Effect of Flow Rate and Wellbore Geometry on Pyrite Scale Formation in Geothermal Well

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ABSTRACT

Mineral scale morphology and texture are significantly influenced by the physicochemical conditions in their formation environment, making these key indicators for interpreting mineral formation processes. In geothermal systems, these features vary greatly depending on whether minerals form through direct crystallization, during boiling, or other cooling mechanisms. Among the factors that impact mineral morphology, fluid flow rate and wellbore geometry play essential roles, particularly in the development of pyrite scales. This study examines pyrite deposits from production wells in the Tiwi Geothermal Field, Albay, Bicol, Philippines, each characterized by distinct flow conditions and wellbore geometry. Comparative analysis reveals that lower flow rates and larger wellbore diameters encourage crystal growth, leading to the formation of larger, well-defined euhedral pyrite crystals. In contrast, higher flow rates and smaller wellbore diameters favor rapid nucleation over crystal growth, resulting in the development of fine-grained, disseminated anhedral pyrite. These observations underscore the effect of flow rate and wellbore geometry on the morphology of pyrite scale and provide insights into a better understanding of the mechanism of pyrite scale formation.

Keywords: Pyrite Scale, Wellbore geometry, Flow rate

1. INTRODUCTION

Formation of sulfide minerals in a geothermal system as scale, especially within the wellbore, is influenced by the presence of hydrogen sulfide (H_2S). When the geothermal fluid undergoes depressurization due to boiling and adiabatic cooling, H_2S gas is released into the vapor phase (Jamero, 2018). Once H_2S reacts with metals such as Fe, sulfide minerals can precipitate. one example is pyrite (FeS_2), which is the most commonly reported sulfide scale mineral in geothermal systems. This reaction is described by Rickard and Luther (2007), as shown in Equation 1:

(1) $Fe^{2+} + H_2S + S^0 \rightarrow FeS_2$ (pyrite) $+ 2H^+$

According to Reyes et al. (2022), both flow rate and wellbore geometry can significantly influence the formation and progression of mineral scales. Moreover, based on the Hagen-Poiseuille equation, flow rate is directly proportional to the pressure difference and the fourth power of the radius of the wellbore, indicating that geometry—specifically, wellbore diameter—affects pressure and, consequently, scale formation dynamics. To date, there are limited studies exploring the impacts of these physical parameters compared to the more predictable thermodynamic factors (Brown, 2013).

A study conducted by Allan et al. (2019) at the Ngatamariki Geothermal Field utilized wellbore simulation to gain a

better understanding of the physical behavior of scale formations, particularly those of calcite and silica. Building upon this, the current study aims to contribute to the growing body of knowledge on the influence of flow rate and wellbore geometry on mineral scaling by focusing on pyrite scale formation. The rationale for selecting pyrite as the target mineral for this investigation is discussed in the methodology section.

Pyrite has a Mohs hardness of 6 to 6.5, making it more resistant to mechanical degradation compared to other scale-forming minerals such as calcite, anhydrite, and amorphous silica. In terms of solubility, pyrite is relatively stable under neutral to slightly acidic conditions and is insoluble in water (Rickard & Luther, 2007). Furthermore, its resistance to rapid dissolution is attributed to its slow oxidation kinetics (Nicholson, Gillham, & Reardon, 1988). For these reasons, understanding pyrite scale formation is equally critical, as it presents potential challenges to both chemical and mechanical remediation strategies in geothermal well maintenance.

2. METHODOLOGY/APPROACH

Available scale samples were collected from various broaching campaigns conducted by the Philippine Geothermal Production Company, Inc. (PGPC). These activities aimed to remove blockages along wellbores, which adversely impact the generation capacity and performance of the affected production wells. Two production wells were selected for this study based on the following criteria: (1) distinct wellbore assemblies in terms of production casing inner diameter, (2) availability of scale samples for analysis, (3) presence of the scale mineral of interest, and (4) availability of flow rate data. Among the candidate wells, only two met the specified criteria and were designated as Well B and Well M. While it would have been ideal to include more wells for comparison, this preliminary study provides a strong starting point using these two. Well B has a production liner with an inner diameter of 8.63 inches, while Well M has an inner diameter of 7.00 inches.

Among the minerals present in the retrieved scale samples from Well B and Well M, pyrite was selected for detailed analysis in this paper. The selection was based on the following considerations: (1) pyrite can form across a wide range of pressure and temperature conditions (Rickard & Luther, 2007), (2) it has a simple crystal structure (Vaughan & Craig, 1978), (3) pyrite can form through both cooling and boiling mechanisms (Reyes et al., 2022), and (4) it is present and well-preserved in both wells included in this study.

Following sample collection, the scale specimens were washed and dried to eliminate mud and other contaminants. Well-preserved pyrite fragments from both Well B and Well M were then carefully selected by hand for qualitative observation. The samples were initially examined under an SZM-LED 1 Optika binocular stereo microscope to assess textures and morphology, including crystallinity, manner of deposition, and relative abundance. A Professional Portable Stand-Alone Desktop 3.5" LCD Digital Microscope, with 10x to 300x optical magnification, was subsequently used to capture photomicrographs highlighting notable textures and mineral features.

Results and significant findings from the qualitative observation of scale samples from Well B and Well M were then correlated with the potential influence of flow rate and wellbore geometry on scale deposition. The theoretical framework for this analysis was based on the Hagen-Poiseuille equation. A hypothesis was subsequently developed from this correlation and supported by both physical and field data.

3. RESULTS AND DISCUSSIONS

Based on qualitative observations, the pyrite scales in Well B are minute (<0.2 μm) and often adhere to and spread across the surfaces of other minerals, with subhedral to anhedral crystal shapes. In

contrast, the pyrite scales in Well M are larger (~1 μm) and tend to be more subhedral to euhedral compared to those in Well B. The pyrite crystals in Well M also appear to be more isolated rather than disseminated. The euhedral and isolated shape of the pyrite indicates that the system conditions favored crystal growth over nucleation (Prol-Ledesma et al., 2010). Photomicrographs of representative pyrite scales in Wells B and M are shown in Figure 1.

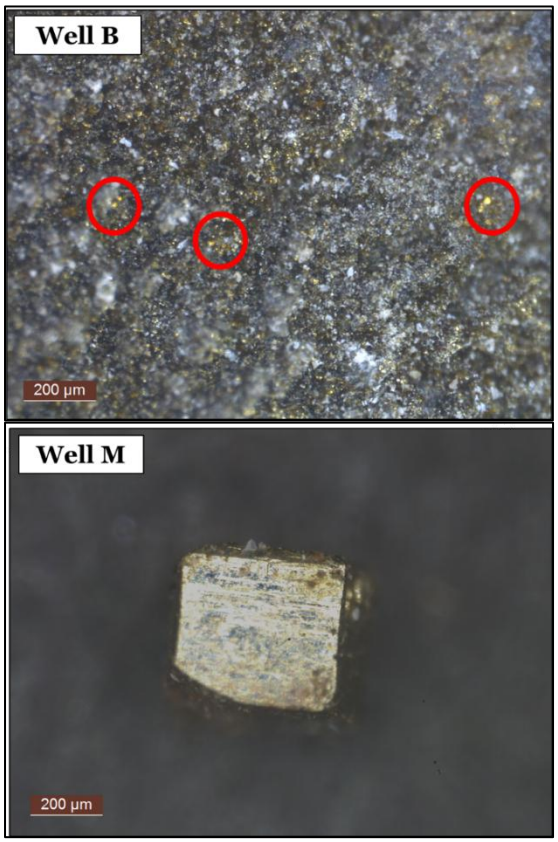

Figure 1. This figure shows photomicrographs with a 200-micrometer field of view of representative pyrite scales from Well B and Well M. Due to the minute size of the pyrite crystals in Well B, the crystals are highlighted with red circles for better emphasis.

The texture and morphology of pyrite in each well suggest that Well B experienced a higher flow rate during deposition compared to Well M. Analyzing the inner diameters of the production liners, Well M has a smaller diameter, supporting this interpretation of flow conditions reflected in the crystal textures. In this study, it is assumed that as the hydrothermal fluid enters the production liner, the flow remains laminar. This assumption is supported by the fact that geothermal fluids typically have relatively high viscosity due to dissolved minerals and elevated pressure, which, based on Reynolds number calculations, favors a laminar flow regime (Geothermal Systems and Technologies, n.d.). According to the Hagen-Poiseuille equation, under laminar flow conditions, assuming all other parameters—such as temperature and pressure—remain constant, the flow rate is inversely proportional to the pipe diameter. This indicates that, when comparing the flow rates of Well B and Well M based on their production liner inner diameters, Well M would have a lower flow rate than Well B. This is confirmed by the actual flow rates of the wells, with Well B averaging 120 L/sec and Well M averaging 20 L/sec.

Although the flow rate does not directly affect the morphology of sulfide scale minerals like pyrite, it can influence the rate and manner of their deposition (Andritsos et al., 1995). This explains why pyrite in Well B appears as disseminated, tiny, and subhedral to anhedral crystals. These crystals had less time to grow and develop well-defined faces, favoring higher nucleation over crystal growth—likely a response to high fluid flow. Conversely, in Well M—where the flow rate is relatively lower—pyrite crystals had more time to grow, resulting in larger, more well-defined crystals. Conditions favored crystal growth in this case, opposite to what was observed in Well B.

Typically, iron (Fe) concentration in neutral geothermal reservoir fluids is less than 1 ppm (Giggenbach, 1988; Brown, 2013). If Fe levels increase beyond this, the likely source is corrosion of the pipe material. Consequently, the presence of pyrite scale can serve as an indicator of wellbore corrosion. Understanding the mechanism of pyrite formation is as important as for other scale-forming minerals like calcite, anhydrite, and silica. The texture and morphology of pyrite

scale can reveal fluid flow rates, which may relate to potential corrosion rates. As noted by Licina and Cubicciotti (1989), higher flow rates promote higher rates of erosion or corrosion.

4. SUMMARY AND CONCLUSIONS

Based on the comparative study conducted, the pyrite scale in Well B consists of disseminated, minute crystals with anhedral to subhedral crystal faces. In contrast, the pyrite in Well M is made up of relatively larger, subhedral to euhedral crystals. Since Well B has a larger diameter than Well M, it follows that the flow rate in Well B is higher. These differences in flow rate are reflected in the texture and deposition pattern of pyrite in each well. In Well B, pyrite deposition favored rapid nucleation, whereas in Well M, the conditions allowed for crystal growth influenced by the flow rates. A summary of the results is shown in Table 2.

The study suggests that the mechanism of pyrite scale formation is shaped by flow rate conditions influenced by wellbore geometry, which may provide insights into corrosion or erosion processes. Because iron (Fe) concentrations are generally low in geothermal fluids, a possible source of Fe is the pipe material itself. These findings could enhance current understanding of scaling and corrosion issues in the geothermal industry.

Table 2: Summary and results of the comparative study

Well Name	Wellbore Inner Diameter (inches)	Flow rate (L/sec)	Texture of pyrite	Crystallinity of pyrite	Size of crystals
Well B	8.63	120 L/sec	Disseminated	Anhedral to subhedral	<0.2 µm
Well M	7.00	20 L/sec	isolated	Subhedral to Euhedral	~1 µm

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