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Mechanisms causing injectivity decline and enhancement in geothermal projects

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ABSTRACT

In geothermal projects, reinjection of produced water has been widely applied for disposing wastewater, supplying heat exchange media and maintaining reservoir pressure. Accordingly, it is a key process for environmental and well performance assessment, which partly controls the success of projects. However, the injectivity, a measure of how easily fluids can be reinjected into reservoirs, is influenced by various processes throughout installation and operation. Both injectivity decline and enhancement have been reported during reinjection operations, while most current studies tend to only focus on one aspect. This review aims to provide a comprehensive discussion on how the injectivity can be influenced during reinjection, both positively and negatively. This includes a detailed overview of the different clogging mechanisms, in which decreasing reservoir temperature plays a major role, leading to injectivity decline. Strategies to avoid and recover from injectivity reduction are also introduced. Followed is an overview of mechanisms underlying injectivity enhancement during reinjection, wherein re-opening/shearing of pre-existing fractures and thermal cracking have been identified as the main contributors. In practice, nevertheless, mixed-mechanism processes play a key role during reinjection. Finally, this review provides an outlook on future research directions that can enhance the understanding of injectivity-related issues.

1. Introduction

Geothermal energy is one of the most promising renewable energy sources for the 21st century and is increasingly attracting attention. However, the geothermal share of the global renewable energy market remains small, accounting for only 0.52% of global renewable power generation (including hydropower) in 2021 [1]. Economic, technical and socio-political challenges still exist, such as the high cost of drilling, continuous injectivity (a measure of how easily fluids can be reinjected into geothermal reservoirs) decline, and potential risk of drinking water contamination. Among the challenges, those occurring during the process of reinjection, including injectivity decline, thermal short-circuiting, and induced micro-seismicity, play a significant role in the success of geothermal projects, since reinjection is a key, sometimes mandatory, process for a geothermal project.

Reinjection techniques started to be applied in the late 1960s in Ahuachapan (El Salvador) [2,3] when low-temperature water was injected back into a high-temperature reservoir for environmental reasons. From the 1970s, the number of reinjection wells has been continuously growing. The initial purpose of reinjection was the disposal of steam condensate [2]. However, a positive influence on extraction well productivity was noticed. In 1987, wastewater was reinjected in the Geysers geothermal field in California when the production declined rapidly, and an improved production was noticed immediately. Consequently, reinjection started to be applied also for reservoir performance improvement [3]. Even though this method originated in high-enthalpy fields, it soon was also applied in low-enthalpy reservoirs. In low-temperature reservoirs, the amount of water produced which needs to be disposed of is substantially higher. Recently, reinjection of heated water into subsurface to store renewable energy from other sources, e.g. solar and hydro power, has been proposed and implemented in different concepts [4–6]. However, the reinjection of heated water is out of the scope of this paper.

The discharge/disposal of geothermal fluids is an important issue, which is addressed by various national regulations, including in the USA and many countries of the EU. An overview of regulations on both reinjection and water discharge is summarized in Table 1. Even though regulations vary between countries, some similarities can be seen. According to the EU Water Framework Directive [7], no uniform obligation

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List of abbreviations

EGS	Enhanced Geothermal System
HDR	Hot Dry Rock
HPF	Hydraulic Proppant Fracture
HWS	Hot Water System
II	Injectivity Index
LDS	Liquid-Dominated two-phase System
MMS	Mixed-Mechanism Stimulation
SI	Saturation Index
SRB	Sulphate-Reducing Bacteria
VDS	Vapor-Dominated two-phase System
WF	Water Fracturing

on reinjection of geothermal brine exists. National governments can decide individually whether geothermal fluid reinjection is required in their countries [8]. It can be also seen that in many cases reinjection is not strictly dictated by law, but often implied by different licensing and management requirements for geothermal fields. Hungary provides one of the most detailed regulations for geothermal reinjection: discharge of produced geothermal water into surface water, e.g., lakes, rivers, is possible if certain requirements are met, otherwise reinjection into the reservoir is mandatory [8].

Field experience has shown that reinjection does not only satisfy the environmental regulations, but also has a positive influence on extraction well productivity. Today, reinjection is widely applied for the following reasons [2,16]:

1) Produced water disposal due to environmental reasons and regulations
2) Recharge of the reservoir/aquifer
3) Pressure compensation to account for fluid extraction and to prevent subsidence
4) Enhancement of thermal extraction from over- and underlying formations
5) Thermal storage (out of the scope of this review).

One key issue that determines the success of reinjection, thus of the whole geothermal project, is to achieve and maintain injectivity, generally represented by injectivity index (the ratio of mass injection rate to pressure change, which can be represented by the wellhead pressure), at acceptable level. Injectivity decline results in one or more of several possibilities: (i) less water injected with the same amount of produced water, (ii) a lower production and injection rate, or (iii) increased injection pressures to allow the same amount of water to be injected. For the first item, there would be less fluid pressure in the reservoir, with a potential consequence of land subsidence. For example, significant subsidence due to lowered reservoir pressure have been reported in Wairakei, Broadlands and Kaweru fields, New Zealand, among which the most serious subsidence (>14 m) has been observed in the Wairakei field since its operations [17]. Another risk related to lowered reservoir pressure is the possibility of invasion of colder ground water, leading to early thermal breakthrough [11]. Additionally, lower reinjection rates directly impact production rate, especially for hot dry rock reservoirs which lack both in-situ fluids and rock permeability and thus cannot be efficiently exploited without sustainable reinjection. Both imbalanced reinjection or higher injection pressures can also increase the potential for micro-seismicity. Of course, reducing both production and injection, has significant effects on the economic performance of a geothermal project. Unfortunately, in many geothermal fields where reinjection has been applied, continuous decreases in injectivity have been recorded. For instance, several geothermal projects in the western basin of the Netherlands have suffered from continuous injectivity decline due to precipitation of carbonates [18]. In some extreme cases, poor injectivity performance has led to the shutdown of the whole geothermal project, such as the Klaipeda geothermal plant in Lithuania, of which the operating company declared bankruptcy in 2017 [19,20]. Interestingly, improved performance during operations has also been widely reported, such as the injectivity increases observed during injection in wells MK20 and MK17 in Mokai, New Zealand [21]. Such an unintentional increase in injectivity is helpful for energy saving, as lower injection pressures are then possible. Understanding the mechanisms underlying both injectivity decline and enhancement is therefore of significant importance for geothermal projects. Such knowledge can help make better reinjection protocols to avoid potential damages to the injectivity, to mitigate encountered injectivity decline or to improve reinjection/production performance.

Injectivity could be influenced by various processes during operations. Disturbances in temperature, pressure, stress field and chemical

Table 1
Overview of worldwide regulations on reinjection and produced water discharge.

Country	Obligatory reinjection?	Regulations on discharge of produced water
Belgium	No [9]	1) Discharge into natural surface system is allowed after comprehensive quality-quantity check and treatment procedures [9]. 2) Radioactivity control of fluids (NORM waste) before discharge is imposed [9].
France	No [10]	1) Discharge into surface water needs to be authorized and requires control of radionuclides, total suspended solids (TSS), chemical oxygen demand (COD), temperature [11]. 2) Radioactivity control of fluids (NORM waste) before discharge is imposed [9].
Germany	No [10]	Water used for balneology cannot be reinjected [12].
Hungary	Yes [11]	1) Water produced for greenhouse and space heating has to be reinjected. Reinjection of water used for balneology is prohibited [10]. 2) Discharge into natural surface system is allowed after comprehensive quality-quantity check and treatment procedures [7]. 3) Increased fees for the discharge of thermal water into surface water exist to promote reinjection [12].
Iceland	No [6]	1) In high-enthalpy reservoirs, reinjection is mostly used for the resource and environmental preservation [6]. 2) Regulations on environmentally hazardous content exist [6]. 3) Water from low-enthalpy reservoirs can be freely discharged into surface waters [11]. 4) Due to low chemical content, water does not pose an environmental threat [6];. 5) Limits on drawdown are established [11].
Italy (Tuscany)	Yes [9]	Discharge to surface/shallow ground water is not allowed in Tuscany. Geothermal fluid is reinjected into the reservoir [9].
Netherlands	Implied [13,14]	1) Permits are needed for discharge into surface water system or sewer system, which are only granted under strict environmental conditions, which would not usually be met with geothermal waste water [13,14], usually meaning that reinjection is the only viable option. 2) Reinjection is allowed with a permit which specifies safe conditions [15].
Philippines	No [11]	Reinjection is an operational requirement for geothermal fields due to environmental protection of agricultural areas [3].
Switzerland	No [10]	Water management laws are determined individually by cantons [10].
USA	Yes [11]	Framework is defined individually by the states. For example, in California reinjection is obligatory to get full property rights [11].

composition in geothermal reservoirs due to reinjection could trigger complex coupled processes (physical, chemical, biological or a combination of them) that influence injectivity. Fig. 1 summarizes the processes that can either deteriorate or enhance injectivity during reinjection. Those processes affecting the near-wellbore area largely control the overall injectivity. The impact of local changes in permeability around the wellbore are also often considered in analysis through the definition of a 'skin' which can increase or decrease permeability. While this bulking parameter is useful for conducting simulations, further insight into the underlying mechanisms has the potential to improve numerical predictions and reservoir management.

This paper aims to provide a comprehensive review on processes and mechanisms that affect either positively or negatively injectivity during reinjection into geothermal reservoirs. A brief introduction to definitions of geothermal systems is firstly presented in the following section, combined with an overview of the general development and operational phases of a geothermal project. Processes that can impair and enhance injectivity during reinjection are described and discussed in Sections 3 and 4 respectively. In Section 5, an outlook for existing gaps to be filled is presented, followed by conclusions.

2. Geothermal systems and thermal energy extraction

Geothermal systems can be classified from different perspectives, such as sources of thermal energy [22], geological settings [23], physical state [24], and reservoir temperature/enthalpy [25]. A brief summary of reservoir classifications based on temperature, physical state and energy source is in Table 2, as these definitions will be referred frequently in the following sections.

Extracting thermal energy from the subsurface is typically a high-cost and high-uncertainty undertaking. To better manage the risks and uncertainties, geothermal projects have been divided into a series of phases, generally including preliminary survey, exploration, test drilling, review and planning, reservoir development, construction, start-up and commissioning, and operation & maintenance [31]. Among these phases, test drilling, reservoir development (including drilling, completion and possible stimulation), and operation and maintenance (including reinjection) give a chance for external fluids to contact in-situ components in the subsurface. In these phases, reservoir permeability could be intentionally or unintentionally influenced, particularly in the near-wellbore area, leading to a reduced or enhanced injectivity. Although the focus of this paper is on the reinjection phase, it is worthwhile to give a brief introduction to the processes that could influence injectivity during drilling and stimulation, as these can also influence processes occurring during the subsequent operation phase.

To extract thermal energy from the subsurface, wells have to be drilled into targeted reservoirs to allow communication between subsurface and surface systems. During drilling, there is inevitably contact between drilling fluids and in-situ components of the reservoirs which generally lead to a positive skin (damaged near-field permeability). Although there are typical features of geothermal reservoirs compared to conventional oil and gas reservoirs, e.g. higher in-situ temperature, the mechanisms for formation damage during geothermal drilling can be inferred from oil and gas drilling. Table 3 presents an overview of formation damage mechanisms which can occur during geothermal drilling, summarizing the work by Vetter & Kandarpa [32]. It is worth noting that these damages are reservoir-specific and mud-system-specific, controlled by factors such as salinity incompatibility between in-situ and external fluids, special ionic species contained in the mud, and in-situ temperatures [33–35].

After drilling, stimulation techniques can be applied to deep geothermal reservoirs, particularly in EGS, relieving the impact of near-field formation damage, or further improving injectivity. Table 4 summarizes stimulation techniques that have been used in the geothermal industry, alongside the corresponding aims and mechanisms, and successful field application examples. The most commonly used stimulation

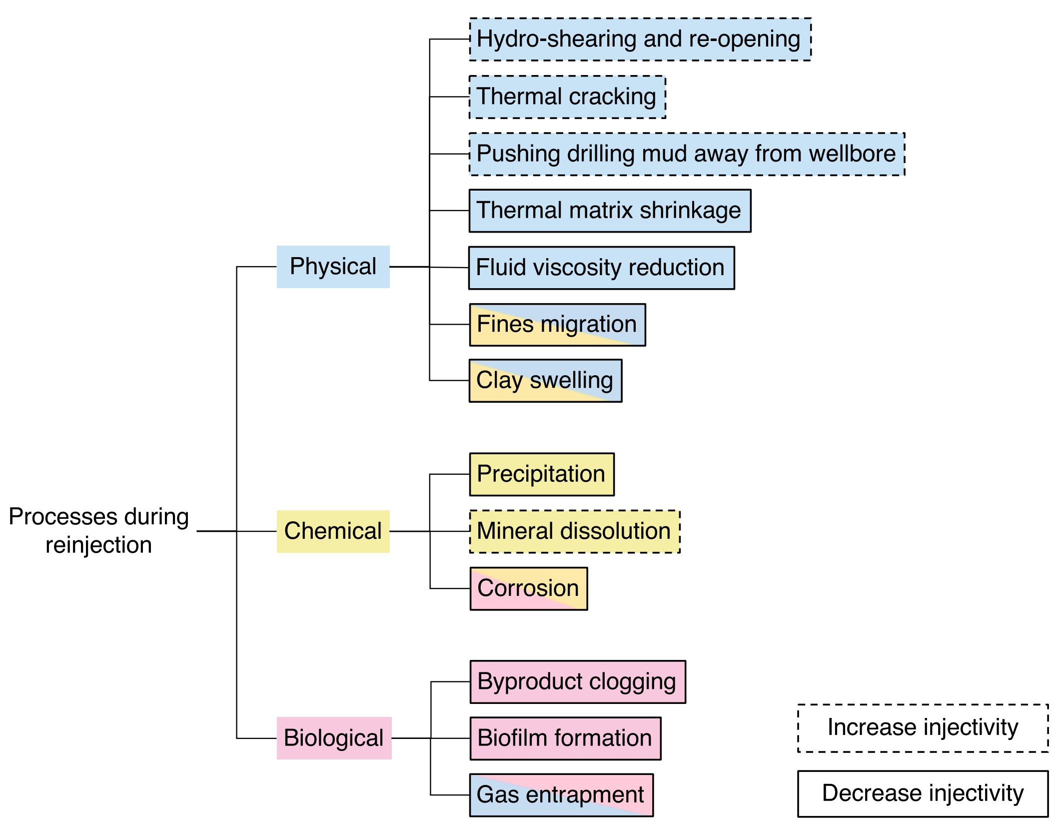

Fig. 1. Overview of mechanisms underlying injectivity decline and enhancement during reinjection. Mechanics are color-coded by type, i.e. whether they are physical, chemical or biological. Mechanisms in two colours include two processes (i.e. physico-chemical, physico-biological, chemo-biological processes).

Table 2
Classifications of geothermal systems based on different perspectives: in-situ temperature, physical state of in-situ fluids and energy source.

Classification based on in-situ temperature [26]	
Category	Definition
Low-temperature reservoirs	<150 °C
High-temperature reservoirs	>150 °C
Classification based on physical state of in-situ fluids [27]	
Category	Definition
Hot water system (HWS)	Only liquid exists, T (temperature) < 220 °C
Liquid-dominated two-phase system (LDS)	Boiling occurs during operations, 220 °C < T < 350 °C
Vapor-dominated two-phase system (VDS)	Steam exists and contain voluminous immobile water, 250 °C < T < 350 °C
Classification based on energy source [28–30]	
Category	Definition
Hydrothermal system	Hot reservoirs with adequate natural permeability and in-situ fluid saturation at economical drilling depths
Enhanced Geothermal system (EGS)	Hot reservoirs with insufficient or low natural permeability and/or in-situ fluid saturation
Co-produced system	Conventional oil and gas reservoirs with large amount of co-produced hot water
Geo-pressured system	Reservoirs with trapped brines at pressure higher than hydrostatic pressure, often containing dissolved natural gas

technology is hydraulic fracturing, including hydraulic proppant fracture (HPF), water fracturing (WF) and hybrid fracturing. HPF uses highly viscous gel as fracturing fluid with high proppant concentration to create and maintain highly conductive but short fractures, mainly used to mitigate formation damage in the near-field reservoirs. In contrast, WF, also known as self-propped fracs, uses water containing friction-reducing chemicals and low-concentration proppant to create narrow but long fractures to reach deep reservoirs. Hybrid fracturing is a combination of HPF and WF, which forms both highly conductive and relatively long fractures. While hydraulic fracturing is popular due to its ability to create long fractures and large fracture networks with sustainable conductivity and its applicability to all types of rock, concerns regarding the induced seismicity and other environmental issues are increasing. Although acidizing fracturing does not require massive injection of fluid under high pressure, the difficulty in controlling the fracturing processes and its high cost and risk of polluting ground water restrict its popularity. Recently, thermal stimulation is attracting increasing interests in the geothermal industry, due to its mitigation of injection of harmful chemicals and its low pumping pressure. However, careful consideration should be taken to avoid scaling-related damage. In addition, a large temperature difference is required to fracture the rock, which is not always possible in sedimentary geothermal reservoirs. Overall, stimulation technology should be carefully selected considering the aims of stimulation, the characteristics of the targeted reservoirs and the advantages and disadvantages of each technology.

Table 3
Summary of formation damage mechanisms during geothermal drilling [32].

Types of damage	Mechanisms
Physical damage	1) Filling of wellbore with particles 2) Generation of filter cake on the wall of wellbore or on the surface of fractures 3) Clogging of perforation holes 4) Plugging of near-field matrix pores
Chemical damage	1) Precipitation of components or salts in the (invaded) mud and in-situ brines due to thermodynamic instability 2) Precipitation of products from chemical interactions between the (invaded) mud and in-situ brines 3) Disaggregation of in-situ clay minerals caused by certain ionic species contained in the (invaded) mud 4) Chemical alterations of drilling additives, such as transformation of non-swelling clays (e.g. sepiolite) to swelling clays (e.g. smectites)

3. Injectivity decline during reinjection

Problems during injection have been widely studied in oil and gas reservoirs [65], and later in deep geothermal reservoirs and thermal aquifer storage systems [66–70]. Table 5 collects geothermal field examples where decreasing injectivity was observed.

There is a typical reduction of injectivity with a decrease of the temperature of injected water due to the impact of the increase in viscosity (in some cases, e.g. in the 2012 injection test in Groß Schönebeck [81], viscosity decreased due to a reduced salt concentration despite the decreased temperature) and thermal shrinkage of the matrix. This is an unavoidable part of a geothermal project where fluid with a reduced temperature is injected. These processes are, in principle, reversible with a subsequent increase in temperature. However, the main process for a permanent reduction in injectivity is clogging. Several studies investigated specific aspects of clogging mechanisms during geothermal operations [27,82,83]. Here an overview of all clogging types common in geothermal fields is provided.

Primary clogging mechanisms can be divided into three groups based on the nature of the responsible processes (Fig. 1): a) physical processes, related to the migration of particles; b) chemical processes, caused by chemical reactions; c) biological processes as a result of bacterial activities. There are, however, processes which could be caused by different mechanisms or a combination of those, such as corrosion, they are therefore highlighted separately. Clogging processes occur at different stages of geothermal system operation (Fig. 2) and will be described in detail in the following sections. While it is mostly clear, where each type of clogging occurs, the time scale can rarely be stated uniformly due to inability to track processes inside the porous media. Physical clogging by external fines has been reported to usually be the first one observed, while clogging due to chemical reactions may take a longer time [68,84].

3.1. Physical clogging

Physical clogging has been identified as one of the primary mechanisms and also most common mechanism of injectivity decline in geothermal reservoirs for some decades [82,85,86]. It was first observed in the early 1980s in the Paris basin, where severe clogging problems led to abandonment of several injection wells [87]. Several different processes can be distinguished within physical clogging, such as migration of injected fines, internal particles transport (due to changes in pH and salinity and due to high flow rate) and clay swelling, shown in Fig. 3 [85]. It is important to mention, that the last two occur as a combination between physical and chemical processes. Two other mechanisms, excluded in the figure, are water viscosity decrease and thermal

Table 4
Summary of current stimulation techniques used in geothermal industry with corresponding aims, mechanisms and successful field examples (II: injectivity index).

Conventional techniques	Aims	Mechanisms	Field Examples	Initial II	Stimulated II
Hydraulic stimulation	1) Create reservoirs, e.g. EGS 2) Connect wellbore and natural fractures 3) Improve near-field permeability	1) Tensile fracture by hydro-fracturing [36] 2) Re-opening of natural fractures [37] 3) Shear dilation [36] 4) Thermal cracking [38]	Awi 18-1 at Salak, LDS, Indonesia [39]	0.64 kg/(s·bar)	1.37 kg/(s·bar)
			Awi-3 at Salak, LDS, Indonesia [40]	0.55 kg/(s·bar)	2.19 kg/(s·bar)
			GtGrSk4/05 at Groβ Schönebeck, HWS, German [41]	0.067 kg/(s·bar)	0.408 kg/(s·bar)
			PX-2 at Pohang, HWS Korea [36]	0.104 kg/(s·bar)	0.281 kg/(s·bar)
			GPK1 at Soultz, HWS, France [42]	0.09 kg/(s·bar)	0.4 kg/(s.bar)
			TR-10 at Berlin Field, HWS, El Salvador [43]	0.88 kg/(s·bar)	(1.21–2.06) kg/(s·bar)
			SN-12 IN Seltjarnarnes, HWS, Iceland [37]	0.1kg/(s·bar)	(5–8) kg/(s·bar)
Matrix acidizing	1) Improve near-field permeability	1) Dissolving minerals blocking the pore or fracture [44] 2) Dissolution of matrix materials [44]	Rossi 21-19 at Beowawe, HWS, U.S. [45]	0.9 kg/(s·bar)	2.3 kg/(s·bar)
			Awi 8-7 at Salak, LDS, Indonesia [46]	4.68 kg/(s·bar)	11.97 kg/(s·bar)
			Op-3D in Bacman, LDS, Philippines [44,47]	0.68 kg/(s·bar)	3.01kg/(s·bar)
			OP-5DA in Bacman, LDS, Philippines [44,47]	0.99 kg/(s·bar)	1.4 kg/(s·bar)
			TR7 at Berlin Geothermal Field, HWS, El Salvador	0.549 kg/(s·bar)	1.561 kg/(s·bar)
			MN_4 at Montieri, VDS Italy [48,49]	0.83 kg/(s·bar)	4.17 kg/(s·bar)
			AZ-68D at Los Azufres, VDS, Mexico [50]	0.23 kg/(s·bar)	0.99 kg/(s·bar)
Acid fracturing	1) Connect wellbore and natural fractures 2) Improve near-field permeability	1) Hydro-fracturing/-shearing [47] 2) Sustaining conductivity through non-uniform etching [47]	AZ-47D at Los Azufres, VDS, Mexico [51]	0.11 kg/(s·bar)	1.39 kg/(s·bar)
			Ottoboni State 22 at The Geysers, VDS, U.S. [52]	NO EFFECT	
Thermal stimulation	1) Improve near-field permeability 2) Develop existing fracture networks	1) Cleaning of mineral deposits [53] 2) Re-opening pre-existing fractures [54] 3) Shearing pre-existing fractures [54] 4) Thermal cracking [54]	HE-8 at Hellisheidi, LDS, Iceland [53]	(1–2) kg/(s·bar)	(6–7) kg/(s·bar)
			Awi 11-6OH at Salak, LDS, Indonesia [55]	2.01 kg/(s·bar)	4.03 kg/(s·bar)
			KA-43 at Kawerau, VDS, New Zealand [56]	6.4 kg/(s·bar)	12.5 kg/(s·bar)
			RK-21 at Rotokawa, VDS, New Zealand [57]	4.2 kg/(s·bar)	10 kg/(s·bar)
			NM08 at Ngatamariki, LDS, New Zealand [58]	0.11 kg/(s·bar)	0.75 kg/(s·bar)
			H-40 at Los Humeros, VDS, Mexico [59]	<1.4 kg/s	>30.5 kg/s
			SA-1 at Sumikawa, VDS, Japan [60]	0.9 kg/((s·bar))	2.0 kg/(s·bar)

Unconventional techniques	Aims	Mechanisms	Field Examples	Results
Explosive stimulation	1) Improve near-field permeability	1) Perforation & bore shooting [61] 2) Massive formation fracturing [61]	LF-30 at Geysers, VDS, U.S. [52,61]	Both skin and transmissibility reduced
High-energy gas fracturing	1) Connect wellbore and natural fractures	1) Using propellants to obtain controlled fracturing [62]	4 experiments GT-1 to GT-4 at Nevada test site, U.S. [62]	Multiple fractures created
Radial jet drilling	1) Connect wellbore and natural fractures 2) Improve near-field permeability	1) Jetting to form laterals from main wellbore [63]	HN-13 at Botn, HWS, Iceland [64] Well 1I at Klaipėda, HWS, Lithuania [63]	Flow improved at various depths Improvement in injectivity of 14%

shrinkage of the matrix due to lower temperature of reinjected fluid.

The most common and first observed among the mentioned physical processes is external particle entrapment [84]. Generally, suspended particles exist in produced water despite complex filtration systems and are, therefore, reinjected into the reservoir [89]. Migrating particles can have different shapes, densities and sizes, which also influences their entrapment. Such entrapment could happen at different locations in the formation. Primarily, they can accumulate at the wellbore face, forming a filter cake or narrowing the wellbore [87]. Similarly, fines may block the perforations. Finally, as particles migrate with fluid flow inside the porous media, they could induce permeability impairment inside the reservoir.

It has been traditionally accepted that at a ratio of particle size to pore diameter smaller than 1/7, no clogging occurs at smaller injection volumes. However, at large injected volumes this rule of thumb may not be satisfied [90]. Particles with smaller size distribution (starting from 5% to 7% of pore throat diameter) can also contribute to clogging if they form bridges due to electrostatic and van-der-Waals interaction [85,91]. Larger injected particles block the pores due to the size exclusion mechanism. Size distribution also influences the penetration depth of such particles. Wang et al. [92] in experiments with a seepage column of plexiglas identified 1 cm penetration depth for particles with sizes in the range of 0.075 to 0.0385 mm and 2 cm depth for fines smaller than 0.0385 mm. In most cases the depth of damage by external particles does not exceed 1–2 cm [85].

Besides external particle entrapment, interaction of internal particles

Table 5
Field examples of changes in injectivity index (II) during reinjection into geothermal reservoirs.

Field example	Reser. Temp.	Inj. Temp.	Injection period	Initial II	Ending II	Water source	Injectivity decline mechanism		Injectivity restoration measures
HN-09, Hellisheiði, (LDS), Iceland [71]	(200–250) °C	120 °C	May2008-Dec.2008	90 kg/s	36 kg/s	Nearby wells	Physical	Thermal expansion in a fractured reservoir	Lowering injection temperature
TR-14, Berlin (LDS), EI Salvador [72]	~290 °C	175 °C	Jul.1998–Oct.1999	40 kg/s	10 kg/s	Nearby TR-2 & −9	Chemical	Silica precipitation in the reservoir	Acid treatment (HCl + HF)
BR34, Broadlands (LDS), New Zealand [73]	>260 °C	94 °C	Nov.1978–Jan.1979	4.35 kg/(s·bar)	3.48 kg/(s·bar)	Nearby BR2		Silica precipitation in the reservoir	N/A
KD-1A, Kizildere LDS), Turkey [74]	195 °C	(20–42) °C	Nov.1975–Dec.1975	3.30 kg/(s·bar)	1.90 kg/(s·bar)	Nearby KD-15		Silica scaling	N/A
R1, Otake (LDS), Japan [75]	(120–162) °C	(50–80) °C	Oct.1983–Jan.1986	148.61 kg/s	1.39 kg/s	Nearby O-15 & O-9		Silica scaling in the well	N/A
R2, Otake (LDS), Japan [75]	(120–162) °C	(50–80) °C	Jul.1984–Sep.1986	91.39 kg/s	27.2 kg/s				
Nag-67, Tiwi (LDS), Philippines [76]	260 °C	(152–171) °C	1989–1999	9.13 kg/(s·bar)	1.30 kg/(s·bar)	Nearby wells		Silica scaling in the well	Scale drill-out, acid treatment
Veysey 1, North Brawley (LDS), U. S [77]	(149–204) °C	N/A	Nov.1975–Dec.1976	1.00 kg/(s·bar)	0.35 kg/(s·bar)	Nearby wells	Chemical/ physical	Silica scaling and consequent fines migration	Acid treatment (HCl + HF)
KD-7, Kizildere (LDS), Turkey [74]	205 °C	(97–98) °C	Jun.1995–Aug.1995	0.73 kg/(s·bar)	0.19 kg/(s·bar)	Nearby KD-20		Calcite scaling and consequent fines migration	Filter system installation & change of water composition
Gt NG 2/89, Neustadt-Glewe (HWS), Germany [78]	99 °C	30 °C	2007–2012	6.11 kg/(s·bar)	3.44 kg/(s·bar)	Nearby wells		Sulphate scaling and consequent fines migration	Acid treatment (HCl) & scale inhibitors
KGDP-1I Klaipeda (HWS), Lithuania [19]	36 °C	11 °C	2002–2015	1.58 kg/(s·bar)	0.36 kg/(s·bar)	Nearby KGDP-2P & 3P		Gypsum precipitation, migration of corrosion products	Radial jet drilling, acid treatment (HCl) & scale inhibitor
KGDP-4I Klaipeda (HWS), Lithuania [19]	36 °C	11 °C	2002–2015	8.58 kg/(s·bar)	0.31 kg/(s·bar)				
N/A (Triassic sediments, HWS), the Netherlands [79,80]	(80–84) °C	(30–40) °C	2017–2019	2.4 kg/(s·bar)	1.1 kg/(s·bar)	N/A	Chemical/ biological	Corrosion & biological clogging of the well	Corrosion inhibitor & biocide treatment

with injected fluids could also damage the injectivity as a result of particles detachment, migration and precipitation [83]. Detachment and adsorption of internal fines is controlled mainly by the equilibrium between electrostatic force and drag and lifting forces [93].

Electrostatic forces acting on particles can be influenced by pH and salinity variations. Mineralogical composition of most sandstone aquifers includes various types of clays. Clay minerals are very sensitive to the ionic strength and pH of injected fluids, as they may deflocculate or, on the contrary, form aggregates inside the porous media [68,94]. This problem is less common for the reinjection processes in geothermal operations, as the primary chemical composition remains unchanged. However, when fluids from external sources are injected, e.g. at Broadlands in New Zealand where cold river water was used [95], permeability could be damaged due to the incompatibility between injected and in-situ fluids. In addition, surface processes of scaling or gas dissolution might decrease the salt concentration, and bacterial activity can lead to changes in pH. These fluctuations can cause destabilization of clay systems and, consequently, fines migration and pore blockage.

Furthermore, drag forces acting on internal particles can be influenced by injection parameters, such as rate of fluid circulation or dynamic viscosity [82,87]. It was identified that an individual critical flow rate exists for each formation, which, if exceeded, can lead to internal fines detachment and migration [96]. For sandstones, critical flow rates in the order of 0.01 m/s have been reported, however, the rates are reservoir-specific [96,97]. Consequently, optimal flow rate is expected to avoid fines detachment and migration and, at the same time ensure efficiency of geothermal production.

Similar processes also influence the swelling of clays, a phenomenon of significant increase in clay volume due to water invasion into layered structure of clay minerals, especially for the montmorillonite group. Up to 6 times increase in clay volume could be induced as a result of water penetration, causing severe permeability impairment [98]. Similarly to fines migration, if the composition of the reinjected water remains the same, clay minerals might not be affected. However, scaling during production could lower the salinity of reinjected fluid, thus leading to clay swelling.

Physical clogging can also be a result of gas entrapment. This can occur due to poor isolation in surface equipment and consequent air leaks [68], or biological activity in the reservoir [86]. Gas clogging is highly influenced by pressure and temperature, although these are typically associated with production. For example, pressure drop or temperature increase can lead to gas exsolution from the infiltrated fluid inside the porous media [86], and pressure fluctuations during production can also lead to gas bubbles formation, reduce rock permeability and disturb the fluid flow [99]. Furthermore, gas exsolution in the production casing can disturb the thermodynamic equilibrium of the geothermal fluid and consequently induce mineral scaling [100].

3.2. Chemical clogging

The problem of scaling and precipitation is quite common for geothermal fields. It was first recognized in the 1980s when serious scaling in the production equipment was noticed at geothermal sites [47]. Around the same time, wellhead injection pressure rise was linked

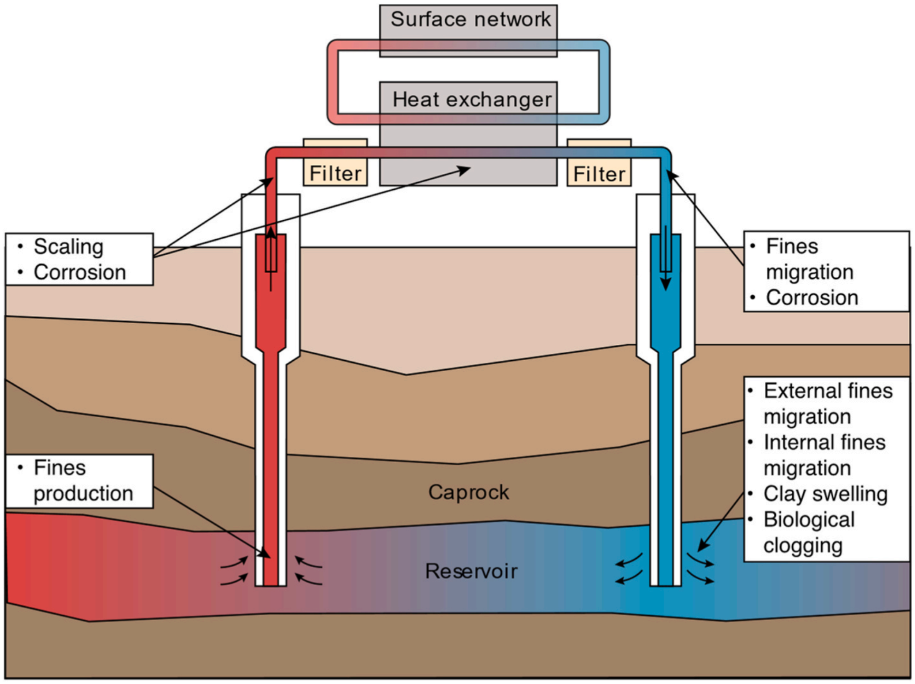

Fig. 2. Schematic diagram of clogging at different stages of reinjection.

to fluid-reservoir incompatibility which resulted in precipitation and blockage [97]. Even though previous studies mostly concentrated on the scaling problems in production lines and power plants, precipitation can also occur in the reservoir pore space during reinjection processes [101,102]. Many field studies report scaling in production and power plant equipment [103,104]. The basic reason for chemical clogging processes is thermo-dynamic equilibrium shift due to changes of external parameters [105]. Precipitation and dissolution are the main chemical processes influencing injectivity, as shown in Fig. 4.

Scaling can significantly decrease well injectivity and reduce operation efficiency [103,106]. The most common natural mineral that could form scales is silica, followed by carbonates and sulfates [70,107,108]. Stability of these minerals can be assessed by the saturation index (SI). It shows if a mineral tends to be dissolved or precipitated in water under certain conditions and is influenced by ionic concentration, temperature and pressure [107]. At SI $<$ 0 a mineral is dissolved (under-saturation), at SI $>$ 0 a mineral precipitates (super-saturation), while at SI = 0 water and minerals are in equilibrium.

SI is strongly temperature- and pH-dependent. Due to temperature changes during production, gas and vapor are released and the brine composition changes, which can lead to brine super-saturation [109].

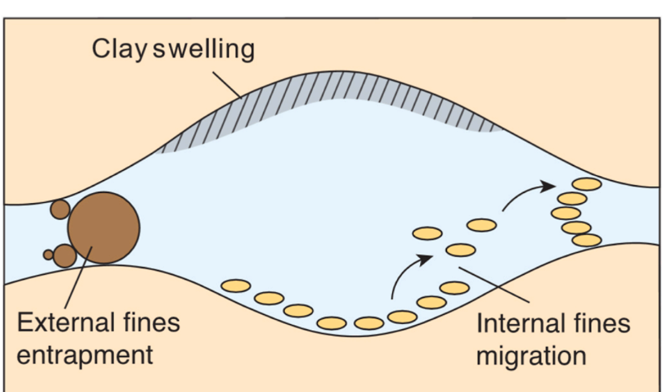

Fig. 3. Illustration of physical clogging mechanisms (modified after [88]).

The injection temperature optimal for scaling prevention is highly dependent on the reservoir conditions and may significantly vary between 130 °C–170 °C for hot reinjection systems and 30 °C–80 °C for cool injection in case of silica scaling [27].

Tut Haklidir et al. [103] studied precipitation tendency for high-temperature geothermal fields. They calculated saturation indices for different minerals at a temperature range from 50 °C–250 °C. The curves for amorphous silica show that sampled fluids are generally supersaturated at temperatures lower than 100 °C–150 °C. Calcite, on the other hand, showed a high scaling risk, as fluids are supersaturated in the whole temperature range studied. Fluids with anhydrite and gypsum showed low risk for operations at temperatures >50 °C. Massive gypsum precipitation, however, has been reported at lower temperatures at a power plant in Lithuania operating at 11 °C – 40 °C [110].

The influence of pH on silica precipitation kinetics has been reviewed by Klein et al. [111]. They showed that the rate of silica polymerization and, consequently, precipitation also increases as a result of ionization of silica with pH, especially at high pH from 7.8 to 9.8 [111]. Therefore, operating with a pH 7 or lower is generally considered to mitigate silica

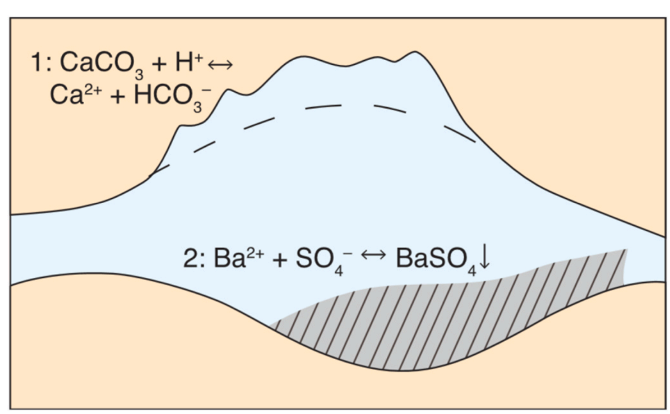

Fig. 4. Illustration of main groups of chemical clogging processes: 1 - dissolution (e.g. of calcite) increases pore space, 2- precipitation (e.g. of barite) decreases pore space.

polymerization kinetics.

Apart from natural mineral deposition, metal precipitation from geothermal brine can also occur. For example, lead scaling has been reported in several cases with high concentration of lead ions in formation water [112,113]. This scaling is caused by redox reactions, where lead ions oxidized metallic iron, resulting in deposition of metallic lead [112,114].

Another major chemical process is mineral dissolution due to rock-fluid interactions (Fig. 4), e.g. dissolution of calcite or muscovite near the wellbore zone [115]. The dissolution of minerals leads to an increase in ionic concentration of the flowing brine, which along with the reduced temperature of the injected fluid can result in secondary precipitation further inside the reservoir [84]. Chen et al. [115] modeled the balance between dissolution and precipitation in a granitic reservoir with SO_4•Cl–Na reservoir fluid type and showed that the balance can be achieved at 35 °C, thus minimizing porosity and permeability variations.

Moreover, corrosion also influences the efficiency of geothermal operations. Corrosion refers to metal deterioration as a result of reactions between metals within engineered systems (e.g. tubulars) and geothermal brines. Various types of corrosion can be defined based on the agents causing chemical reactions: oxygen, hydrogen, chloride and others [116]. One of the major reasons for corrosion is saturation of brine with oxygen at different stages of geothermal operations, e.g. in the reinjection line, which further oxidizes Fe^{2+} to Fe^{3+} and leads to precipitation. It has been observed that the concentration of Fe^{3+} ions increases from the production to the injection site [101]. The presence of chloride ions also enhances corrosion, even at temperatures less than 50 °C. Moreover, increase in concentration of hydrogen ions, i.e. decrease of pH level may also promote corrosion. Production of hydrogen sulphide (H_2S), due to bacterial activity, is a common example of this process [117].

If the corrosion products are not filtered completely in the power plant, they could further migrate with the fluid flow into the reservoir and become a source of clogging as external fines. Some studies show that corrosion products make up to 60% of the external fines [101].

3.3. Biological clogging

Bacterial clogging has been reported widely at geothermal sites, sometimes quite severe with permeability impairment up to 4 orders of magnitude [67,101,118,119]. Such clogging primarily occurs in the near-wellbore zone but it has also been reported in the surface equipment, and thus can further be transferred into the reservoir during reinjection [68,84,120]. Several mechanisms of bacterial clogging have been observed [82,85,121]. Bacterial cells can accumulate in porous media: an increased concentration of organic matter on the rock surface leads to biofilm formation and impedes fluid flow. In addition, accumulated bacteria secrete high amounts of viscous polymer by-product as they grow [122]. This polymer increases the viscosity of moving fluids with decreased temperature due to reinjection and thus can decrease permeability [82]. Furthermore, bacterial activity could promote scaling, e.g. iron oxide, and gas entrapment, e.g. H_2S, which could also reduce permeability (Fig. 5).

Generally, two different sources of bacteria can be defined. Primarily, groundwater may already contain anaerobic bacteria [68]. Sulphate-reducing bacteria (SRB) are the most common anaerobic bacteria in the subsurface, they can produce H_2S, which leads to further problems [121]: a) it decreases the pH and shifts thermodynamic equilibria of geothermal fluids; b) the produced gas can accumulate in bubbles, which, if large enough, can block porous channels; c) H_2S promotes oxidation of iron and magnesium irons, which can cause severe corrosion and produce dispersed scaling in the system [66]. Burte et al. [67] also reported that deposits produced during these reactions promote further microbial activity on the surface, thus aggravating the clogging process. Secondly, external aerobic bacterial cells can be accumulated during production, separation and reinjection processes. Their growth is mainly promoted due to contact with oxygen, e.g. during pumping [124].

Bacterial activity is greatly influenced by the temperature variations. Generally, this activity is observed at temperatures lower than 90 °C [85]. SRB's activity has been reported for temperatures up to 80 °C [125]. Even thermophilic bacteria are active at temperatures of 85 °C–93 °C [125]. It can therefore be assumed that these bacteria are not active in high-enthalpy reservoirs, but might start their activity in the power plant and reinjection systems. In middle- or low-enthalpy geothermal systems, these bacteria are common and often cause clogging problems. Ma et al. [126] investigated SRB in hot springs and identified their peak activity at temperatures between 30 °C–80 °C, depending on the population. Brehme et al. [101] reported increase in bacteria population by a factor of 2.7 as a result of optimal growth environment over several years in the low-enthalpy Klaipeda reservoir. However, the main bacterial activity was related to the surface infrastructure of the power plant, rather than the reservoir. The growth of bacteria in the power plant infrastructure, in combination with viscosity increase due to lowering of the temperature could cause obstructions of flow paths and injectivity problems.

Different types of clogging can occur in the geothermal reservoir, and many of them are coupled processes, occurring simultaneously or consequently. Ma et al. [127] made a comparison between different types of clogging at the same temperature of 70 °C. It showed highest permeability reduction by chemical clogging, being 15.3%, followed by clogging by suspended particles at 12.6% and microbial clogging with 11.2% damage. Studying the combination of these effects and the prediction of total damage to the reservoir is a comprehensive task still to be solved.

3.4. Strategy to avoid and recover injectivity decline

As discussed above, physical, chemical and biological clogging occurs as a result of incompatibility between injected fluids and targeted reservoirs, leading to injectivity decline. A thorough investigation of the characteristics of injected fluids (pH, compositions, solid contents,

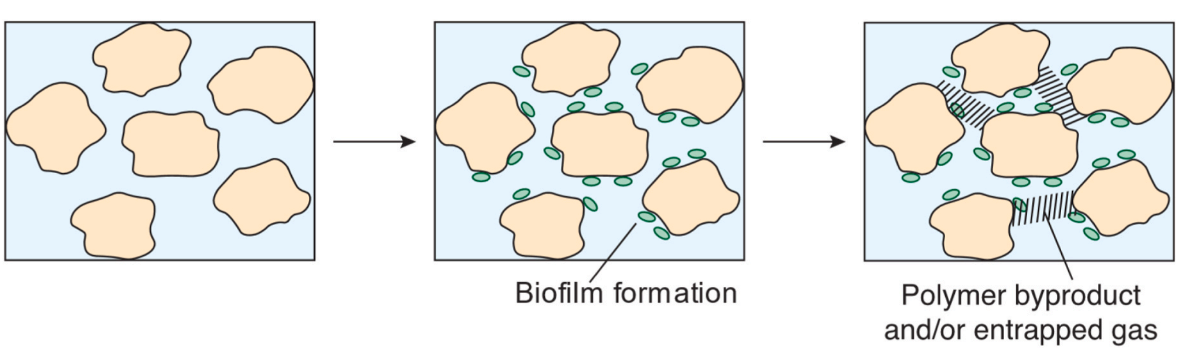

Fig. 5. Illustration of biological clogging processes (modified after [123]).

temperature, etc.) and targeted reservoirs (porosity/permeability distribution, in-situ temperature and pressure, brine compositions, mineralogy, etc.) is therefore necessary before operations. Based on the detailed understanding of the specialty and characteristics of injected fluids and targeted formations, actions can be taken before reinjection operations to avoid injectivity decline and during reinjection to recover injectivity if it has been damaged already. Several studies have provided comprehensive reviews of the clogging prevention and control measures throughout the reinjection cycle [128–130]. Here the most common methods applied as well as some new proposed techniques are discussed.

As shown above, particle entrapment is one of the most common causes of damaged injectivity. Primarily, filtration systems allow the removal of most particles in the reinjection water. Additionally, monitoring the particles at key locations allows knowledge of where the particles are produced and thus prevents particle entrapment in the wellbore, perforation holes or near-field formation [131]. Kindle et al. [131] provided a general guideline for preventing particle entrapment, i.e. particles with a diameter between 0.45 μm and 10 μm should be removed from the injected water. Depending on the solid contents and particle size, different technologies can be used to remove the particles, including gravity separation, centrifugation and filtration.

The 'backwashing method' can also be used to remove an external filter cake if it has formed with a reversed flow in the well, while acid treatment can be used to clean the near-wellbore zone [24,87]. However, interaction of different reservoir minerals with acid might lead to scaling and further clogging [47], thus care should be taken. This can be eliminated with the use of suitable chemical additives, aimed at preventing chemical reactions in the reservoir. Clogging due to clay swelling can be avoided by adding clay swelling inhibitors, such as potassium chloride (KCl) if the formation is proven to be clay-rich. If clay swelling already occurs, strong acids, alcohols or certain ketones can be added to mitigate the effects [131]. Prevention of scaling and precipitation can be performed with different strategies, depending on the type of scaling. To prevent the migration of scales into the reinjection system, cooling ponds or precipitation basins can be installed and scaling inhibitors can be added [27], typically in high-enthalpy reservoirs due to larger temperature gradient and changes in chemical composition of in-situ brines [109,132]. Controlling the injection temperature above a certain value to keep silica concentration below the amorphous silica saturation level is another widely-used approach to avoid silica scaling [131].

Pressure control is an effective method to avoid carbonate scaling by keeping CO_2 in solution, thus maintaining mineral solubility [133]. Additional injection of CO_2 can not only be used to control the pressure but also to shift the chemical equilibrium of carbonate, thus avoiding or mitigating the carbonate scaling. Modification of the pH level is another approach, particularly common for silica scaling prevention [133], as it strongly influences the rate of scale formation. However, acid-related corrosion is a major concern of this technique.

Corrosion prevention is commonly done with the use of different chemical inhibitors. However, various temperature and pressure conditions in geothermal reservoirs challenge the selection of working chemicals. New methods aimed at removing iron from the geothermal fluid are also being developed, such as oxidation and filtration [134], ultrafiltration or usage of bioadsorbents [135,136].

Control of biological clogging can be challenging. One of the main challenges is the need for a detailed classification and characterization of bacteria in specific geothermal fluids [120]. Where there is a potential identified for biological clogging, minimization of such clogging is usually achieved by addition of bactericides, which requires extensive laboratory pre-testing, e.g. on fluid compatibility. Reduction of aerobic bacterial activity can be achieved by operating in closed surface loops without oxygen contact with water at the surface. Another way is sterilization of injected water, with chemicals or ultraviolet ray. Ma et al. [127] observed the positive effect of that method, as sterilization decreased the microbial clogging rate from 15.3% to 4.1%.

In general, controlling reinjected fluid composition can help eliminate the negative effects of fluids incompatibility or thermodynamic effects. This can require comprehensive expensive laboratory testing, individually for each geothermal reservoir. In the case of bio-clogging detailed fluid analysis and time-consuming tests to identify bacteria origin can be required as well as experiments at the field conditions.

To the best of authors' knowledge, despite the development of advanced reservoir properties evolution models, no uniform system exists for prediction of the effect of different clogging mechanisms during well operation. Both experimental and numerical research, combined with field testing are required to approach this challenging task, aiming to predict and prevent injectivity decline in geothermal wells.

4. Injectivity enhancement during reinjection

4.1. Individual mechanisms

Previous discussions have shown that injectivity is strongly temperature-dependent, mostly because chemical clogging and biological activities can be triggered at lower temperatures, as well as increasing viscosity of colder injected fluids can largely increase flow resistance. However, some field experiences have illustrated the positive effects of lower injection temperatures on injectivity, such as cold water injection into wells Th2 in the central Molasse basin (Germany) [137,138], HN-09 in Hellisheiði field (Iceland) [21] and MK-20 in Mokai field (New Zealand) [71]where increasing injectivity has been observed. Table 6 collects field examples that experienced unintentional increase in injectivity during reinjection. (Note these examples are different from the intentional thermal stimulation presented in Table 4). Although the potentially positive consequences of cold water injection have been well recognized and applied in thermal stimulation in deep geothermal reservoirs, it is often not easy to identify the predominant mechanisms for each specific reservoir during regular injection, as the mechanisms

Table 6
Field examples where unintentional increasing injectivity was observed during reinjection.

Type of system	Field	Injection period	Initial injectivity[a]	Final injectivity	Inj. Temp.	Res. Temp.
Hot water	Th2, Molasse, Germany [137,138]	Jan. 2006–Jan. 2012	0.8 kg/(s·bar)	1.3 kg/(s·bar)	60 °C	105 °C
Liquid-dominated	BR13, Broadlands, New Zealand [73,95]	Jul. 1979–Aug. 1979	3 D·m	12 D·m	98 °C	275 °C
	BR23, Broadlands, New Zealand [73,95]	Jun. 1979	Increase in injectivity reported		98 °C	272 °C
	BR7, Broadlands, New Zealand [73,95]	Jun.1981–Aug.1981	Increase in injectivity reported		(110–150) °C	>260 °C
	BR28, Broadlands, New Zealand [73,95]	Jan.1980–Mar.1980	Increase in injectivity reported		155 °C	>260 °C
	HN-09, Hellisheiði, Iceland [71]	Feb.2009	4.5 kg/s/bar	5.2 kg/s/bar	(15,90,120) °C	~250 °C
	HN-12, Hellisheiði, Iceland [71]	Jul.2010–Aug.2010	Increase in injectivity reported		(20,100,120) °C	~250 °C
	HN-16, Hellisheiði, Iceland [71]					
	MK17 & MK20, Mokai, New Zealand [96]	Increase in injectivity reported in Ref. [21], but no details				
	OK-2, Southern Negros, Philippines [139]	Apri. 1981–Dec. 1981	1.3 kg/(s·bar)	2.5 kg/(s·bar)	–	257 °C
	4R1, Tongonan, Philippines [95,139]	Feb.1978–Dec. 1981	2.3 kg/(s·bar)	13 kg/(s·bar)	170 °C	324 °C
Vapor-dominated	A-7 & A-8, Los Azufres, Mexico [140]	Increase in injectivity reported [140], but no details			20 °C	(200–280) °C

[a] injectivity here is represented by transmissivity (D·m), or injectivity index (kg/(s·bar)).

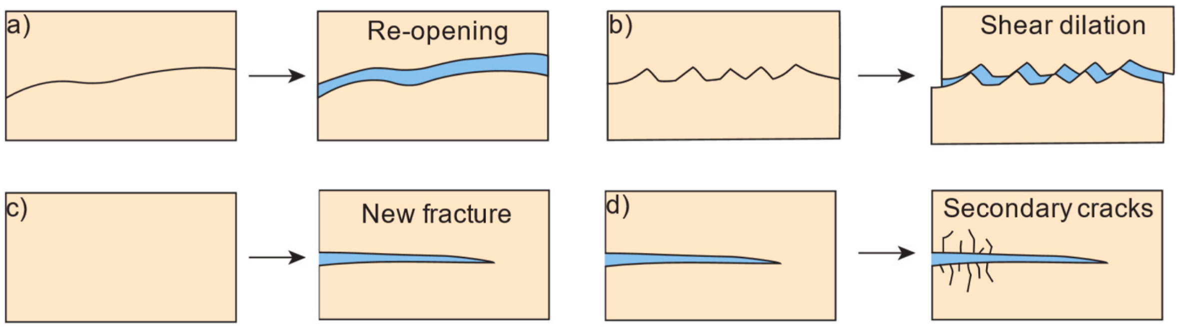

Fig. 6. Four mechanisms of thermally induced permeability increase during reinjection.

depend on the reservoir characteristics, e.g. fracture or non-fracture, in-situ temperatures and rock types.

Generally, there are four main possible physical mechanisms for thermal enhancement of permeability, shown in Fig. 6, a) re-opening of pre-existing fractures, b) shear dilation of pre-existing fractures, c) new thermal fractures, d) secondary thermal fractures perpendicular to main fractures. In addition, the condensate of steam in high enthalpy reservoirs containing two-phases of water, increases water saturation thus increasing relative permeability of water can contribute to increasing injectivity. This has been observed through decreasing injection pressure while reinjection into BR7 in the Broadlands field already in 1981 [95]. In addition, although cleaning of debris or mineral precipitation from near-field fractures is also believed to contribute to injectivity enhancement during reinjection, it occurs most likely when injection/-stimulation tests are carried out immediately after drilling, e.g. stimulation operations at the Reykir geothermal field in Iceland in 1970s [53].

The re-opening of pre-existing fractures is a result of cooling thus contraction of the rock matrix [21] as well as the increase in fluid pressure in fractures, which is confirmed by various numerical simulations [28,141,142]. In subsurface, rocks are laterally constrained. Thus, once the rock matrix is cooled down, thermal stress increments occurs in the tensile direction, pulling the fracture faces apart. The thermally-induced tensile stress increments reduce the stresses at the contacting asperities of pre-existing fractures, increasing permeability. High stresses at contacting asperities has been shown experimentally to cause pressure dissolution creep that can lead to further decreasing fracture permeability [143–145]. The re-opening of pre-existing fractures is considered to be underlying the increase in injectivity of wells BR13 and BR23 from the Broadland field, New Zealand, during the reinjection in 1980 [21], as well as the success of thermal stimulation of the KJ-14 well in 1980 (Krafla, Iceland) [146]. The increase in injectivity caused by re-opening pre-existing fractures is often reversible (e.g. BR23 showing reversible injectivity changes) [21], which means injectivity will decrease if reinjection stops and increase again if reinjection re-starts. However, during cyclic injection, irreversible injectivity changes may be caused by frictional and mating effects on fracture surfaces [145].

In contrast, increase in injectivity caused by shear dilation is irreversible as observed during an injection test in GPK1 at Soultz Hot Dry Rock (HDR) site [147] and a low-pressure stimulation in NWG-55-29 at Newberry Volcano EGS site [148]. The fracture aperture increases as a result of self-propping of fracture asperities (Fig. 6, b). The irreversible increase in permeability is also confirmed in laboratory tests on granite rocks, e.g. Refs. [149–151]. However, no change or even decrease in permeability has been observed during shearing tests on low-porosity sandstone samples, likely due to fault core compaction [152]. When stimulating fractured reservoirs, shear dilation is increasingly thought to be the dominant mechanism [153]. Consequently, hydro-shearing now is becoming a popular stimulation technology with the injection of cold fluids at pressures far below fracture pressure to shear natural fractures. Although increasing pore pressure is considered as the primary reason for shear slip of pre-existing fractures, thermal stresses are attracting more attention as re-injection pressure is generally insufficient to shear natural fractures [154,155]. Abundant numerical works have illustrated that thermal stresses play a significant role in shear stimulation due to reinjection [154–156]. For instance, modeling results by Jeanne et al. [157] have shown that shear failures of pre-existing fractures were induced by thermal contraction around the wellbore, where strong cooling effects occur during cold water injection into well P32 at Geyser geothermal field, California. Thermal stresses have also been believed to partly contribute to post-injection micro-seismic events caused by shear slip of fractures/faults, such as post-injection seismic events at Soultz-Sous-Forêts [147] and at Basel [158], since heat transfer in subsurface is much slower than fluid flow that can induce micro-seismic events right after reinjection.

Thermal fractures are believed to be a result of nucleation, growth, interaction and coalescence of micro-cracks, which include inter-granular and intra-granular micro-cracks, resulting from mismatches of thermal expansion between adjacent mineral particles and from the temperature gradient in the rock [159]. New thermal fractures are most likely induced around a wellbore, where there the highest temperature gradient occurs [160]. However, secondary thermal cracks that are perpendicular to the main fractures, shown in Fig. 6 (d), can also occur in the deeper reservoir, and have been believed to be of great importance for increasing injectivity, particularly in EGS [161,162]. For instance, tracer, micro-seismic and geochemical measurements indicated that thermally-induced secondary crack growth contributed to the observed reservoir growth during stress-unlocking experiments at well EE-1 at the Fenton Hill site, New Mexico, where hydraulic fracturing and sidetracking from the GT-2 well created the primary reservoir [163]. However, the results from Refs. [161,164] showed that thermal energy production was only increased by 25–30% by means of non-interacting secondary fractures. Numerical simulations [162,165] indicate that continuously-growing and interacting secondary fractures, that can be induced deeply into the reservoir, contribute largely to the increase of injectivity and energy extraction efficiency.

4.2. Combined mechanisms

Each main mechanism that explains injectivity enhancement during reinjection was introduced separately in the last section. However, in practice, these processes generally happen at the same time and are difficult to distinguish from each other. For instance, the successful

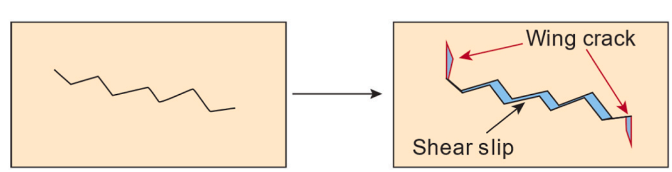

Fig. 7. Schematic drawing of a shear slip of a pre-existing fracture with wing cracks initiated.

stimulation test at KJ-14 at Krafla, Iceland, was attributed to both re-opening of pre-existing fractures and initiation of new thermal fractures [57]. Also at the Coso EGS site, evidence for both mode I and mode II fractures have been reported during stimulation experiments [28]. One particular example of mixed mechanisms is wing cracks (shown in Fig. 7), an out-of-plane growth of pre-existing fractures occurring meanwhile shear slip happens [166]. These wing cracks indeed fail in tension, in the orientation of the most compressive stress [167]. The mixed-mechanism shear slip and tensile wing cracks have been studied in forward models to explain the micro-seismic signals during water injection into well P32 at the Geysers field [167]. Wing cracks were also observed in experimental works by Ye and Ghassemi [168], in which the equivalent permeability of the sample was enhanced by 17–35 times as a result of initiation and coalescence of wing cracks.

Inspired by the fact of the mixed mechanisms behind reinjection and stimulation, mixed-mechanism stimulation (MMS) has been proposed [169–171], to stress the difference from pure fracturing/shearing stimulation. Norbeck et al. [171] believed that the stimulation to Pohang EGS, South Korea, where operations caused shear stimulation in one well while hydraulic fracturing in another well located in close proximity and at same depth [36], provides possible evidence for potential MMS success. The idea of MMS is that MMS guarantees interaction and coalescence of new and pre-existing fractures and the formation of large-scale fracture networks, which can largely increase flow surface and heat transfer efficiency. Pioneering modelers have worked on MMS to shale reservoirs, but application to geothermal reservoirs still need to attract attention [171].

5. Future outlook

Although knowledge and experience have been inherited from oil and gas industry, as well as plenty of studies and projects have been undertaken to understand injectivity issues in geothermal operations, the processes are still not fully understood.

As shown above, multiple processes can contribute individually or simultaneously to injectivity decline. Individual processes occurring during reinjection have been investigated quite extensively. The influence of the most common operation parameters such as temperature, flow rate or pH has been investigated and proven by many studies. However, the effect of some parameters still remain unclear. Heterogeneity and complex mineralogy of reservoirs are still a challenge for predicting chemical reactions and consequent changes in the pore geometry. In addition, time scale of the processes, especially in case of several competing clogging mechanisms in the system, is still uncertain and requires additional studies.

Another significant challenge regarding clogging processes is the coupling or interconnection of the processes. There are numerical studies on this subject [172–174], however, obtaining experimental data would significantly improve the understanding of the process mechanisms. It is challenging to distinguish between different mechanisms and processes during experimental work, but, using modern visualization techniques, such as micro-CT scanning and particle image velocimetry might help gain additional knowledge in this topic.

As for the positive effects of cold water reinjection, the mechanisms underlying injectivity enhancement are still in question, especially for fractured reservoirs. How to identify the exact mechanism occurring in a specific reservoir under specific conditions is challenging but worthwhile in order to be able to predict changes in injectivity and to be able to design stimulation campaigns to improve injectivity if needed. Micro-seismic signals, produced by cracking or/and shearing events during reinjection, can be used to infer the failure mechanisms. For example, Johnson studied source mechanisms for induced micro-seismic events during injection into well P32 at the Geysers field, California, and proposed that a combination of shear failure and wing cracking can give a possible interpretation of estimated moment tensor [167]. More high-quality field data are needed to link geological conditions, injection conditions and micro-seismic events. A good example is the Delft University of Technology campus geothermal project (Netherlands) where three monitoring boreholes equipped with both geophones and novel fibre optical sensors are to be deployed to detect micro-seismic events [175]. In addition, there are improvements needed in order to understand micro-seismic mechanisms and source characterisation, as well as forward/inversion modeling of synthetic seismic wave forms to interpret available micro-seismic signals [176].

Numerical models can provide better understanding of processes occurring via history matching. However, current models usually only consider single failure modes, either mode I or mode II, e.g. Refs. [160, 177]. Nevertheless, mixed mechanisms are expected to play a key role. Although some numerical studies have considered mixed mechanisms, e.g. Refs. [170,171], the geometry of their problems is pre-assumed and relatively simple. Thus, further development of numerical models considering interaction of mixed-mechanism multiple fractures with a more realistic geometry is needed. A consideration of both physical and chemical clogging into the numerical models is further expected. Moreover, constitutive laws that reflect cyclic loading history of rocks are needed for understanding response of the reservoir to long-term cyclic reinjection, in particular if thermal energy storage is considered. Although rapid development of computing technology has been seen during the last two decades, it is challenging to efficiently address essential details mentioned above, typically for large-scale reservoir simulation with complex geometry and non-linear couplings. More efforts to develop advanced techniques, e.g. such as parallel computing and physics-based machine learning models, to speed up the calculation are therefore required. Experimental works on mechanical response of fractured rock samples subject to long-term cyclic cooling can provide additional insights. However, current research mainly focuses on intact rock samples or samples with simple man-made cracks, e.g. Refs. [178, 179]. Experiments on rock samples with natural fracture sets should be considered.

On the basis of better understandings of mechanisms underlying both injectivity decline and enhancement during reinjection, injection strategies can be further optimized. A focus should be on how reservoirs respond to different injection strategies, including varying injection parameters (i.e. temperature and pressure) and injection schemes (i.e. period of cyclic reinjection, out-field or in-field reinjection), taking into account different reservoir types, i.e. fractured or non-fractured, single-phase or two-phase, high-temperature or low-temperature, in-situ fluids and rock types.

6. Conclusion

Reinjection is a key process for geothermal projects that is critical for environmental and project performance. The injectivity is, however, influenced by various processes throughout installation and operation. This review provides a comprehensive discussion on how injection can cause both positive and negative effects. Both effects should be carefully considered when planning the reinjection strategy. Typically, the injection temperature is of great importance for both sides, either triggering clogging, which can reduce injectivity or inducing thermal cracking that may significantly enhance injectivity.

Injectivity can be significantly affected by different clogging processes, which result in pore blockage and permeability decrease. Three major groups of physical, chemical and biological processes are distinguished, of which all can be interconnected. Injectivity impairment reasons are unique to every geothermal field due to different reservoir types and properties, as well as fluid and rock composition. Different parameters affect individual mechanisms, the most common being decreased temperature due to the principle of geothermal energy extraction. Due to the systems complexity and uniqueness, the prediction of clogging processes is not a trivial task, especially taking into account the interconnection between different processes. Even though a variety of preventive measures for maintaining rock permeability has been developed and applied in the geothermal industry, the problem of clogging is still relevant and requires individual comprehensive analysis for every case.

Although lowering the injection temperature can trigger various clogging problems and increase fluid viscosity, leading to increasing flow resistance, injectivity enhancement during reinjection has been widely reported in such cases. Thermally-induced re-activation of pre-existing fractures and thermal cracking are believed to be the main reason. While reversible changes in injectivity have been ascribed to re-opening of pre-existing fractures, irreversible changes are generally owing to shear dilation of pre-existing fractures and formation of new fractures. However, it is not easy to identify exact stimulation mechanisms for each specific reservoir, as the mechanisms are reservoir-specific and depending on the reservoir characteristics, e.g. fracture or non-fracture, in-situ temperatures and rock types, and operating conditions. In practice, various processes related to thermal stresses occur at the same time during reinjection, and it is difficult to distinguish one from another. Future development of methods to identify or simulate mixed-mechanisms is therefore suggested.

Contributions

Wen Luo: Conceptualization, Methodology, Data curation, Writing-Original draft preparation, W.L. and A.K. equally contributed to the manuscript. **Anna Kottsova:** Methodology, Visualization, Writing-Original draft preparation, W.L. and A.K. equally contributed to the manuscript. **Philip J. Vardon:** Writing-Reviewing and Editing, Supervision, Project administration, Funding acquisition. **Anne-Catherine Dieudonné:** Writing-Reviewing and Editing, Supervision. **Maren Breme**: Writing-Reviewing and Editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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