

Effect of chemical clogging on the permeability of weakly consolidated sandstone due to reinjection at different temperatures

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ABSTRACT

While utilizing hydrothermal resources, it is necessary to reinject wastewater into the reservoir through reinjection wells to extract heat without mining groundwater. Chemical clogging is a serious problem in the process of reinjection. The precipitation of minerals can lead to reservoir clogging and the reduction of permeability. Therefore, to study the effect of chemical clogging on permeability, the weakly consolidated sandstone of the Neogene Guantao Formation geothermal reservoir in northern Shandong (Eastern China) was taken as the research object. A long-term thermal-hydro-mechanical-chemistry (THMC) coupling reinjection experiment was carried out. The results showed that when the temperature of wastewater was higher than 45 °C, there was a temporary phase of permeability enhancement in the first 10 min of reinjection. However, wastewater with higher temperatures would cause more chemical clogging eventually. XRD and ion analysis results showed that the precipitation of minerals was mainly potash feldspar, illite, calcite, and other carbonate minerals during reinjection. According to the characteristics of low-TDS wastewater in the Guantao Formation, it is recommended to adopt low-temperature wastewater reinjection and reduce the concentration of Ca²⁺ and Mg²⁺ in wastewater before reinjection.

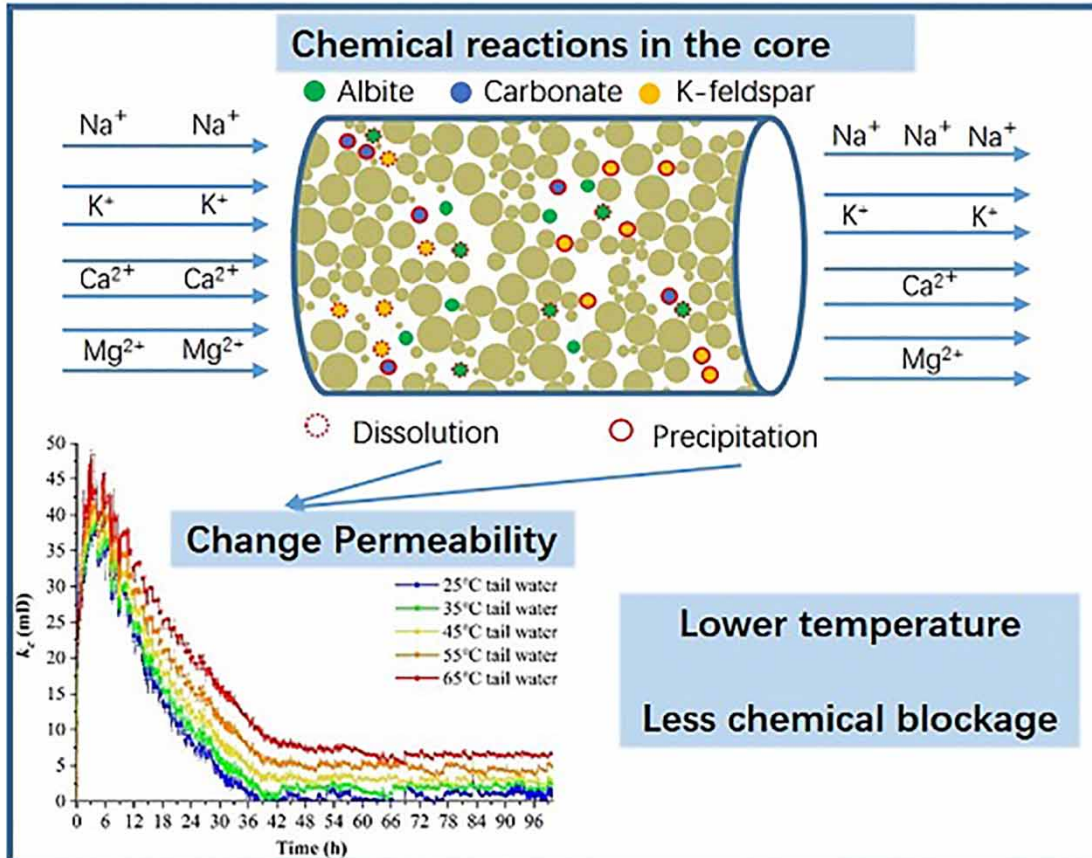
Key words: chemical clogging, geothermal reinjection, permeability, weakly consolidated sandstone

HIGHLIGHTS

- Water–rock chemical reactions cause the precipitation of minerals.
- Permeability is an important parameter to characterize blockage.
- XRD and ion concentration were used to analyze chemical blockage.
- There was a temporary phase of permeability enhancement in the first 10 min of reinjection.
- Tailwater with higher temperatures will cause more blockage eventually.

GRAPHICAL ABSTRACT

Effect of chemical blockage on permeability of weakly consolidated sandstone due to reinjection at different temperatures.



Conclusion: Low temperature tailwater reinjection and low concentration of Ca²⁺ and Mg²⁺ in tailwater can reduce the effect of chemical blockage.

1. INTRODUCTION

With the progress of human civilization and the rapid development of social economy, people are urgently looking for renewable energy to optimize the energy structure. Geothermal energy has attracted more and more attention because of its huge reserves, stable temperature, and low carbon dioxide emissions. China is actively developing and utilizing geothermal resources (Zhao *et al.* 2022). Also, Chinese geothermal resources account for 8% of the whole world (Zhao & Wan 2014).

China is rich in geothermal resources, but only 2.3% of shallow geothermal resources have been exploited (Wang *et al.* 2017). Medium–low temperature hydrothermal geothermal resources are rich in northern Shandong (Wang *et al.* 2015; Kang *et al.* 2021), Kaifeng basin (Lin *et al.* 2007), Qinghai Xining (Zhang *et al.* 2021, 2022a), Guanzhong Basin (Xv *et al.*

2019), and Tianjin (An *et al.* 2016). Most of them occur in sandstone thermal reservoirs, which are loose porous media. In the process of wastewater reinjection, clogging reduces the permeability, and even causes damage to the reservoir irreversibly (Ungemach 2003; Cui *et al.* 2021a, 2021b, 2022; Zhang *et al.* 2022a, 2022b). Bouwer (2002) proposed that the causes of geothermal reinjection clogging can be mainly divided into suspended solids, microorganisms, bubble clogging, and chemical clogging; Brehme *et al.* (2018) subdivided clogging processes into physical, chemical, and biological processes. Among them, chemical clogging is caused by the change of the original hydrogeochemical equilibrium after wastewater enters the thermal reservoir. To reduce the impact of clogging, it is vital to optimize geothermal reinjection technology (Allow 2013; Diaz *et al.* 2016). At present, all hydrothermal geothermal projects in China require reinjection operations, and the rate of reinjection depends on provincial regulations (Kong *et al.* 2017). However, in actual projects, most geothermal wells cannot achieve continuous reinjection due to clogging. For example, the average reinjection rate of the Neogene Guantao Formation in Tianjin is 34.7%, and 6.3% for the Minghuazhen Formation (Wang 2014). Typical minerals of chemical clogging include carbonates, silicates, sulfates, metal oxides, and clay minerals (Scheiber *et al.* 2012; Haklidir & Haklidir 2017; Ma *et al.* 2017).

The main precipitation in the chemical clogging of geothermal reinjection was the carbonate scale in Xianyang, NW China (Ma *et al.* 2012). Pokrovsky *et al.* (2009) studied the dissolution of calcite and dolomite under different pH, temperature, and CO₂ partial pressure environments rate. The study by Eppner *et al.* (2017) showed that the increase in temperature would reduce the solubility of calcite, which is beneficial to the precipitation of calcite. Moreover, the increase of temperature would also reduce the solubility of CO₂, leading to the precipitation of calcium carbonate. Yang *et al.* (2022a, 2022b) found that the precipitation of carbonate minerals (calcite, dolomite) caused clogging at the back of the column. The concentration of Mg²⁺ can determine the form of carbonate minerals precipitation. Boyd *et al.* (2014) found the higher the Mg²⁺ concentration, the slower the rate of calcite formation, but the faster rate of aragonite formation.

Silicate is prevalent in wastewater and reservoirs, especially in geothermal fields with moderate mineralization and pH (Gallup 1997). Gunnarsson & Arnorsson (2005) stated that the silica scale mainly originates from the monomer amorphous silicas in the process of high-temperature geothermal water recovery and reinjection. Kunan *et al.* (2021) used hydrogeochemical modeling software Phreeqc to reproduce the scaling and the results indicated that silicate precipitation is strongly controlled by kinetic. Potassium feldspar is a kind of silicate. Ngwenya *et al.* (1995) confirmed by SEM, XRD, and ion assay that potassium feldspar can precipitate during reinjection resulting in lower permeability.

Sulfate minerals consist of SO₄²⁻ and cations. The excess of Ca²⁺ and SO₄²⁻ ions can lead to the formation and precipitation of sulfate scales (Cobos *et al.* 2021). Hastie *et al.* (2011) found that the polysulfide can be oxidized to sulfate during the reinjection due to the oxidation of water. Bedrikovetsky *et al.* (2006) combined experimental and mathematical analysis methods to simulate sulfate mineral scaling patterns. Wagner *et al.* (2005) found that gypsum precipitated in warmer regions of the reservoir. Brehme *et al.* (2019) stated that gypsum is more prone to precipitation than barite. Pape *et al.* (2005) investigated the precipitation mechanism of anhydrite. Their results implied that for the same super-saturation anhydrite crystals did not nucleate in small pores, but formed preferentially in large pores.

Metal oxides, especially iron oxides will cause serious clogging if Fe²⁺ is oxidized to Fe³⁺. Ni *et al.* (2018) found that the presence of both nitrate and oxygen caused Fe³⁺ precipitation. Cobos & Sogaard (2020) stated that reducing iron concentration did not seem to be an efficient method to reduce precipitates if oxygen had not been removed from the fluid. Yin *et al.* (2019) observed that Fe²⁺ was oxidized to Fe³⁺ to generate Fe(OH)₃ colloids and adsorbed them in the seepage channels, causing chemical clogging.

Clay minerals are very common in sandstone. Liu *et al.* (2017) stated that the composition of clay minerals is the most important factor that affects the permeability of bine aquifer. They detected that the montmorillonite led to the largest permeability reduction, followed by kaolinite and illite in their further work. Temperature can influence the precipitation of clay minerals. Rosenbrand *et al.* (2014, 2015) discovered heating caused permeability reduction in sandstone formations containing kaolinite clay particles. And a permeability reduction due to heating from 20 to 80 °C was largely reversible with cooling.

Researchers have conducted studies on various aspects of chemical clogging. The reasons for clogging during reinjection depended on the geothermal reservoir and wastewater types. However, nearly all precipitation was affected by temperature, and geothermal wastewater reinjection will form the temperature gradient. Therefore, in this study, we took the weakly consolidated sandstone thermal reservoir of the Guantao Formation in Lubei as an example, simulating the reinjection process at different temperatures. Compared to previous studies, we minimized the impact of physical clogging by setting very low flow velocity. Our study aims to determine the influence of the temperature of wastewater on the chemical clogging in the Lubei

area. The influence of mineral dissolution and precipitation caused by the change of ion concentration of displacement water on the permeability of the reservoir is emphatically discussed. The results from this study can be used for reducing chemical clogging during wastewater reinjection in the Lubei area.

2. MATERIALS AND METHODS

2.1. Sample characteristics

In the Lubei area, only a small part of bedrock is exposed, and most of them are covered with quaternary sediments, which play a role in the thermal insulation of the lower geothermal reservoir. At present, the main geothermal resource reservoir in this area is the Guantao Formation of Neogene in Cenozoic. The lower part of the Guantao Formation is siltstone, conglomerate, and sandy aquitard. The upper part is mainly siltstone, fine sandstone, and medium sandstone, belonging to fluvial facies (Zhang *et al.* 2019; Xv *et al.* 2021).

Guantao Formation sandstone is weakly consolidated fine-grained lithic feldspar sandstone, which is mainly composed of albite, microcline, quartz, Illite/montmorillonite mixed layer, montmorillonite, tremolite, kaolinite, and illite. The particle size ranges from 1.88 to 454 μm and the pore diameter ranges from 20 to 200 μm . The geothermal wastewater is weakly alkaline, and the main ion concentration from high to low is HCO_3^- , Na^+ , Cl^- , SO_4^{2-} , CO_3^{2-} , K^+ , Ca^{2+} , Mg^{2+} , which is classified as Bicarbonate-sodium water-B type according to the Schukalev classification method (MGMR 1983).

2.1.1. Water sample

To exclude the effects of physical and biological clogging on the results, desanders were used to remove most of the microorganisms, large particles, and suspended particles. The pH of the reinjection water was 8.45, the TDS was 5,237.41 mg/L, and the results of ion analysis are shown in Table 1. The wastewater in the Lubei area has a lower TDS compared with others (Regenspurg *et al.* 2010; Öner *et al.* 2011; Tomaszewska *et al.* 2017; Sasaki *et al.* 2021; Yu *et al.* 2021). A control group of deionized distilled water was also set up to exclude the effects of clogging caused by particle transport, suspended particle transport, water absorption, and swelling of clay.

2.1.2. Rock sample

The rock samples are collected from the Neoproterozoic Guantao Formation in the Lubei geothermal area, and the depth of the samples taken was about 1,100 m, which was in the upper part of the Guantao Formation. Due to the loose cementation, it was difficult to collect, and the complete rock samples obtained were less and small. High-precision rock wire-cutting technology was used to prepare the standard cores required for the reinjection simulation experiments as shown in Figure 1. The

Table 1 | Results of chemical analysis of reinjection water

ion type	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}
Mass concentration (mg/L)	470.9	7.66	16.5	2.34	409.3	294.9	3,900.4	135.41

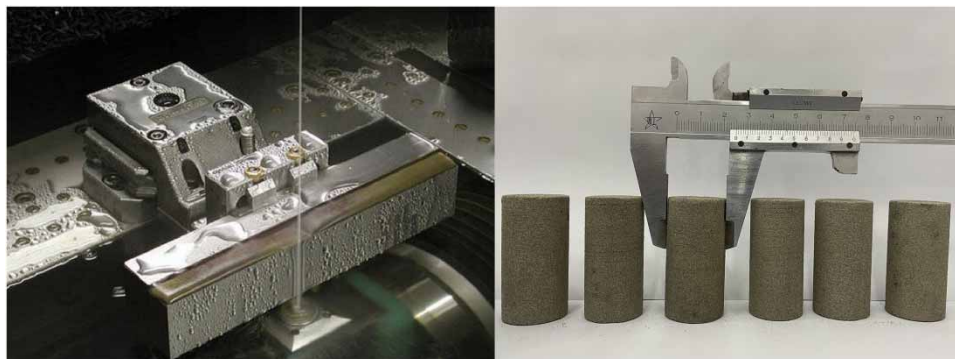


Figure 1 | Rock sample wire-cutting machine and experimental cores.

median diameter is 0.192 mm initial porosity is 63.821 mD. Rock samples of C1–C6 were prepared for the reinjection experiments. Also, their parameters are shown in Table 2.

2.2. Experimental method

2.2.1. Experimental device

The high temperature and pressure percolation experiment platform is mainly composed of an injection system, model simulation system, metering system, automatic control system, data acquisition, and processing system. The working pressure of the experimental platform can reach up to 60 MPa and the working temperature can reach up to 200 °C. The following steps are required before the experiment begins (Figure 2). In order to exclude the influence of bubble clogging, vacuuming and fulling water should be carried out before the reinjection.

Table 2 | Average of rock sample size and density parameters

Parameters	Unit	C1	C2	C3	C4	C5	C6
Diameter (D)	cm	2.499	2.519	2.509	2.528	2.519	2.520
Length (L)	cm	4.985	4.988	4.990	4.988	4.995	4.989
Area (A)	cm ²	4.906	4.985	4.946	5.025	4.985	4.985
Volume (V)	cm ³	24.458	24.866	24.678	25.063	24.900	24.870
Mass (M)	g	41.91	42.05	43.24	43.63	42.10	42.42
Density (ρ)	g/cm ³	1.714	1.691	1.752	1.741	1.691	1.706

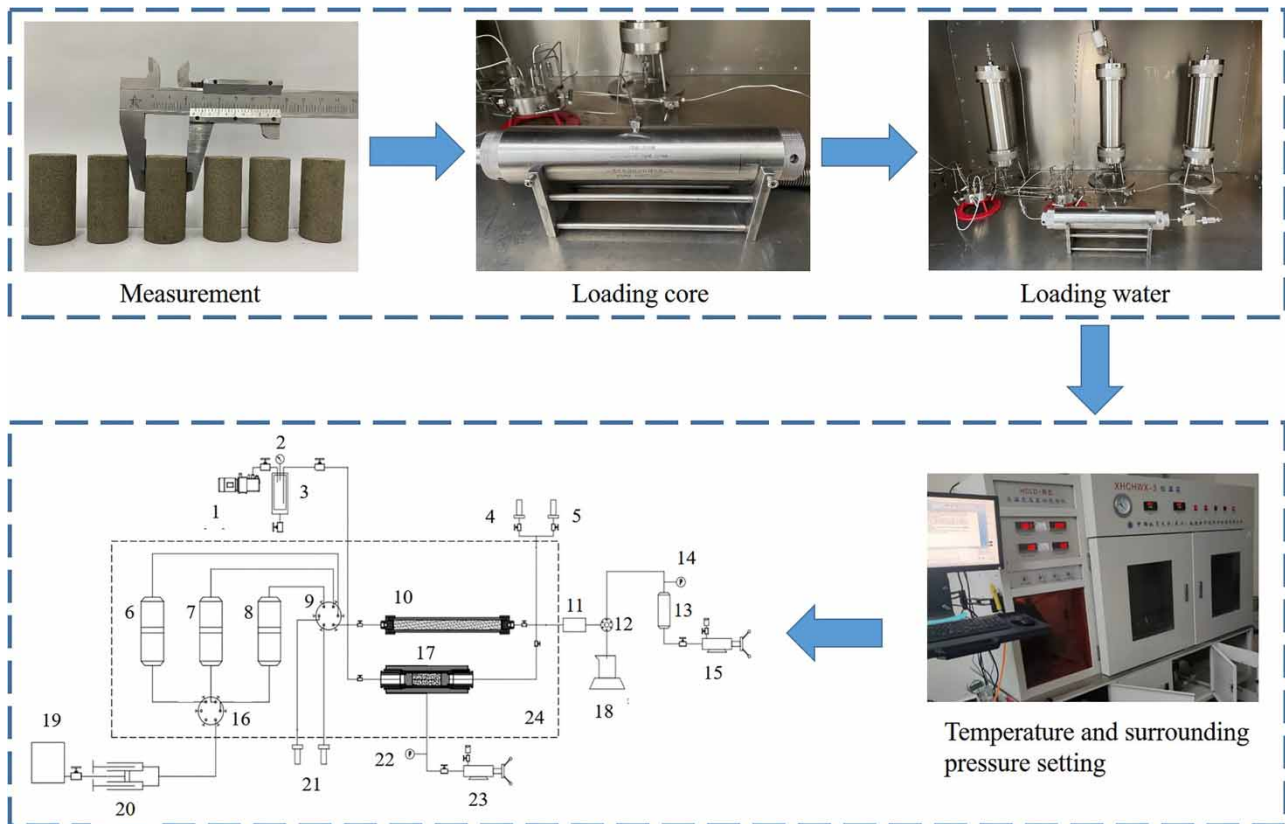


Figure 2 | Test equipment and process diagram. (1) Vacuum pump; (2) Vacuum gauge; (3) Vacuum container; (4) and (5) Pressure sensor (10 MPa); (6)–(8) 1 L container with piston; (9) Six-port valve; (10) Sand-filled pipe; (11) Cooler; (12) Back pressure valve; (13) Back pressure container; (14) Pressure gauge; (15) Hand pump; (16) Six-port valve; (17) Core gripper; (18) Electronic scale; (19) Water Container; (20) Hand pump; (21) Pressure sensor (10 MPa); (22) Pressure gauge; (23) Hand pump; (24) incubator (200 °C).

2.2.2. Experimental condition

Considering the different temperature gradients caused by low-temperature water and long-term heat extraction, the temperature was set to 25, 35, 45, 55, and 65 °C in this experiment. The depth of the reservoir was about 1,100 m, therefore the surrounding pressure was set to 10 MPa. To fully investigate the effect of water chemistry on clogging during reinjection, and to let the fluid fully contact with the rock sample, the reinjection time was set to 100 h, and the reinjection flow rate was set to 0.5 ml/min (0.0083 cm³/s). The low flow rate was used to avoid the effect of physical clogging caused by particle migration. The experiments were conducted in constant flow mode, and the pressure values at both ends of the cores were collected in real-time to calculate the permeability. The data were collected every 20 s for each group of experiment, and a total of 120,000 data were collected for 100 h. The experimental conditions were set as shown in Table 3.

2.2.3. Experimental parameters

According to the Core Analysis Method (GB/T 29172-2012), the Darcy expression for the permeability measured by horizontal laminar flow fluid is:

$$k = \frac{\mu q L}{A(P_1 - P_2)} \cdot \frac{1013.25}{600} \quad (1)$$

$$A = \frac{\pi D^2}{4} \quad (2)$$

$$Q = qt \quad (3)$$

where μ is the fluid viscosity, mPa·s; k is the permeability of the medium, mD; q is the volume flow rate, ml/min; A is the cross-sectional area of the core, cm²; L is the length of the core, cm; D is the diameter of the core, cm; P_1 is the inlet pressure, MPa; P_2 is the outlet pressure, MPa; Q is the reinjection volume, cm³; t is the reinjection time.

The permeability measured at a certain time may be influenced by various factors, and the chemical clogging permeability measured in this paper is the permeability excluding the effect of particle transport, suspended particle transport, and water absorption and swelling of clay. It is obtained by measuring the permeability of the reinjection displacement group at a certain time minus the permeability of the control group at that time.

$$k_c = k_h - k_d \quad (4)$$

where: k_c is the chemical clogging permeability at a certain moment, mD; k_h is the permeability measured at a certain moment of the wastewater reinjection group, mD; k_d is the permeability measured at a certain moment of the control group, mD.

3. RESULTS

3.1. Evolution of chemical clogging permeability

The change in permeability k of sandstone in each group during the reinjection is shown in Figure 3, and the change of permeability is larger in the 2 h at the beginning of reinjection. The control group was deionized distilled water, which excluded

Table 3 | Experimental condition

Rock sample	Temperature	Flow rate	Surrounding pressure	Displacement time	Fluid type
C1	25 °C	0.5 mL/min	10 MPa	100 h	Deionized distilled water
C2	25 °C				Wastewater
C3	35 °C				Wastewater
C4	45 °C				Wastewater
C5	55 °C				Wastewater
C6	65 °C				Wastewater

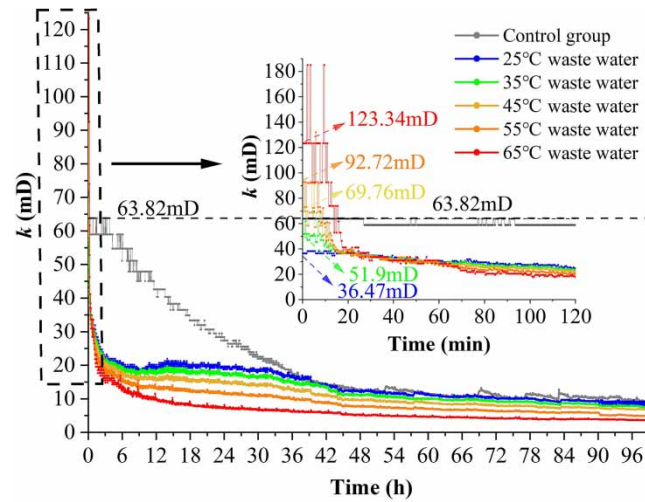


Figure 3 | Permeability k variation in 0–100 h.

the water chemical reaction with bubble clogging and biological clogging that occurred in it. At the beginning of the reinjection, the physical clogging was extremely weak. Therefore, the core permeability of the control group measured at the beginning was chosen to be k_o of all sandstone samples in this experiment, which is 63.82 mD.

From **Figure 3**, it can be found that the permeability of each group showed a downward trend over time. The permeability of the control group decreased rapidly in the first two days and then decreased slowly. The permeability of the control group decreased by 7.69, 14.28, 33.33, 80, and 84.46% from 63.82 mD at 1, 6, 12, 48, and 100 h, respectively.

The permeability of the control group did not change within the first 25 min of reinjection displacement. This indicates that the physical clogging and water absorption expansion clogging of the rock sample are very weak when it begins to contact with the wastewater. After 25 min, the physical clogging gradually grew, which indicates that the physical clogging and water absorbing expansion clogging developed gradually through the continuous action of the fluid, and the size of the particles became larger and larger. In the first two days, the pore and throat structure changed and caused the clogging, after that, the pore and throat structure was relatively stable and the permeability was maintained at a low state.

The variation of chemical clogging permeability k_c is obtained by calculation as shown in **Figure 4**.

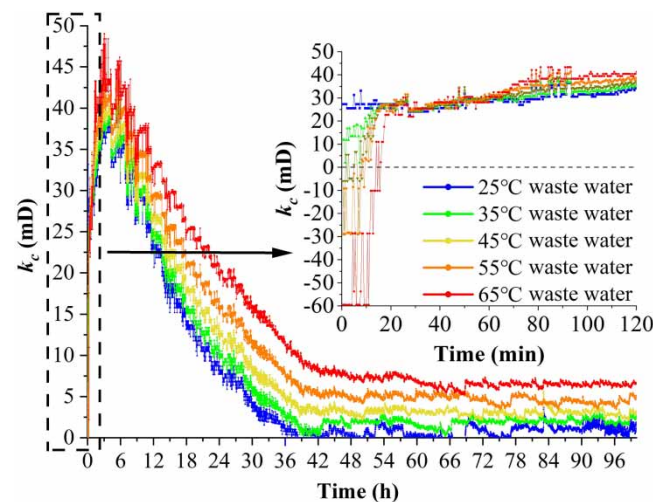


Figure 4 | Permeability k_c variation in 0–100 h.

On the whole, k_c in all reinjection groups had similar patterns, increasing rapidly in the first 4 h, and the increasing rate gradually decreased. Then k_c started to decline rapidly. The rate of decline gradually decreased, and then it stabilized. In the rapid descent stage, the descent speed first increased and then decreased. The k_c of 25, 35, 45, 55, and 65 °C reinjection groups reached their maximum value at 3.7, 3.9, 4, 4.2, and 4.3 h, respectively. In the first 20 min of reinjection, the higher the temperature of the wastewater, the more drastic the k_c changed. Moreover, in the first 10 min, the k_c of 45, 55 and 65 °C reinjection groups showed negative values, indicating that chemical clogging improved permeability. While the k_c of reinjection groups at 25 and 35 °C was positive, that is, chemical clogging reduced permeability. After 2 days of reaction, k_c of each reinjection temperature group decreased to a relatively stable value. Also, the higher the temperature, the greater the k_c .

3.2. Composition changes during reinjection

The permeability changes of all reinjection groups are generally similar. Taking the reinjection group at 45 °C as an example, XRD test of rock sample C4 was carried out on rock samples before and after reinjection. The changes in mineral composition in rock samples are shown in Table 4. According to the table, after 100 h of wastewater reinjection, the content of albite, tremolite, montmorillonite, and illite/montmorillonite mixed layer in the rock sample decreased. The content of potassium feldspar, illite, and dolomite increased. Kaolinite content did not change. Quartz content increased slightly (Figures 5 and 6).

We collected displacement water of 1, 6, 12, 24, 48, 72, and 100 h at the displacement exit, and analyzed their ion concentration and pH. The results of 45 °C reinjection group after normalization are shown in Figure 7. The original wastewater composition and pH are shown in Table 1. As can be seen from Figure 7, in the reinjection process at 45 °C, the pH of the displacement water decreased in the first 1 h. Then the pH gradually increased, 6 h later slightly higher than the original wastewater. Then, the pH of the displacement water is lower than that of the original wastewater, showing weak alkalinity. After 48 h, the pH of the displacement water was close to the original wastewater, and the reaction was stable.

Taking the 45 °C reinjection group as an example, it is not difficult to find that if we collected displacement water during the whole reinjection process, only the concentrations of Na^+ , Cl^- and SO_4^{2-} will be higher than the original wastewater. Although the concentration of K^+ increased by 26.5% in 1 h. It was lower than original wastewater for the next 80 h. From the aspect of mineral composition, the minerals containing Na^+ , Cl^- and SO_4^{2-} were dissolved during the reinjection. XRD results proved that the contents of albite and montmorillonite decreased by 19.64 and 28.61%, respectively, after reinjection, and both of them contained Na^+ . Similarly, minerals containing K^+ , Ca^{2+} , and Mg^{2+} , such as potash feldspar and

Table 4 | The mineral content changes before and after reinjection

Mineral	Albite	Potassium feldspar	Quartz	Tremolite	Montmorillonite	Illite	Kaolinite	Dolomite
Before reinjection	32.49	24.62	24.26	2.47	3.88	0.65	1.78	0
After reinjection	26.11	32.3	24.46	1.96	2.77	0.73	1.78	1.13
Change value	-6.38	7.68	0.2	-0.51	-1.11	0.08	0	1.13
Change degree	-19.64%	31.19%	0.82%	-20.65%	-28.61%	12.31%	0%	-

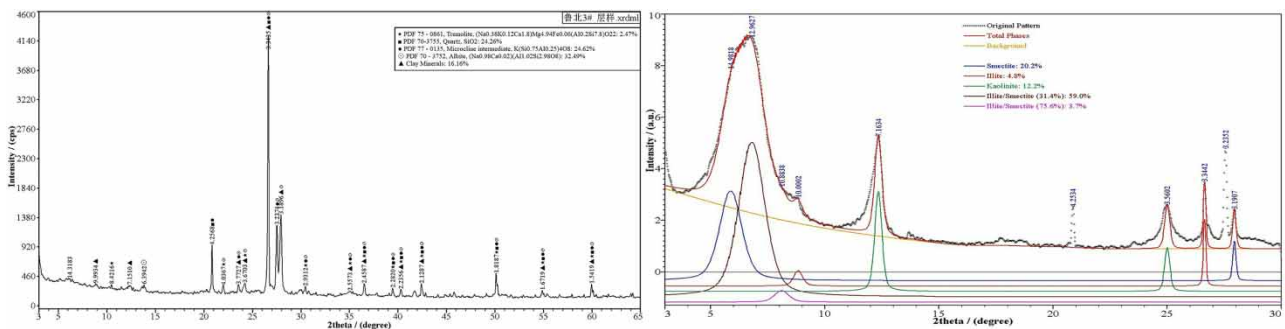


Figure 5 | XRD before reinjection.

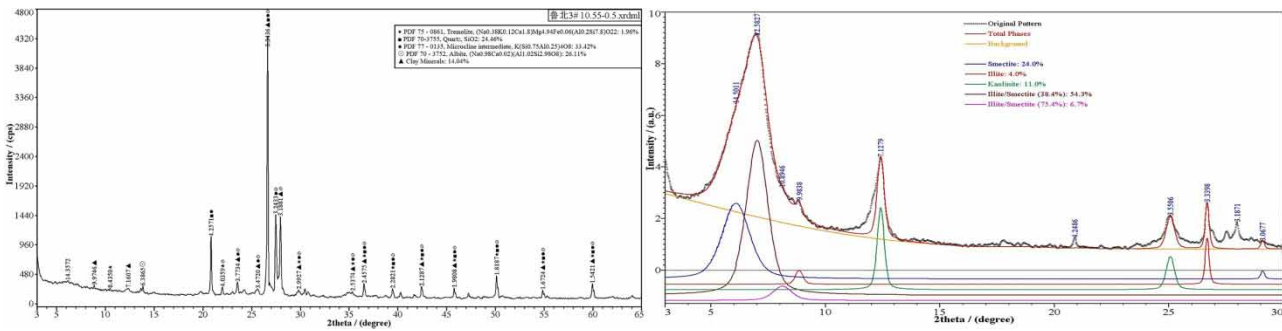


Figure 6 | XRD after reinjection.

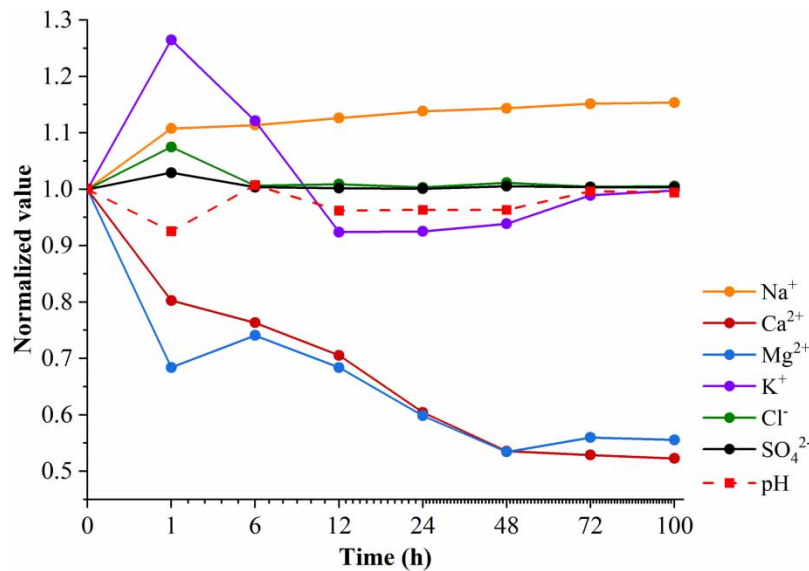


Figure 7 | Normalized ion concentration and pH variation in 0–100 h.

illite, increased by 31.19 and 12.31%, respectively, after reinjection. The calcite was not detected in the original rock samples, but the content increased to 1.13% after reinjection. In general, when the wastewater at different temperatures was reinjected, the reaction inside the rock sample is roughly the same. The increase in temperature will accelerate the rate of chemical reaction, resulting in more precipitation blocking pores.

4. DISCUSSION

4.1. Changes in ion concentration during reinjection

The chemical clogging is due to the change in hydrogeochemical balance after the reinjection water enters the geothermal reservoir (Brehme *et al.* 2018). The composition and structure of water quality and reservoir are changed by water chemical reactions such as dissolution and precipitation. There are many influencing factors of chemical clogging. At present, it is considered that the composition of reinjection water, formation water, mineral composition of geothermal reservoir, temperature, pressure, structure, time, and other factors are the controlling conditions of chemical clogging. (Brehme *et al.* 2019; Song *et al.* 2020; Zhang *et al.* 2021; Gan *et al.* 2022a).

This study recorded the ion concentrations of Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻ and the pH at the temperature of 25, 45 and 65 °C (Figure 8). The results indicated that the concentration of Na⁺ in the displacement water was higher than in the original wastewater. Increasing temperature can promote the dissolution of minerals containing Na⁺. The concentration of K⁺

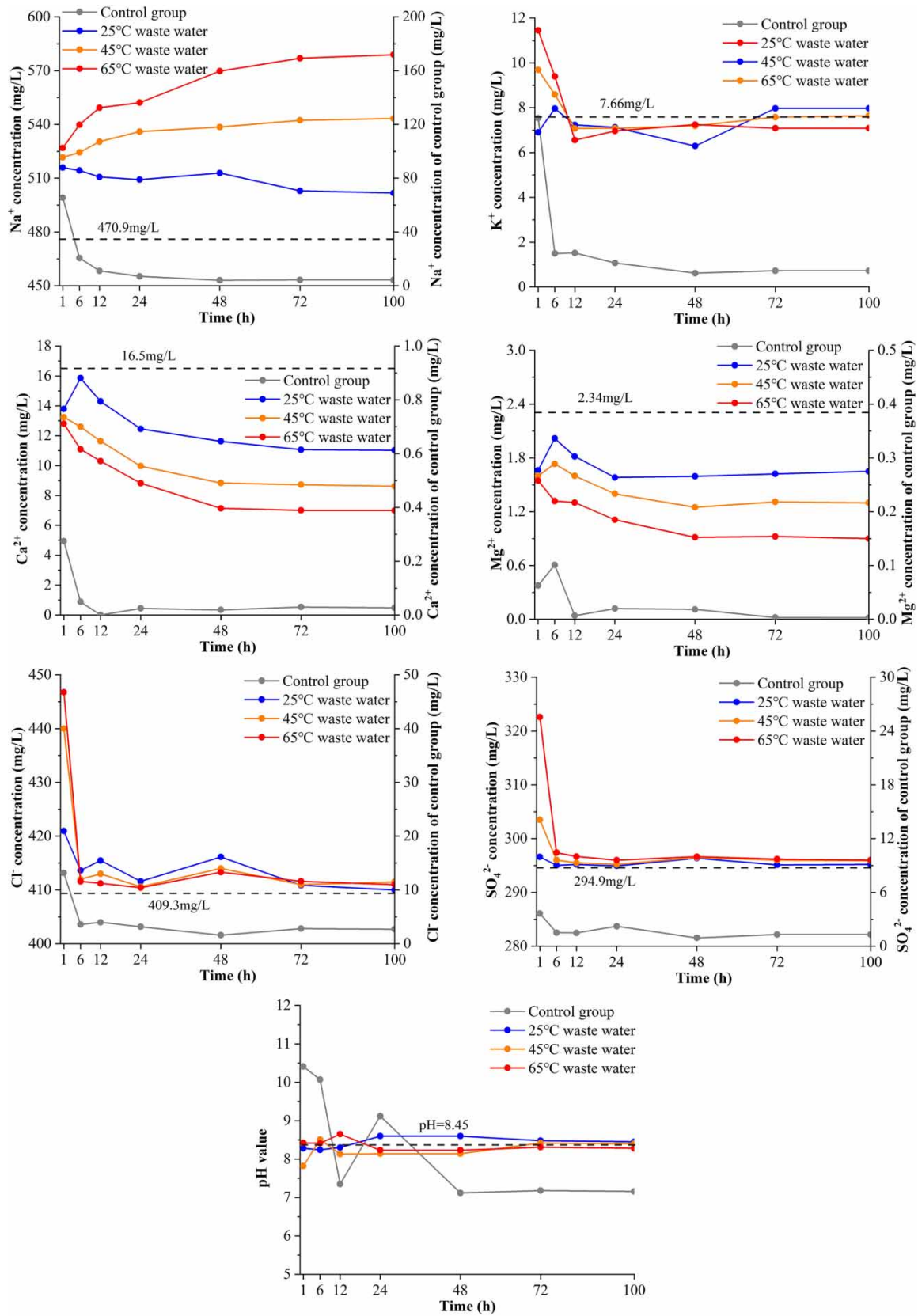


Figure 8 | Ion concentration and pH variation in 0–100 h.

decreased with the increase of temperature before 6 h, and the concentration of 25 °C reinjection group was lower than that of the original wastewater. Gan *et al.* (2022a; 2022b) observed similar results after 8 h of reinjection. However, they only tested the elements changes before and after the reinjection. We selected seven moments for continuous testing. In our study, the concentration of K⁺ in the displacement water increased with the increase in temperature, and the concentration of 65 °C reinjection group was lower than the original wastewater after 72 h. The concentrations of Cl⁻ and SO₄²⁻ were higher than the original wastewater, and the change was dramatic in the first hour. Both Cl⁻ and SO₄²⁻ concentrations increased with increasing temperature except Cl⁻ concentration decreased with increasing temperature from 6 to 48 h. The pH of the displacement water changed frequently in the first 24 h and then became stable. The pH of the 65°C reinjection group was lower than that of the original wastewater, indicating that high temperature promoted the production of H⁺.

4.2. Dissolution and precipitation of minerals

The essence of ion concentration change in displacement water was the dissolution and precipitation of minerals. When the albite (NaAlSi₃O₈) encounters K⁺ in the wastewater, it will dissolve and react to form illite, and release Na⁺. Yang *et al.* (2022a, 2022b) found the reduction of albite content after 63 days of reinjection was 13.97%. Our XRD results of 45 °C reinjection group showed that the albite decreased by 19.64% and illite increased by 12.31%. As can be seen from the ion concentration in displacement water, the higher the temperature, the faster the reaction. The chemical reactions are provided as following equation:



Ngwenya *et al.* (1995) observed that the potash feldspar is dissolved at the displacement inlet and precipitated at the exit. Our results of XRD showed that potassium feldspar increased by 31.19% at 45 °C. Also, the decreasing of pH in displacement water indicates that the reaction moves toward the formation of potassium feldspar. The chemical reactions are provided as the following equations:



Montmorillonite ((Na,Ca)_{0.33}(Al,Mg)₂[Si₄O₁₀](OH)₂·*n*H₂O) contains K⁺, Na⁺, Ca²⁺, and Mg²⁺. It will promote the formation of carbonate precipitation and sulfate precipitation during the dissolution process. The XRD of 45-°C reinjection group showed that montmorillonite decreased by 28.61% and calcite was not detected before reinjection, but 1.13% after reinjection. wastewater contains large amounts of CO₃²⁻ and SO₄²⁻, which can promote the dissolution of tremolite to form carbonate and sulfate precipitation. The XRD of 45°C reinjection group showed that the tremolite decreased by 20.65%. The chemical reactions are provided as Equations (8)–(11):



The precipitation of minerals is affected by the temperature, especially the carbonate precipitation. Its solubility decreases with increasing temperature (Pokrovsky *et al.* 2009; Ma *et al.* 2017). On the contrary, the solubility of sulfate minerals such as gypsum (CaSO₄) increases with increasing temperature (Pape *et al.* 2005).

To reduce the impact of chemical clogging, low-temperature wastewater should be used for reinjection (He *et al.* 2018; Kamila *et al.* 2021; Gan *et al.* 2022a). High-temperature wastewater can only dissolve some minerals in the reservoir at the beginning, temporarily improving the permeability of the reservoir. In the end, due to higher temperature, the chemical reaction in the reservoir is accelerated, which will reduce the reservoir permeability more. In addition, Ca²⁺ and Mg²⁺ can be removed before reinjection, which can avoid the decline of permeability caused by the production of potash feldspar, illite, and calcite.

5. CONCLUSIONS

In this paper, the permeability evolution of weakly consolidated sandstone in the process of wastewater reinjection at different temperatures was analyzed through reinjection and hydrochemical experiments. The main conclusions are as follows:

- The permeability of the rock samples was 63.821 mD, and the permeability decreased due to chemical clogging at the end of reinjection. It decreased faster in the first 2 days. After 100 h of reinjection, the permeability of rock samples C1–C6 decreased to 15.39, 13.64, 11.68, 10.71, 7.87 and 5.68%, respectively.
- In this paper, we used the permeability of wastewater reinjection group minus the permeability of the control group at a certain moment as chemical clogging permeability k_c to express the degree of chemical clogging during reinjection. If the wastewater temperature reached 45 °C or higher, the chemical clogging permeability will be negative in the first 10 min, so that the reservoir permeability can be temporarily improved. After that, the chemical clogging permeability became positive, and the higher the temperature, the more clogging will eventually be caused.
- Compared with the original wastewater, the concentration of Na^+ , Cl^- and SO_4^{2-} in the displacement water increased, while the concentration of K^+ , Ca^{2+} , and Mg^{2+} decreased finally. It is suggested that the chemical clogging of reinjection is mainly caused by potash feldspar and illite, calcite, and other carbonate precipitation. As the temperature increased, the chemical clogging in rock samples became worse. To reduce the influence of chemical clogging, it is recommended to adopt low-temperature reinjection for the low TDS of wastewater in the Lubei area, and reducing the concentration of Ca^{2+} and Mg^{2+} in wastewater before reinjection is also beneficial for reducing chemical clogging.

FUNDING

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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