes thus provided new geological data that could not be obtained from conventional geothermal wells. They provided cost-effective temperature, pressure and permeability data from the reservoir to the north and east, some 3 km beyond the previous area of proven resource. This new information was used to guide the geothermal exploration/development strategy for the mining operation.

Laguna del Maule (Mariposa), Chile

Magma Energy Corp had largely completed field geology, geochemistry and geophysical surveys at Laguna del Maule by the end of March 2009, but the exploration concession was due to expire in July and the positive results indicated by the field studies prompted the company want to apply for an exploitation concession. To do that, they had to prove that the concession contained a resource of a suitable size and temperature to support a geothermal development.

The resource size was indicated by the MT geophysics survey data, but at least one well had to be drilled into the reservoir to prove the resource temperature. With the resource located 10 km from the nearest road, and 1,200 m higher in elevation, full sized production wells were not an option within the available timeframe. However, with a helicopter supported drilling operation (Figure 15), by early June, a vertical slimhole was completed to a sufficient depth (659 m) and a sufficiently high downhole temperature (over 200°C) was recorded. An inferred resource of 140 MWe was declared, and an application for an exploration concession was submitted before the deadline in July.

Figure 15: Helicopter supported slimhole drilling campaign at Laguna del Maule, Chile

In this example, helicopter supported slimhole drilling was the only feasible option to prove reservoir temperatures in the time available. Because of equipment weight limitations, a relatively small rig was used. Despite the small rig size and challenging conditions, including the modification of Kuster PT logging procedures for running in a BQ (46 mm) sized hole and the onset of winter in the Andes, the initial well at Laguna del Maule achieved its objective by drilling down to 659 m so that downhole temperatures could be measured.

CHALLENGES OF DEEP SLIMHOLE DRILLING

The biggest challenge with using deep slimholes for reservoir exploration is achieving the required depth. The relatively small hole sizes means that there are small tolerances between drilling string and the hole such that equipment can easily be stuck. Additionally, there are fewer options for adding additional casings in the event of problems. The small diameter tubulars also can face torque issues at deep levels.

The solutions to these problems lie in planning and drawing on the available geothermal experience with slimhole drilling. Riza and Berry (1998) give a good description of the measures they took with materials and procedures at Darajat in the 1990's. Some recent slimhole drilling programs have used contractors that are familiar with coring for mineral exploration, but have not budgeted for contracting geothermal drilling engineering expertise nor the use of suitable materials. The use of high temperature drilling fluid lubricants and rod/barrel grease is essential.

The small rigs used for coring operations may limit the depth that the upper casings can be placed. However, provided that shallow upper cool aquifers are cased off, a production casing does not necessarily need to reach the top of reservoir, and setting a "production" casing in the clay cap region may be fine for exploration purposes.

In situations where a slimhole fails to meet its exploration objectives or is unable to reach the target total depth it is usually challenging to successfully work the well over in the same way that can be done for conventional sized wells. This is mainly due to the smaller equipment and casing configuration that is used for slimhole drilling, although there are some examples of slimholes that have been successfully modified during drilling due to formation related difficulties encountered. An example of this is at Darajat where several holes were either deepened and/or sidetracked to depths in excess of 2,000 m due to caving formation and stuck pipe incidents (Riza and Berry, 1998).

Slimholes can be flowed, but not at the same mass flow rates at larger diameter wells, so while they can determine the existence of good permeability, they cannot readily test for reservoir drawdown effects.

Various attempts have been made to extrapolate slimhole productivity to full sized production well productivity (e.g. Garg and Coombs 1997). While it is not possible to accurately determine the expected behaviour of production wells, modelling can provide useful indications that are good enough to evaluate expected project economics for the purpose of justifying the higher cost of larger wells in an appraisal drilling program.

ADDITIONAL USES OF SLIMHOLES

While slimholes are typically too small for production on large scale projects, they do have valuable use if retained open on a project:

Pressure Monitoring:

Slimholes are ideal for monitoring pressure in a reservoir, providing valuable early tracking of reservoir pressure possibly within the main production areas but possibly also on the margins of the field if used as delineation wells. This is highly valuable, as typically all successful wells are used on most projects, leaving none for designated long-term monitoring purposes. With no central monitoring wells, it can be challenging to measure pressure change in some systems if relying only on well shut surveys during plant shutdown and maintenance periods.

Sentinel Monitoring:

Slimhole wells located on margins of field can monitor both pressure and temperature changes that may occur from the incursion of marginal groundwaters or previous outflows for the system. This acts as an early warning system of undesirable effects in the productive reservoir. Sentinel wells can also be used for monitoring the effects of production on neighbouring undeveloped systems to assist with proactive protection of areas which may be culturally or environmentally sensitive.

Condensate Injection:

In smaller projects (10-25 MWe) condensate flows can be modest and may be accommodated by a slimhole with good injectivity characteristics. The need for condensate disposal is often a last minute consideration after the prioritisation for obtaining the main production and injection capacity, and a good slimhole in the central part of a field may suit the purpose.

Production and Injection for Small Projects:

Slimholes drilled to explore resources in remote locations can be used for small scale geothermal generation projects that may serve long-term as remote power generation (Vimmerstedt, 1998). Such small developments may also provide the confidence for considering the cost of drilling larger wells and a transmission connection for a remote system that would not otherwise be explored.

Table 4. Comparison between slimhole drilling and conventional wells

Feature	Slimhole Drilling	Conventional Drilling
Data collected		
Geology	Full core and accurate depth and thickness information (cored slimholes) Fracture characteristics visible and measurable	Yes - Cuttings with occasional core. Sophisticated logs (FMI, acoustic) needed to get fracture imaging
Temperature	Can measure temperatures more reliably while drilling. PT logs at completion	Yes – Requires heating after well completion to get reliable temperatures
Permeability	Completion tests and injectivity	Yes - Completion tests and injectivity
Productivity (well flow)	Can flow. Must estimate larger well capacity.	Yes – can flow and test at operational conditions
Chemistry	Samples can be taken from flowing well. Less flowrate during drilling may give quicker stabilisation of flow chemistry	Samples can be taken from flowing well.
Infrastructure and Costs		
Roads and well pads	Small well pads (40 x 40 m) Single lane track (temporary) or helicopter	Large well pads (70 x 100 m) 2 lane road with no steep grades
Water Supply	Coring rig operations may need as little as 40 lpm	Circulation rates up to 3000 lpm. Major water supply infrastructure.
Land permits	Possibly temporary lease (plug and abandon) to reduce time for access	Permanent ownership / rights needed to retain wells for later production / injection.
Cost		
Infrastructure costs	Modest	Can be high for difficult terrain
Wells costs	Typically 25-40% of conventional wells	
Development Implications		
Cost of failure	Modest	High
Schedule	Reduced time to start drilling and complete Exploration stage Assist delineation and appraisal stages at lower cost	
Overall project cost	Can be less than conventional wells	

CONCLUSIONS

Some concerns commonly expressed about using slimholes for geothermal exploration are that they do not reach deep enough into the reservoir, cannot demonstrate well productivity and simply introduce another drilling stage that adds to overall project schedule and cost.

While some recent projects in Asia have had drilling problems and struggled to complete slimholes to the target depth in reasonable timeframe, slimhole wells drilled over 20 years ago were successfully drilled to depths of over 2,000 m in Indonesian geothermal systems. This approach has also been applied elsewhere in the world with good results in terms of completing wells safely and successfully, while also achieving desired exploration outcomes.

When conducting slimhole drilling programs for geothermal exploration, it is not sufficient to only draw from local mineral drilling industry experience. The special characteristics of subsurface geothermal conditions, and the complex terrain associated with many geothermal environments needs to be factored into slimhole well design and drilling plans. Supervision by personnel with geothermal-specific expertise is essential during slimhole drilling, just as it is for conventional well drilling.

With a downward pressure on tariffs because of the availability of lower cost alternative energy options, and the exploration of more challenging, higher risk prospects, the geothermal industry cannot afford the high cost of exploration drilling in many cases. This barrier of high equity capital at high risk early stages of geothermal project is stopping projects from moving forward in many regions globally. Reducing the magnitude of capital at risk in exploration through the use of slimhole drilling programs has the opportunity to get more projects proven and eventually “bankable”.

A full set of comparisons between slimhole drilling and conventional wells is provided in Table 4

ACKNOWLEDGEMENTS

The support of Jacobs in supporting the writing of this paper is gratefully acknowledged.

REFERENCES

Aravena, D. and Lahsen, A. A geothermal favourability map of Chile, preliminary results. GRC Transactions, v. 37, 2013.

Asturias, F. Reservoir assessment of Zunil I & II geothermal fields, Guatemala. UNU-GTP Reports, no. 3, 2003.

Barnett, P.R., Mandagi, S., Iskander, T., Abidin, Z., Amadaloss, A., and Raad, R. Exploration and Development of the Tawau Geothermal Project, Malaysia. Proceedings World Geothermal Congress, 2015.

Bogie, I., Kusumah, Y.I., and Wisnandary, M.C. Overview of the Wayang Windu geothermal field, West Java, Indonesia. Geothermics, Vol. 37, No. 3, pp. 347-365, 2008.

Bogie, I. and MacKenzie, K.M. The Application of a Volcanic Facies Model to an Andesitic Stratovolcano Hosted Geothermal System at Wayang Windu, Java, Indonesia. Proceedings 20th New Zealand Geothermal Workshop, 1998.

Boseley, C., Bignall, G., Rae, A., Chambefort, I., and Lewis, B. Stratigraphy and hydrothermal alteration encountered by monitor wells completed at Ngatamariki and Orakei Korako in 2011. Proc. New Zealand Geothermal Workshop, 2012.

Code of Practice for Deep Geothermal Wells. New Zealand Standard: NZS 2403:2015.

Combs, J., Garg, S. K. and Pritchett, J.W. Geothermal slim holes for small off-grid power projects. Renewable Energy, Vol. 10, No. 2/3, pp. 389-402, 1997.

Combs, J., Garg, S. K. Discharge Capability And Geothermal Reservoir Assessment Using Data From Slim Holes. Proceedings World Geothermal Congress, 2000.

Cumming, W.B., Vieytes, H., Ramirez, C.F., and Sussman, D. Exploration of the La Torta geothermal prospect, Northern Chile. GRC Transactions, v. 26, 2002.

Dal – In.te.sa. SpA. and Geotermica Italiana S.r.l. Estudio de prefactibilidad geotermica en la region central de Honduras, 6) Perforacion exploratoria y geo-petrographia, Informe Final. ENEE, Impresa National de Energia Electra, Tegucigalpa, Honduras, 1988.

Daud, Y., Nuqramadha, A., Fahmi, F., Pratama, S.A., Rahman, K.R., and Subroto, W. Discovering “hidden” geothermal reservoir in Blawan-Ijen geothermal area (Indonesia) using 3-D inversion of MT data. Draft paper, 2017.

Delahunty, C., Nielson1, D.L. and Shervais, J.W. Deep Core Drilling of Three Slim Geothermal Holes, Snake River Plains, Idaho. GRC Transactions, Vol. 36, 2012.

Finger, J.T. and Jacobson, R. Slimhole drilling logging and completion technology – an update. Proceedings World Geothermal Congress 2000.

Finger, J., Jacobson, R., Hickox, C., Combs, J., Polk G. and Goranson, C. Slimhole handbook: procedures and recommendations for slimhole drilling and testing in geothermal exploration. Sandia Report SAND99-1976, 1999.

Garg, S.K. and Combs, J. Use of slim holes for geothermal exploration and reservoir assessment: A preliminary report on Japanese experience. Sandia National Laboratories Technical Report SAND93-7029, 1993.

Garg, S.K. and Combs, J. Slim holes with liquid feed zones for geothermal reservoir assessment. Geothermics Vol. 26, No. 2, pp. 153-178, 1997.

Gehringer, M. and Loksha, V.C. - Geothermal Handbook: Planning and Financing Power Generation. Washington DC: World Bank Group, Energy Sector: 2012.

Goff, S.J., Duffield, W.A., Goff, F.E., Heiken, G.H., and Janik, C.J. Application of scientific core drilling to geothermal exploration: Platanares, Honduras and Tecumaburro volcano, Guatemala, Central America. Proc. 7th Int’l Symp./Observation of Continental Crust Thru Drilling, Santa Fe, NM, April 25-30, 1994.

Goff, S.J., Goff, F., and Janik, C.J. Tecuamburro volcano, Guatemala: Exploration gradient drilling and results. Geothermics, v. 21, no. 4, 1992.

Gunderson, R., Ganefianto, N., Riedel, K., Sirad-Azwar, L. and Suleiman, S. Exploration Results in the Sarulla Block, North Sumatra, Indonesia. Proceedings World Geothermal Congress, 2000.

Haraldsson, I.G. Geothermal activity in South America: Bolivia, Chile, Colombia, Ecuador, and Peru. UNU-GTP and LaGeo Short Course on Conceptual Modelling of Geothermal Systems, El Salvador, Feb 24-Mar 2, 2013.

Henkle, W.R. Phase 2 Reese River geothermal project – Slim well 56-4 drilling and testing. Western Geothermal Partners Technical Report, 2008.

Hickson, C., Rodriguez, C. Siefeld, G., Selters, J., Ferraris, F., and Henriquez. Mariposa geothermal system: A large geothermal resource in Central Chile (320 MWe inferred). Sernageomin Bulletin, 583-585, 2011(?).

Hochstein, M, Sudarman, S. History of geothermal exploration in Indonesia from 1970 to 2000. Geothermics 37, 2008.

Khubaeva, O. Geothermal mapping in the Krysuvik geothermal field. UNU-GTP Reports, no. 8, 2007.

LaFleur, J. and Hoag, R. Geothermal exploration on Nevis: A Caribbean success story. Proc. GRC Transactions, v. 34, 2010.

Lahsen, A., Sepulveda, F., Roja, J., and Palacios, C. Present status of geotermal exploration in Chile. Proc. World Geothermal Congress, 2005.

Lobato, M.L., Fujino, T., and Ayala, J.C.P. Amatitlan geothermal field exploration in Guatemala. GRC Bulletin, Nov/Dec, 2000.

Libbey, R., Bogie, I., Peng, W.F., Duasing, J., Payer, A., Zamhari, Z., Lojingau, D., Urzua, L., Ussher, G.N., and

Brotheridge, J. Insights into the Apas Kiri Geothermal System from AK-1D – Malaysia's first geothermal exploration well. GRC Transactions 41; 2017

Melosh, G., Fairbank, B., and Niggeman, K. Geothermal drilling success at Blue Mountain, Nevada. Proc. Stanford Geothermal Workshop, 2008.

Melosh, G., Moore, J., and Stacey, R. Natural reservoir evolution in the Tolhuaca geothermal field, Southern Chile. Proc. Stanford Geothermal Workshop, 2012.

Moore, J.N., Norman, D.I., Ellis, R. Geochemicalevolution Of The Vapor-Dominated Regime At Karaha-Telaga Bodas Indonesia: Insights From Fluid Inclusion Gas Compositions. Proceedings 24th NZ Geothermal Workshop, 2002.

Nakanishi, S., Abe, M., Todaka, N., Yamada, M., Sierra, J.L., Gingins, M.O., Mas, L.C., and Pedro, G.E. Copahue geothermal system, Argentina – Study of a vapor-dominated reservoir. Proc. World Geothermal Congress, 1995.

Nielson, D.L. and Garg, S.K. Slim Hole Drilling and Testing Strategies. Proceedings 6th ITB International Geothermal Workshop, Bandung, 2017.

Nielson, D.L. and Garg, S.K. Slim Hole Reservoir Characterization for Risk Reduction. Proceedings 41st Workshop on Geothermal Engineering, Stanford, 2016.

Nielson, D.L. and Shervais, J.W. 2014. Conceptual model for Snake River Plain geothermal systems. Proc. Stanford Geothermal Workshop, 2014.

Nordquist, J. and Delwiche, B. The McGinness Hills geothermal project. GRC Transactions, v. 37, 2013.

Osborn, W., Hernández, J., George, A. Successful Discovery Drilling in Roseau Valley, Commonwealth of Dominica. Proceedings, Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, 2014.

Procesi, M. Geothermal Potential Evaluation for Northern Chile and Suggestions for New Energy Plans. Energies 2014, 7. ISSN 1996-1073, www.mdpi.com/journal/energies.

PT Madani Alam Lestari. Slimhole drilling. Brochure, July 2016.

Rejeki, S., Rohrs, D., Nordquist, G. and Fitriyanto, A. Geologic Conceptual Model Update of the Darajat Geothermal Field, Indonesia. Proceedings World Geothermal Congress, 2010.

Reyes, N., Vidal, A., Ramirez, E., Arnason, K., Richter, B., Steingrimsson, B., Acosta, O., Camacho. Geothermal exploration at Irruptuncu and Olca volcanoes: Pursuing a sustainable mining development in Chile. GRC Transactions, v. 35, 2011.

Riza, I. and Berry, B.R. Slimhole Drilling Experience at Darajat Geothermal Field, West Java, Indonesia. Proceedings 20th New Zealand Geothermal Workshop, 1998.

Siong, L.P., Intang, F., and On, C.F. Geothermal prospecting in the Semporna Peninsula with emphasis on the Tawau area. Geo. Soc. Malaysia, Bulletin, v. 29, pp. 135-155, 1991.

Sudarman, S., and Hochstein, M.P.. History Of Geothermal Exploration In Indonesia (1970-2010). Proceedings 36th New Zealand Geothermal Workshop 24 - 26 November 2014.

Thorhallsson, S. and Gunnsteinsson, S.S. Slim wells for geothermal exploration. Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 11-17, 2012.

Vázquez, M., Nieto, F., Morata, D., Droguett, Carrillo-Rosua, F.J., and Morales, S. Evolution of clay mineral assemblages in the Tinguiririca geothermal field, Andean Cordillera of central Chile: an XRD and HRTEM-AEM study. Journal of Volcanology and Geothermal Research, v. 282, 2014.

Vimmerstedt, V. Opportunities for Small Geothermal Projects: Rural Power for Latin America, the Caribbean, and the Philippines. NREL report : NREL/TP-210-25107, 1998.

White, P.J, MacKenzie, K.M., Brotheridge, J., Seastres, J., Lovelock, B.G. and Gomez, M. Drilling Confirmation of the Casita Indicated Geothermal Resource, Nicaragua. Proceedings 34th New Zealand Geothermal Workshop, 2012.

White, P.J., MacKenzie, K.M., Verghese, K. and Hickson, C. Deep Slimhole Drilling for Geothermal Exploration. GRC Transactions, Vol. 34, 2010.

Witter, J.B., Ronne, J.A., and Thompson, G.R. Exploration at the Reese River geothermal prospect in Nevada. GRC Transactions, v. 33, 2009.

Rosenberg, M., Wallin, E., Bannister, S., Bourguinon, S., Sherburn, S., Jolly, G., Mroczek, E., Milicich, S., Graham, D., Bromley, C., Reeves, R., Bixley, P., Clotworth, A., Carey, B., Climo, M., Links. GNS Science consultancy report, 2010/138.

Table A1. Examples of geothermal projects where slimholes have been utilised. Depth column colours indicate if the wells were drilled deep enough to assess the geothermal reservoir (green = yes, red = no). Outcomes column colours indicate if the well was successful in encountering a geothermal reservoir (green = yes, red=no, orange = possibly).

Project	Depth mMD	Outcomes	Flow	References
Argentina				
Copahue	1065-1414	Dry steam discharged from all 3 wells (max flow 2.5 kg/s). Max temps of ~230°C.	Yes	Nakanishi et al., 1995
Chile				
Apacheta	700	Found 210 °C. Not enough information to determine whether or not it intersected a reservoir.		Procesci 2014
Mariposa	659-900	Helicopter rig access for first well. Downhole temperatures of ~205°C measured delineate the top of the reservoir. Dominantly conductive gradients to the base of the wells.	Yes	Haraldsson, 2013; Hickson et al., 2011
El Tatio	571-735	6 slimholes Found the main outflow structure including temperatures over 250 °C	Yes	Cumming et al, 2002
Irruputuncu	800-1430	Downhole temperatures of 150 to 195°C. Well appears to be drilled to the west of a potential reservoir (as suggested by MT).	No	Reyes et al., 2011
Puchuldiza	428-1013	Max downhole temperatures of 175°C Not deep enough or on outflow	No	Lahsen et al., 2005
Tinguiririca	815	Max downhole temperatures of 230°C. Encountered a dry steam reservoir, thickness unknown	Yes	Aravena and Lahsen, 2013; Vázquez et al., 2014
Tolhuaca	1073-1274	Max downhole temperatures of 280-300°C. Wells flowed vigorously. Kicks experienced during drilling helped delineate steam zone.	Yes	Haraldsson, 2013; Melosh et al., 2013
Dominica				
Wotton Waven	1200 - 1613	Wells discovered productive reservoir and guided delineation 2 wells flowed (up to 29 kg/s). Max temp of 246°C.	Yes	
Guatemala				
Amatitlán	135	Intersected shallow 200°C aquifer. Helped refine conceptual model of system and locate upflow beneath higher elevation area.	?	Lobato et al., 2000
Mita	1200-1530	6 wells drilled. 4th well was discovery well. Max temps of 195-217°C. Resource was delineated at much lower cost than conventional wells. Flow tests provided information about the wider permeability characteristics of the reservoir.	Yes	McDowell and White, 2011
Tecuamburro	808	Max temps of 238°C measured. Well was temporarily flowed after swabbing, but stopped after drilling fluids were purged from the hole. Fish in the hole at 772 to TD.	Yes	Goff et al., 1992; Goff et al., 1994
Zunil	364-576	Step out exploration of existing field. Downhole temperatures of 235-247°C encountered. Help confirm the existence of steam zone above deeper liquid reservoir.	?	Asturias, 2003
Honduras				
Azacualpa	500-650	Downhole temperatures of 130-140°C Multiple shallow hot inflows encountered in AZ-1 (related to prominent fault target). AZ-1 was discharged Confirmation of low temperature resource.	Yes	Dal and Geotermica Italiana, 1988
Platanares	401-679	Many hot (160-165°C) water entries were encountered in the three wells. Flows obtained from 2 out of the 3 wells (PLTG-1 and -3); 5.5 to 8 L/s at WHP of 2 to 4 barg.	Yes	Goff et al., 1991; Goff et al., 1994; Finger et al., 1999
Iceland				
Krísuvik	800	Downhole measured temperatures of up to 262°C, but temperature reversals with depth.	?	Khubaeva, 2007
Indonesia				
Bedugal	685 – 1607	Found top of reservoir, but not permeability for production	No	
Darajat	1342-2310	Encountered reservoir in several wells. 2 had to be deepened to reach reservoir. Proved norther extent of the reservoir.	Yes	Riza and Berry, 1998
Karaha	1200 - >1500	Found > 250 °C and flowed in the southern Karaha area Flowed with acid fluids at Telaga Bodas.	Yes	Moore et al 2002
Blawan-Ijen	2000	High temperature (283°C) neutral pH fluid discovered. Temperature at the base of conductor in 3D MT data determined to be ~220°C (1400 mMD).	?	Daud et al., 2017; PT Madani Alam Lestari, 2016
Sarulla,	1709 – 2330	Used hybrid slimhole : rotary to deep levels, and cored bottom section. Successful discovery of two production areas. Max temps of 276-310°C measured.	Yes	Gunderson et al., 2000

Project	Depth mMD	Outcomes	Flow	References
Ulubelu	~1000 -1200	Wells helped delineate the reservoir that is an outflow system. ULB-2 had 224 °C and flowed.	Yes	Hochstein and Sudarman (2008)
Wayang Windu	~1500	Cost effective approach to delineating the margins of the productive resource. ~24 hr flow from one well	Yes	White et al., 2010
Japan				
Hohi	110-1800	About 15 slimholes drilled for deep exploration Penetrated the outflow which constituted the reservoir, but not deep enough to full demonstrate temperature inversion below 1600 m.	No	Garg and Combs, 1993
Oguni	500-700 1000-1950	15 slimholes drilled Achieved steam flowrates on 7 wells(3-8 tph steam)	Yes	Garg and Combs, 1993 Combs and Garg, 2000
Kirishima	500 -2000	23 slimholes drilled 10 wells flowed	Yes	Finger et al., 1999 Combs and Garg, 2000
Sumikawa	1600	15 slimholes drilled Penetrated reservoir and used for interference testing, 4 wells flowed	Yes	Garg and Combs, 1993 Finger et al., 1999
Takigami		11 slimholes drilled , 7 wells flowed	Yes	Finger et al., 1999 , Combs and Garg, 2000
Malaysia				
Apas Kiri	1449	Successful discovery well, with indications of permeability and high temperatures. Downhole temperatures of ~200°C measured. Unperforated NQ pipe from bottomhole to surface.	No	Libbey et al., 2017
Nevis				
Nevis	762-1127	Downhole temperatures of ~260°C measured in all 3 holes. N-3 flowed at 9.5 kg/s	Yes	LaFleur and Hoag, 2010
New Zealand				
Ngatamariki-Orakei Korako	1003 – 1570	Sentinel wells to test connection to adjacent protected system. Providing vital information for assessing the impact of the operation on the Orakei Korako thermal manifestations.	No	Boseley et al., 2012
Tauhara	880	Well encountered permeable horizons lateral equivalent to reservoir even if outside hot reservoir	No	Rosenberg et al, 2010
Nicaragua				
Casita	842	Despite wellbore restrictions (fish in hole), discharged dry steam for 10 days at ~4 tph (0.5 MW_e). Max temp of 232°C measured. Drilling difficulties highlighted need for on-site experience with geothermal conditions.	Yes	
Managua-Chiltepe	1000	Results suggested that the geothermal resource is sub-economic.	No	
PNG				
Lihir	1500	Proved significant temperatures(>220°C) 3 km beyond proven area.	Yes	
USA				
Blue Mountain, NV	645-1128	Would not sustain flow, but was air-lifted to collect chemical samples. Max temps of 148-163°C.	Yes	Melosh et al., 2008
Emigrant, NV	896		?	
Fort Bliss / McGregor Range, TX	615-1207	Max temps of 88°C reached.	No	Finger and Jacobson, 2000; Finger et al., 1999
McGinness Hills, NV	752	Max temps of 153°C reached. Flowed at 8.6 L/s. Success resulted in twinning of the well with a full-sized well (58B(P)-22).	Yes	Nordquist and Delwiche, 2013
Newberry Caldera, OR	1475-1634	High temperature (~200°C) but low permeability. Difficulties encountered during drilling (116 days to TD)	No	Finger and Jacobson, 2000; Finger et al., 1999
Pueblo Valley, OR	451	25 L/s artesian flow at wellhead P of ~5 barg (~150°C).	Yes	Finger et al., 1999
Reese River, NV	1198	Max temps of 124.5°C reached. Airlift flow test to collect chemical samples.	Yes	Henkle, 2008; Witter et al., 2009
Snake River Plains, ID	1821-1959	Max temps of ~150°C reached. Artesian flow from one well.	Yes	Delahunty et al., 2012; Nielson and Shervais, 2014
Salt Wells, NV	162	Successful discovery well for shallow low temperature resource. Stabilized flow of ~16 L/s. Max temperatures of 133°C	Yes	Finger et al., 1999
Steamboat Hills, NV	1220	Proven capability of extrapolating slimhole flow tests to larger diameter wells. Significant permeability encountered at deeper levels (possible 165°C resource or injection area)	Yes	Finger and Jacobson, 2000; Finger et al., 1999
Vale, OR	1775	Temp (max ~140°C) and permeability too low for commercial production.	No	Finger and Jacobson, 2000; Finger et al., 1999