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Causes of abundant calcite scaling in geothermal wells in the Bavarian Molasse Basin, Southern Germany

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ABSTRACT

The carbonate-dominated Malm aquifer in the Bavarian Molasse Basin in Southern Germany is being widely exploited and explored for geothermal energy. Despite favorable reservoir conditions, the use of geothermal wells for heat and power production is highly challenging. The main difficulty, especially in boreholes > 3000 m deep with temperatures > 120 °C, is that substantial amounts of calcite scales are hindering the proper operation of the pumps within the wells and of the heat exchangers at the surface. To elucidate the causes of scaling we present an extensive geochemical dataset from the geothermal plant in Kirchstockach. Based on chemical analyses of wellhead water samples, chemical and mineralogical analyses of scales collected along the uppermost 800 m of the production well, and chemical analyses of gas inclusions trapped in calcite-scale crystals, four processes are evaluated that could promote calcite scaling. These are (i) decompression of the produced fluid between the reservoir and the wellhead, (ii) corrosion of the casing that drives *pH* increase and subsequent calcite solubility decrease, (iii) gas influx from the geothermal reservoir and subsequent stripping of CO_2 from the aqueous fluid, and (iv) boiling within the geothermal well. The effectiveness of the four scenarios was assessed by performing geochemical speciation calculations using the codes TOUGHREACT and CHILLER, which explicitly simulate boiling of aqueous fluids (CHILLER) and take into account the pressure dependence of calcite solubility (TOUGHREACT). The results show that process i causes notable calcite supersaturation but cannot act as the sole driver for scaling, whereas ii and iii are negligible in the present case. In contrast, process iv is consistent with all the available observations. That is, scaling is controlled by the exsolution of CO_2 upon boiling at the markedly sub-hydrostatic pressure of 4–6 bar within the production well. This process is confirmed by the visible presence of gas inclusions in the calcite scales above the downhole pump, where the production fluid should nominally have been in the homogeneous liquid state. Whereas minor calcite scaling may have been triggered by fluid decompression within the production well, we conclude that the abundant scaling along the pump casing is due to cavitation induced by operating the pump at high production rates.

1. Introduction

The precipitation of mineral phases from geothermal fluids (i.e., scales) may pose a serious economic risk to the successful operation of geothermal plants (Thomas and Gudmundsson, 1989). Typical scaling phases include carbonates (Ámannsson, 1989; Arnórsson, 1989; Benoit, 1989; Lindal and Kristmannsdóttir, 1989), amorphous silica and silicates (Gunnarsson and Arnórsson, 2005 Kristmannsdóttir, 1989; Zarrouk et al., 2014), sulphates (Regenspurg et al., 2015) as well as mixed metal oxides and sulfides (Gallup, 1989; Regenspurg et al., 2015; Wilson et al., 2007), which are often associated with corrosion of parts of the geothermal plant (Honegger et al., 1989; Mundhenk et al., 2013). Scaling phases precipitate when they become supersaturated along the geothermal loop due to gas exsolution or due to a solubility decrease induced by changes in temperature and/or pressure as well as mixing between aqueous solutions with different chemical compositions (Bozau et al., 2015; García et al., 2006; Thomas and Gudmundsson, 1989). Typical problems associated with scaling include clogging of pipes and wells, reduced efficiency of pumps and heat exchangers, reduced reinjection capacity as well as accumulation of hazardous materials (e.g., Pb- and Ra-bearing scales) that require costly disposal (Bozau et al., 2015; García et al., 2006; Scheiber et al., 2013).

Over the past 15 years the Bavarian Molasse Basin in southern Germany has become a veritable hotspot for geothermal power

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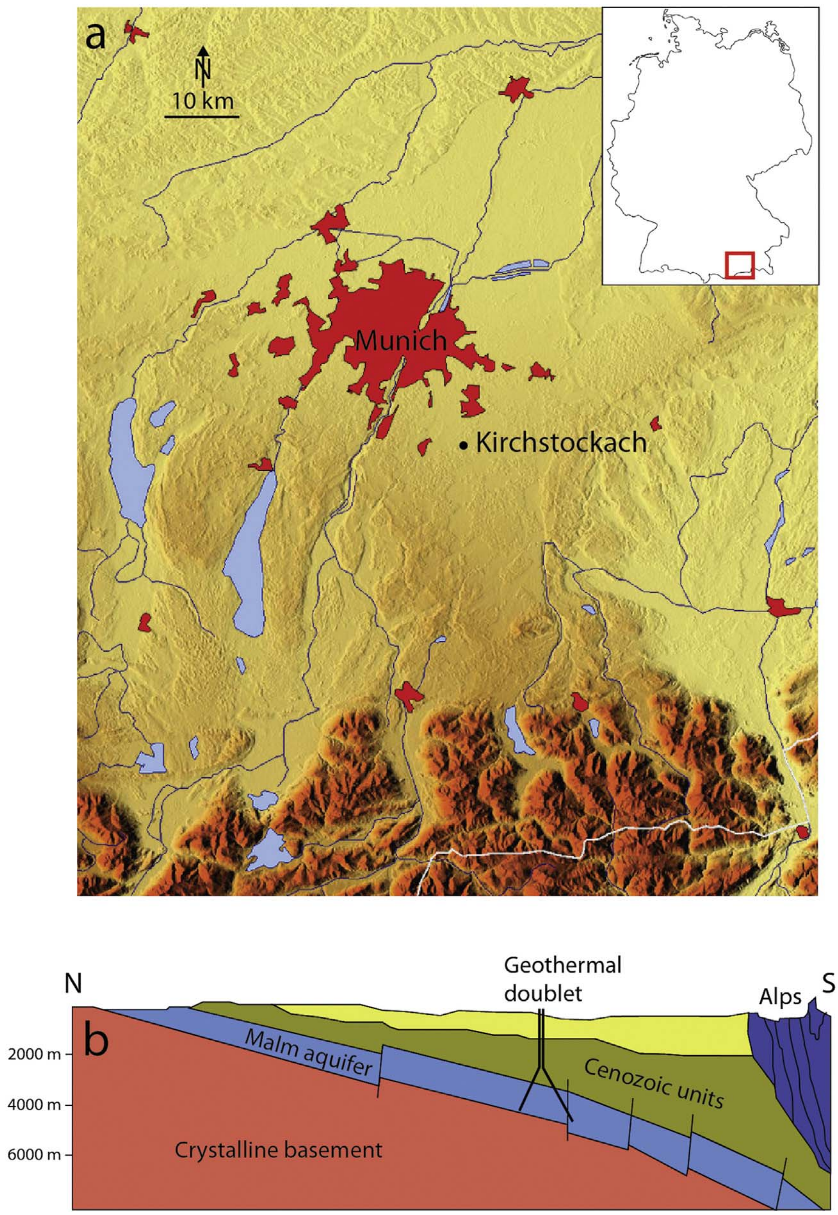

Fig. 1. Geographical and geological overview of the studied site. (a) Relief map showing the location of the geothermal plant at Kirchstockach. (b) Schematic cross section through the Bavarian Molasse Basin illustrating that the Malm aquifer dips southward and that geothermal wells are aimed to intersect permeable fracture zones (modified from Mayrhofer et al., 2014).

production. Currently 22 geothermal power plants are being operated (Dussel et al., 2016; Lentsch et al., 2015; Mayrhofer et al., 2014). Most of them are located within the greater Munich area. The thermal reservoir for all these plants is the Upper Malm aquifer of Upper Jurassic age, which is about 500–600 m thick. This aquifer is dominated by carbonates and has elevated fracture-porosity owing to karstification during the late Cretaceous and early Cenozoic. During the subsequent Alpine orogeny the Malm unit was situated within the evolving northern foreland depression and hence it was progressively buried by the erosional products of the uplifting Alps, creating the Molasse Basin. As a consequence, the upper Malm aquifer now dips southward and reservoir temperatures chiefly depend on the depth of the aquifer at a given location (Fig. 1). A maximum reservoir temperature of about 150 °C is observed to the south where the reservoir depth reaches 4–5 km. The various geothermal plants produce fluids at rates between 40 and 140 L/s. Most of the plants are producing thermal energy. However, SE and S of Munich, where the production temperature is > 120 °C, electrical energy is produced as well. Despite the favorable reservoir conditions, the successful operation of the plants located SE and S of Munich is highly challenging. In about two thirds of the plants producing thermal water with temperatures > 120 °C, substantial calcite scaling is hindering the proper operation of the pumps within the wells and of the heat exchangers at the surface. Worldwide, the formation of calcite scales is mostly attributed to boiling of the geothermal fluid or to CO_2-stripping via degassing of sparingly soluble gases that have a lower solubility than CO_2 (Arnórsson, 1989; Benoit, 1989; Simmons and Christenson, 1994). Thus, the formation of calcite scales in the plants SE and S of Munich is an unexpected phenomenon, because all the plants are being operated at wellhead pressures of 10–20 bar to exceed the experimentally determined degassing pressures, which are in the range of 2–10 bar.

This study aims at identifying the main processes controlling calcite scaling in geothermal plants in the area SE of Munich in order to aid in optimizing the operation of these plants. To do so we focus on a particular production period from December 2014 to March 2015 at the Kirchstockach plant. This period was chosen because we have good data on the amount of scales formed over this period, on the corresponding production rates and on the evolution of the chemical fluid composition at the wellhead. In addition, we have found liquid and gas inclusions in calcite crystals precipitated from the geothermal fluid during the investigated production period.