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Geothermal Drilling: A Review of Drilling Challenges with Mud Design and Lost Circulation Problem

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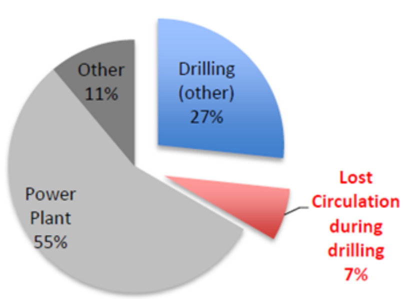
ABSTRACT

The most expensive problem routinely encountered in geothermal drilling is lost circulation, which is the loss of drilling fluid to pores or fractures in the rock formations being drilled. Lost circulation represents an average of 10 percent of total well costs in mature geothermal areas, and often accounts for more than 20 percent of the costs in exploratory wells and developing fields. Well costs, in turn, represent 35 percent to 50 percent of the total capital costs of a typical geothermal project. Therefore, roughly 10 percent of the total costs of a geothermal project can be attributable to lost circulation. Geothermal reservoirs are typically underpressured, and this increases their susceptibility to lost circulation. In many cases, geothermal wells have been abandoned because of lost circulation issues, which can quickly put a geothermal project into economic difficulty. Thus, developing improved methods and smart materials that can effectively seal the cavernous-type rocks in geothermal wells can positively impact the total cost of the project. In this paper, different methods of curing lost circulation are discussed. The types of materials, classifications, application conditions, and limitations are reviewed. The fluid additives and LCM's that are used for drilling high or low permeability sandstones are different from those that can be used to effectively drill carbonate rocks, vuggy, and cavernous formations. In addition, the fluids that is suitable for drilling wells with bottom hole temperature (BHT) up to 200 ºF may not be suitable for drilling wells with BHT up to 400 ºF. Placement of lost-circulation materials (LCM) is difficult because the top and bottom of the loss zone often are not well known. The LCM or cement being used to heal the loss zone are especially likely to migrate away from the targeted placement zone if drilling has continued well past it into another loss zone, or if there is considerable rat hole below the original loss zone. Typical drilling fluids additives (cellulose materials, calcium carbonate, graphite) used in drilling conventional and unconventional oil and gas wells may not be suitable for drilling geothermal wells because of temperature limitations. Some of the physical attributes that govern the performance of LCM's in geothermal wells were identified and correlated with laboratory test results.

INTRODUCTION

One of the major challenges with developing geothermal resources is high drilling cost (William et al. 2008; Tester et al. 2006). Several studies have established that drilling can make up to 30% to 70% of overall project cost (Lowry et al. 2017, Dumas et al. 2013, Gehringer, Finger and Blankenship, 2012). A recent study identified that geothermal wells on average takes 56.4 days longer to be drilled than comparable and oil and gas wells (Denninger et al. 2015). Finger and Blankenship (2012) provided a summary of the potential problems that are associated with the drilling and completion of geothermal wells. Drilling cost is either because of low ROP (rate of penetration) or attributed to other drilling problems such as lost circulation and severe wellbore stability issues. Lost circulation is very common in geothermal wells because of the typically fractured nature of the formations in a geothermal field or lost circulation while cement operation (Cole et al. 2017). Lost circulation is a persistent problem in geothermal drilling and is frequently the root cause of other wellbore integrity problems including sloughing, caving, washouts, or bridging. The time and material costs for lost circulation can represent 10% of the total well costs in a mature geothermal field, and often exceeds 20% of the costs for exploratory wells and reservoir development (Finger and Blankenship 2012; Almagro et al. 2014). In many cases, geothermal wells have been abandoned due to lost circulation, which can quickly put a geothermal project into economic difficulty (Mansure 2002). One recent study found that the largest cause of nonproductive time in geothermal wells is advancing through lost circulation zones. A cost in the range of $2M to $28M per field was reported (Figure 1). Another study for analysis of about 4,500 LC (lost circulation) zones found that 65% of LC is total loss (no circulating mud returned to the surface, however, loss severity depends on the pumped rate) in geothermal wells. Cement is used in 65% as a treatment material for total loss, and LCM is used in 30%. However, the proportion of success is about 15% with cement and about 10% with LCM (Hydo et al., 2000, Table 1).



Single well drilling cost:	USD $1-7 Million
Lost circulation drilling cost component:	~ 20%
Lost circulation cost:	USD $200,000-$1.4M
Wells per field:	10-20
Total drilling cost per field:	USD $10M-140M
Lost circulation cost per field:	USD $2M-28M

Figure 1: Breakdown of capital cost for an average 50-MW geothermal plant Cole et al. (2017)

Table 1. Analysis of about 4,500 LC (lost circulation) zones (Hydo et al., 2000)

Key Word	Number Of Data	Percent of Success	Percent of success with Cement (effective, Failure)	Percent of success with LCM (effective, failure)
No(from all data)	4,468	24.2%	13% (12%,20%)	9% (12%,11%)
Depth(0 to 500m)	3,047	28.8%	16% (12%,21%)	11% (11%,10%)
Depth(501 to1,000m)	1,027	17.5%	10% (12%,20%)	7% (16%,12%)
Depth(more 1,001m)	393	6.6%	3% (6%,12%)	3% (12%,13%)
Bit size(17-1/2")	41	31.7%	17% (2%,32%)	12% (7%,20%)
Bit size(12-1/4")	203	42.4%	32% (16%,20%)	9% (6%,4%)
Bit size(8-1/2")	67	14.9%	10% (33%,21%)	4% (6%,13%)
Bit size(HQ)	2,531	22.2%	10% (12%,19%)	11% (14%,13%)
Bit size(NQ)	552	12.5%	7% (7%,11%)	3% (17%,10%)
LC severity(0 to 30%)	829	26.7%	9% (4%,6%)	14% (12%,7%)
LC severity(31to 99%)	789	23.2%	9% (10%,11%)	11% (19%,9%)
LC severity(100%)	2,830	23.8%	16% (14%,27%)	7% (10%,13%)
Hokkaido Area	992	22.3%	5% (16%,10%)	15% (20%,14%)
Honshu Area	1,709	29.1%	17% (8%,18%)	10% (13%,9%)
Kyusyu Area	1,767	20.6%	14% (12%,28%)	6% (7%,11%)

There are two distinguishing differences between lost circulation in oil and gas drilling and geothermal well drilling. First, the type of rocks in geothermal applications are usually cavernous hard rocks, and drilling environments tend to be under-pressurized with multiple zones of highly fractured and altered material (Finger and Blankenship 2012). This makes lost circulation more common in geothermal drilling than in other applications. Figure 2 (left) shows a typical fracture in a geothermal well. Figure 2 (right) shows a conventional core sample after a fracture-wellbore strengthening test at the University of Oklahoma. In this figure, a wellbore strengthening material was used to seal the part of the two-fracture entrances to reduce the losses at high temperature. The fracture orientations are similar to those shown in Figure 2 (left). However, the fracture dimensions (width, aperture, and length) in geothermal wells are bigger, compared to conventional formations. Thus, the severity of lost circulation in geothermal drilling. The second difference is that the cement design and planning are quite different in geothermal wells, and likelihood of losses while cementing is higher (Cole et al. 2017). For those reasons, lost circulation deserves special attention as a means of reducing NDT.

Figure 1: A typical fracture in a geothermal well (courtesy of US DOE) and a core sample after a fracture-wellbore strengthening test at the University of Oklahoma

To combat lost circulation issues, a combination of different lost circulation materials has been applied and studied in the past. Some of the physical attributes that govern the performance of LCMs in geothermal wells were identified and correlated with laboratory test results. A study conducted by Sandia National laboratory revealed that thermoset rubbers had superior performance compared to other LCMs (Loeppke et al. 1990). Other factors such as particle size distribution (PSD) and LCM brittleness and resiliency were found to be important. In addition to materials, LCM placement and other operational procedures have to be critical in curing lost zones (Ezeakacha and Salehi 2018). One recent study discussed the application of controlled-porosity ceramic materials in controlling lost circulation geothermal wells.

Ceramic materials are formed using downhole sealing systems, with thermite as the energy source, and additives to control the reaction and product properties (Lowry and Nielson 2018). More recently, new techniques such as wellbore strengthening which increases the near-wellbore stress have shown promising results in loss prevention and curing (Aston et al., 2004, Salehi and Nygaard 2012, Ezeakacha et al. 2017).

Corrective and Preventive Lost Circulation Solutions

Proactive approach or corrective remediation are two general approaches presented in the literature to obtain wellbore strengthening technique (Wang et al., 2008; Fuh et al., 2007). Proactive approach is based on isolating the fracture tip to stop fracture propagation. The pressure improvement from this approach relies on the fracture length, and will decrease significantly when the fracture length is increased. In order to implement this approach effectively it is very important to arrest the fracture as quickly as possible as to stop fracture propagation. Sealing micro cracks and short fractures are one of the steps applied in industry for proactive strengthening. In a normal drilling there would be several micro fractures created or they might exist as natural fractures or caused by depletion, when these fractures are open and conduct fluid, any wellbore pressure exceeding the minimum horizontal stress will extend these fractures.

This phenomenon is also confirmed by Onya (1994) with the laboratory results for pre-fractured samples showing much lower breakdown pressures compared with intact and un-fractured samples. Dudley et al (2001) experiments, on fracture-reopening pressure with different core samples, confirmed that when resilient graphite materials were added to the base mud, the fracture opening pressure improved significantly. Wellbore breakdown pressure with the higher value of the Kirsch Hoop-stress equation were reported in the same study, indicating that materials play a major role in borehole strengthening where higher pressure than ideal may be observed in successful operations.

Corrective borehole strengthening can be achieved by widening the fracture width and increasing the compressive strength or fracture closure stress as mentioned previously by Dupriest (2005). By creating an appropriate fracture width and propping it by the bridging material, an increase in fracture closure stress will be achieved if the material isolates the tip effectively and no drilling fluid bypass to the propagation zone. Deformable, Viscous and Cohesive (DVC) materials have been proved to be useful in wellbore strengthening applications in the field (Wang et al., 2007). These materials can deform under pressure or stress. When fracture width increases with wellbore pressure, the seal body can maintain the seal by deforming.

Salehi and Nygaard, 2011 developed finite element models for wellbore strengthening applications and simulations of fracture creation and sealing (Figure 3). Their study showed that wellbore strengthening can be effective in restoring wellbore Hoop stress around the wellbore. The work showed the need for advanced design of materials to seal the fracture tip and mouth. Further, laboratory experiments showed the importance of pre-existing fractures in the rock and drilling fluid's LCM type, concentration and size.

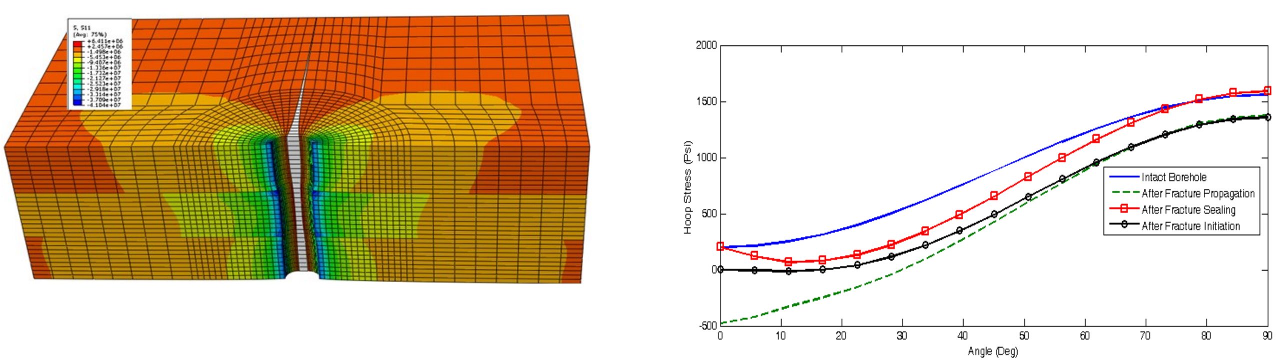


Figure 3. Finite-element's model to study wellbore strengthening (left), near wellbore Hoop stress results (right) (Salehi and Nygaard, 2011)

Wellbore strengthening lab experiments conducted on Sandstone and Dolomite samples using an advanced wellbore strengthening equipment set-up at Missouri University of Science and Technology (Salehi and Nygaard, 2011). Figure 4 illustrates the two cycles of re-opening pressure for Sandstone sample using 8% Bentonite Water-Based Mud. Fracture initiation pressure for this sample occurred at 1850 Psi and pressure increased until ultimate breakdown which happened at 1928 Psi pressure. Shortly after the first cycle, the second injection was conducted and ultimate reopening pressure was recorded at 1794 Psi. The pressure difference between the two peaks can be explained by the tensile strength of the sandstone; the average value from conducted Brazilian tests reported to be 377 Psi.

According to the theoretical equation, it was expected to observe the reopening pressure at 1551 Psi (tensile strength subtracted from original pressure breakdown). However, due to fracture healing caused by 8% Bentonite WBM, higher reopening pressure can be justified. This indicates using 8% Bentonite Water Based Mud can result in about a 243 psi increase in pressure. In addition, lower breakdown pressure was observed for sandstone when compared with dolomite using similar mud. This is due to low permeability of Dolomite samples, which creates perfect non-penetrating conditions for wellbore breakdown pressure.

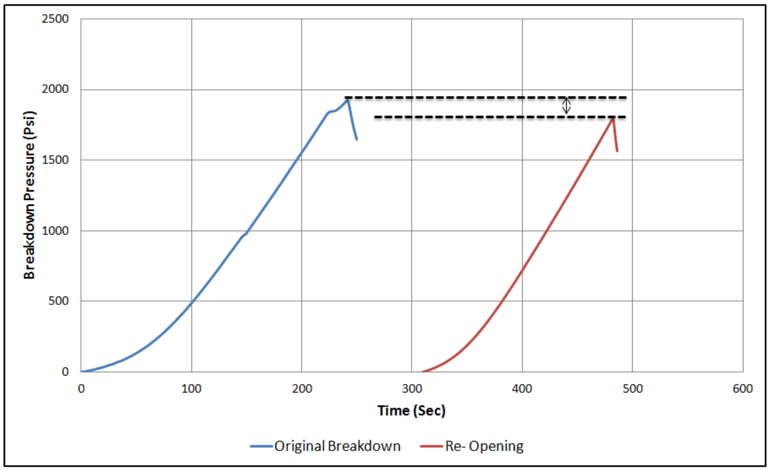


Figure 4. First and second cycle of fracturing versus time for the Sandstone sample using 8% Bentonite Water Based Mud (WBM), from Salehi and Nygaard, 2011

WBS (Wellbore Strengthening) Techniques

There are a number of methods to avoid lost circulation; by far the most common one is the use of LCMs, which are additives used in the mud to seal the fractures present in the formation. Many LCMs have been tested in geothermal conditions with varying grades of success, some of them are Walnut Shells, Fibers, Marble, Calcium Carbonate, Mica Flakes, Perlite (Loeppke et al. 1990). In general terms, the effectiveness of all these additives is reduced when dealing with wide fractures (Loeppke et al. 1990) or extreme temperatures. It must be considered that using Lost Circulation Materials (LCM) in this high permeability fractured reservoirs can permanently reduce the long-term productivity of the well, so the use of LCMs in productive intervals must be done with caution. LCMs can be added to the mud before contacting the lost circulation as an extra additive, or it can be used as a corrective treatment in the form of pills.

Compared to conventional LCM addition, there exists novel techniques that are applied and called as "Wellbore Strengthening" (WS) as defined in the literature as a set of techniques to deliberately increase wellbore fracture gradient by sealing and plugging open fractures near wellbore (Salehi, 2011). The two main theories, Stress Cage (SC) and FCS (Fracture Closure Stress) were repeatedly mentioned for strengthening boreholes based on increasing hoop stress around the wellbore (Figure 5). The Stress Cage method allows small fractures to form in the wellbore wall and keep the fracture surfaces apart by using bridging materials near the fracture mouth. If the fracture is successfully bridged at the wellbore wall or close to it, the hoop stress around the wellbore increases. In the FCS approach, tip isolation is very crucial for a successful operation and also bridging can take place anywhere inside the fracture; but in the Stress Cage, tip isolation is not reported to be an essential part and also it is very important to keep the bridging materials close to the fracture mouth. Even though these techniques have been successfully applied in depleted formations, its success in geothermal wells or high temperature conditions need further research.

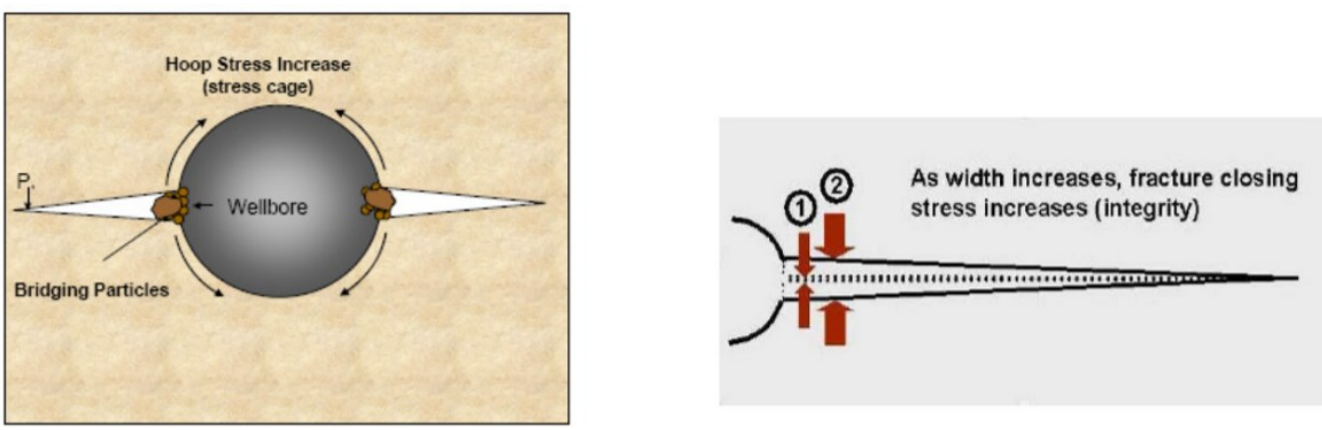


Figure 5. Stress Cage method (left), Fracture Closure Stress method (right) (Aston et al., 2004, Dupriest et al., 2005)

LCM and Additives for Geothermal Drilling Lost Circulation Control

Unlike oil and gas well, one of the characteristics of geothermal wells is the high temperature ranges and fractured lithology. Typical drilling fluids additives (cellulose materials, calcium carbonate, graphite) used in drilling conventional and unconventional oil and gas wells may not be suitable for drilling geothermal wells because of temperature limitations. Some of the physical attributes that govern the performance of LCM's in geothermal wells were identified and correlated with laboratory test results (Loeppke et al. 1990). The authors mentioned that other factors such as particle size distribution (PSD) and LCM brittleness and resiliency were found to be important. In addition, LCM placement and other operational procedures have to be found to be critical in curing lost zones (Ezeakacha and Salehi 2018).

Table 2 shows some of the drilling fluid additives and lost circulation materials (LCM) that have been used in high temperature oil, gas, and geothermal well drilling applications. In the roller oven test conducted by Loeppke et al. (1990), the authors reported that some of the conventional LCMs started to degrade from 200oF upwards. According to the authors, a study conducted by Sandia National laboratory revealed that thermoset rubbers had superior performance compared to other LCMs. One of the recent studies in this table discussed the application of controlled-porosity ceramic materials in controlling lost circulation in geothermal wells. Ceramic materials are formed using downhole sealing systems, with thermite as the energy source, and additives to control the reaction and product properties (Lowry and Nielson 2018).

Table 2: Lost circulation materials (LCM) and drilling fluid additives for high temperature and/or naturally fractured geothermal well application

Additive and Type	Classification	Temperature (^oF)	Testing Conditions	Literature
Polyurethane Foam	Fluid	300^{o}F	Laboratory and Field	Glowka et al. 1989
Thermoset Rubber	Granular, mixed with different sizes	110 to 192	Laboratory	Loeppek et al. 1990
Coal	Granular (powdery)	250 to 330	Laboratory	Loeppek et al. 1990
Expanded Aggregate	Granular (grainy)	>500	Laboratory	Loeppek et al. 1990
Gilsonite	Granular (powdery)	345 to 375	Laboratory	Loeppek et al. 1990
Black Walnut	Granular (grainy)	360 to 500	Laboratory	Loeppek et al. 1990
Foamed Cement	Cement Plug	265	Field (Central Wyoming)	Moore et al.2003
Foamed Calcium Aluminate Cement Blend	Cement Plug	1000	Field (Central California)	Moore et al. 2003
Foamed Latex Perlite Cement Blend	Cement Plug	180	Reverse Circulation in field (Central California)	Hernández and Nguyen 2009
Ground Rock Wool and Wood Fiber,	Drilling Fluid Pill	>400	Laboratory	Listi and Longyear 2010
Foamed Latex Cement	Cement Plug	180	Reverse Circulation in field (Central California)	Hernández and Nguyen 2010
Hydrophobically Modified Polysaccharide	Drilling Fluid Pill	400	Laboratory and Field (Texas and Spain)	Brandl et al. 2011
Shape Memory Polymer	Swellable (grainy)	200 to 600	Laboratory	Mansour et al. 2017
Controlled Porosity Ceramic Material	Ceramic Plug with different porosities	Up to 1000	Laboratory	Lowry and Nielson 2018

In addition, degradable thermoplastic composites can be mixed with high temperature resistant conventional LCMs for curing lost circulation. The degradation pattern of thermoplastic composites after exposure to harsh downhole conditions can be used to develop high-strength materials for temporal application (Celestine and Zhu 2018). These high-strength materials can be used for drilling production zones in geothermal wells because they have high mechanical properties and can resist fracture reopening and propagation. They are less prone to formation damage because of their degradable polymeric structure and other additives when exposed to completion fluids during completion.

In a recent study by Cole et al., 2017, the time and cost for 38 geothermal wells were analyzed that are drilled between 2009 to 2017. The study disclosed that, the major cause of non-productive time in geothermal wells is advancing through lost circulation zones, which have added over 100 h of non-productive time, adding $185,000 to each well in rig costs. According to Cole et al. (2017) the factors that affect success of remediation techniques includes temperature, pressure, pill and plug base materials, density, depth, length of loss zone, and type of circulation loss. Fig. 6 and Fig. 7 which are plotted from the data extracted from Cole et al. (2017) study show statistical comparison between the successful and failed attempts to regaining lost circulations performed in 15 geothermal wells that exhibited multiple loss events. The successful attempt is defined by being able to completely restore the mud circulation in case of partial loss and decrease loss rate to less than 25 bbl./hr. In case of severe and total loss. Among different techniques, the failure rates were 71.25% for seepage and partial loss, 68.5% for severe, and 83.6% for total loss. The mud-mixed LCM experienced a higher success-to-failure ratio in partial and severe loss, however in total loss, LCM pills and cement were more successful.

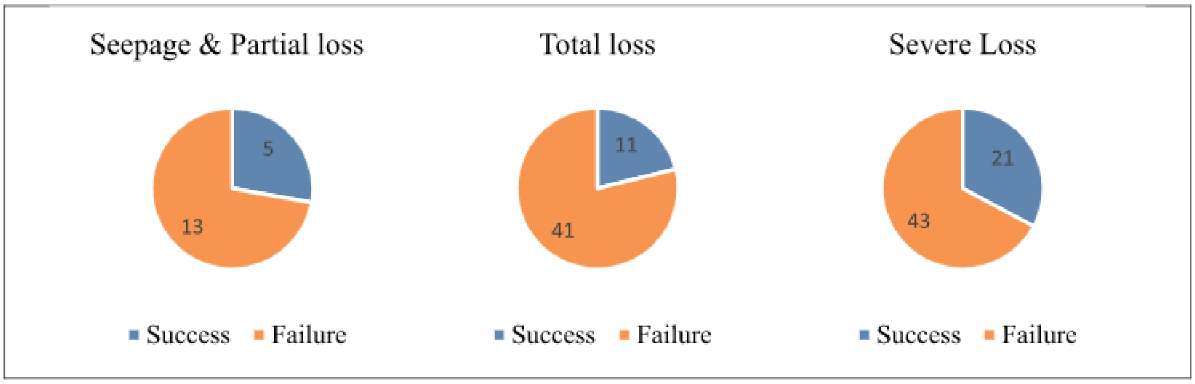


Figure 6: Using LCM pills and cement plugs for geothermal wells (modified after Cole et al., 2017, and Magzoub et al., 2019)

Figure 7: Using mud-mixed LCM for geothermal wells (modified after Cole et al., 2017, and Magzoub et al., 2019)

Cole et al. (2017) also concluded that more than 69 hours was spent on LCM treatments most of which failed. Taking another look at the red box in Figure 8, it may not be far-fetched why most of the LCM treatments failed. Most conventional LCM's tend to fail (degrade) at high temperatures (350ºF above). However, most of these events occurred below 302ºF. Thus, the cavernous nature of the formations (especially between 1000 ft and 4000 ft), is the most likely reason the LCM treatments failed. Moreover, the right type(s) and size(s) of LCM's may have not been used, given the testimony of trial and error LCM selection by two drillers.

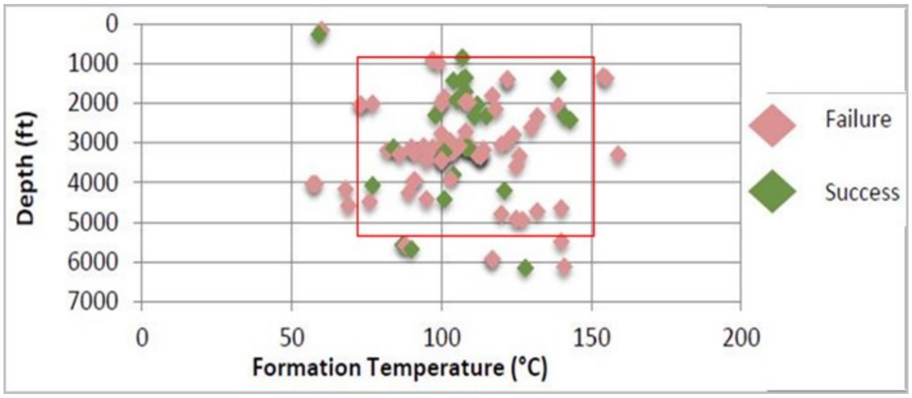


Figure 8: Depth versus temperature map for success and failure trials of using LCM for 15 geothermal wells.

Summary and Conclusions

In the literature reviews presented here, the importance of characterizing drilling fluid additives for application in HTHP conditions and cavernous-type rocks in geothermal wells have been discussed. One specific study showed that The percentage of successful LC (lost circulation) treatment from all the data is about 24%. Cement is used as a treatment material in 47% and LCM in about 35% of the cases.

One critical wellbore condition that can impact drilling fluid, LCM, and cementitious drilling fluid performance is temperature. This report has shown that some conventional LCM's will start degrading after 200^{o}F, while others have high thermal resistance up to 500^{o}F or even more.

With increasing demand of energy and exploring deeper targets, HPHT formations, and geothermal resources, the loss control materials need to be improved to cope with these extreme drilling conditions, large fractures and complex geological structures.

Wellbore strengthening techniques are proved efficient in reducing NPT resulted from loss circulation and well instability problems in conventional depleted formations, however their feasibility and application in geothermal basins require further research. Advancements in new materials design such as smart polymers have potentials for application in geothermal drilling.

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