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Mitigation Strategies and Geologic Context of Lost Circulation at Steamboat Hills, Nevada

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ABSTRACT

Losing circulation of drilling fluids remains one of the most common and expensive problems facing geothermal energy development today, representing up to 20% of exploratory drilling costs and 10% of the costs of reservoir development. This is the third of four reviews of geothermal fields that experienced problems with lost circulation and will focus on the Steamboat Hills Geothermal Field in western Nevada. Steamboat Hills is on the eastern margin of the Sierra Nevada in an area where dextral shear and east-west extension predominate. The Steamboat Hills reservoir is within crystalline basement rocks (Cretaceous granodiorites and Paleozoic metasediments) at relatively shallow depths of 1000-2000' and much of the heat is thought to be associated with Plio-Pleistocene rhyolitic volcanism. Permeability in this field is dictated by fractures in resistant formations that are related to extensional normal faulting. Depths of wells and lost circulation vary significantly, but losses are commonly associated with faults and fault intersections and preceded by secondary mineralization related to hydrothermal alteration of the host rock. Strategies to address lost circulation in Steamboat Hills include the use of large amounts of lost circulation materials, cement plugs in the cased interval, and drilling blind once in the production zone of the well. Common lost circulation materials and polymers used include proprietary blends, bentonite chips (in the cased interval), cottonseed hulls, and rice straw. In contrast to the previous fields examined, large amounts of lost circulation materials were observed to "cure" lost circulation on a semi-regular basis. Further experimental and modeling studies addressing lost circulation materials and strategies, informed by these case studies, are underway in order to develop a systematic understanding of contextually informed efficient and effective responses to lost circulation.

1. INTRODUCTION

Lost circulation occurs when some or all the drilling mud is lost to the formation and does not return to the surface and commonly occurs when drilling geothermal wells (e.g., Lavrov, 2016). Multiple studies have found that lost circulation may induce significant project delays, cost increases, and even the abandonment of wells. One of these studies identified problems caused by lost circulation as the largest cause of nonproductive drilling time (Cole et al., 2017). Of 77 wells examined by Svenbjornsson and Thorhallsson (2014), 20% experienced increased completion times and costs due to problems caused by lost circulation and collapsing formations. The Sandia Best Practices Geothermal Drilling Handbook states that "the most expensive problem routinely encountered in geothermal drilling is lost circulation" and attributes up to 10% and 20% of drilling costs for developed and exploratory fields, respectively (Finger and Blankenship, 2010). Considering the costs and delays associated with lost circulation, developing systematic methods of mitigating these problems will aid in the US DOE's goal of increasing the accessibility and economic feasibility of geothermal energy.

Lost circulation occurs in geologic settings where the permeability is high such as volcanic areas with lava tubes, poorly consolidated sediments, and especially in fractured and faulted formations and when the fluid in the wellbore is over-pressured relative to the formation. Excessive pressure within the wellbore drives the fluid into the formation and can also hydro-fracture the formation. Losing circulation when drilling at production depths is often an indicator of a potential well feed zone but must still be managed, especially when severe (>100 bbls/hr) loss occurs, to avoid problems such as stuck drill string, reduced reservoir productivity, insufficient flushing and thus packing of the annulus, and wellbore collapse. Above production depths in the cased interval of the well the same problems can occur, as well as poor cement jobs if cement is lost to the formation (Finger and Blankenship, 2010). These problems can lead to nonproductive drilling time, potential fishing operations, the need for large volumes of lost circulation materials and drilling mud, and even the abandonment of wells, all of which result in significant cost increases during geothermal drilling and development.

This study is part of an ongoing joint effort between SNL, LBNL, and Ormat Technologies to review the geologic context of, and common mitigation strategies used to, address lost circulation in four different case studies. The first case study reviewed lost circulation in McGinness Hills Geothermal Field in Nevada (Winn et al., 2021a) and the second case study examined drilling records from Don A. Campbell Geothermal Field, also in Nevada (Winn et al., 2021b). Here, detailed drilling records for Steamboat Hills, Nevada were reviewed to determine the geologic context and mitigation strategies for lost circulation in this field.

2. STEAMBOAT HILLS GEOLOGY AND GEOTHERMAL SYSTEM

The Steamboat geothermal system consists of two distinct areas: Steamboat Springs (or Lower Steamboat), and Steamboat Hills (or Upper Steamboat). It is located just south of Reno, Nevada, at the southern end of Truckee Meadows, along the western margin of the Basin and Range province. It differs from most Basin and Range geothermal systems in that it is associated with Quaternary volcanism. At least four Pleistocene-age rhyolite domes have intruded into Tertiary volcanics and Mesozoic basement rocks (metasediments and intrusives) (White, 1968; Silberman et al., 1979; Flynn et al., 1994; Ramelli et al., 2011). The geothermal reservoir is primarily within fractured and faulted Cretaceous granodiorite. Several different steeply dipping fault systems have been mapped in the area, striking NE-SW, N-S, and NW-SE (Fig. 1). The structural setting for this area is a combination of fault terminations, fault intersections, and accommodation zones (Faulds et al., 2013).

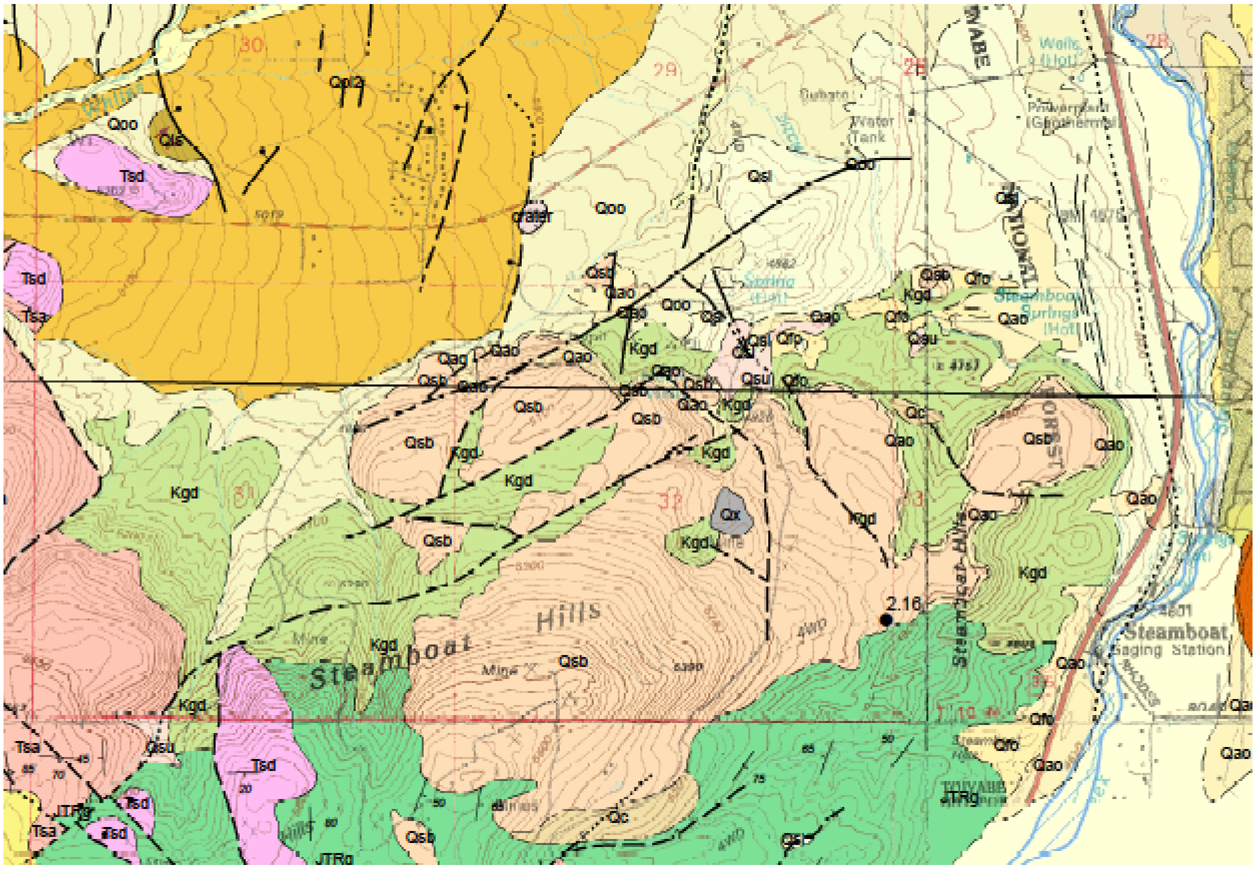

Figure 1: Geologic map of the Steamboat geothermal system (Ramelli et al., 2011). The geologic units are as follows: JTRg – Jurassic-Triassic metasedimentary rocks; Kgd – Cretaceous granodiorite; Tsd – Tertiary Steamboat Hills dacite; Tsa – Tertiary Steamboat Hills andesite; Qsb – Quaternary Steamboat Hills basaltic andesite; Qoo – Quaternary older outwash; Qoi2 – Quaternary intermediate outwash; Qfo – Quaternary older fan deposits; Qao – Quaternary older alluvium; Qsu – Quaternary sands; Qc – Quaternary colluvium; Qsi – Quaternary sinter.

Thermal discharge into Steamboat Creek has remained relatively constant, likely due to replenishment of the resource by reinjection of produced fluids (White, 1968; Sorey and Spielman, 2017). There is an extensive silica sinter (Fig. 2) that blankets much of the lower elevation regions near where the springs once discharged silica-rich fluids (White, 1968; Lynne et al., 2008). Hot spring resorts were developed in the area starting in the late 1800s, and the first geothermal wells were drilled in the 1920s to supply hot water to these resorts (Garside and Schilling, 1979; Combs and Goranson, 1994). The first commercial geothermal power generation began in 1987, and field operations have recently been upgraded, with current generation of 84 MW (Combs and Goranson, 1994; Walsh et al., 2010; Akerley et al., 2021).

Figure 2: Silica sinter terrace at Steamboat, with Ormat binary power plant in the background (photo by P. Dobson).

The conceptual model for the Steamboat geothermal system (Fig. 3) consists of upflow in the Steamboat Hills area to the SW, where the highest temperatures are observed, with outflow and surface discharge to the NE in the Steamboat Springs area (Mariner and Janik, 1995; Walsh et al., 2010). Much of the permeability within the basement rocks that host the geothermal reservoir appears to be controlled by faults and fractures, which have been observed from cores, PTS (pressure/temperature/spinner) logs, and image logs in production, injection, and slimhole wells (e.g., Finger et al., 1994; Flynn et al., 1994; Combs and Goranson, 1994; 1995; Goranson and Combs, 1995; 2000; Walsh et al., 2010).

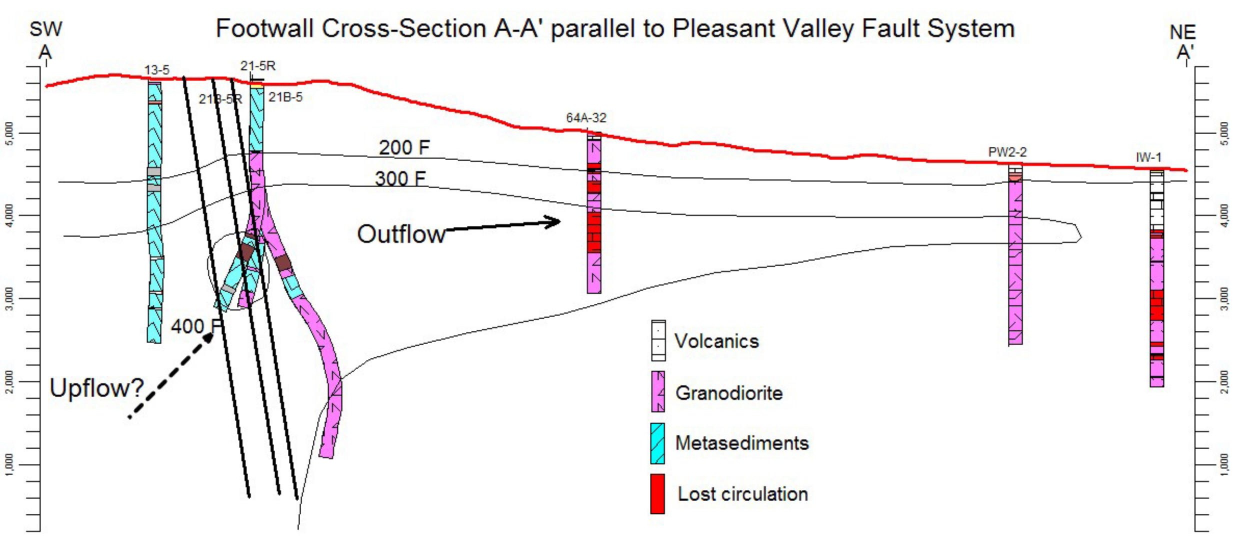

Figure 3: Conceptual model of Steamboat system (Walsh et al., 2010). Upflow occurs along faults and fractures to the SW (Steamboat Hills area), with outflow to the NE (Steamboat Springs area).

3. METHODS

Ormat Technologies provided the drilling records and mud logs for 12 wells from Steamboat Hills. The drilling records were provided via RIMbase, a powerful software system designed to integrate wellsite information such as construction, completion, interventions, and visualization of cost, depth, and time data (https://www.infostatsystems.com/well-operating-companies/), and included production, injection, and monitoring wells. Mud logs and drilling operations activity reports were surveyed for evidence of lost circulation, noting associated depths, mitigation responses including materials commonly used, and lithologic information when available. When lithologic information was not available in the drilling records, a 3D geologic model, was also provided by Ormat to examine the geologic context of lost circulation. This Leapfrog 3D model includes information about feed zones for the wells, directional drilling, lithologies and stratigraphy along the wellbores, and estimates of subsurface fault planes and intersections (Figure 4). These 3D models are constructed using wellbore information, geologic mapping, and often geophysical data (seismic, magnetotellurics, airborne electromagnetics, etc.).

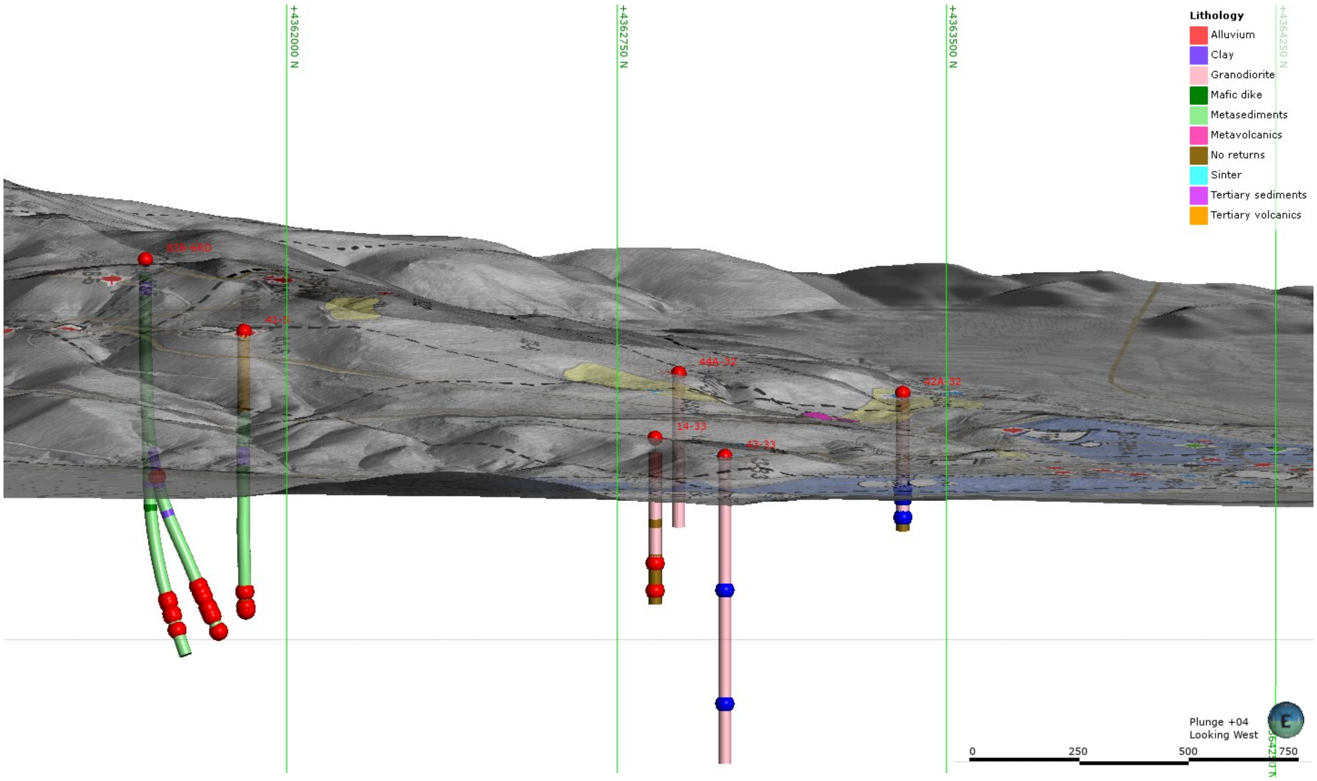

Figure 4: Overview of the 3D geologic model of Steamboat Hills geothermal, looking west. Note that some wells are filtered out to focus on those that experienced problems with lost circulation and fault planes are not shown in this overview. Red spheres represent feed zones in production wells, while blue spheres are injection zones.

4. RESULTS

4.1 Geologic Setting of Lost Circulation

Well depths at Steamboat Hills vary greatly between 850' and nearly 4000' deep, with shallower wells typically in the lower NE region in the geothermal field and deeper production wells in the upper SW region. Wells in the lower region are predominantly drilled through granodiorites, and wells in the hills are drilled into Tertiary volcanics and metasediments. Wells were frequently targeted to intersect faults or fault intersections and zones of total lost circulation (no returns in the 3D model; refer to the brown colors shown along the wellbore in Figure 4) often coincide with faults. Secondary mineralization that is commonly associated with hydrothermal alteration along faults, such as clay minerals and epidote, are commonly reported in the mud logs preceding loss of circulation. Three wells that experienced severe lost circulation, two production and one injection, were examined more closely for mitigation responses. One of the production wells, 41-5, is in the SW portion of the field and drilled into metasediments and volcanics while the other two, 14-33 (production) and 42A-32 (injection), are in the lowlands and drilled into granodiorites.

4.2 Well Case Studies

4.2.1 Case Study of Well 14-33

Well 14-33 was drilled to a total depth of 1240 ft and cased to 1100 ft. It extends through several hundred feet of alluvium, prior to encountering granodiorite and regions where there were no returns (Table 1). Several troublesome episodes of lost circulation occurred in the reservoir while drilling this hole. At 446-458 ft a small loss rate occurred and was healed by a sweep of undetermined lost circulation material (LCM). From 558 to 649 feet, 204 bbl mud was lost. This was cured by another sweep of LCM at 649 ft. Following that, losses of over 200 bbl/hr occurred while circulating. 100 bbl of UltraSeal™ was spotted at 698 ft, and 40 bbl Geo's StopLoss™ LCM pill was spotted at 650 ft. These remediations allowed partial returns, and time was allowed for the LCM to set up. No flow was returned after pumping 100 bbl, and a 100 bbl UltraSeal™ LCM pill was mixed. A high-viscosity LCM pill was spotted at 698 ft, but circulation was not achieved. A 100 bbl StopLoss™ pill and 40 bbl of cottonseed LCM were pumped in, after which circulation was achieved with no losses. 144 bbl was lost washing down the last 3 joints from 560 to 650 ft, followed by the total loss of circulation. Another 114 bbl was lost trying to regain circulation. A 50 bbl StopLoss™ pill was spotted at 698 ft and 100 bbl containing cottonseed pellets was spotted at 690 ft, resulting in regaining circulation. Observations indicated that after spotting an LCM pill, circulation could be achieved *above* the pill, however circulation at the location where losses occurred caused circulation loss. Circulation was lost while mixing the next LCM pill. This was spotted at 698 ft and a cement plug was placed at 698 ft. Drilling to this depth and waiting on the cement plug took 4 days.

While drilling down further at 882 ft total circulation was lost. An LCM sweep was pumped, followed by spotting a LCM pill on the bottom. The drill string was pulled out, and tripped in with open-ended drill pipe to 871 ft. A LCM pill was mixed and pumped. The drill string was pulled out to 500 ft, and LCM was mixed in. The drill string was tripped in to 800 ft and the LCM pill was pumped in. The drill string was tripped out of hole, and then tripped in to 871 ft to drill the 17-1/2-in hole with no returns to 882 ft. The next LCM pill was pumped to the bottom and the drill string was tripped out. An open drill pipe was tripped in to 872 ft and cement was placed. Continued drilling with losses of about 40 to 45 bbl/hr while emplacing LCM pills. At 947 ft, all returns were lost to 1004 ft. At 1004 ft, a LCM pill was mixed and pumped, followed by 150 linear ft of cement. When the drill string was tripped back in, no cement was encountered. Another 110 bbl of LCM was mixed and pumped in followed by 100 linear feet of 14.5 ppg cement. When the drill string was tripped in, cement was again not encountered. 100 bbl of LCM was mixed and pumped followed by 100 linear ft of 14.5 ppg cement. Circulation was attempted at 880 ft and all returns lost. The drill string was tripped in and tagged “bottom” at 830 ft. Cement was drilled with no losses to 871 ft where the string fell through to 883 ft, and all returns were lost. The drill string was tripped out and the shock sub was laid down. A total of 9 bales of rice straw were dumped in the hole interspersed with numerous trips in and out, and the straw was pushed to 886 ft.

Numerous attempts to fill the hole were not successful. The materials introduced included bentonite, rock, gel, and synthetic polymer from surface, all flushed to bottom with water. The drill string with bit and bottom hole assembly was tripped into the hole and tagged the LCM at 875 ft. Attempts were made to fill the hole and circulate, yet there were fluid losses of 180 bbls/hr occurred. The drilling was continued without any returns. The remainder of the hole through the production interval was drilled blind to the total depth of 1240 ft.

Table 1: Reports of lost circulation and mitigation strategies, including which lost circulation materials were used, in well 14-33.

Depth (ft)	Lithology	Loss (bbl)	Steps taken to remediate	Material	Function Satisfactory
446		13	LCM sweep		Yes
649		204	Sweep at 649 (LCM Pill - UltraSeal™)	UltraSeal™	Yes
698		200/hr	100 bbl UltraSeal™	UltraSeal™	
			40 bbl StopLoss™ at 650	StopLoss™	Yes
		165			
698		100	100 bbl LCM pill	UltraSeal™	No
		200	Hi-Vis LCM pill		No
			100 bbl StopLoss™ Pill	Cottonseed	Yes
				StopLoss™	Yes?
		144			
		Total			
		114			
			50 bbl StopLoss™	StopLoss™	
			100 bbl cotton seed pellets	Cottonseed	Yes?
			LCM pill (not specified)		
			Cement plug	Cement	Yes
717		3-4/hr			
871		Total	LCM sweep (not specified)		
			LCM pill (not specified)		
			LCM pill (not specified)		
			31 bbl Cement plug	Cement	Yes

882		3/hr			
935		40-45	LCM pill (not specified)	LCM pill	No
947		Total	Continued drilling blind		
1004			LCM pill (not specified)	LCM pill	No
			150 linear ft cement	Cement	No
			110 bbl LCM	LCM	No
			100 linear feet of 14.5# cement	14.5# cement	No
			Lost cement		
			100 bbl LCM Pill (not specified)	LCM pill	No
			100 linear ft 14.5# cement	14.5# cement	No
		Total			
881		Total	1 bale rice straw	Rice Straw	No
			2 bales rice straw	Rice Straw	No
			6 bales rice straw 100 bbl water	Rice Straw	No
1060		180/hr	Drilling blind		
1150		Total	Drilling blind (no circulation)		
1240			TD		

4.2.2 Case Study of Well 41-5

Well 41-5 was drilled to 2130 ft through Tertiary volcanics and metasediments and cased to a depth of 1900'. Losses of up to 65 bbls/hr occurred with sudden losses occurred in the upper regions of the well, which were cured with PrimaSeal™ and sawdust (1 sack of each per hour). At a depth of 1680 ft, rapid losses on the order of 30 to 60 bbl occurred with continued minor seepage on the order of 10 bbl/hr. An LCM sweep was run at 1906 ft curing losses. All returns were lost between 1954 to 1957 ft, but this was healed with PrimaSeal™. All returns were lost again between 1991 and 1992 ft, and the remainder of the hole was drilled blind to 2130 ft.

4.2.3 Case Study of Well 42A-32

Well 42A-32 was drilled through 200ft of alluvium before continuing to total depth of 1030 ft in granodiorite, and cased at 750'. At shallow depths, small losses on the order of 35 bbbl/hbl/hr occurred. These were healed using a high viscosity LCM pill. At 790 ft, losses were on the order of 90 to 300 bph. 50 bbl of FracAttack™ LCM were applied. The cinders were tagged at 768 ft (14 ft of fill), and it was thought that the FracAttack™ had not hardened. This was circulated out slowly and another 50 bbl pill of FracAttack™ was spotted on the bottom of the hole. After several hours, the hole was circulated clean and mud loss of 30 to 90 bbl/hour occurred. A high viscosity LCM sweep was performed but losses of 30-40 bbl/hr continued. A high viscosity microfiber plug was spotted on the bottom of the well and cleaned out to 760 ft. It was possible to circulate with full returns, at which point casing was run and grouted. This lost circulation event consumed 4 days of rig time. Losses on the order of 130 to 200 bbl/hr began at 812 ft and continued until all returns were lost at 930 ft. A 40 bbl high viscosity sweep was injected, following drilling blind to 1030 ft.

5. CONCLUSIONS

Multiple wells drilled in the Steamboat Hills Geothermal Field and especially the three examined here experienced significant issues related to lost circulation. Lost circulation occurred in wells drilled in both the metasedimentary basement and granodiorites and was often preceded by secondary hydrothermal mineralization and spatially associated with faults and fault intersections. The association of lost circulation zones with faults and fault intersections is a common theme here and in the other fields reviewed in this effort (i.e. McGinness Hills and Don A. Campbell). Lost circulation in the cased intervals of wells was addressed and sometimes cured by large amounts of both proprietary lost circulation materials and commonly used materials such as cottonseed hulls and rice straw, and when LCM did not work to cure the. That lost circulation in this field was cured by the addition of LCM contrasts with reports from other fields, where LCM was used but often did not "cure" the losses (e.g., Winn et al., 2021a,b). Like the other fields, losses in the production or injection intervals of the wells were addressed by drilling blind but seemingly without the air assist reported at both Don A. Campbell and McGinness Hills.

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