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Unclogging the Future: Tackling Biochemical Barriers in Geothermal Energy

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1 INTRODUCTION

Geothermal energy is increasingly considered as a sustainable and low-carbon alternative to conventional fossil fuels (Kassem and Moscariello, 2025). Its potential for providing reliable baseload energy while reducing greenhouse gas emissions has made it a key component in energy transition strategies worldwide (Goldberg et al., 2025). Recent research has focused on optimizing geothermal heat recovery and improving system efficiency under varying geological and operational conditions, including addressing interferences between doublets (Willems et al., 2017), reservoir heterogeneity and faults (Crooijmans et al., 2016; Daniilidis et al., 2021), the coupled thermo-hydro-mechanical-chemical processes in fractured reservoirs (Salimzadeh and Nick, 2019), and stimulation techniques such as radial jet drilling to enhance recovery from fractured systems (Salimzadeh et al., 2019), among others. These contributions, along with novel approaches for reservoir stimulation and integrated modeling frameworks, underscore the complexity of geothermal systems and the need for multidisciplinary strategies to maximize efficiency and sustainability. One of the most persistent and operationally important issues with geothermal resources is mineral scaling, which refers to the precipitation of minerals from geothermal fluids as they undergo changes in temperature, pressure, and chemical composition throughout the production and reinjection cycle (Hassani and Zheng, 2025; Waldmann and Rütters, 2016).

Scaling can occur throughout the geothermal cycle, from the reservoir and production wells to surface installations and injection systems (Kazmierczak et al., 2022a). Common scale-forming minerals include carbonates (e.g., calcite, aragonite), sulfates (e.g., barite, anhydrite), silica, and metal oxides or sulfides, depending on the fluid chemistry and operational conditions. These deposits can reduce the flow efficiency, damage equipment, and increase operational costs, which may lead to unplanned shutdowns (Kazmierczak et al., 2022b; Tonkul et al., 2025). The precipitation of salt (e.g., halite) can also occur when the geothermal brine is a high saline brine (Nitschke et al., 2017). During the production and reinjection of high-salinity geothermal brine, physicochemical perturbations such as temperature and pressure alterations or degassing can shift the system away from equilibrium, promoting mineral scaling throughout the production-surface-injection pathway. Injection strategies can further influence scaling behavior; for example, the use of carbonated water or mixed CO_2-water injection has been shown to trigger dissolution and precipitation reactions within the reservoir, altering mineral stability and potentially impacting permeability (Nick et al., 2015). Several studies have explored the mechanisms and impacts of scaling in geothermal systems. For instance, Bozau et al. (2015) used equilibrium and reactive transport modelling to show that in deep geothermal wells of the North German Basin, barite ($BaSO_4$), strontium sulphates ($SrSO_4$), and iron sulfide (FeS) can form in response to combined temperature, pressure, and chemical shifts. Köhl and Baumann (2021) documented the carbonate scaling in the Bavarian Molasse Basin, and attributed it to CO_2 degassing and disruption of the lime-carbonic acid equilibrium during the geothermal fluid production.

The geothermal brine may also contain dormant microbial communities (Katayama et al., 2024) that can become metabolically active when thermal and chemical conditions become favorable. For instance, Sulfate-Reducing Bacteria (SRB) are among the microbial communities known to persist under anaerobic conditions, and their activity is often associated with various subsurface water-injection processes such as biocorrosion, reservoir souring, and mineral precipitation (Kermani et al., 2023; Lerm et al., 2013; Mahmoodi et al., 2023). The biofilm generation because of microbial activity can also contribute to the injectivity restrictions in the geothermal systems.

Geochemical modeling provides a tool for predicting these complexities and for informing the design of effective mitigation strategies. Numerous studies have focused on the geochemical mechanisms that drive mineral scaling in geothermal systems. For example, Garcia-Rios and Jacquemet (2025) used PHREEQC to model mineral scaling risks in a geothermal loop supplied by a carbonate reservoir, and identified calcite and barite as the dominant precipitates under specific pressure-temperature conditions. Kumar et al. (2025) developed a 3D

thermal-hydrological-chemical (THC) model using FALCON and The Geochemist's Workbench to simulate mineralogical evolution during a circulation test at the Utah FORGE EGS site. Their results indicated that calcite is the major precipitate, particularly within the fracture zones.

In this study, we examine the biogeochemical interactions within geothermal systems (with a sandstone reservoir) that can lead to solid deposition, including mineral scaling, salt precipitation, biologically induced mineral formation, and biomass accumulation. Our analysis is based on a biogeochemical modeling framework capable of predicting the risk of solid formation under a wide range of operating conditions, including variations in pressure and temperature, oxygen exposure, CO_2 availability and degassing, brine salinity, and microbial activity. The novelty of this work is the model's ability to capture solid-phase formation driven by multiple mechanisms using both equilibrium and kinetic approaches, which can be adapted to diverse scenarios and site-specific conditions. Although the model provides a generalized predictive platform, it can be further refined for particular case studies using relevant experimental data. Figure 1 presents an overview of the key biogeochemical processes that promote mass deposition and are evaluated in this study. The specific objectives of the work are to:

a- Review the minerals that are thermodynamically prone to precipitation as pressure and temperature alter.
b- Assess the impact of CO_2 degassing during geothermal brine production on mineral scaling.
c- Investigate the influence of surface air exposure on the formation and precipitation of metal-oxide scales.
d- Evaluate biologically induced mineral precipitation and biomass formation.

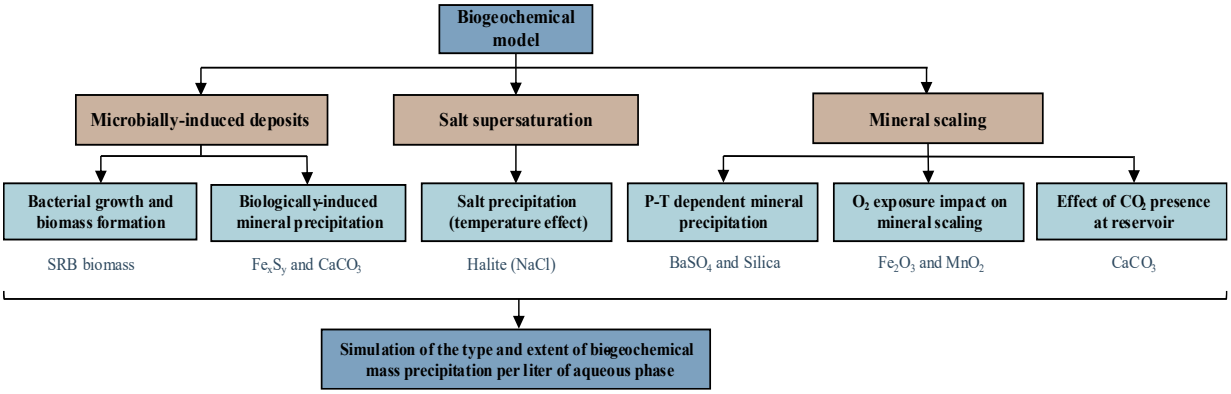


Figure 1. Overview of the biogeochemical processes that promote solid deposition in geothermal systems and are represented in the modeling framework.

2 METHOD

We employed the PHREEQC geochemical simulator to develop and implement biogeochemical simulations. The ionic composition of the geothermal brine and the mineralogical data of the reservoir rock belong to the Margretheholm geothermal reservoir in Denmark, as reported by the Geological Survey of Denmark and Greenland (Kazmierczak et al., 2019). These data are summarized in Table 1. The simulations were carried out by first equilibrating the gas-brine-rock system under reservoir conditions (pressure of 310 bar and temperature of 72 °C), followed by an assessment of mineral precipitation during geothermal brine production. All simulations were based on 1 kg of brine, which was equilibrated with the relevant proportions of reservoir minerals. The solubility of gas components in the brine was accounted for using the Peng-Robinson equation of state. Most model outcomes are derived using an equilibrium approach (time-independent), except for biologically induced scaling and biomass formation, which were treated kinetically. Kinetic rate parameters for the minerals were taken from the database compiled by Zhang et al. (2019). To explore different scenarios of solid formation, the brine composition was adjusted to reflect the conditions of each scenario. For instance, when assessing the effect of CO_2 degassing on scaling, dissolved CO_2 was added to the brine, even though it was not reported in the original composition. Similarly, when investigating bioactivity, the presence of sulfate-reducing bacteria (SRB), a carbon source (assumed as acetate), and Fe availability were included. SRB growth was modeled using the Monod formulation, in which SRB utilize sulfate as the electron acceptor and acetate as the electron donor to produce HS^-. Similar to the work of Kermani et al. (2023), the SRB metabolic rate with the upper-bound values of the rate constants for bacterial activity was used in the modeling. The details regarding the formulations and further explanations can be found somewhere else (Kermani et al., 2023).

Table 1. Ionic and mineralogical composition of the geothermal system used as input for the modeling.

Brine composition						Reservoir Mineralogy	
Species	Concentration (mg/L)	Species	Concentration (mg/L)	Species	Concentration (mg/L)	Minerals	Mass fraction
HCO_3^-	29.7	Na^+	53974	Zn^{2+}	3.67	Calcite	0.0355
Ba^{2+}	17.28	Mg^{2+}	2938	Li^+	9.67	Dolomite	0.0684
Br^-	814	Sr^{2+}	724.85	Pb^{2+}	0.55	Quartz	0.5639
Cl^-	133963	K^+	636	Ni^{2+}	0	Unreactive	0.3321
Ca^{2+}	20505	Fe^{2+}	0-15	Cu^{2+}	0		
SO_4^{2-}	230	Mn^{2+}	16.75	Si	5.58		

3 RESULTS

In the first modeling scenario, we use the brine composition and reservoir mineralogy listed in Table 1 to examine how temperature reductions during geothermal brine production influence mineral scaling. Starting from reservoir conditions (72 °C), the temperature is sequentially reduced to 55 °C, 35 °C, and 20 °C. At each step, an equilibrium calculation is performed, and the updated brine composition is used for the next temperature stage. As shown in Figure 2a, barite and silica are the primary minerals predicted to precipitate in response to cooling. To evaluate the potential effect of dissolved CO_2 and pressure decline from the wellbore to the surface, CO_2 is dissolved in the brine at 310 bar, and the temperature is kept constant at 72 °C while pressure is reduced in steps. The associated CO_2 degassing promotes calcite precipitation, in combination with barite and silica (Figure 2b). We also assess salt precipitation by dissolving halite in the brine at reservoir conditions until saturation is reached. As shown in Figure 2c, at constant pressure, halite becomes supersaturated during cooling and can precipitate alongside sulfate and silica minerals. Surface exposure of produced brine to air is further considered. Dissolution of atmospheric gases, particularly oxygen, can lead to the formation of Fe- and Mn-oxide scales such as hematite and pyrolusite (Figure 2d). Finally, to represent microbial activity, we incorporate sulfate-reducing bacteria under conditions favorable for bacterial growth at the surface (e.g., 20 °C). Assuming the presence of organic matter (represented here as acetate at an initial concentration of 5 mM), SRB consume acetate and reduce sulfate to sulfide. The produced sulfide reacts with Fe to form pyrite (FeS_2), while the simultaneous production of HCO_3^- may lead to calcite precipitation when supersaturation is reached (Figure 2e,f). In these simulations, Fe^{2+} availability is the limiting factor. Once Fe^{2+} is fully consumed by pyrite formation, pyrite precipitation ceases, resulting in the plateau observed in Figure 2f.

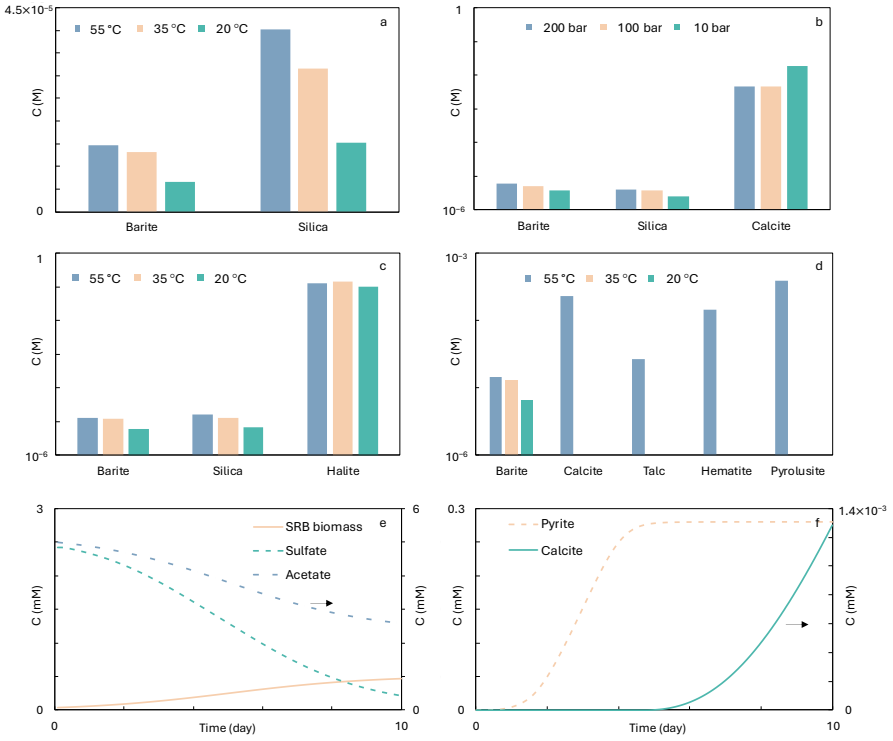


Figure 2. Predicted mineral and biologically induced solid formation under various geochemical and biogeochemical scenarios: (a) temperature-driven scaling during brine cooling; (b) CO_2 degassing and

pressure-related precipitation; (c) halite supersaturation during cooling; (d) oxidation-induced Fe- and Mn-oxide formation upon air exposure; and (e-f) SRB-driven pyrite and calcite precipitation under favorable surface conditions.

4 DISCUSSION

The modeling results show that solid deposition in geothermal systems arises from multiple interacting thermal, chemical, and biological processes. Temperature reduction alone leads to supersaturation of barite and silica, indicating that cooling during production is a primary driver of mineral scaling. When CO_2 is dissolved in the brine, pressure decline along the wellbore further enhances calcite precipitation, which highlights the sensitivity of carbonate scaling to gas liberation and pressure management. Halite precipitation becomes relevant in high-salinity systems, as cooling can shift saturated brine into supersaturation even when halite is fully dissolved at reservoir conditions. Exposure of the produced brine to air introduces additional pathways for solid formation. Dissolved oxygen promotes Fe- and Mn-oxide precipitation, showing that even limited atmospheric contact can trigger rapid metal-oxide scaling. Biological activity adds another layer of complexity. Under surface temperatures and in the presence of organic substrates, sulfate-reducing bacteria generate sulfide that reacts with Fe to form pyrite, while bicarbonate production may drive calcite formation. Because Fe availability limits pyrite growth, systems with higher Fe concentrations may be more vulnerable to bio-induced scaling.

5 CONCLUSION

This study presents a biogeochemical modeling framework capable of predicting multiple pathways of solid deposition in geothermal systems, including mineral scaling, salt precipitation, metal-oxide formation, and bio-induced mineralization. Using reservoir-specific brine and mineralogical data, the model captures the effects of temperature and pressure variations, CO_2 degassing, oxygen exposure, and microbial activity on solid-phase behavior. The results demonstrate that:

- Cooling promotes the precipitation of barite and silica.
- CO_2 degassing can trigger calcite scaling.
- Oxygen exposure can lead to metal oxide scales formation such as iron oxides.
- SRB activity can drive sulfide and carbonate scaling under favorable conditions.

These findings highlight the complex, multi-mechanism nature of scaling in geothermal operations. The framework provides a foundation for evaluating scaling risks and designing mitigation strategies, and it can be adapted for specific geothermal sites through integration with targeted experimental data.

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