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Horizontal Hydrothermal Wells: An Idea Whose Time Has Come

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ABSTRACT

With Fervo Energy having demonstrated that it is possible to cost-effectively drill >1,500 meter long horizontal wells in the types of igneous and metamorphic rocks that host most of our planet's geothermal energy resources, it is timely to ask whether this well geometry could improve the economics of hydrothermal energy projects. This question is pertinent since horizontal wells offer distinct advantages for locating and recovering hydrothermal fluids from permeable portions of steeply dipping fault zones compared to the vertical and moderately-deviated wells historically used for these purposes. Employing horizontal wells for hydrothermal energy production also makes sense based on the evolution of well designs within the oil and gas industry, with horizontal wells having become the predominant design used not only in unconventional hydrocarbon reservoirs, but also in numerous conventional fields. This has occurred because horizontal wells can deliver significantly higher production rates and ultimate recoveries than vertical wells in many types of hydrocarbon reservoirs, including, but not limited to, naturally fractured reservoirs with low matrix permeability, an application largely analogous to the use of horizontal wells for hydrothermal developments. Widespread adoption of horizontal wells for conventional oil and gas applications has also occurred because the cost of drilling horizontally has fallen precipitously over the past quarter century thanks to learning curve improvements resulting from industry drilling over 100,000 horizontal wells during this period. Furthermore, it is likely that horizontal multi-lateral, fishbone, horseshoe, and other innovative well geometries deployed in some oil and gas reservoirs could be useful for developing certain types of hydrothermal fields. There are of course unique challenges associated with using horizontal wells for hydrothermal applications that must be overcome – namely, challenges associated with operating at high temperatures while drilling through underpressured high-permeability fractures. Fortunately, between underbalanced drilling approaches commonly used by the geothermal industry and the innovation capabilities demonstrated by the oil and gas industry, there are reasons to believe cost-effective engineering solutions will be forthcoming. It is therefore hoped that companies operating existing hydrothermal fields or exploring for new ones begin using horizontal wells – a design that has long been successfully deployed by the oil and gas industry and has recently been proven to be an effective method for improving the economics of EGS developments.

1. INTRODUCTION

It has been often observed that "history does not repeat itself, but it rhymes" (O'Toole, 2014). Applying this aphorism to explain parallels in the histories of the oil & gas and geothermal industries suggests that the time is ripe for employing horizontal wells to explore for and develop hydrothermal fields. The primary drivers supporting this assertion include: i) the oil and gas industry has perfected horizontal drilling techniques over the past twenty-five years, making it nearly as cost effective to drill horizontally through a formation as it is to drill vertically through it, ii) Fervo Energy has recently demonstrated that the technologies, workflows, and knowledge used by the oil and gas industry to drill horizontal wells in sedimentary basins can be applied successfully in the types of basement rocks that host most of our planet's potentially recoverable geothermal energy resources (Norbeck et al., 2024;), and iii) the geothermal industry's historical reliance on vertical and moderately-deviated wells was not due to a lack of recognition that using high-angle to horizontal wells would be desirable, as demonstrated by Tester et al. (2006) noting nearly twenty years ago that "the first well (in a prospective area) should be directionally drilled to maximize the intersection with critically oriented joints", but rather was seemingly attributable to widely held concerns about the viability of successfully drilling horizontal wells in fractured underpressured basement rocks.

It is important to mention at the outset of this paper that the idea of drilling horizontal wells in hydrothermal fields is not new. Rather, just as occurred in the oil and gas industry, where horizontal drilling was first applied to conventional hydrocarbon reservoirs before unconventional applications were attempted, the first geothermal horizontal drilling attempts predate the drilling of horizontal wells to create Enhanced Geothermal Systems (EGS). For example, in 2003, the Northern California Power Agency contracted for the drilling of an injection well at The Geysers Field that was planned to reach 80° deviation (Capuano et al., 2005), which is generally recognized as the angle beyond which a well is considered to have been drilled horizontally. While the well only attained a maximum deviation of 75°, it was considered a technical success since it intersected numerous permeable fractures in the 750 meters of open hole section drilled below the kickoff point. This enabled the well to achieve injection rates of over 1,400 gallons per minute (i.e., > 48,000 barrels per day) while concurrently reducing induced seismicity compared to injection from vertical wells, presumably by distributing the injectate over a wider area (Capuano et al., 2005). However, this initial success employing horizontal well geometries in hydrothermal fields was not extensively followed up on, with large-scale use for geothermal power production first occurring nearly twenty years later when Fervo Energy used horizontal wells for EGS applications, first on a 2 to 3 MW demonstration project in Nevada (Norbeck and Latimer, 2023) and then at Fervo's 400 MW Cape Station commercial development in southwestern Utah (Norbeck et al., 2024).

In this paper we will briefly describe the oil and gas industry's journey from drilling mostly vertical wells during the first 150 years of its existence to today deploying horizontal wells not only as the exclusive well design in unconventional fields but also for developing many of our planet's largest conventional hydrocarbon accumulations. We then describe the potential benefits of employing horizontal wells in hydrothermal exploration and development programs along with some of the challenges likely to be encountered. Next, common barriers to adopting new technologies will be covered, emphasizing extensive academic research on this topic and lessons learned during the author's forty-year career promoting innovation in the oil and gas industry. And finally, we end the paper by offering a series of conclusions and recommendations.

2. THE OIL AND GAS INDUSTRY'S EXPERIENCE TRANSITIONING FROM VERTICAL TO HORIZONTAL WELL DESIGNS

2.1 A Synopsis of the 150 Year Journey from Drilling Exclusively Vertical Wells to the Broad Adoption of Horizontal Well Designs

In the beginning, back in the mid-to-late 1800s, every oil and gas well was drilled vertically (although some wells invariably deviated in an uncontrolled manner due to natural causes). In the 1920s, after the invention of gyroscopes and steel whipstocks, the ability to reliably hit subsurface targets offset from the location of the drilling rig was achieved (Devenish et al., 2015), and by the end of that decade, the first true horizontal well had been drilled (King and Morehouse, 1993). However, although from 1930 onwards it was technically possible to drill horizontal wells, because of the high cost of drilling horizontally due to the immaturity of drilling technology in general and horizontal drilling techniques in particular, horizontal drilling did not achieve commercial viability for nearly a half century, first being deployed at scale in the 1980s to extract oil from naturally fractured portions of the Austin Chalk in South Texas and the Bakken in North Dakota, and to minimize water coning in the supergiant Prudhoe Bay Field on the North Slope of Alaska (King and Morehouse, 1993; LeFever, 2005; Helms, 2008).

For a brief time in the early 1990s, there were over 1,000 horizontal wells being drilled globally each year, largely in the Austin Chalk (King and Morehouse, 1993). This burst of activity helped drive down the cost of drilling horizontal wells, although cost reductions were not large enough to offset the deleterious impact of declining oil prices, which fell throughout the decade, reaching a level that shutdown nearly all drilling programs as the 20th century came to an end. This made the years either side of Y2K a difficult time for western oil and gas companies, especially when coupled with western companies' limited ability to economically find or access undeveloped giant conventional fields, which were almost exclusively held by OPEC+ nations. The combined impacts of the price collapse and giant-fields-access-challenge were particularly hard felt in the United States where 140 years of exploration and development activity had resulted in almost all large conventional oil and gas fields having been discovered long ago and largely depleted by the start of the 21st century. Fortunately, this period of adverse conditions spawned a wave of innovation (as adversity often does), resulting in industry, amongst other advancements, learning how to cost effectively develop unconventional reservoirs using multi-stage-hydraulically-fractured horizontal wells. Interestingly, this was a well type that had first been successfully used in the late 1980s (White, 1989) and had seen growing adoption for a number of applications as the 20th century drew to a close. Beginning around 2004, this well type was applied at enormous scale, first to produce gas from unconventional reservoirs, and then a bit over a half-decade later, to recover unconventional oil. As most readers will be aware, learning curve related improvements quickly enhanced the economics of unconventional reservoir investments, which drove the proportion of horizontal wells being drilled in the U.S. ever higher, so that by 2010 more than half of the rigs drilling for hydrocarbons in the United States were drilling horizontally, with the ratio of horizontal to non-horizontal wells increasing steadily thereafter to the point that as of year-end 2024, nearly nine out of ten rigs were drilling horizontal wellbores (Figure 1).

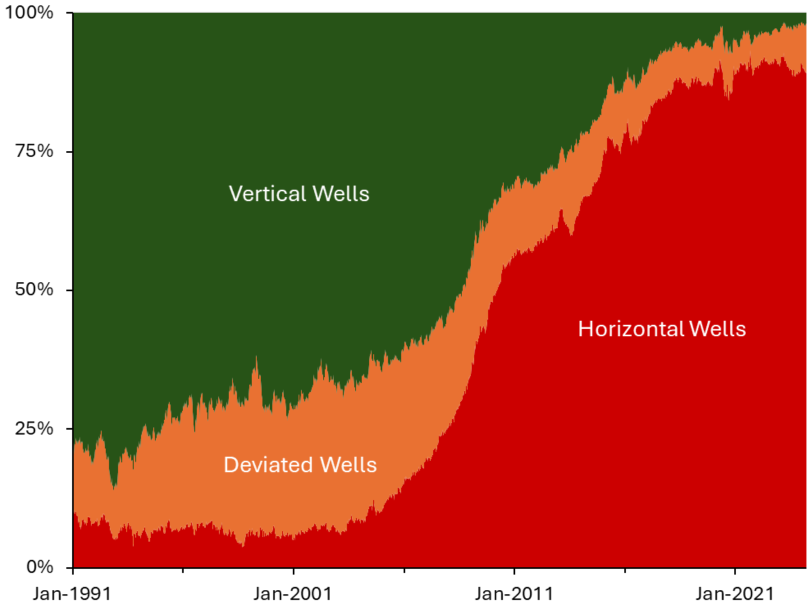

Figure 1: Graph showing changes in the trajectories of oil and gas wells being constructed by drilling rigs active in the United States over the past third of a century. Prior to the onset of large-scale drilling of hydraulically fractured horizontal wells in unconventional reservoirs during the middle part of the 2000s, most wells drilled onshore in the Lower 48 States were vertical, whereas wells drilled offshore and in Alaska were deviated. As the economics of drilling unconventional reservoir wells improved, the proportion of horizontal wells rose rapidly, reaching nearly 90 percent by the start of the 2020s. Data shown in this graph were retrieved from the weekly rig count spreadsheet available on Baker Hughes' website as of March 2024, at which time Baker Hughes stopped reporting well trajectory information.

And while the majority of the horizontal wells being drilled in America today are targeted at unconventional reservoirs, it may surprise readers to learn that the perfection of techniques for drilling horizontal wells over the last few decades has resulted in horizontal wells becoming the well design of choice in numerous conventional oil and gas fields, not only in America, but across the globe, with the application of horizontal wells to conventional oil and gas developments being the topic covered (briefly) in the next section of this paper.

2.2. Large-Scale Application of Horizontal Wells for Developing Conventional Hydrocarbon Reservoirs

While horizontal drilling had been deployed on a niche basis in conventional oil and gas fields since it first became available in the late 1920s, dramatic improvements made in the technologies, workflows, knowledge, and supply chains needed to cost effectively drill horizontal wells led operators to deploy this well type in an ever-increasing number of conventional fields from the 1980s onward. Most notably, horizontal wells have been extensively utilized outside the United States over the past 40 years in the Middle East, Canada, Venezuela, North Sea, and Former Soviet Union (Hamada et al., 2001; Stark, 2003; Gallivan et al., 2008; Mohamed et al., 2024).

As an example of how ubiquitous the use of horizontal wells in conventional fields have become, in the Ghawar Field in Saudi Arabia, our planet's largest oil field, horizontal wells have since the 1990s become the design of choice, with horizontal wells having had a particularly positive impact in the southern "Haradh" portion of the field where the prolific Arab D reservoir is extensively fractured (Stenger et al., 2001; Al-Mubarak et al., 2007). In this area, steeply dipping fracture zones that extend for many kilometers parallel to S_{Hmax} and perpendicular to the N-S trending Ghawar anticlinal structure act as water encroachment superhighways allowing water injected at the downdip edges of the field for pressure support purposes to travel long distances laterally, causing many vertical production wells in the Haradh area to water out prematurely. To mitigate this problem, all production wells are now drilled horizontally, with the horizontal portion of the wells aligned parallel to and away from potentially problematic fracture zones (Al-Mubarak et al., 2007; Aljeshi, 2012).

Interestingly, while horizontal production wells in Ghawar are aligned to avoid intersecting high permeability fracture zones, in many conventional reservoirs, horizontal wells are used to intersect steeply dipping fractures, thereby penetrating as many high permeability zones as possible with a single well, which increases per well production rates and optimizes the recovery of resources. The applicability of deploying horizontal wells in an analogous manner in hydrothermal reservoirs is discussed in the next section of this paper.

3. APPLICATION OF HORIZONTAL WELL GEOMETRIES TO HYDROTHERMAL EXPLORATION AND DEVELOPMENT

3.1 How the Nature of Fault Zone Related Hydrothermal Systems Makes Horizontal Drilling an Attractive Option

Fault zone related hydrothermal systems tend to be structurally complex, consisting of interconnected networks of steeply dipping faults and fractures in areas with complicated deformational histories (Curewitz and Karson, 1997; Faulds et al., 2011). As shown in Figure 2, which is modified after a diagram contained in Faulds and Hinz (2015), in the Great Basin of the western United States, an area that is highly prospective for geothermal energy production due to high heat flow across the region, very few of the known hydrothermal systems are associated with major range-front bounding normal faults. Rather, the most common structural setting for active hydrothermal systems in the Great Basin are step-overs and relay ramps associated with normal fault zones, which while being much more subtle features than the range bounding faults, comprise nearly a third of the over 250 active geothermal systems categorized by Faulds and Hinz (2015). This propensity towards subtlety holds true for the other most common structural settings for fault related hydrothermal systems in the region, with the subtle but complex nature of the systems being a significant challenge that geothermal development companies need to overcome to achieve acceptable economic results.

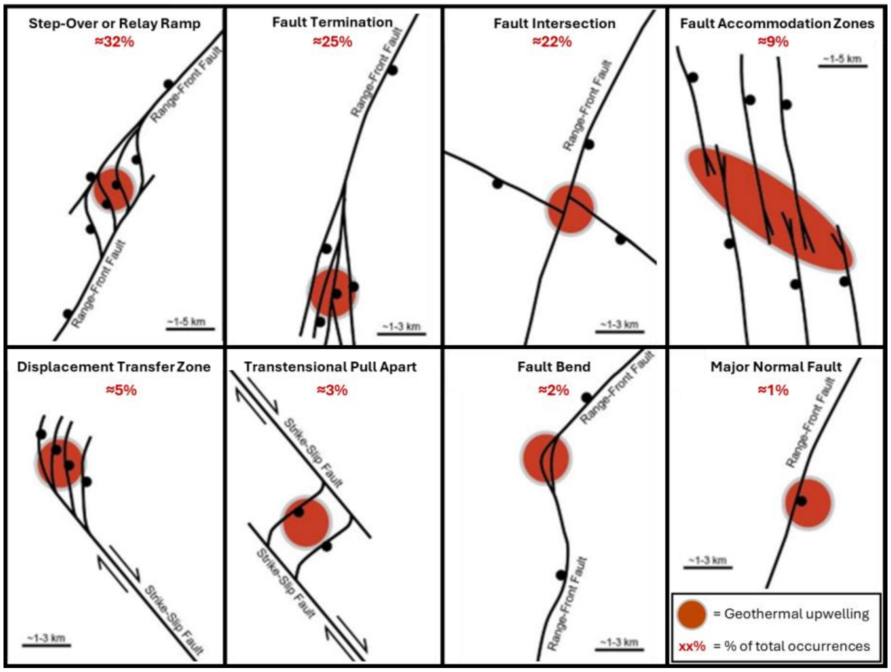

Figure 2: Characteristic structural settings for geothermal systems in the Great Basin, modified after Faulds and Hinz (2015). Notice that the zones of interest are generally several kilometers wide, which is a distance a single horizontal well could traverse.

A second non-trivial challenge associated with finding and optimally developing hydrothermal systems relates to the fact that transmissive portions of fault zones tend to be limited to areas that have experienced recent seismic activity because hydrothermal mineral precipitation is very efficient at filling open fractures and void spaces (Curewitz and Karson, 1997; Siler et al., 2018). This factor, when coupled with the propensity for loci of deformation to frequently move about within complex fault zones (Curewitz and Karson, 1997; Pastoriza et al., 2018; Fletcher et al., 2020), results in considerable uncertainty regarding where within a fault zone one should target exploration, appraisal, and even development wells. This challenge can in part be overcome using rigorous geothermal play fairway mapping techniques (Faulds et al, 2016; Faulds et al, 2021; Jolie et al., 2021) and detailed, prospect-scale, three-dimensional geologic mapping (Siler et al, 2019; Faulds et al., 2024), both of which are best practices that can help identify areas where conditions are right for permeable flow paths and deep fluid circulation to exist. However, considerable uncertainty will in most cases still exist as to the location and nature of hydrothermal fluid flow pathways during exploration for new hydrothermal fields and during development drilling programs because (a) much of the hydrothermal potential in the Great Basin and other transtensional terranes with high heat flow is associated with "blind" hydrothermal systems, systems that have no manifestation at the surface and potentially misleading distributions of heat and other flow indicators in the shallow subsurface (Richards and Blackwell, 2002), and (b) seismic methods generally do a poor job of resolving steeply dipping faults in the basement rocks in which most high enthalpy hydrothermal systems are located (Eaton et al., 2003).

Given the above-described challenges, it is worth considering how horizontal wells might be employed to minimize the probability of drilling dry holes and maximizing per well production. As is shown in Figure 3, the scale of fault zones that are either known or expected to host active hydrothermal systems in the Great Basin is such that to intersect a statistically meaningful number of fault strands in favorable locations within the prospective area, numerous vertical exploration wells would be required, whereas one or a few horizontal wells could penetrate a far larger number of the prospective fault strands. Likewise, during the development of hydrothermal projects, horizontal wells drilled from one or a few pads would be an uber-efficient method for increasing the number of penetrations of permeable portions of a complex fault zone, thereby improving production rates and heat recovery. The use of horizontal wells would also help reduce the surface footprint of a project and minimize infield surface piping between well heads and a field's power generation facility, which could favorably influence the process of receiving permit approval and enhance project economics.

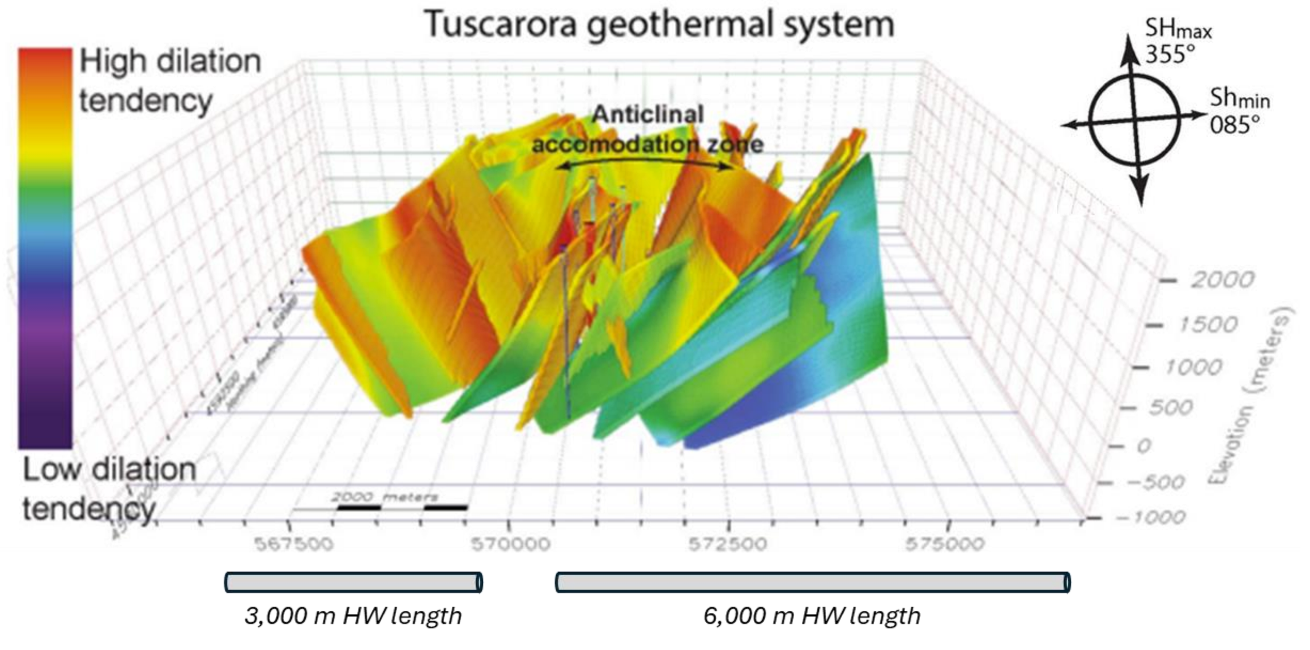

Figure 3: Three-dimensional geologic map from Siler at al. (2019) showing interpreted fault zone complexity and fault dilation tendencies in the Tuscarora hydrothermal field in north-central Nevada. Warm colors indicate high potential for a fault to be critically stressed, with these features being more likely to conduct fluids relative to cooler colored fault segments. Also shown in the figure is the modeled horizontal stress field and scaled representations of the length of horizontal wellbores commonly drilled in unconventional oil and gas reservoirs across America (HW = horizontal well). Given uncertainties related to limitations on being able to resolve fault zone complexity and determine the transmissivity of fault strands in fault-zone-hosted hydrothermal fields, maximizing the number of fault intersections using horizontal wells holds great promise for increasing the probability of exploration success and maximizing returns for projects that are developed. Because drilling 3,000-meter-long horizontal wells is today considered routine in the oil patch, with laterals over 6,000 meters in length becoming common, hydrothermal industry operators should evaluate the robustness of exploration and development plans that employ horizontal wells. In addition, it is worth noting that while the horizontal laterals shown in the figure have been depicted as single wellbores not deviating in either strike or dip, this is not a requirement, with "horseshoe" horizontal wells that turn 180° in the horizontal plane having been successfully drilled by numerous oil and gas companies, multi-laterals and fishbone designs having been utilized for over three decades, as have wells that after reaching 90° of deviation move up and down section (or laterally) by tens to several hundreds of meters in order to string together a series of compartmentalized hydrocarbon accumulations (with angles reaching up to 120°).

To elucidate the scale of the potential benefits associated with using horizontal wells, comparisons between the production rates and recovery achieved from vertical and horizontal wells in fractured hydrocarbon reservoirs are provided in the following section.

3.2 Analogies between using Horizontal Wells to Develop Naturally Fractured Hydrocarbon Reservoirs and Hydrothermal Fields

Since the 1980s, horizontal wells have been used extensively to develop low-permeability, naturally fractured oil and gas reservoirs (Shelkholeslaml et al., 1991; Stark, 2003). Many of these reservoirs were first developed using vertical wells and only later redeveloped using horizontal drilling techniques. This allows for comparisons to be made between the flow rates and ultimate recoveries achievable for each type of well (Figure 4).

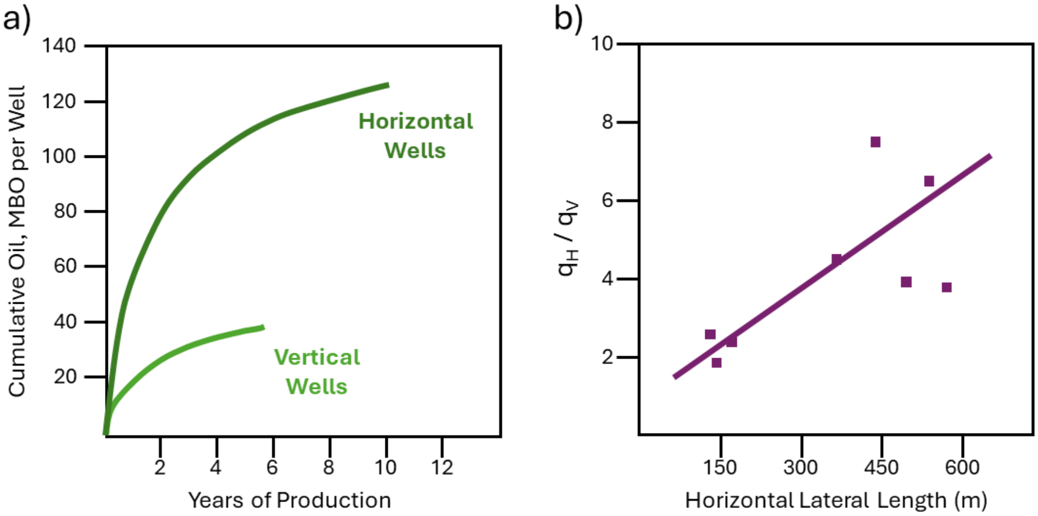

Figure 4: a) Plot showing average cumulative production from 235 horizontal wells and 1,669 vertical wells in the Pearsall Austin Chalk Field, South Texas. Cumulative production from the horizontal wells was over three times that of the vertical wells even though many of the horizontal wells were drilled in areas that had been partially pressure depleted by earlier drilled vertical wells. Plot modified after Stell and Brown, 1992. B) Productivity ratio plotted versus horizontal lateral length for Austin Chalk horizontal and vertical wells in the Giddings Field in South Texas (from Shelkholeslami et al., 1991). It is worth noting that the lateral lengths commonly drilled in the late 1980s and early 1990s are a fraction of the lengths being drilled in similar geologic settings today, with most modern laterals being at least 3,000 meters in length, and some exceeding 6,000 meters.

While there are undoubtedly exceptions, in general, horizontal wells can achieve significantly higher flow rates and ultimate recoveries from naturally fractured hydrocarbon reservoirs than can vertical wells (Joshi, 1988; King and Morehouse, 1993).

Given this generality, and assuming it applies to production rates and recoveries from hydrothermal reservoirs, which it probably does in most cases, if the cost of drilling horizontal wells is not significantly higher than drilling vertical wells, then it will be economically beneficial to drill horizontally in fractured hydrothermal reservoirs. We therefore in the next section address questions about the cost effectiveness of horizontal drilling in the type of fractured crystalline basement rocks that comprise most hydrothermal reservoirs.

3.3 Learning Curves and Other Factors that Should Make Horizontal Drilling Economically Attractive for Hydrothermal Projects

Drilling long horizontal wells in hydrothermal reservoirs will in most cases mean contending with high temperatures throughout the target section and low pressures in the fault zones that comprise the reservoir. This is a combination of environmental parameters that the oil and gas industry seldom encounters because in petroliferous sedimentary basins, high temperatures are usually associated with high pressures, with well construction in such settings commonly being described as “HPHT drilling”. Overcoming the specific challenges associated with Low Pressure High Temperature (LPHT) horizontal drilling will therefore require innovative solutions – solutions drawing upon the knowledge of experts from both the geothermal and oil & gas industries – experts who understand how to mitigate the detrimental effects loss circulation can have in horizontal wells on hole cleaning, cooling of the drill string and bottom hole assembly, and MWD performance. That the geothermal and oil & gas drilling communities will be up for this part of the challenge is strongly suggested by: (a) the oil and gas industry’s impressive track record with developing engineering solutions to horizontal well challenges, (b) the success of the beforementioned nearly horizontal injection well drilled into the Geyser’s reservoir, and (c) learnings garnered from drilling thousands of vertical to moderately-deviated hydrothermal LPHT wells (Capuano, 2016, 2025).

Lending credence to the supposition that geothermal operating companies will be able to perfect the ability to drill horizontal wells in hydrothermal fields, the oil and gas industry has significantly reduced the time and cost required to drill horizontal wells in unconventional reservoirs over the past two decades (Figure 5). These results were attained because (a) companies were able to learn from experience as the number of wells drilled grew rapidly, (b) more capable technologies such as PDC bits, rotary steerable systems, and rigs with automated controls and top drive drilling units came to be widely adopted, and (c) the supply chain capabilities required to execute horizontal drilling operations at scale were fully built out. This allowed the industry to achieve over a 50% reduction in the cost of drilling like-kind wells, drill far fewer “train wreck” wells, realize greater precision at hitting well targets, and deliver much less tortuous wellbores, all of which are outcomes that contributed to improved economic performance.

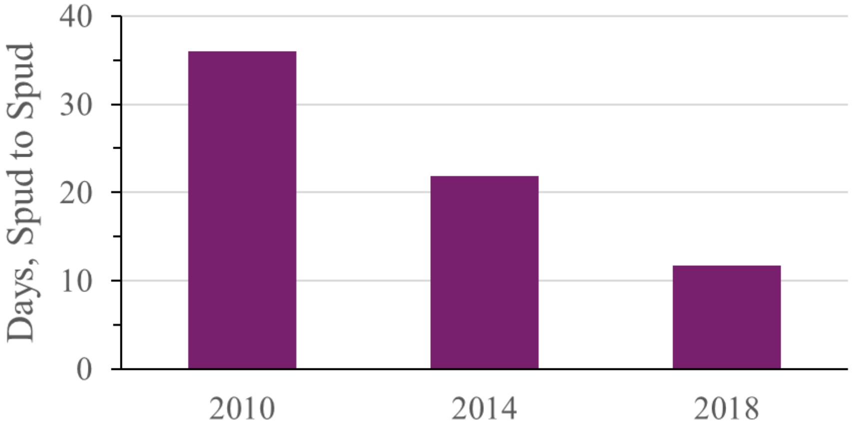

Figure 5: Plot showing days required to drill hydraulically fractured horizontal wells in the liquids-rich portion of the Eagle Ford play in South Texas. Full-scale development of the Eagle Ford commenced in 2010. Since then, over 21,000 wells have been drilled. As shown in the plot, significant improvements in the time required to drill a well and move to the next location were achieved during the first eight years of development activity. Please note that the plot somewhat undersells the level of achievement this represents since the average lateral length increased significantly over this period. Data from ConocoPhillips 2014, 2018.

That the geothermal industry will be able to attain similar improvements has already been demonstrated by the Utah FORGE consortium and Fervo Energy, both of whom have proven that it is possible to cost effectively drill high-angle wells in the types of crystalline basement rocks that host most of our planet's geothermal resources (Dupriest and Noynaert, 2022; El-Sadi, 2024). As shown in Figure 6, Utah FORGE was the first to apply the full suite of learnings and technologies developed by the oil and gas industry to the drilling of extremely high angle geothermal wells (> 60°). Then shortly thereafter, building on Utah FORGE's success, Fervo Energy demonstrated that it is possible to go fully horizontal in these lithologies, successfully drilling and fracture stimulating 900 meter long laterals at their Project Red in Nevada (3,000'), followed by 1,500 meter laterals at their Cape Station Project in Utah (5,000').

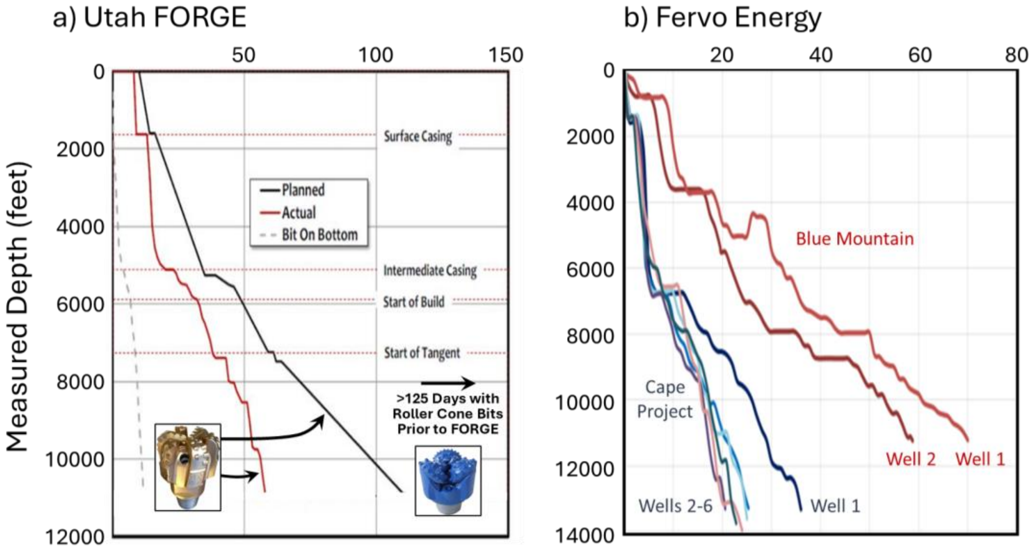

Figure 6: a) Plot modified after Winkler and Swearingen (2021) showing planned and actual drilling days from spud to total depth (TD) for the Utah FORGE 16A(78)-32 well. This well reached TD in about half the planned time and even further ahead of what would have been considered typical using prior geothermal industry practices by adopting technologies and workflows perfected by the oil and gas industry for unconventional reservoirs (e.g., PDC bits, physics-based drilling). b) Plot modified after El-Sadi et al. (2024) showing days from spud to TD for Fervo Energy's two Project Red horizontal wells that are located on the edge of the Blue Mountain hydrothermal field in Nevada and their first six horizontal wells drilled at their Cape Station Project in southwestern Utah, directly adjacent to the Utah FORGE site. Fervo Energy have now drilled over 20 wells at Cape, with increased drilling efficiencies having cut costs nearly in half, from $9.4 million to $4.8 million per well (Gallucci, 2024).

Given these results, the probability that deploying horizontal drilling techniques to hydrothermal development projects will deliver improved economics is high. In fact, improvements are likely to extend far beyond those realized on a well-cost-only basis, with horizontal well designs enabling pad drilling, which given current extended reach drilling capabilities, will minimize a project's surface footprint and reduce the amount of piping needed to transport fluids on the surface to and from wells by enabling power plants to be located near centralized drilling pads instead of needing to pipe fluids to and from well sites scattered across a development area.

In addition, given the plethora of innovative horizontal well designs utilized in oil and gas developments since the 1980s, there will likely be creative ways in which horizontal wells can be used to develop hydrothermal energy resources, which is the topic covered in the next section of this paper.

3.4 Multi-Lateral, Fishbone, Horseshoe, and Other Innovative Horizontal Well Designs

While many of the 100,000 plus horizontal wells drilled to recover hydrocarbons consist of a single lateral that varies little in direction or depth after penetrating the targeted reservoir, maintaining a straight course once in the reservoir is by no means a requirement, nor are well design options limited to single laterals. Rather, over the past half-century, numerous innovative well designs have been conceived, tested, and, for designs that have been found to be particularly useful, deployed at scale. Notably, what all the successful designs have in common is that they are meant to increase flow rates, maximize ultimate recovery, and/or decrease overall project costs, thereby improving project economics. The applicability of creative horizontal well geometries should therefore be considered when building plans for how to optimally explore for, appraise, and develop a hydrothermal field, with non-horizontal versions of these well designs having already been deployed successfully in several hydrothermal fields (e.g., multi-lateral wells in The Geysers Field in California, Henneberger et al., 1993; and the Tiwi and Bulalo Fields in the Philippines and the Salak reservoir in Indonesia, Stimac et al., 2010)

One of the simplest ways to increase reservoir contact area or maximize the number of high permeability zones a well encounters is by increasing the number of laterals drilled below a single wellbore at the Earth’s surface, creating what is referred to as a multi-lateral well. As shown in Figure 7, for oil and gas applications, this has generally been done by drilling a lateral into the reservoir followed by kicking off one or more sidetracks from the mother bore. Multi-lateral horizontal wells have been broadly utilized around the planet for more than two decades and today are a relatively mature and easy to deploy technology. Applications include both cased and open hole varieties (or some combination thereof), with horizontal multi-laterals having been used to improve the economics of heavy oil reservoirs in Venezuela (i.e., “cold production” from the Orinoco Heavy Oil belt; Briceño et al., 2002), supergiant fractured oil reservoirs in the Middle East and Caspian Sea region, and numerous offshore hydrocarbon developments.

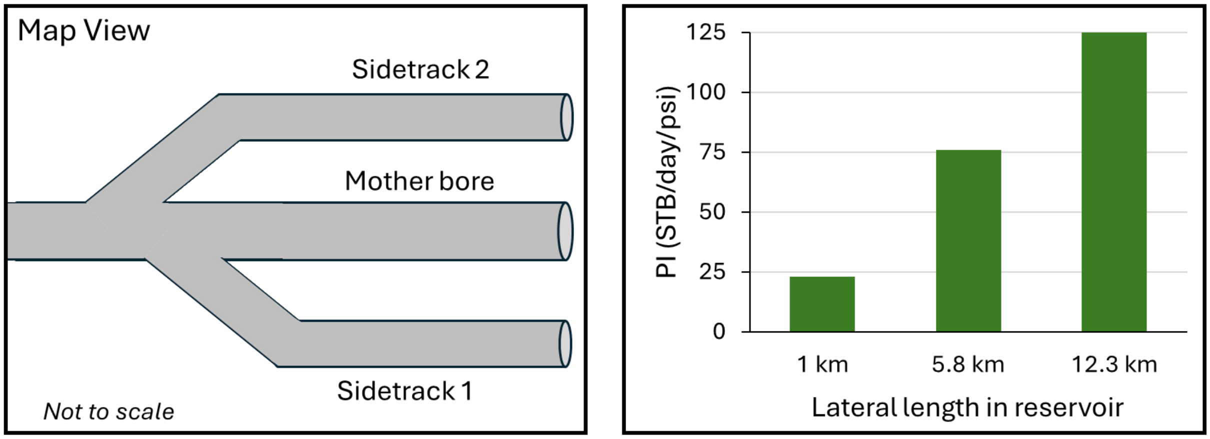

Figure 7: On the left, a schematic drawing showing one of the multi-lateral well designs used in the Shaybah Field in Saudi Arabia to maximize reservoir contact area. On the right, a plot showing how the use of multi-laterals has greatly increased the productivity index (PI) of wells drilled in the field. This has allowed Saudi Aramco to maximize per well oil flow rates and ultimate recoveries while concurrently reducing water coning and the rate of increase in gas to oil ratios, which were problems threatening the long-term viability of the project (Saudi Aramco, 2025). Using multi-lateral wells, Aramco was able to ramp up production to one million barrels per day. The drawing and plot in this figure were modified after ones contained in Salamy et al. (2008).

A specific multi-lateral well design that is worth describing in additional detail since it has been successfully deployed to maximize reservoir contact in a variety of settings, including highly-fractured, stratigraphically-complex, and low-matrix-permeability hydrocarbon-bearing formations, is what is commonly referred to as “fishbone” multi-laterals (Stadler et al., 2001; Ozdemirtas et al., 2015; Szymczak, 2024). In a fishbone well, a main lateral called a “spine” is drilled through the reservoir, usually horizontally, with numerous “ribs” either being drilled or jetted off of the main bore, creating what appears in map view to be a fishbone (Figure 8). Numerical modeling of the application of fishbone well designs to Hot Sedimentary Aquifers (HSAs) has been performed by Ouadi et al. (2023). Application of fishbone multi-laterals to hydrothermal developments seemingly could be beneficial given the approach offers a low-cost way to maximize the number of open fractures intersected within a fault zone, which given the complex nature of most large-scale fault zones both structurally and in terms of mineralization sealing up some fractures while others remain open due to periodic reactivation during seismic events, should be a priority in selecting the optimal well design.

Also shown in Figure 8 is a well design that has become popular for developing leases in unconventional hydrocarbon reservoirs in the United States where the size of the lease limits the length of the lateral that can be drilled. In cases like these, industry has moved to drilling what is commonly referred to as “horseshoe” or “U-turn” wells. This well design is interesting for hydrothermal developments not because it would be used in the same way that it is in oilfield applications, but rather because it highlights the tremendous flexibility that exists in designing well paths that do not conform to simple geometric patterns, with horseshoe wells demonstrating the ability of drillers to turn a horizontal well considerable distances in a map view perspective. In addition, a consideration that should be kept in mind for hitting multiple targets within the complex, steeply-dipping fault zones that commonly host hydrothermal systems, is that it is possible to increase and/or decrease the drilling angle by significant amounts along the path of a “horizontal” lateral, with an example of a well that was drilled for over 1,000 meters at 90° through a portion of a Southern North Sea reservoir and then deviated to a 120° angle to intersect the same formation in another fault block also being depicted in Figure 8.

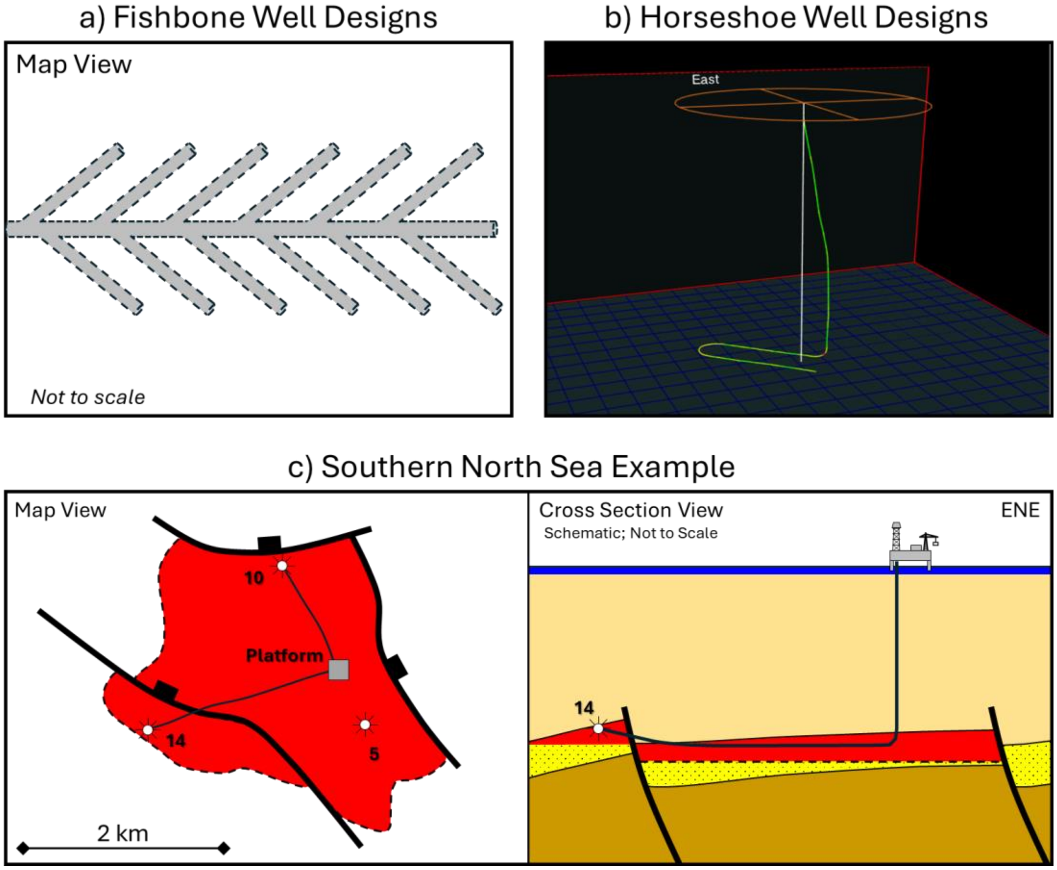

Figure 8: a) Schematic map view depiction of a fishbone horizontal well design. Fishbone wells have been successfully used in many petroleum provinces to increase flow rates and recovery factors. b) Oblique 3D representation of the world’s first horizontal horseshoe well, which was drilled by Shell in the Permian Basin in 2019. Figure from Jacobs (2020). c) Map and cross-sectional view of the Europa Field in the Southern North Sea showing a horizontal well (i.e., Well 14) that penetrated the main reservoir in the field, drilled horizontally through the gas filled portion of the reservoir for a long distance, and was then further deviated to 120° to recover gas from an adjacent upthrown fault block. Figure modified after Leveille et al. (1997).

4. ACCELERATING ADOPTION OF DISRUPTIVE TECHNOLGIES AND INNOVATIVE IDEAS

As of the time of the 50th Stanford Workshop on Geothermal Reservoir Engineering, there exist in the world approximately 20 horizontal geothermal wells with laterals that extend over 1,500 meters, which is a relatively short distance by oil and gas industry standards. All these wells are located in one county in Utah in the western United States. All have been drilled by one company, Fervo Energy. And all are intended to be or already have been hydraulically fractured to create Enhanced Geothermal Systems (EGS). While this represents a start towards achieving widespread adoption of horizontal well designs by the geothermal industry, expanding the number of companies employing horizontal well designs and broadening the number of types of applications in which horizontal wells are utilized (e.g., by using horizontal wells in hydrothermal fields) will be crucial for reaching a tipping point like that achieved by the oil and gas industry – an industry that today generally asks “why would I not want to use horizontal wells” when considering well design options.

There has been much written about challenges associated with securing broad adoption of disruptive technologies (Rogers, 1962; Moore, 1991). A key finding of this research is that it generally takes one or more mainstream entities within the population of entities that would benefit from adopting an innovation to be the first to do so before others in the mainstream will follow suit (entities = companies, organizations, or individuals). This however creates a dilemma, since those in the mainstream generally like to stick with tried-and-true approaches (Parker, 2024). As a result, books written on this topic tend to have titles that emphasize how hard it is to rapidly secure widespread adoption of a disruptive technology, titles such as (a) *Diffusion of Innovation* (Rogers, 1962), with the word diffusion describing how slow this process can be, and (b) *Crossing the Chasm* (Moore, 1991), which makes the process sound ominous, with “the chasm” often being represented as a period in which adoption grinds to a halt as per the diagram shown in Figure 9. This depiction of the challenge involved turns out to be overdramatic since adoption seldom ceases for an extended period for technologies that ultimately achieve widespread usage. Rather, “the chasm” should be thought of as a mental construct that emphasizes how hard it can be to gain traction with mainstream entities, most of which would prefer that one of their peers be the first to try the new technology and prove the advertised benefits.

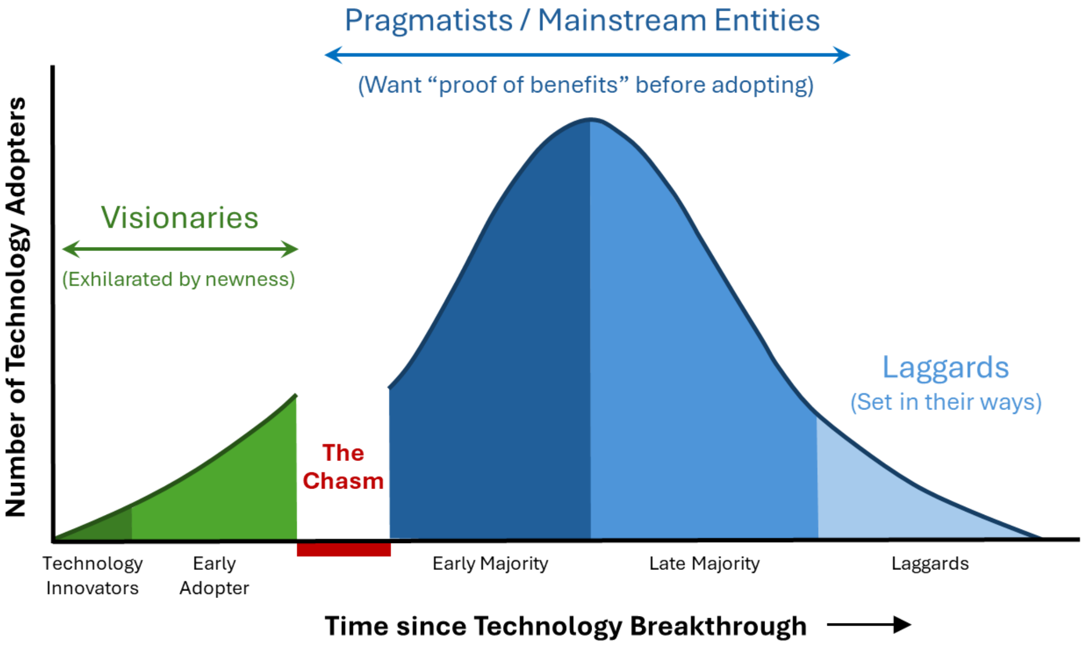

Figure 9: Diagram modified after Moore (1991) showing a conceptual model for how adoption of disruptive technologies often proceeds. For example, for unconventional gas reservoirs developed using hydraulically fractured horizontal wells, the "chasm" was crossed in 2004. For unconventional oil, it took over a half-decade longer (since most in industry and academia were convinced that oil molecules were too big to move through nanodarcy scale pores). Today in geothermal, the use of horizontal wells > 1,500 meters in length has only been demonstrated by a single firm pursuing EGS, although there are other visionary entities that are planning to drill wells with horizontal trajectories. How long it will be before adoption by a mainstream hydrothermal player occurs is hard to predict. Hopefully this will happen soon given the size of the economic prize is large and the potential societal benefits immense since increased geothermal electricity production could provide enormous amounts of the firm, affordable, low-carbon power needed to combat energy poverty, provide energy security, and limit the impacts of climate change.

Within any given industry, the customary reluctance of mainstream players to adopt disruptive technologies often leads to niche players and outsiders securing a first mover advantage. If the disruptive technology is significant enough, this may allow them to grow quickly, becoming formidable competitors before the mainstream players awaken to the fact that the new technology warrants being pursued. This reasonably describes what happened in unconventional reservoirs, with none of the supermajors or majors having been involved in the initial surge of shale gas related leasing, which allowed many small independent producers and private equity backed startups to establish outsize positions – positions that became extremely valuable as cost of supply was reduced by successive waves of innovation.

Finally, it is worth noting that in extreme cases, mainstream players that were slow to adopt a disruptive technology were totally displaced by one or more much smaller and nimbler competitor(s), with the most often cited example of such an outcome being Netflix's destruction of Blockbuster's business model. While such an outcome is rare, because the scale of the geothermal industry is small compared to the overall size of the energy sector, it is not impossible to imagine current large geothermal companies being marginalized or bought out if horizontal wells prove to be an invaluable tool for developing hydrothermal resources and they are slow to adopt the technology. It therefore seemingly would make sense for mainstream companies to experiment with the use of horizontal wells to rejuvenate and/or expand existing fields, which should be a highly economic endeavor given the ability to leverage existing data, infrastructure, and permits. Utilizing horizontal wells to develop new hydrothermal fields also offers great promise for delivering superior returns on investment, and could after a few successes lead to broadscale adoption of this well type across the geothermal industry, as has already occurred in oil and gas.

5. CONCLUSIONS

- There are many reasons to believe that the use of horizontal wells holds potential for enhancing hydrothermal project economics.
- The cost of drilling horizontal wells has fallen precipitously over the past quarter century thanks to learning curve improvements resulting from the oil and gas industry drilling over 100,000 horizontal wells during this period.
- Fervo Energy has demonstrated that it is possible to drill long horizontal wells (> 1,500 meters) in the types of crystalline basement rocks that contain most of our planet's high-enthalpy geothermal resources.
- Horizontal wells are near certain to increase flow rates and ultimate recovery of heat from geothermal deposits associated with complex fault zones such as those found in the Great Basin of the western United States because of the inherent advantages horizontal drilling has when it comes to intersecting steeply dipping structural features.

- Between the geothermal community, which has expertise in drilling LPHT wells, and the oil and gas industry, which drills tens of thousands of horizontal wells a year and has an impressive record of being able to engineer solutions to complex challenges, the equipment, workflows, knowledge, and skilled people required to successfully execute a horizontal hydrothermal drilling program are readily available.

- The geothermal industry as a whole should therefore embrace horizontal drilling technologies starting in 2025 – the 50th year in which the Stanford Geothermal Workshop is being held – and thereby attempt to cross the proverbial “adoption chasm”.

- Doing so will accelerate the production of clean, firm power from geothermal resources, which is a form of power that the world desperately needs to provide energy security, minimize energy poverty, and reduce climate-change-inducing-energy-production-related carbon emissions.

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