PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 15-17, 2021
SGP-TR-218

When, Where, and Why: The Geologic Context of Lost Circulation While Drilling in a Crystalline Geothermal Reservoir

Carmen Winn[1], Patrick Dobson[2], Craig Ulrich[2], Timothy Kneafsey[2], Tom Lowry[1], Zach Cesa[3], Robin Zuza[3], John Akerley[3], Ben Delwiche[3], Abraham Samuel[4], and Stephen Bauer[1]

[1]Sandia National Laboratories, Albuquerque, New Mexico, USA

[2]Lawrence Berkeley National Laboratory, Berkeley, California, USA

[3]Ormat Technologies Inc., Reno, Nevada, USA

[4]Geothermal Resource Group Inc., California, USA

clwinn@sandia.gov

Keywords: lost circulation; lost circulation materials, geology, drilling, McGinness Hills

ABSTRACT

Lost circulation is a common problem in geothermal drilling that can represent 20% of the costs for reservoir development. Here we examine the McGinness Hills Geothermal Field to determine the geologic context of and the most common and effective responses to lost circulation. This field, operated by Ormat Technologies, is located in central Nevada on the eastern flanks of the Toiyabe Range and is the fourth largest geothermal complex in the United States. The regional geology is typical of the Basin and Range region, consisting of Paleozoic metasedimentary strata that are intruded by Jurassic granitic plutons at depths greater than ~300m, which represent the main production zone, and are overlain by Oligocene to Miocene volcanic deposits and Quaternary alluvial fan deposits. Faults in the area predominantly trend NNE and NNW with normal movement; the greatest permeability is found at the intersections of these faults. Deep geothermal wells commonly experience problems with lost circulation during drilling, with several wells well losing thousands of barrels of drilling fluids. We examine the depths, lithologies, proximity to faults, and common responses to lost circulation as the first step in forming a comprehensive strategy to address lost circulation in varying contexts. Lost circulation in McGinness Hills generally occurs at depths greater than 2000 ft, well into the metasedimentary basement, Jurassic intrusions, and production interval. Because the depths of lost circulation at McGinness Hills usually corresponds with the production zone, correcting lost circulation adds the challenge of not permanently damaging permeability, which limits the approaches available to solving the problem. The most common approaches to lost circulation mitigation at McGinness Hills include pumping high viscosity sweeps of lost circulation materials, aerating the drilling fluid, and drilling blind without returns. Further study of this and other fields may demonstrate more in-depth correlations between depths, lithologies, and responses and will contribute to a larger effort to develop a systematic understanding of contextually informed responses to problems with lost circulation.

1. INTRODUCTION

Lost circulation (LC) is a common occurrence in drilling geothermal wells, where not all of the drilling mud circulated in the wellbore returns to the surface (e.g., Lavrov, 2016). Lost circulation can result from drilling with excessive mud weight, leading to forcing drilling mud into the formation (and causing skin effects and formation damage), and potentially hydrofracturing of the formation. Lost circulation can also occur when drilling in highly permeable formations, such as poorly consolidated sediments, highly porous lava flows, or fractured and faulted rocks. Lost circulation occurs on different scales, ranging from partial losses (10-100 bbl/hr.), to severe losses (> 100 bbl/hr.) to total losses. Problems caused by lost circulation can lead to large delays in drilling, increased mud costs, poor cement jobs, reduced reservoir productivity, inadequate hole cleaning causing the annulus to be packed with cuttings, and in extreme cases, wellbore collapse that could lead to a stuck drill string and the need for sidetracking or abandoning a well.

The Sandia Best Practices Geothermal Drilling Handbook (Finger and Blankenship, 2010) states that "***The most expensive problem routinely encountered in geothermal drilling is lost circulation***", and notes that lost circulation results in 10% of drilling costs for mature fields and over 20% of drilling costs in exploration drilling. A study of geothermal drilling in Iceland (Sveinbjornsson and Thorhallsson, 2014) noted that loss of circulation and collapsing formations were the primary problems encountered in the 77 wells that were evaluated, with over 20% of these wells having these issues, leading to prolonged drilling times and increased costs. A recent survey by Cole et al. (2017) noted that advancing through lost circulation zones is the largest cause of nonproductive time when drilling geothermal wells. Thus, developing improved methods to resolve lost circulation while drilling has the potential to make a major contribution towards the DOE's goal of lowering the cost of accessing geothermal resources through developing improved methods and technologies to deal with lost circulation events (LCEs).

This paper represents a preliminary review of detailed proprietary geothermal drilling records provided by Ormat. This evaluation of the geologic and drilling conditions that are associated with lost circulation and the mitigation methods that were used at the McGinness Hills geothermal field is part of an effort to develop a series of case studies that can be used to identify distinct types of lost circulation (LC) conditions and characterize the most effective ways to cope with them conducted by Sandia, LBNL and Ormat on behalf of the DOE GTO.

2. GEOLOGIC CONTEXT OF MCGINNESS HILLS

The McGinness Hills geothermal system is located in central Nevada, ~20 km NE of Austin, Nevada, on the east flank of the Toiyabe Range, within the Basin and Range province (Fig. 1). The stratigraphy of the area is marked by a basement sequence of Paleozoic metasedimentary rocks (the Ordovician Valmy Formation, an orthoquartzite, and the Devonian Slaven Chert) that have been locally intruded by Jurassic granites. These rocks are unconformably overlain by a sequence of Tertiary (Oligocene to Miocene) volcanic rocks, consisting of basal andesite and dacite flows, which are overlain by the Bates Mountain rhyolitic ash-flow tuff (Wendell, 1985). The area is distinguished by both fossil hydrothermal alteration as well as extensive (~2 km^2) Plio-Pleistocene sinter deposits, which prompted precious metals mineral exploration efforts in the area (Casaceli et al., 1986). Prospecting boreholes drilled to a depth of 1000 ft (300 m) encountered near-boiling water, with water chemistry suggesting the presence of higher temperature (150-200°C) fluids at greater depths (Coolbaugh et al., 2006). Extensive Quaternary alluvium is present within the valley.

The permeability of this geothermal system is controlled by faults and fractures. Faulds et al. (2013) characterized the structural geology of this area as a hybrid setting (Fig. 1), having both an accommodation zone, consisting of overlapping, opposite dipping normal fault systems that lead to multiple fault intersections in the subsurface, as well as having fault stepovers, with minor faults connecting the overlapping fault segments. The highest permeability within the system appears to be related to the intersection of NNE-striking faults with steeply dipping NW-striking faults within a left stepover (Faulds, 2013; Faulds et al., 2013). Older regional structures, such as the Roberts Mountain thrust fault, which juxtaposes the Devonian Slaven Chert on top of the Ordovician Valmy Formation to the west in the Toiyabe Range (Casaceli et al., 1986), may contribute to upwelling of mantle-derived fluids along such structures in this area, expressed by increased $^3He/^4He$ values (Siler and Kennedy, 2016).

The McGinness Hills geothermal field is the largest producing geothermal system in Nevada (Ayling, 2020) and the 4th largest in the United States. The geothermal field was developed in three stages: the first unit (36 MW nominal) came online in 2012, the second unit (also 36 MW nominal) came online in 2015, and production at the third unit (48 MW nominal) was initiated in 2018. The project has exceeded its nominal capacity, with a net combined generation of ~140 MW (Nordquist and Delwiche, 2013; Lovekin et al., 2016; Akerley et al., 2019; Ayling, 2020). The field has a total of 15 production wells and 8 injection wells – the production wells are located in a fractured graben to the north, and the injection wells are sited in another fractured graben to the south. The NNE-striking faults that define these structural features (including the Main Sinter Terrace fault and the Eastern Sinter Terrace fault) are favorably oriented for both slip and dilation (Lovekin et al., 2016; Akerley et al., 2019). The locations and orientations of the faults were defined using a combination of surface mapping (alteration zones and lithologic offsets), drilling and wellbore observations (such as fracture mapping from image logs and flow zones identified from PTS surveys and drilling data), and geophysical surveys (e.g. gravity modeling). Brine from the production wells has a temperature of 168°C. Most of the production occurs within the basement quartzite and intrusive rocks (Knudsen et al., 2014).

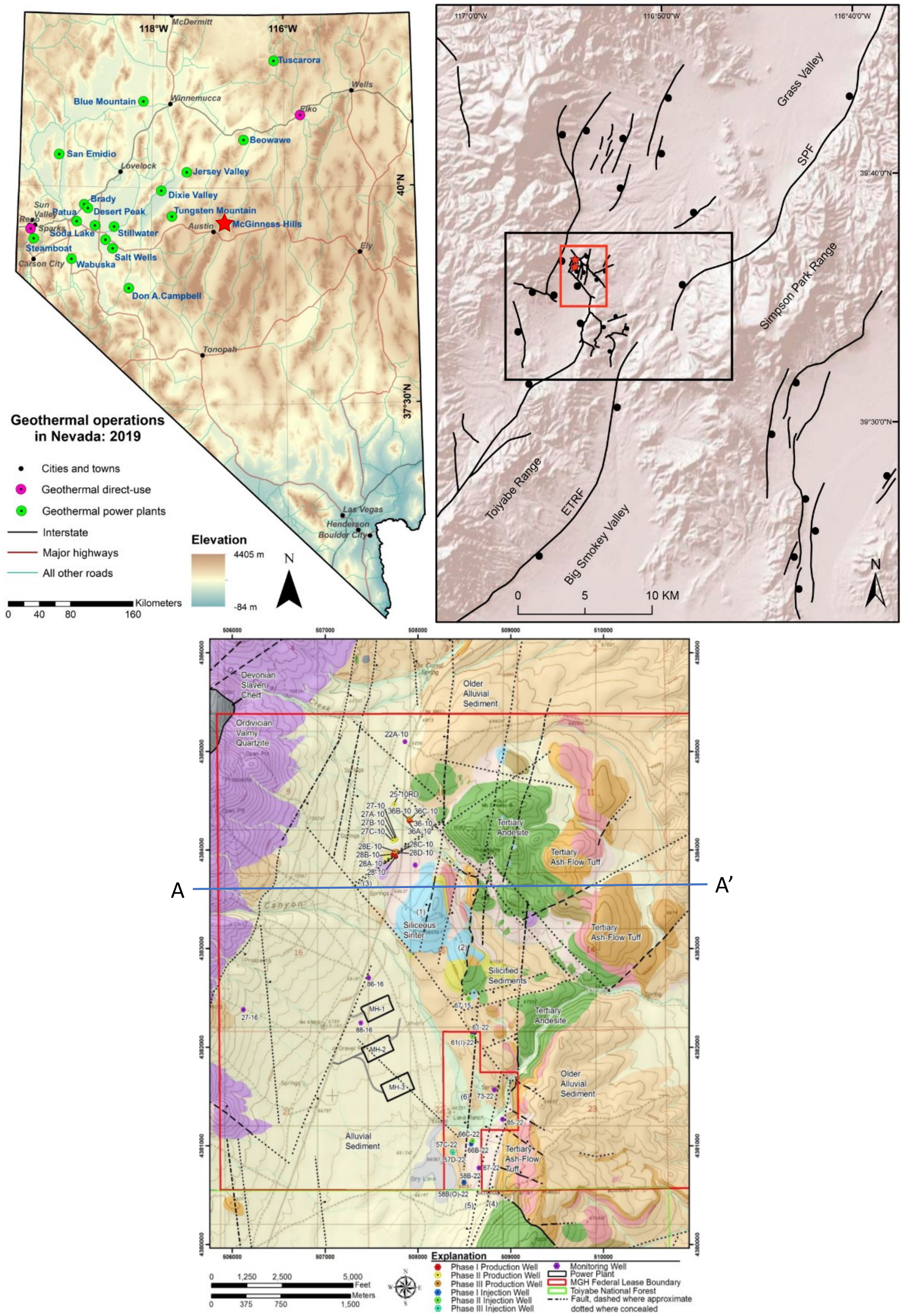

Figure 1: Top left: Location map of geothermal fields in Nevada. Red star indicates McGinness Hills. (Ayling, 2000). Top right: Structural and digital elevation map of the McGinness Hills geothermal area (Faulds et al., 2013). Accommodation fault zone outlined by black box; geothermal field with fault stepover outlined by red box. ETRF = Eastern Toiyabe Range Fault; SPF = Simpson Park Fault. Bottom: Geologic map of the McGinness Hills geothermal field (Akerley et al., 2019). The faults are numbered as follows: 1) Main Sinter Terrace fault, (2) Eastern Sinter Terrace fault, (3) Silica fault, (4) Eastern Ridge fault, (5) Pediment Ridge fault, (6) Steep fault.

3. METHODS

Proprietary drilling records for 28 wells in McGinness Hills geothermal field were provided by Ormat using the software program RIMbase, an integrated wellsite information system that covers all aspects of well construction, completion and intervention and facilitates data visualization and analysis (https://www.infostatsystems.com/well-operating-companies/). Drilling records for all wells provided were reviewed, which included production, injection, and monitoring wells. This review focused predominantly on the operations activity reports and comments, looking for evidence that lost circulation was encountered, and on the records of materials put down hole to adjust viscosity and address lost circulation where it was noted. Where lost circulation was noted, particular attention was paid to responses depending on depth, to determine differences between the cased and production intervals, and lithology when available, to determine differing responses based on the likely type of lost circulation (seepage, fractures, faulting, etc.). For a more detailed look at strategies in response to lost circulation, two of the most recent wells in the field, a production and an injection well, were selected to examine in detail. These details include the exact lost circulation materials (LCM) used, detailed lithology from mud logs, and well geometries and fault intersections from a Leapfrog 3D geologic model of the field provided by Ormat.

This model (Fig. 2) is a 3D representation of the subsurface geology of McGinness Hills, including directionally drilled wellbores, stratigraphy and feed zones along the wellbore, and faults and their estimated subsurface projections and intersections. It provides a wealth of information about the intervals, lithologies, and proximity to faults of no return zones due to lost circulation along wellbore paths as well as offering visual representation of geologic patterns below ground. The development of 3D geologic models for geothermal fields incorporates many types of data such as well data (drilling and production), surface geophysical data (magnetics, magnetotellurics, seismic, airborne electromagnetics, etc.), geologic mapping, and many others. In the recent decade powerful geological modeling software, such as Leapfrog, have been developed that can incorporate all of these data in order to visualize this data within a 3D space to perform spatial analyses, look for visual trends and find correlations (e.g., Poux et al., 2018; Baxter et al, 2019). An example of a generated fault and stratigraphy model is shown in Figure 2.

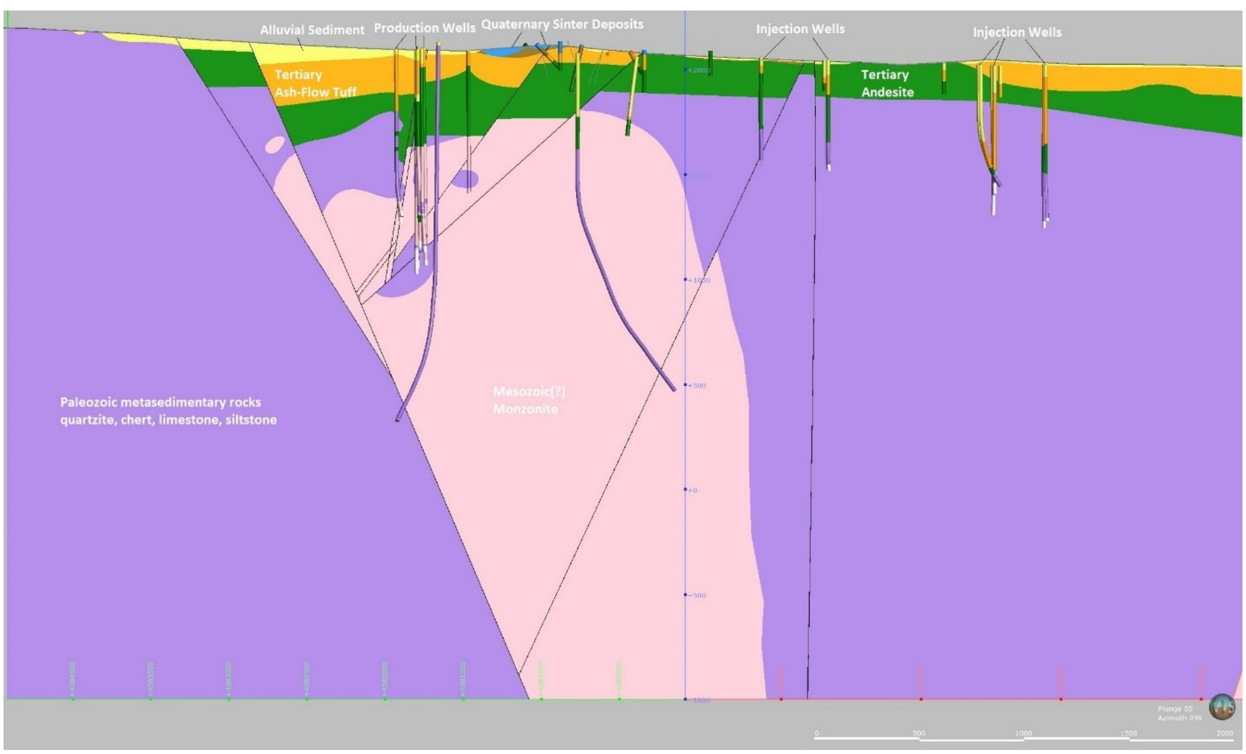

Figure 2: East-West Leapfrog geologic cross section (A-A') cutting through the McGinness Hills geothermal field. Scale is in meters. Note that some of the wells have been projected onto this section – thus the lithologies depicted in the well bore traces do not always agree with the cross-section stratigraphy.

4. RESULTS

4.1 Geologic Context of Lost Circulation in McGinness Hills

Lost circulation in the McGinness Hills geothermal field is generally reported at average depths of approximately 2200 ft. It predominantly occurs at depths between 1600 ft and 2500 ft, (Fig. 3) is found in production, injection, and monitoring wells alike, and is usually associated with the intersection of the well and a fault. These depths generally represent the production interval or slightly above it and are below the depths of valley fill alluvium and into the Valmy Quartzite, Slaven Chert, and granitic intrusions.

Injection wells are mainly located in the southern portion of the field, are drilled to ~2000 ft depths, and intersect very little of the Jurassic intrusions and significantly more alluvium and tuffaceous material. Lost circulation in these wells is reported at slightly shallower depths (~1800 ft) than in production wells, occurs in the Bates Mountain Tuff, underlying andesites and dacites, and the Valmy Quartzite. Severe injection well lost circulation frequently initiates when drilling across a NNE trending, W dipping normal fault or system of faults, after which the most common strategy is to drill blind with aerated mud.

Production wells, in contrast, are located in the northern end of the field, nearer to Quaternary sinter deposits, and are typically drilled to ~3000 ft depths. These wells encounter very little basin fill alluvium, noticeably thicker packages of Bates Mountain Tuff and the underlying andesites and dacites, and significant amounts of granitic intrusions into the Valmy Quartzite. Lost circulation in the production wells is initially reported at slightly greater depths (~2000 ft), with some overlap, and most frequently occurs in the granitic intrusions. Severe lost circulation in the production wells is associated with drilling through NNE to NE trending normal faults that dominantly dip NW and appear as part of a NW trending accommodation zone. Like the injection wells, the most common strategy once severe lost circulation was encountered at these depths was to drill blind with aerated mud and occasionally pump LCM sweeps.

Monitoring wells are distributed throughout the valley, although they are typically drilled within or near the faults defining the left stepover noted by Faulds (2013). As such, the thickness of different strata varies according to the location of the well within the field. Wells in the southern area are drilled through more alluvium and less granitic material, while wells in the northern part of the field are drilled through more volcanic and intrusive rocks. These wells are drilled to similar depths as the injection wells with two notable exceptions drilled in excess of 5000 ft deep. Lost circulation is frequently reported at depths of greater than 1500 ft and often in association with a fault. One monitoring well experienced more than 20,000 bbls of mud loss when drilling nearly directly down the intersection of a NE trending, W dipping normal fault and one of the major NW trending stepover faults, although this appears to be an outlier and not the norm. Strategies for severe lost circulation include lost circulation materials of varying sizes, for example sawdust, different size fractions of walnut shells, and cottonseed hulls, as well as drilling blind with aerated mud.

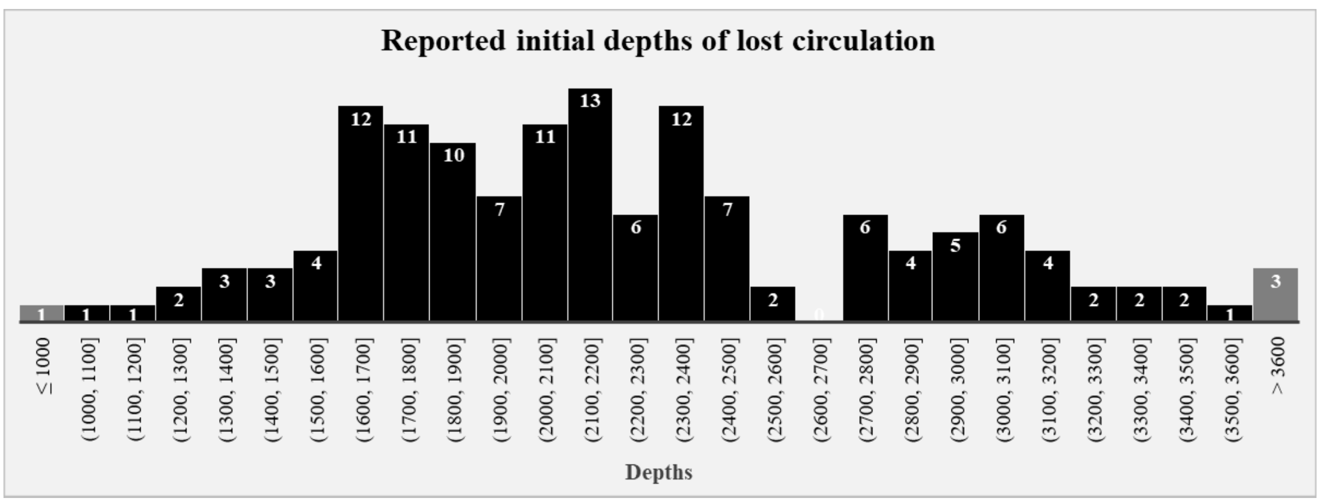

Figure 3. Measured depths at which lost circulation was first reported to occur in the McGinness Hills drilling records.

4.2 Mitigation Materials and Strategies

Our review of Ormat's drilling records indicated a common strategy used during drilling operations. This strategy differs for the portion of the well above the basement rock reservoir, and the portion within the reservoir. Above the reservoir, much of the drilling occurs in alluvium and the Bates Mountain Tuff. Within this zone, like in the oil and gas industry, the drilling fluid is generally modified by increasing viscosity and adding fibrous materials (see Table 1). These materials aid in building an effective filter cake on the borehole walls, hindering fluid loss to the host rock, limiting severe fluid loss into some fractures, and allowing the mud to carry out the cuttings. Interestingly, it was rare to find the use of cement plugs to block lost circulation in this zone, although one or two wells experiencing more severe losses did utilize cement plugs. Many of the records indicate that when severe fluid loss occurs in the hot basement rock, lost circulation materials are no longer added to the mud, and the hole is further drilled using water, air, and compounds optimizing the use of water and air to carry the cuttings to the location of the loss. The change in strategy is most likely because plugging the fracture intersections within the well is not desired in the production zone, as these are likely feed zones for the well. Drilling records do not frequently indicate that circulation was restored while drilling within the production interval. High viscosity sweeps were commonly done immediately before making a connection or a wiper trip above the reservoir and periodically within the reservoir to maintain and clean the hole.

The application of the LCMs tends to reasonably consider economics, with cheaper materials such as sawdust and gel often selected and used first. Slightly more expensive processed materials such as sized waste agricultural products (nut shells, cottonseed hulls) and sized minerals are used next, and expensive manufactured chemical blends used only to the extent needed. Often experience with drilling in the same field helps determine the strategy for managing circulation. The cost of lost circulation products ranges from several hundred to several thousand dollars per day or more depending on the severity of the loss. This is in addition to the required engineering time to manage the process.

Table 1: Common lost circulation and viscosity-adjusting materials mentioned in drilling records from McGinness Hills

Lost Circulation Material	Viscosity and filtration control
Calcium carbonate squeeze material	Gel
Cedar fiber	High molecular weight polymers
Cotton seed hulls (CSH)	Cross-link polymer plug
Diatomaceous earth squeeze material	Crystalline synthetic polymer
Fine grained cellulose	Xanthan gum
Flaked calcium carbonate	
Graded mica	
Graphite	
Ground pecan shell	
Lost circulation squeeze material	
Magnesia based plug	
Mineral fiber	
Pelletized CSH	
Seepage loss additive	
Shredded organic fiber	
Sized calcium carbonate	
Proprietary blends of sized LCM blends	
Sized magnesium oxide	
Sized salt	
Walnut shells	
Water insoluble sized cellulose material	
Wood sawdust	

4.2.1 Case Study: Third Phase Production Well 36C-10

We examined a production and an injection well in detail for strategies used to combat lost circulation in both cases. Well 36C-10 (Fig. 4A) is a third phase production well in the northern part of the McGinness Hills geothermal field. It is part of a cluster of four distinct wells, all targeting the same set of NE trending, NW dipping faults, and looks similar in its stratigraphy to other northern production wells. This well has two small feeder zones and a zone of no returns coinciding with the intersections with the two W dipping fault splays; these faults also intersect other production wells west and south of 36C-10 at greater depths. Injection well 57D-22, the second well examined in detail, is visible in the background (red sphere on the top left in Fig. 4A). Above 1800 ft depth in this well, drilling fluid loss was controlled by increasing viscosity with gel, and using cottonseed pellets and sawdust. Casing was cemented to a depth of 1800 ft and high viscosity sweeps of these materials were usually pumped immediately before cementing to clean the hole, form patched meshwork across any loss zones, and ensure a good cement job. Subsequent drilling in the granitic rock below 1800 ft occurred with little loss of fluid until crossing a fault splay at approximately 2040 ft. Circulation was lost at 2063 ft, regained, and lost again at 2067 ft. Because different methods were used to estimate the fault splay intersection and circulation loss depth, it is possible the loss occurred when crossing this splay. It is unclear from the drilling records if anything other than a large amount of Xanthan gum and soap was used in attempt to mitigate the losses or clean the hole. Once circulation was lost again, the remainder of the hole was drilled blind with 400-900 CFM air assist to decrease the density of the drilling fluid. The well intersected another fault splay at ~2150 ft, associated with the main feed zones of the well, and was drilled to a total depth of 2275 ft with the final 200 ft of the well drilled blind with aerated mud.

4.2.2 Case Study: Third Phase Injection Well 57D-22

The third phase injection well we examined in detail is 57D-22 (Fig. 4B), located in the southern region of the McGinness Hills geothermal field. This well is drilled near another injection well, both of which seem to target a NE trending, NW dipping fault that intersects the major NW trending stepover faults. There is a small feeder zone near the intersection of this fault that coincides with a small zone of no returns. In 57D-22, circulation was maintained through the upper portion of the well, where it intersected porous sands, alluvium, and tuff, by using small amounts of gel, fine walnut, sawdust, and cottonseed hulls. Intermittent sweeps of the borehole required increased amounts of viscosity enhancers and cottonseed pellets to maintain wellbore stability and clean the hole. A 120 bbls loss occurred while drilling through slate, most likely a unit within the Slaven Chert, at 1813 ft and is likely related to crossing the targeted fault associated with the main feed zone of the well. This depth is within the injection interval, 240 ft below the base of the casing at 1573 ft. The response was to use a significant quantity of xanthan gum and gel to recover and sweep the well. From 1859 ft the well was drilled blind with water and air assist to a final depth of 1995 ft. The drilling of both holes followed the general strategy described above – use conventional LCM methods above the reservoir to maintain wellbore integrity, sweeping the hole with higher viscosity mud to clean it, setting and cementing the casing (with top jobs as needed), and finally, drilling blind with aerated mud in the reservoir to avoid fouling permeable zones.

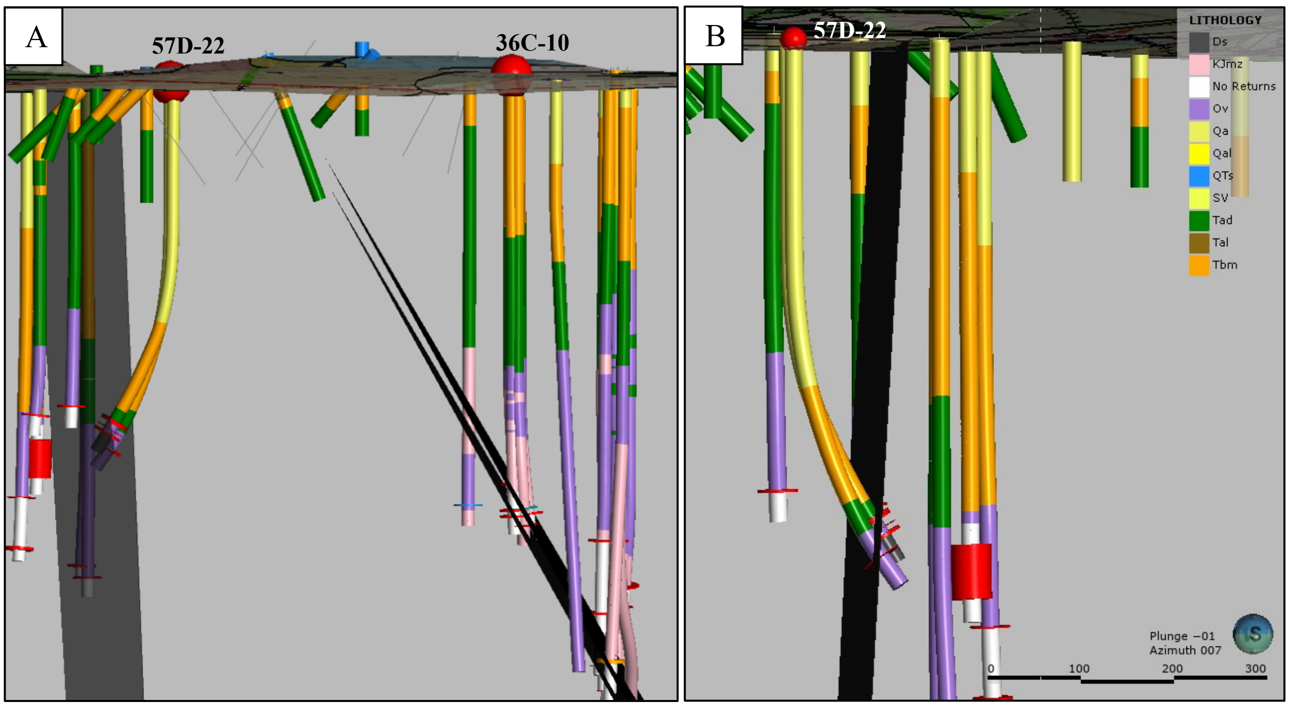

Figure 4: Image of the Leapfrog 3D geologic model of McGinness Hills showing A) phase three production well 36C-10 (marked by the red sphere on the top right of A), looking south. B shows the zoomed in view of well 57D-22 looking north. Colors of the wellbores indicate the stratigraphy: alluvium (Qal, SV) is yellow; the Bates Mountain Tuff (Tbm) is orange, underlying andesites and dacites (Tad) are green, the Valmy Quartzite (Ov) is purple, the Slaven Chert (Ds) is grey, and Jurassic granitic intrusions are pink (KJmz). White intervals on the well indicate blind drilling zones, or zones of extreme lost circulation, while the larger red cylinders indicate feeder zones for the wells. Note: only faults that intersect the wells of interest are shown. Scale bar is in meters.

5. DISCUSSION

Specific drilling records examined include those with notations of fluid losses and materials incorporated into the mud to address the fluid losses. Attempts were made to evaluate these observations with respect to depth and stratigraphy to identify correlations for where lost circulation zones occur. This was not possible in all cases, however, as not all records contained the complete set of desired information and records in RIMbase were often in disparate locations. In some cases, the mud composition indicated that fluid losses were experienced, however other available records did not mention the loss. In other cases, there were no available mud composition data but the operations records recorded extreme loss. In the latter cases, the response to the lost circulation was frequently to drill blind with aerated mud to the final depth or until circulation was restored and we assume that no LCM was used beyond gelling compounds. This is particularly interesting in comparison to the mud composition records, when sweeps of LCM were run before cementing or as part of routine wellbore maintenance. However, we feel relatively comfortable in stating the most common causes and strategies used in response to lost circulation in McGinness Hills based on our examination of the drilling records and the 3D geologic model provided.

6. CONCLUSIONS

Wells within the McGinness Hills Geothermal Field commonly experienced problems with lost circulation during drilling. Observations about lost circulation were borne out by a review of available McGinness Hills drilling records and a comprehensive, in-depth review of production well 36C-10, and injection well 57D-22, both of which were drilled within the last five years. Lost circulation problems range from minor to losing >20,000 bbls of drilling fluid, depending on the proximity of the wellbore to major fault zones. Reported depths of loss of circulation are typically around 1600-2500 ft for the production wells and slightly shallower for the injection wells. These depths are dominantly within the production zones of the wells and usually within metamorphosed Paleozoic strata and granitic Jurassic intrusions, although some of the shallower depths can be in overlying andesites and dacites. Lost circulation at McGinness Hills is almost always related to drilling through a fault zone, most commonly NNE-NE normal faults, although extreme lost circulation events are noted at intersections with major NW trending faults that delineate a left stepover accommodation zone. Lost circulation mitigation strategies include sweeps of common LCMs, such as sawdust, cottonseed pellets, and walnut hulls, as well as viscosity-controlling gels, polymers, and Xanthan gum within the cased interval and drilling blind with aerated mud within the production interval. The goal of these split strategies seems to be to ensure a clean, stable hole for cementing in the casing interval, and to not damage permeability within the production interval while still ensuring that the drill bit is cooled and cuttings are flushed away, presumably to be reincorporated into the formation. These studies are headed towards analyses to develop systematic methods and materials for LC mitigation. Contextual observations and responses examined here will inform a systematic methodology of where to expect LC and, depending on geologic context, the most cost effective and efficient responses. Minimizing the expensive impact of lost circulation in geothermal drilling with effective mitigation strategies may greatly improve its economic viability in the renewed push for renewable energy sources in the U.S.A. and elsewhere.

ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of Technology Development, Geothermal Technologies Office, under Award Number DE-AC02-05CH11231 with LBNL. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2021-2126 C. The earth model output for this paper was generated using Leapfrog Software. Copyright © Seequent Limited. Leapfrog and all other Seequent Limited product or service names are registered trademark or trademarks of Seequent Limited. Drilling records were reviewed through the software package RIMbase, v. 7.5.366.0. Copyright © Infostat Systems Inc. RIMbase is a registered trademark of Infostat Systems Inc.

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