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Waesano, Indonesia: Application of Slimhole Drilling at Waesano Within the GEUDP Program

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ABSTRACT

The Geothermal Energy Upstream Development Program (GEUDP) has been initiated in Indonesia as a joint World Bank and Government of Indonesia initiative to de-risk new geothermal developments by funding and implementing the drilling and evaluation of several exploration wells in selected projects.

When testing prospect areas with lower estimated "probability of discovery" (POD), minimizing the cost in case of a negative result becomes more important, particularly with the GEUDP program which intends to recover exploration cost back into the drilling fund once projects are successfully adopted for further development. The use of slimhole drilling was an important component of geothermal exploration of several fields in Indonesia in the 1990's and has been widely used in Japan, the USA and central America and so was considered as an option for Waesano.

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. Deep slimhole drilling using equipment that is smaller and requires less road and water supply infrastructure can achieve exploration outcomes at lower cost. Our experience of historic slimhole drilling combined with review of global experience indicates that it is possible to obtain exploration and resource characterization equal to that provided by full sized exploration wells.

This paper outlines some of the financial, technical and risk management challenges that greenfield exploration drilling faces and why the response has been the application of slimhole drilling at Waesano as the first project in the program. The merits of different types of well size, depth and drilling technology for Waesano are compared in terms of "exploration effectiveness" and cost. Of more general interest, we present the background information we gathered on slimhole drilling to support the selection of this technology for Waesano drilling, and which may be applicable to many projects in Indonesia and elsewhere.

1. INTRODUCTION

The Government of Indonesia has established a government-sponsored geothermal exploration drilling program in partnership with the World Bank under the Geothermal Energy Upstream Development Program (GEUDP), with the objective of de-risking projects prior to offering them for development by either private sector or SOE developers. PT. Sarana Multi Infrastruktur (PT SMI) is the implementing agency for the program based on assignments of prospects by the Ministry of Finance (MOF) on behalf of the Ministry of Energy and Mineral Resources (MEMR) and is currently preparing to start exploration drilling of the Waesano prospect on Flores Island. The project is funded by the World Bank using the Clean Technology Fund (CTF) and the Global Environment Facility (GEF) combined with funding from the Government of Indonesia's Pembiayaan Infrstruktur Sektor Panas Bumi (PISP). The project is intended to establish a rolling fund for its activities by recovering the exploration drilling costs from subsequent private sector or State Owned Enterprise (SOE) developers.

The typical plan for GEUDP drilling is to drill 2 or 3 deep exploration wells to confirm the hypothetical reservoir model postulated on the basis of surface exploration, prove the existence of a useful geothermal resource and provide an indication of the resource's development potential with much higher certainty than is possible with present surface exploration data alone. While these exploration wells may provide some production and reinjection capacity, the principal objective is to provide sufficient information to confirm the resource quality and better quantify the resource capacity. This will provide the resource information to facilitate tendering to the private sector or assignment to an SOE to develop a power generation project.

The first project selected for exploration drilling under this program is that at Waesano in the SW corner of Flores Island. The prospect is centred near the 2.5 km diameter crater lake (Sano Nggoang lake) on the northern side of G. Waesano. High temperature thermal activity occurs just southeast of the lake, with historic silica sinters and geothermometry indicates the presence of a 240-250 °C resource. Geophysical surveys indicate that the system may be extensive, but geological and hydrological considerations and presence of acid waters in the lake indicate possible limitations on resource size and possible chemical risks to production. The resource has uncertainty regarding whether a usefully large, hot, permeable, neutral pH system will be discovered.

Initially it was planned to only use standard sized exploration wells for the first GEUDP projects to achieve high certainty on exploration (positive or negative), particularly achieving target depth to definitively prove the presence (or otherwise) of a useful reservoir and to secure some useful production if possible from the exploration wells so that smaller projects get a "head start" in terms of steam available. However, initial feasibility assessment showed that drilling of three standard wells combined with costs for road upgrades, new well pads and water supplies would stretch the available budget and limit the number of projects that could be explored under the overall program. The uncertainty in the resource also presented a risk to the GEUDP fund if exploration was done at high cost but failed to prove a useful system existed and the cost of drilling could not be recovered. This led to a complete evaluation of well options and the eventual selection of deep slimholes for the initial resource proving, with ability to drill larger diameter wells once a reservoir is proven to exist.

2. WHY CONSIDER ALTERNATIVES TO STANDARD DRILLING?

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 optimize 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 (or other low-cost alternatives) is twofold:

- to reduce the overall risk (cost) of failure in exploration drilling
- to improve the probability of success of subsequent 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).

Contrary to commonly entrenched negative views on the effectiveness of slimhole drilling (reinforced by a few unfortunate failures recently), 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; Libbey et al., 2017).

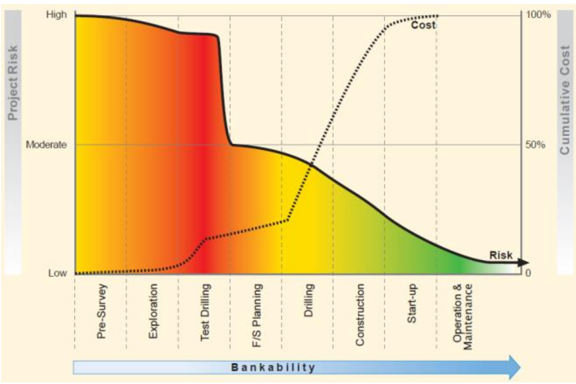

Figure 1: Bankability versus risk for a geothermal project, note the strong drop in risk engendered by successful test drilling. From: Gehringer and Loksha (2012).

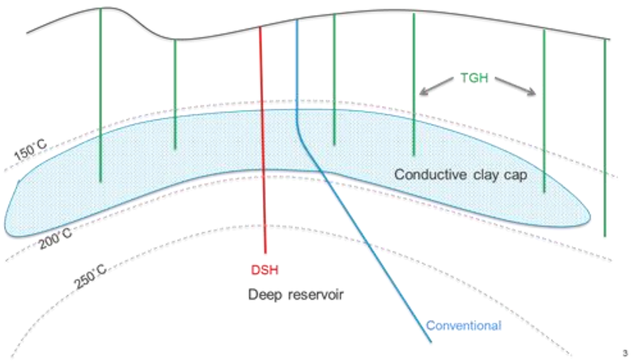

Figure 2: Generic drilling options (TGH = temperature gradient hole, DSH = deep slimhole)

3. 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 summarized 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

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, and 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. While not generally sufficiently deep to test reservoir characteristics shallow temperature gradient holes can contribute other useful information to potential future project development such as informing the design of shallow drilling approaches and in the investigation of shallow groundwater for drilling water supply.

4. 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 and cost associated with stuck pipe incidents.

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.

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 characterize the conditions over the full length of the well.

Permeability:

Permeability will be noticed when encountered 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 MW_e. 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 MW_e (See an example from our experience in Figure 3).

Chemistry:

Provided that 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 characterized 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.

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 MW_e.

5. 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 centralizing 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 K55, 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, open out to 5-3/4"	400	210 °C	Cement casing back to surface. Set-up 7-1/16" (or 4-16") BOP equipment on 4-1/2" casing
3-1/2" OD Schedule 40 flush jointed connection perforated	HQ	1000	250 °C	Squat on bottom (can core NQ and leave NQ rod perforated if encounter HQ coring difficulties). Uncemented liner.

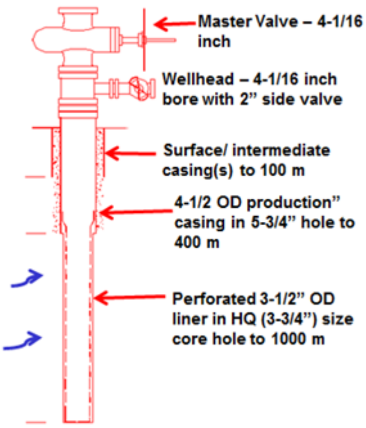

Figure 4: Typical well construction details for a 1,000 m cored slimhole.

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.

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).

Figure 5: Typical slimhole coring rig.

Figure 6: Blowout Preventer for slanted slimhole drilling.

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.

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 meter (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 1000 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 1000 m	40 days (24 hours per day, 7 days per week)	20 days (25 days for 1500 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	2000 cu m per day for small rotary holes, 60 cu m per day for coring HQ holes.	3500 cu m per day.

6. 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. For smaller slimhole rigs, roads may be of a quality typical to those used for mineral exploration drilling and only upgraded later if the resource is discovered and a decision is taken to proceed with delineation drilling and project development. However, deep slimhole rigs need road quality similar to that for conventional drilling. 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 with a lower environmental footprint which has proven to be very important in recent projects.

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.

Schedule:

The time for construction of roads, well pads, water supply and rig mobilization 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.

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. Slimholes, take longer to drill than conventional wells however, typically being 50% longer for similar depths.

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 1500 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.

7. PROJECT FINANCIAL IMPACTS

Return on Investment - Internal Rate of Return (IRR):

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 MW_e 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.

An argument often made in favor of full-size exploration wells is that since slimholes produce very little if any MW_e (megawatt electrical equivalent), then more appraisal wells will be required and all the slimholes do is add more total cost to the project. But actual analysis shows that the increased success rates of subsequent 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.

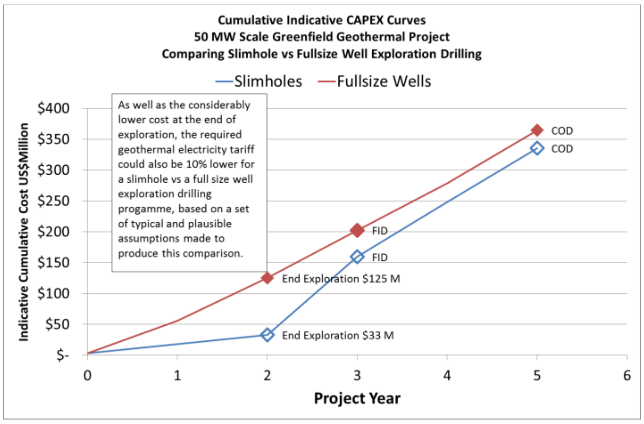

Figure 7: Indicative CAPEX for a 50 MW_e project with and without use of deep slimholes. Red curve is using only conventional drilling, blue curve is using deep slimholes for the exploration phase. FID = Financial Investment Decision, COD = Commercial Operation Date.

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 emphasizes 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"]

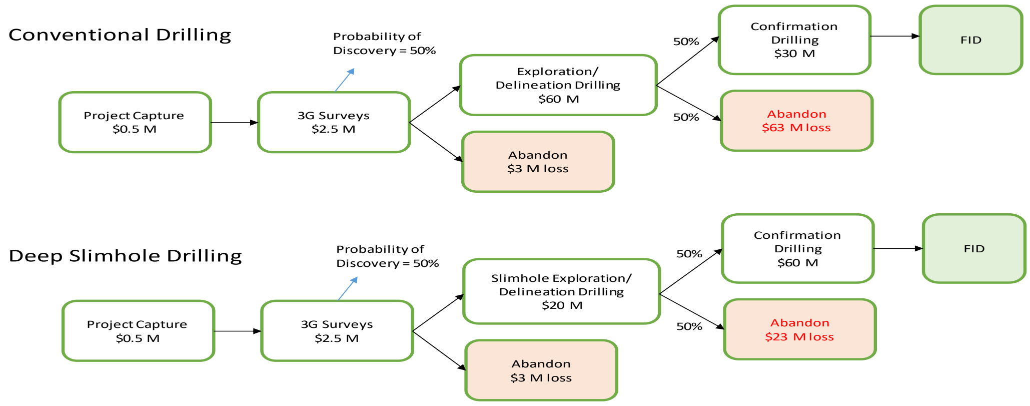

Figure 8: There is potential to exit a project at each major phase if the project does not prove viable. If Probability of Discovery from exploration drilling is low, then the use of deep slimholes puts less capital at risk than when using conventional wells for the exploration phase.

A big reason for following this approach is that a geothermal developer with a portfolio of projects, has 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.

8. GLOBAL EXPERIENCE

We have compiled a dataset of 45 geothermal fields from 14 countries where slimholes have been utilized (Figure 9). Slimholes have been flowed at 28 of these projects (62%), and slimholes at 33 of these projects (73%) have successfully intersected the target reservoir.

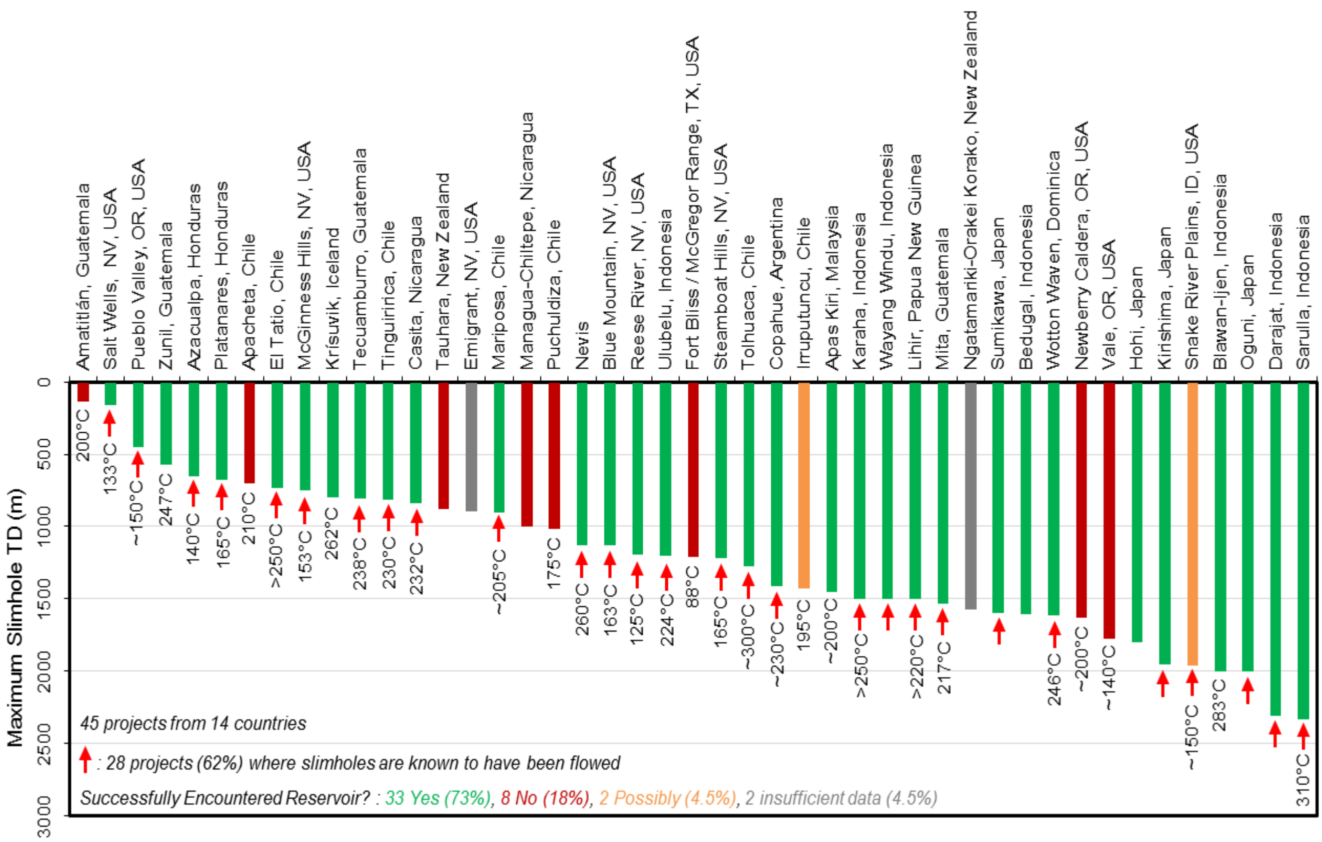

Figure 9: Maximum depth of slimholes utilized at geothermal projects. Maximum temperatures intersected also shown. Red arrows delineate projects where slimholes are known to have been flowed. See Table A1 for more detailed information.

9. 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.

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 2000 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 Combs, 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.

10. 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.

Condensate Injection: In smaller projects (10-25 MW_e) 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.

11. SUMMARY COMPARISON OF SLIMHOLES AND CONVENTIONAL DRILLING

A full set of comparisons between slimhole drilling and conventional wells is provided in Table 3.

Table 3: Summary comparison of slim holes and conventional wells for exploration and delineation drilling

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 stabilization 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	

12. EVALUATION OF OPTIONS AT WAESANO

A comparison of different drilling option scenarios for the Waesano campaign was prepared considering cost, schedule and how effective the various well options may be for the GEUDP program. This analysis was conducted to determine budget reduction options for the Waesano campaign while considering the impact of these options on the probability of realizing the exploration objectives.

While cost can be compared objectively, the exploration effectiveness is not so readily compared. This led to the development of a semi-quantitative parameter of "Exploration Effectiveness" to compare the scenarios in terms of how reliable they may be for the purpose of exploration. The "Exploration Effectiveness" parameter for this case, where targets are relatively deep, assumes variables of depth (chance to test sufficient reservoir), number of wells (opportunities for successful reservoir intersection), number of well pads available (flexibility), and vertical/deviated well options. Effectiveness values were subjectively applied for this case by agreement of the exploration team as follows.

- 2000 m deep wells are 80% as effective for exploration as are 2500m deep wells
- Vertical wells are 90% as effective as deviated wells
- A 2 well program would be 75% as effective as a 3 well program
- Having no flexibility with well pads (just 3 pads) would be 90% as effective as having a spare one (4 pads)

Estimates were also made for productive capacity arising from the exploration program for each of the drilling program options that were considered for Waesano. The results are listed in Table 4 and were calculated using the following assumptions:

- The reservoir is found (i.e. not weighted for Probability of Discovery)
- A typical 50% success rate applies to exploration wells
- Average successful well productivity would be 7 MW for standard wells, 5 MW for intermediate diameter wells, and 1.5 MW for deep slimholes, if all intersecting the same depth of reservoir
- Wells intersecting less than the base case depth of reservoir will have proportionally less chance of success (and hence in this case 2000 m wells will get approximately 40% less MW expected than 2500m wells)

Using these quantifications of exploration effectiveness and expected productivity at wellhead, a range of variations from a typical drilling program using standard size (9 5/8" production casing) wells (Base Case A) were evaluated using detailed cost models prepared for the base case and slimhole drilling based on recent international and Indonesian experience. The results are presented in Table 4. The budget, well productivity and exploration effectiveness are all referenced as percentage relative to the Base Case A. Note that where slimhole and conventional well programs are combined, it is assumed that conventional wells are drilled near prior slimholes and so the later wells do not add much to exploration effectiveness (proving area), but add some depth and with an increased Probability of Discovery (POD).

While the Base Case A is highly effective in terms of exploration, it has the highest capital cost, and also has the highest cost should a useful resource not be found. Reducing well depth (Cases D and E) has some cost saving but also reduces exploration effectiveness. Case I using 3 slimholes has lowest cost and is as effective as most other alternatives and has lowest "walk away" cost in case of failure but delivers almost no fluid production. Case J with initial slimholes then one bigger well for delivering some steam has a low walk away cost, good exploration effectiveness, provides steam and useful cost savings (with the comparatively high cost of conventional well drilling only expended if a good resource is found).

Table 4: Results of evaluation of different well drilling options for Waesano (data is all relative to Base Case A)

#	Case Description	Overall Budget Estimate	Budget Reduction*	Schedule Impact (Months +/-)	Success Case Productivity	Exploration Effectiveness	Cost of Failure***
A	3 standard size 2500 m wells, 4 pads, deviated drilling (current program)	100%	0%	-	100%	100%	100%
B	3 Standard size 2500 m wells, 3 pads, deviated drilling	97%	3%	0	100%	90%	97%
C	3 Standard size, 2500 m wells, 3 pads, vertical, no air drilling	89%	11%	0**	100%	81%	89%
D	3 Standard size, 2000 m wells, 3 pads, vertical, no air drilling	85%	15%	< -1**	62%	65%	85%
E	3 Standard size, 2000 m wells, 3 pads, vertical, no air drilling, smaller rig	80%	20%	< -1**	62%	65%	80%
F	3 Smaller size, 2000 m wells, 3 pads, vertical, no air drilling, smaller rig, smaller pad size	69%	31%	0**	44%	65%	69%
G	2 Standard size 2500 m wells, 3 pads, deviated air drilling	76%	24%	-1	67%	68%	76%
H	2 Slimhole (2000 m) plus 2 standard size 2500 m wells vertical, no air drilling	87%	13%	+10**	115%	61%	40%
I	3 Slimhole wells to 2000 m	39%	61%	-5	13%	72%	39%
J	3 Slimhole wells (2000 m) plus 1 standard size 2500m well, no air drilling	73%	27%	+10**	80%	72%	43%

* Budget reduction calculated with respect to the overall project budget.

** Not using air drilling (only water drilling) can extend well heat-ups anywhere from 2-6 months for standard sized wells based on Jacobs' previous project experience, this additional time has not been added to the schedule impact due to its unpredictability – results will vary for different geothermal fields.

*** Cost of Failure for Case's A, B, C, D, E, F, I, and J with 3 wells, assumes that all wells are drilled, at the end of which the failure is declared. Depending on the results of drilling the first two wells, it may be possible to reduce the Cost of Failure by stopping after the second well and thus saving the cost of one well. However, this option will have to be exercised before the first two wells have been discharge tested (the second well must be complete to provide a potential fluid disposal location for the first well testing), and this would require that the quality of these wells be obvious from the limited amount of data that will be available during actual drilling.

11. 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 2000 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".

The GEUDP Waesano project has taken a balanced approach and adopted the use of slimholes to conduct the early reservoir proving and then will follow through with the drilling of at least one standard sized production well to secure useful steam production to assist with the uptake of the project in the normal Indonesian competitive tender processes. This approach minimizes the funds at risk for Government and World Bank funded exploration drilling while accelerating the progression of projects towards development.

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