

Kaolinite fines colloidal-suspension transport in high temperature porous subsurface aqueous environment: Implications to the geothermal sandstone and hot sedimentary aquifer reservoirs permeability

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ABSTRACT

Phyllosilicates, specifically, the kaolinite clay mineral ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), which is a layered silicate mineral with one silica tetrahedral sheet connected with oxygen atoms to one alumina octahedral sheet is ubiquitous and abundant in sedimentary basins, especially sandstone formations. This particular type of clay mineral fine particles can easily and rapidly cause reservoir formation damage in high temperature aquifers, geothermal, and petroleum reservoirs by detaching from the porous rock surface and migrate, and plug the pore-throats of the rock matrix. Several factors such as, reservoir temperature, pressure, geochemical alteration, permeating fluid, reactive flow, and multi-phase flow are attributed to the permeability decline of the porous rocks and subsequent fluid flow reduction, and consequently, leading to well productivity loss. Therefore, this paper presents laboratory modeling of fines transport in the hot porous sedimentary aquifer. This type of aquifer is located in sedimentary basins with the elevated heat flow and having a characteristic of a shallow depth and a high volume, which indicates a high natural porosity and permeability. In this work, we have conducted three sets of coreflood experiments in the temperature ranges of 125 °C, 150 °C, and 175 °C. Kaolinite suspension water has been injected into the porous sandstone core at these temperatures to investigate the feasibility of a permeability and injectivity decline. The major experimental results revealed that there is an increase in water saturation and heat transfer rates. The concentration of fines surges with increasing PVI and permeability declines with increased time. Pressure soars with increasing Pore Volume Injection (PVI), but it stabilized after some time. Actually, PVI is a ratio of cumulative water injection to each pore chamber volume of the rock core. Importantly, the water discharge rate decreases with increasing suspension injection and on the other side, with fresh water injection, the rate of water discharge rises steadily. Furthermore, the experimental and mathematical models were tested against statistical model, multiple linear regression for validation. The modelling results showed good agreement and, therefore, this paper has explicated the significance of fines transport in aquifers under hot sedimentary basins.

1. Introduction

A hot sedimentary aquifer (HSA) is a primary candidate for geothermal energy extraction and aquifer thermal energy storage since these are associated with the sedimentary basin that has the

permeability potential, which is mainly required for the efficient fluid flow and in these formations, density driven fluid flow is the major challenge (Winterleitner et al., 2018; King and Miller, 2010). HSA is predominantly held in sedimentary basins with inflated heat propagation and the rock formations, which hold the water tend to possess high

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porosity and permeability. These aquifers are located in shallow depth and just few kilometers below the vadose zone and its extraction is economical, but the development of tectonically deformed aquifers is a great challenge. Fig. 1 a) shows the schematic diagram of a hot sedimentary aquifer and 1 b) shows the tectonically deformed aquifer. Actually, exploration and exploitation of an HSA is becoming popular and emerging rapidly as a novel and alternative energy resource. Christ et al. (2017), conducted a techno-economic analysis of geothermal desalination using an HSA and the pre-feasibility analysis was carried out in Western Australia. The main highlight of their investigation is at the geothermal aquifers, which are in low grade geothermal systems. The authors have incorporated an advanced multi-effect distillation process for the effective use of the heat sources from the geothermal reservoirs. From the authors' survey, it was found that this region is economically viable and has a good thermal potential for geothermal desalination employing hot sedimentary aquifers.

Willems et al. (2017a), studied the impacts of doublet reduction well spacing on the net present value (NPV) and the lifespan of fluvial HSA doublets. Their research makes an analysis of the NPV of doublet well spacing below the current West Netherlands Basin 1000–1500 m standard and a sensitivity analysis was carried out by the authors to indicate the favorable occurrence of reduction in NPV. Specifically, it was found from their study that well spacing reduction from 1400 m to 1000 m could improve the NPV rate by 15 % and that would be economical in this basin. In another research of these authors, it was explored that the net sandstone volume and anisotropy of the reservoir determines the fluid flow path. These are needed in order to economically extract geothermal energy from HSA (Willems et al., 2017b).

Comerford et al. (2018), analyzed the influencing factors on geothermal heat recovery from a hot sedimentary aquifer in Gaurdridge, Scotland. The authors have carried out field investigations and numerical modelling. The authors have emphasized that the hot sedimentary aquifer fault architecture can influence and dominate the permeability and water flow. They correlated the heat transport model with groundwater flow and field survey data (including field mapping). The major results revealed from their work that well spacing is a governing factor in the determination of effective recovery of geothermal heat from an HSA.

Actually, this paper conducts an investigation of the subsurface kaolinite clay fines transport and an invasion into a high temperature aquifer. The most frequent cause of formation damage and well productivity decline in oilfields, HSAs and artesian aquifers is bottom laying

clay fines migration mainly due to hydrodynamic and thermodynamic forces (Chequer et al., 2018a). Yang et al. (2018), made cumbersome laboratory investigations on fines migration in aquifers and oilfields. The main results indicated that there was an observation of fines migration at a high rock temperature and upon an invading aquifer, fines will suspended and drift in the aqueous media. Russell et al. (2018), examined the delayed particle detachment effects on the water injectivity decline due to fines migration. The authors have developed a semi-analytical model to predict pressure drawdown increase and water injection rate due to fines detachment. Their specific coreflood experimental outcomes revealed that initially, at high injection velocities, the huge fine particle suspension was recorded and gradually mobilized leaving behind the low-salinity phase. Also, an independent deep bed filtration occurrence was noted and it delayed particle detachment, and straining triggers the well injectivity deterioration. It was specifically mentioned that the high water injection rate can cause fines to detach and mobilize in the permeating fluid, which overall results in well injection decline. Furthermore, it was explored that kaolinite clay fines migration due to high saline water injection rates can lead to a well injectivity decline and this was confirmed by authors' newly developed analytical models (Chequer et al., 2018b).

Actually, kaolinite occurs in porous sedimentary rocks (especially, sandstone) due to the dissolution of feldspar at extreme subsurface temperatures and geochemical alterations (Kanimozhi et al., 2019a). Generally, kaolinite clays are rich in sedimentary formations, which are highly susceptible to fines migration and permeability deterioration under an external fluid invasion (Wan et al., 2017; Wu et al., 2012). In recent times, **emphasis has been given** to clay mineral migration in aquifers that affect the thermal efficiency and performance of the geothermal reservoirs and aquifer thermal energy storage. Generally, in sedimentary basins the kaolinite clay minerals play a vital role in triggering reservoir formation damage (permeability decline) and well productivity deterioration. Its magnitude, geometry, and morphology play a critical role in reducing the permeability of porous rocks (Pranesh et al., 2019; Chequer et al., 2018a; Civan, 2007; Shapiro et al., 2007; Sen and Khilar, 2006). Fig. 2 shows the molecular structure of kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$).

Russell et al. (2017), studied the kaolinite presence impacts on rock due to fines migration. The authors have conducted laboratory based modelling and analysis of the permeability changes in the rock containing kaolinite during the injection of low salinity water. The major observations from their experiments are an increase and a decrease in

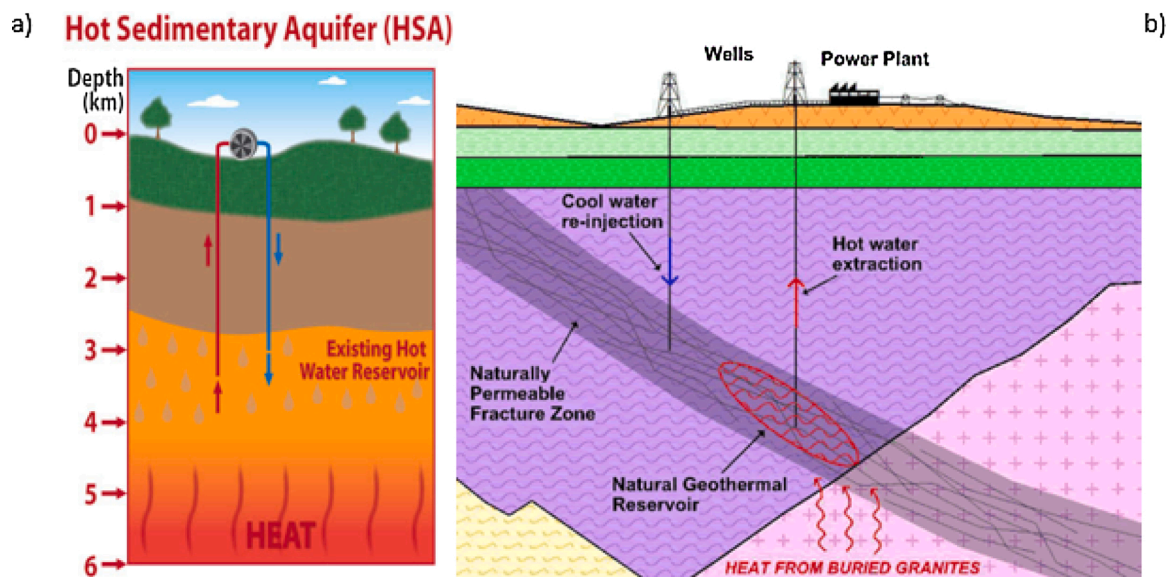


Fig. 1. a) Schematic diagram for hot sedimentary aquifer (Hotrockenergy, 2018), b) Simplified concept for geothermal power generation (Kuth Energy, 2010).

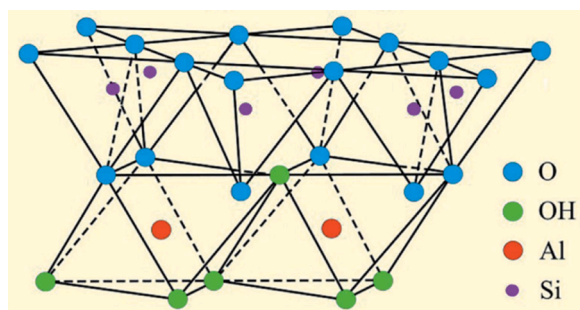


Fig. 2. Molecular structure of kaolinite (Rivera et al., 2016).

permeability as well as the alternation in the water salinity during flow in porous rocks. Also, this has major effects on fines transport and permeability obstruction. Overall, their results highlighted that kaolinite clay containing rocks are frequently prone to formation damage and well productivity decline. Also, Rosenbrand et al. (2015), studied the different effects of salinity, fluid velocity and temperature on the permeability decrease by fine particles migration in Berea Sandstone. Authors' have conducted serious of coreflood test containing kaolinite particles and heated the core at 20 °C and 80 °C and found that those varying parameters has a significant effect on fines detachment and mobilization. Authors' state that fines transport would increase the solid, specific area with fluid contact and decrease the permeability. Additionally, Zeinijahromi et al. (2015), studied the sweep efficiency improvement of edge water drive reservoirs using induced fines migration. The problem they identified is that from an adjacent aquifer the intruding water exceeds the oil phase and as a result, there is a considerable volume of the trapped residual oil left. The early occurrence of these water fingers triggers the premature production of water, which simultaneously leads to a well shut-down. Authors' proposed an innovative solution to tackle this problem. They applied the concept of induced formation damage by injecting slow saline water into the water-up wells which creates a barrier of low permeability layer against the water fingers. This was numerically studied by them and its outcomes reveals that small volume of low salinity water injection provides a prolongation in the life of the well that consequently gives an approximately 3–5 % linear recovery, but not exponential when compared with normal depletion. Therefore, from these literature, it is clear that subsurface kaolinite clay mineral fines are prone to formation damage of aquifer wells and a great threat to ground water contamination. So, this paper investigates the thermodynamics of kaolinite clay mineral fines migration and the suspension flow in the hot sedimentary aquifer. In this paper an attempt is made to elucidate the significance of kaolinite clay mineral fines migration in an HSA and its impact on geothermal energy extraction and aquifer thermal energy storage. Overall, this paper may serve as a guideline for the reservoir formation damage characterization in high temperature aquifers and reservoirs caused by clay mineral transport and straining.

2. Materials and methods

This section presents the material and methods that were employed in this paper.

2.1. Sample preparation

As indicated earlier that this is a laboratory based investigation and for this purpose, we have procured a sandstone core of length 30 cm and 10 cm in diameter. The core has a porosity of 25 % and 250 mD. The origin of this sandstone rock is in Cauvery Basin, South East India. Table 1 shows the sandstone rock core details. This rock core is purely customized to the length and diameter to the value mentioned in the above table. Even the stainless steel core holder was fabricated to fit this

Table 1
Sandstone rock core specifications.

Parameters	Value
Length	30 cm
Diameter	10 cm
Porosity	25 %
Permeability	250 mD
Kaolinite Clay Content	37 %
Origin	Cauvery Basin

sandstone rock core.

2.2. Experimental setup

Fig. 3 shows a schematic diagram of the experimental setup. It can be seen from the figure that the sandstone core is placed in a stainless steel cylindrical core holder and in turn placed inside the oven. The oven is equipped with a thermocouple and three pressure transducers (for measuring the pressure difference across the core). One pressure transducer is connected to the inlet and outlet flow lines of the core center and another two are connected to the inlet and outlet flow lines of the core. One side of the core holder has provisions for a pneumatic piston pump (for pressure exertion) and water flow. The water tank is fitted with the piston pump containing kaolinite clay and the other side of has the flow line for effluent collection. The water tank is fitted with a high pressure pump and the flow lines are provided with ball valves and the whole core-oven thermal system is connected to the data acquisition system and subsequently, connected to the computer.

2.3. Experimental procedure

- Three sets of experiments were conducted at 125 °C, 150 °C, and 175 °C. Initially, the oven was set to these high temperatures.
- Then the water flow line valves is opened and 2 L of water is pumped to the oven in order to saturate with the core. Even during this time, steam is observed and this is due to the system and rock temperature.
- After that the kaolinite clay is pumped to the water tank to form a suspension and then suspended water is pumped to the core to saturate with the existing water.
- Next the pressurized air is injected into the core for fines and water mobilization at these temperature regimes. This pneumatic piston is serving as an external pressure source.
- The mobilized clay fines and water are collected in the effluent collector.
- This procedure is repeated for another two temperatures and subsequently, a series of curves are obtained, such as water saturation, heat transfer coefficient, enthalpy release, fines concentration, permeability decline, pressure change, and water discharge rate. The experimental outcomes are explored and discussed in the following section.

3. Results and discussion

This section analyzes the results that were obtained from the experimental work. Fig. 4 shows the variation of water saturation with respect to increasing time.

It can be observed from the Fig. 4 that the water saturation increases with increasing injection time. An increased saturation was observed at 175 °C and it can also be stated that an increase in reservoir rock temperature increases the water saturation level. Temperature regimes such as 125 °C and 150 °C exhibited close water saturation values. After 1000s, the saturation tends to stabilize slightly and then it soared to 1500s and levelled at 1800s. An increased water saturation is also attributed to the surface energy of the hot porous sandstone aquifers. Indirectly, surface energy determines the water holding capacity of a

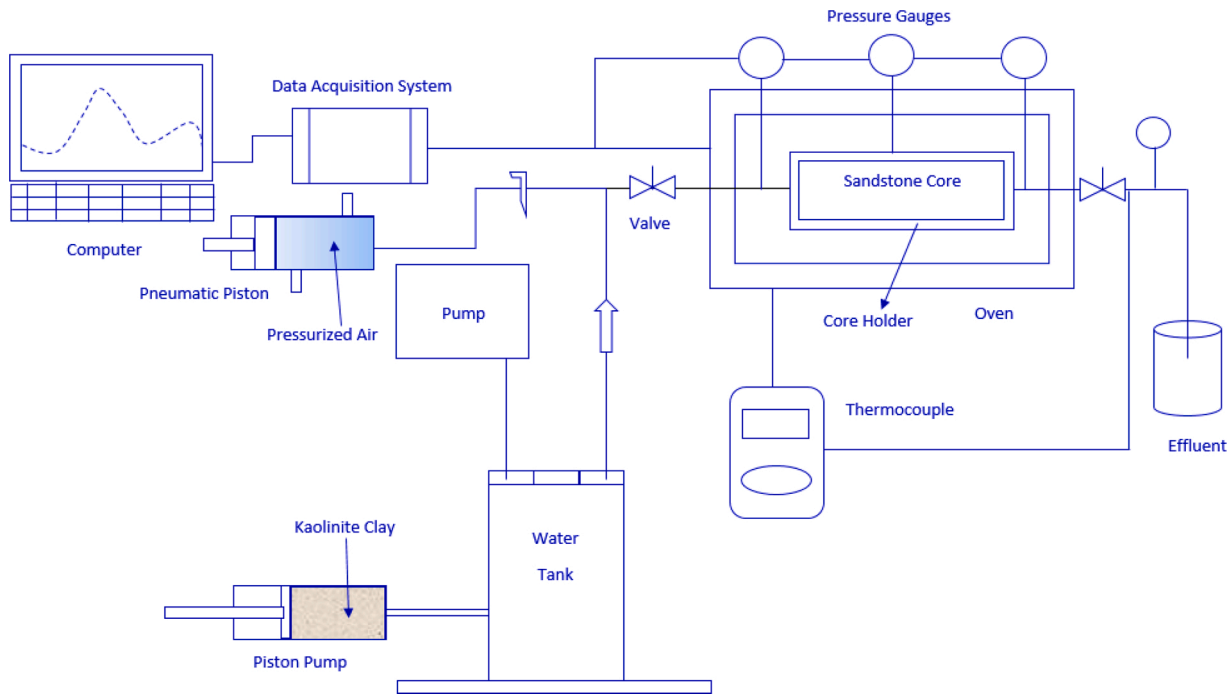


Fig. 3. Schematic diagram of the experimental setup.

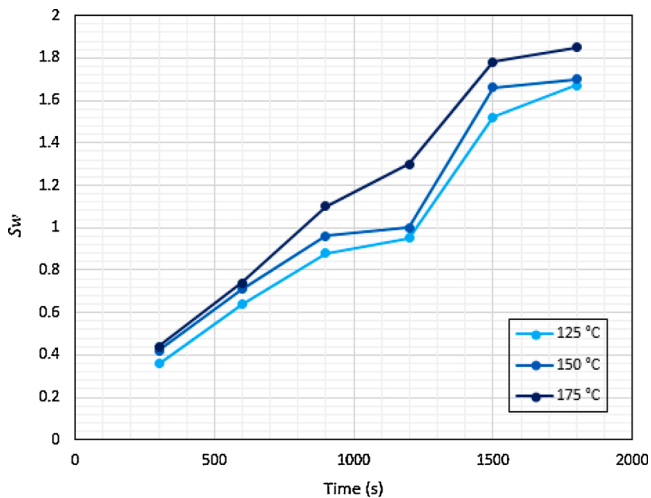


Fig. 4. Water saturation variation with increasing time.

high temperature porous rock formation. Furthermore, readers may argue that the saturation level in the rock core would not exceed 1 and the cases reaching above 1 are generally considered meaningless. Actually, water saturation was measured by a counter current imbibition (CCI) technique (McPhee et al., 2015). During water injection in the hot porous sandstone rock core, the water and suspensions are being saturated in the core and this is detected by a flow sensor, where the data were fed in the data acquisition system/software to record weight changes as a function of time. Recent reports of Kanimozhi et al. (2020; 2019a) suggest that saturation above 1 is possible and it has been experimentally proved and established. At a reservoir rock core temperature above 100 °C, the water becomes vapour and this vapour has been included in the water saturation calculations. Additionally, kaolinite fine particle suspensions in the water increase the saturation level. Overall, a water, vapour, and kaolinite suspension at a high temperature increases the saturation level in the rock core to above 1. Also, the change in the weight/mass of the sandstone rock core indicates

the weight of the water and water-vapour and kaolinite suspensions.

Fig. 5 shows the heat transfer coefficient and enthalpy variations with respect to water saturation and time. It can be observed from Fig. 5 a) that the increasing water saturation increases the heat transfer coefficient of the reservoir rock. As already indicated an increased temperature elevates the water saturation and subsequently, heat transfer as well. Therefore, there is a heat rejection in the interface between the water and rock surfaces (Kanimozhi et al., 2019b), and subsequently, there is a large amount of heat release. A similar observation was observed for Fig. 5 b), there is a substantial enthalpy release for an increasing injection time. Usually, porous aquifer reservoir rocks, which are used for geothermal energy extraction possess a high enthalpy (Avena et al., 2016). Factors such as water flow, pressure, and temperature in the reservoir rocks controls the enthalpy release rate and the water-rock surface interaction determines the enthalpy release rate (Scott et al., 2016). During this condition, the water in the porous rock formation will be in a supercritical state or in supersaturated steam. During well inflow and surface production, huge volumes of supersaturated steam will be present.

Fig. 6 (a) shows the fines concentration variation with respect to an increasing PVI. It can be seen from the figure that at 1 PVI the concentration of fines was 7 ppm, 12 ppm, 13 ppm for the elevated temperatures 125 °C 150 °C, and 175 °C. At 2 PVI the fines concentration increased to 10 ppm, 13.5 ppm, 11.6 ppm for these temperature regimes and finally, reaching 30 ppm, 25.1, and 23.8 ppm at 9 PVI. It is observed that between 4 and 5 PVI at 175 °C there was a dramatic shift in the fines concentration. Actually, during this period, the fines concentration rises linearly. Clay fines are excited at increased temperatures and as a result, the concentration rises with an increase in pore volume injection. Fig. 6 b) shows the permeability decline rate with respect to an increasing injection time. This reduction is mainly due to fines lifting, suspension, and straining, and water pH may also contribute to this behavior (Zejnijahromi et al., 2011). It is reported that higher temperature decreases the permeability of the rock core. As it is evident from the graph that at 175 °C a heavy decline rate is displayed when compared to other temperature regimes. It should be noted that the temperature and injection time drastically reduce the permeability of a sandstone core. Even, large and small brine water injections can trigger fines detachment and

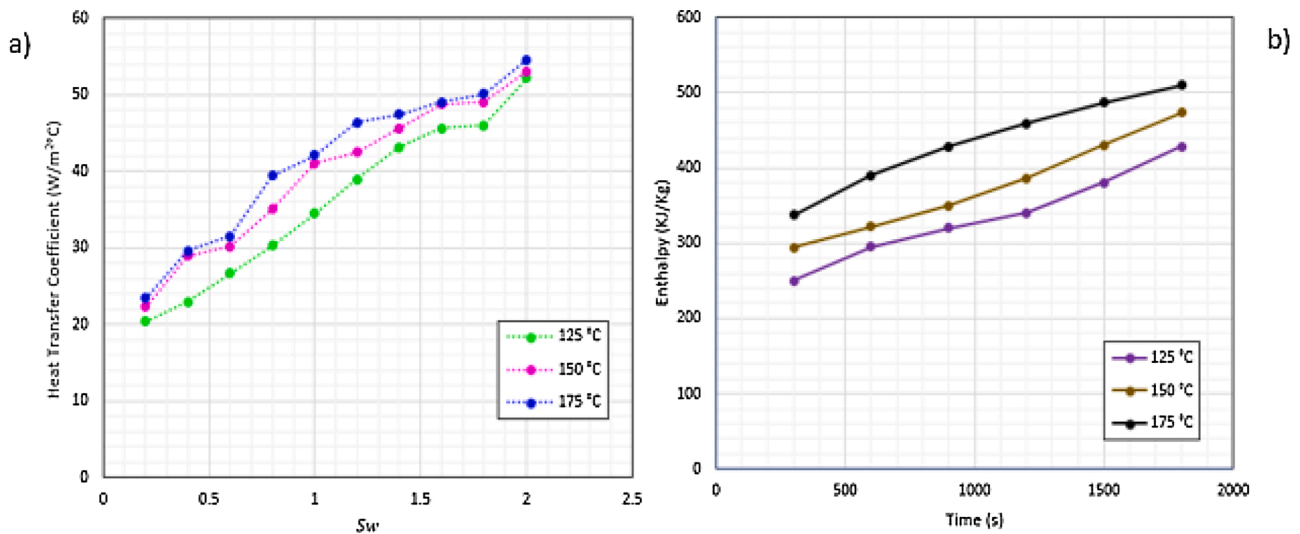


Fig. 5. a) Heat transfer coefficient variation with increasing water saturation, b) Enthalpy variation with increasing time.

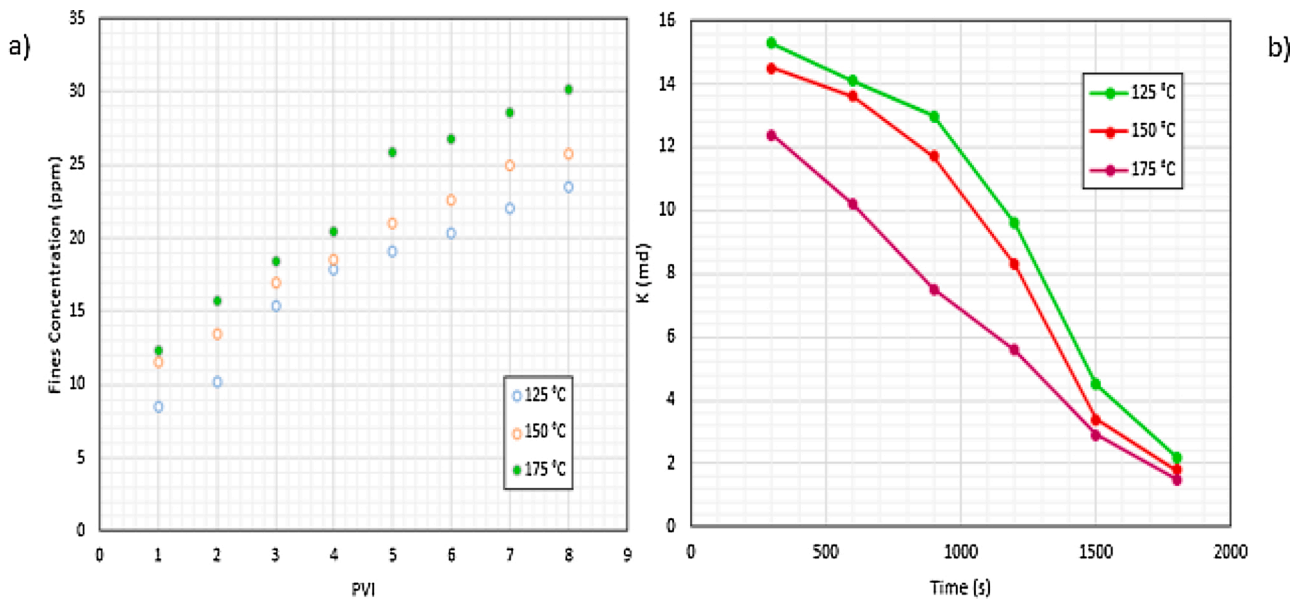


Fig. 6. (a) Fines concentration variation with increasing pore volume injection (PVI) and (b) Permeability decline with increasing time.

suspension flow, and an 80 % decline rate in permeability was reported in a Berea sandstone cores (Yu et al., 2018). Hence, a water-fines suspension flow can harshly decrease the permeability of the hot rock formation. Table 2 shows the experimental data for water discharge after a clay fines intrusion. Additionally, Fig. 7 shows a sample photo of clay and water production during experiment. It was dispersed and dried in a stainless steel plate at room temperature.

Fig. 8 shows the pressure change for an increasing pore volume injection (PVI). It can be observed from the figure that at all rock temperature regimes such as in 125 °C 150 °C, and 175 °C, the pressure increases steadily for gradual increases in the PVI. 175 °C exhibited a

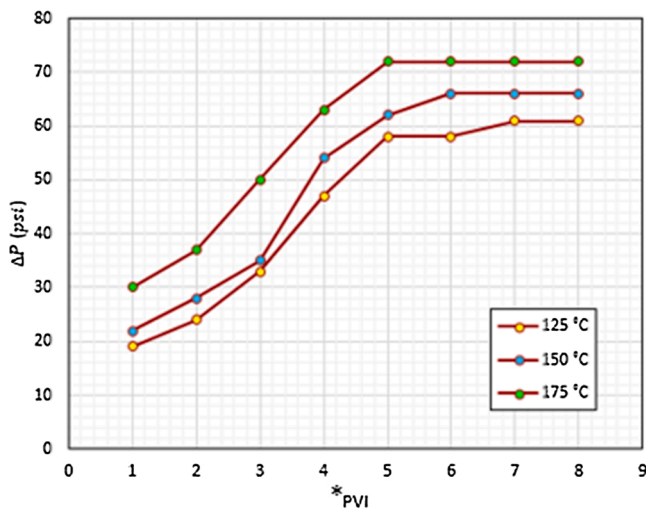
Table 2
Water discharge data after fines intrusion.

S. No	Temperature (°C)	Water Discharge Decline Time (s)	Amount of Colloidal Suspension (g)
1	125	536	53.62
2	150	942	72.97
3	175	1473	78.45

higher rise in the rock pressure and at 5 PVI the pressure at this temperature regime gradually stabilizes. This stabilization was noted for 125 °C and 150 °C at 7 and 6 PVI. So stabilized pressure can be achieved at extreme rock temperatures and a minimum pore volume injection as well. Generally, in these cases, the pressure tends to decline, but interestingly, it was found to have increased and this is absolutely due to reservoir rock and fluid temperature. Typically, the pressure in the aquifer increases and at higher temperatures the pressure will rise rapidly (Stober and Bucher, 2013). Fig. 9 shows the water discharge rates with respect to times of fines suspension water injection and fresh water injection. It can be observed from Fig. 9 a) that the rate of water discharge from rock core is decreasing rapidly for all three temperature regimes. As suspension water injection time increases the discharge rate decreases rapidly. During a suspension flow the fines will be captured in the pore-throat and consequently, the permeability will be drastically reduced. This causes a decline in the water discharge rate with taking temperature into an account. Fines are easily detached and strained at high temperatures and subsequently, will lead to a formation damage and an injectivity decline as well (You et al., 2016). On the other hand,



Fig. 7. A photo of clay and water production during experiment.



*Correspondent Fluid is Water

Fig. 8. Pressure variation with increasing pore volume injection (PVI).

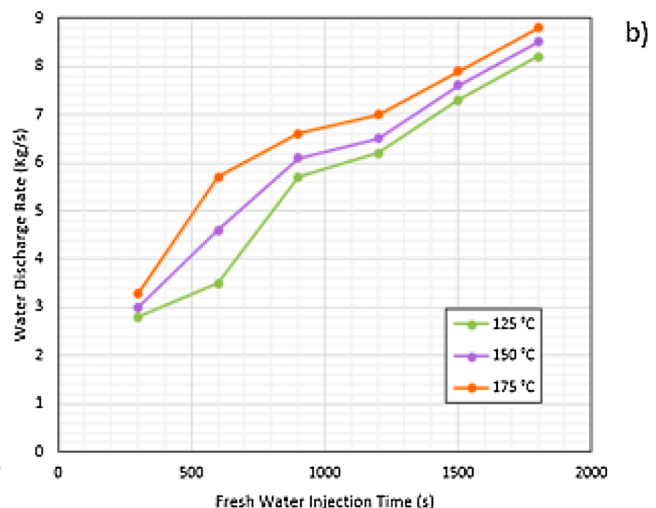
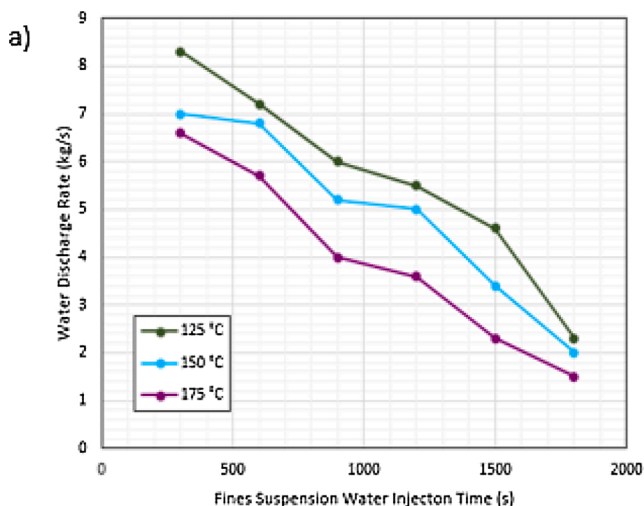


Fig. 9. a) Water discharge decline rate with increasing fines suspension water injection, b) Water discharge decline rate with increasing water injection time.

there is an observation of higher discharge rate for fresh water injection, as shown in Fig. 9 b). Commonly, fresh water thermal conductivity is higher in clay intruded water and as a result, the water injectivity and discharge rates are higher (Mideen, 2015).

Fig. 10 shows microstructure that is from FESEM (Field Emission Scanning Electron Microscopy) of produced effluent samples. Each effluent sample was tested in 1 μm at a core temperature of 125 °C, 150 °C, and 175 °C. In common, the structure and geometry of clay mineral fines that determine the transport characteristics in a porous environment are determined by the microstructural examinations (Khilar and Fogler, 1998). It can be seen from the Figs. 10 a, b, and c that there are an identifiable observation kaolinite clay mineral fine geometrical structures such as platelets and flakes present. The fines under these geometric structures have a great potential to obstruct the permeability of the porous media and lead to fluid flow deterioration (Pranesh et al., 2019; Chequer and Bedrikovetsky, 2019). It can be seen from Fig. 10 a) that there is a clear appearance of kaolinite fine platelets and water spots, which are indicated in black. It should be noted that the kaolinite fines in suspension at 125 °C have undergone flocculation and sedimentation. This is accurately indicated in Fig. 10 a) and a similar observation was noted in Fig. 10 b) microstructural image at 150 °C, but in this case, the flake geometry of the kaolinite fines was detected and additionally, a platelet structure, flocculation and water spots were found. Furthermore, at 175 °C regime, the FESEM image indicated only the flocculated and plugging behavior of kaolinite clay fines. Actually, the detection of kaolinite fines plugging could lead to a conclusion on permeability impairment and fluid flow decline of porous rocks (Mahalingam et al., 2019). Also, water spots have been identified in this case and altogether the fines geometry, flocculation and plugging contribute to the permeability decline and well impairment of the hot sedimentary aquifer. Nevertheless, the reservoir rock temperature, pressure and even water-rock chemistry dominate the fines migration in water saturated porous media (Pranesh and Ravikumar, 2019; Civan, 2010; Rosenbrand et al., 2015).

Fig. 11 shows the model validation, which was plotted between temperature and water saturation (Fig. 11a) and temperature and water injection decline time (fig.11b). The experimental data model was tested against the statistical model, multiple linear regression. Actually, multiple linear regression is the statistical data analysis method, which uses many variables to predict the response variable outcomes (Pranesh et al., 2018; Pandya et al., 2014). Hence, the experimental data of these two variables in the Figs. 11 a) and b) separately fed in the statistical package for social science (SPSS) simulation tool to quantify the model performance and validity. On the whole, the modelling results indicated good agreement and this is apparent in Figs. 11 a) and b). It can be seen

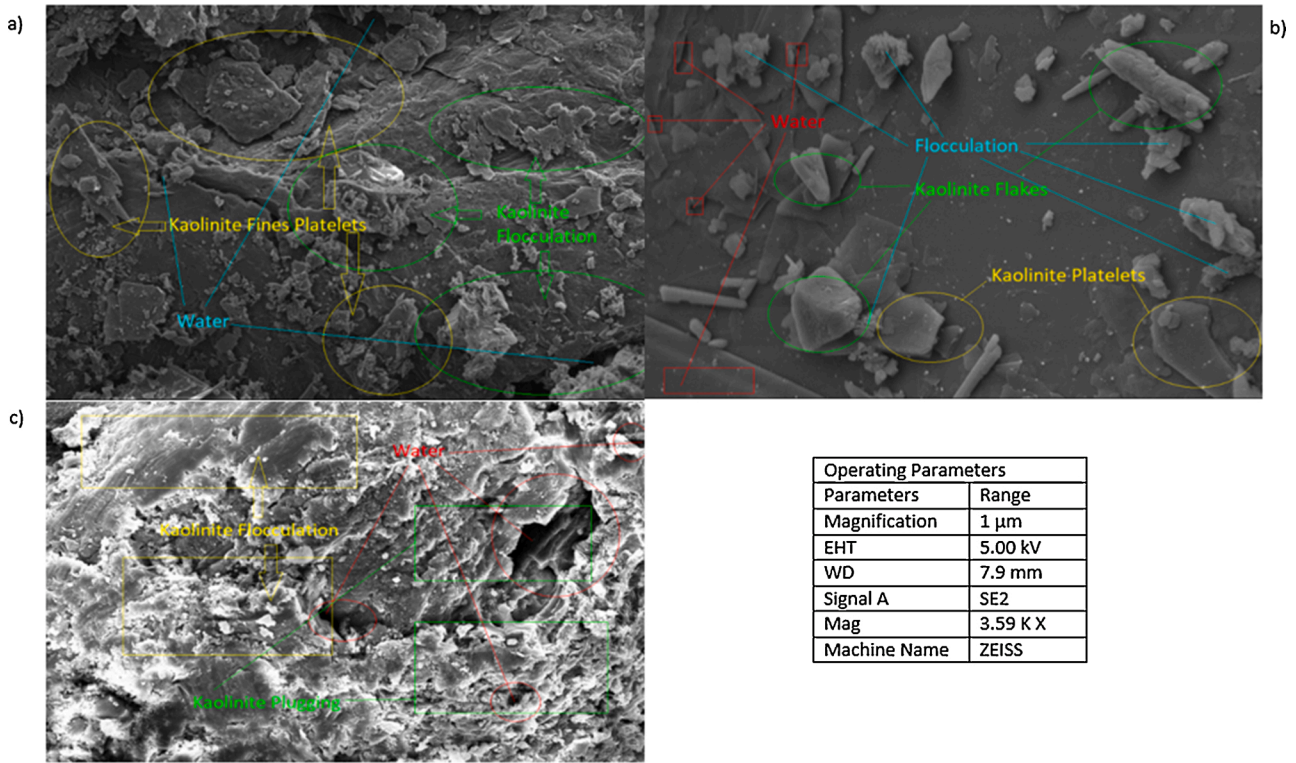


Fig. 10. Produced effluent FESEM images: a) 125 °C, b) 150 °C, c) 175 °C.

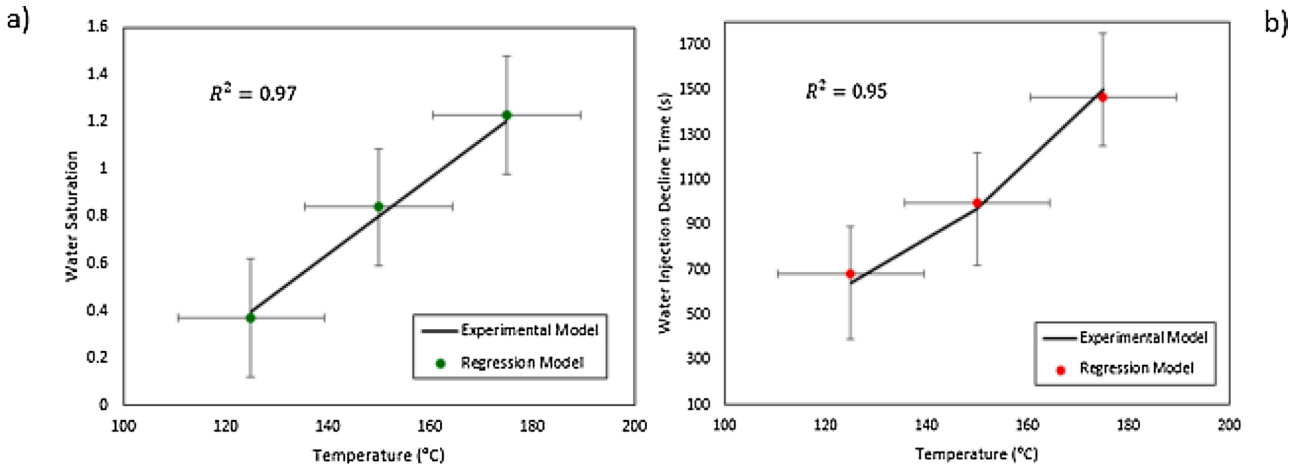


Fig. 11. Model validations: a) Water saturation Vs Temperature, b) Water injection decline time Vs Temperature.

from these figures that both experimental and statistical model curves overlap, which indicates that their performances are good and reliable. Generally, the curves overlap and merge revealing a high correlation between the testing and response variables (Kanimozhi et al., 2020; Pranesh, 2016). Also, it can be seen from these figures that uncertainties (error bars) level is very small. Therefore, both figures confirm that the geothermal sandstone reservoirs and hot sedimentary aquifers are highly prone to formation damage due to kaolinite fines migration during water flow.

4. Discussion

From the coreflood results it is inferred that aquifers are not exempt from formation damage and greatly prone to clay mineral, sand and other similar particle migration that leads to pore clogging, permeability

decline and alteration in the water chemistry (Konikow et al., 2001). Furthermore, colloidal releases in porous media can impede the fluid transport and also can barricade the wellbore (Gravelle et al., 2011). In general, clay mineral fines have a size of the order 1 μm and a net surface charge (Raha et al., 2007) and a fines mass balance equation over a rock surface is given by (Yang et al., 2016; You et al., 2016):

$$\frac{\partial(\phi c + \sigma_s + \sigma_a)}{\partial t} + \alpha U \frac{\partial c}{\partial x} = 0 \tag{1}$$

where, $\sigma_s + \sigma_a$ = Concentrations of attached and strained fines, U = Darcy velocity, c = Volumetric concentration of suspended particles, t = time, ϕ = Porosity, x = Distance, and finally, α = Drift delay factor

Additionally, fines are held in porous rocks under the dominance of four forces namely, lift (F_l), drag (F_d), gravity (F_g), and electrostatics (F_e), as shown in Fig. 12. The gravity and electrostatic forces hold the

fines to the pore surface (Zeinjahromi et al., 2016). According to Narasimhan (2012), there is continuous and high degree of heat flow in porous media and this has an impact on the mass balance and transfer in porous media. So this heat flow will affect the mechanical stability of the in-situ porous fines and tend to oscillate and rotate heavily. Furthermore, the higher heat flow in porous media from the geothermal gradient reduces the electrostatic forces of the rock and subsequently, the fines will detach from the rock surface and tend to migrate along the direction of heat or else with the permeating fluid (You et al., 2016). Fines rapid detachment at a high reservoir temperature is a common and perplexing phenomenon (Schembre and Kovscek, 2005) and this itself is one hypothesis that needs to be investigated in connection with the reservoir formation damage. It can be seen from Fig. 2 that the detached fines have migrated to the top layer aquifer and some fines are plugged and bridged in the porous interspace. This transport is through upper layer porous rocks, which is a high permeability and also, it was driven by heat flow. Even the aquifer receives heat from the geothermal gradient. Upon intruding the aquifer the fines will undergo a state of suspension. Now the aquifer reservoir is completely intruded with fines and due to the high temperature of the aquifer the fines in that will start to be excited and collide heavily. Moreover, a certain amount of fines will block the well space and thereby, restricting the fluid flow towards the well. This fines induced formation damage of well blockage is due to the nature of the kaolinite clay fines flocculation in water. Kaolinite will easily form a suspension and undergo a flocculation in water and some amount of suspended kaolinite will convert to sediments (Jeldres et al., 2017; Poorni and Natarajan, 2013; Lee et al., 2012; Divakaran and Pillai, 2001).

Furthermore, Civan (2010), investigated the non-isothermal impairment of porous media due to fines migration and deposition and also studied their dispersive transport. He claims that the phenomenon is due to a variation in temperature and fines mobilization by dispersion and advection. The author developed an analytical model to predict the fines detachment and transport in a porous medium and

compared with the results which he obtained through a finite difference numerical scheme. Modelling was performed with and without the consideration of a temperature variation and dispersion mechanism. From the numerical results it was revealed that a correlation was present between a varying temperature and fines dispersive mechanics. The difference in porous temperatures causes fine particles to disperse which causes a spreading effect and then, impairs the permeability. Overall, the author's research demonstrated that the porous medium temperature variation has a potential effect on fines migration and permeability reduction because it harms the porous matrix thermal deformation, pore throat constriction, and the filter coefficient. Therefore, from his findings, we all can understand that permeability damage is severe under non-isothermal and elevated temperature. Hence, it can be seen from Fig. 12 that after fines intrusion of HSA, there is a high degree of heat transfer to the impermeable upper rock layer and even up to the vadose zone.

Fig. 13 shows the schematic diagram indicating the mechanism of kaolinite flocculation in the aquifer as a function of temperature. Actually, Chequer et al. (2020), analyzed and reported the changes in the water level, hydrophilicity and particle size affect the mechanical equilibrium of fines in the reservoir that eventually detach and migrate in the porous rocks. Finally, the fines are densely deposited in the well, and thus result in well clogging and consequently, reduce the surface energy production. Ultimately, the temperature influences the electrostatic and drag forces of the fine particle that in the end result in reservoir rocks' permeability decrease and well productivity deterioration (You et al., 2018, 2015).

It can be seen from Fig. 13 that the kaolinite clay fine particles are migrating and intruding to the aquifer zone and subsequently, forming a suspension. Under the effects of aquifer temperature the suspended fines are undergoing a flocculation and the flocculated fines are building a structure. The fines with an irregular geometry migrate and plug the well and overall, contribute to a well productivity decline. Some flocculated fines had settled as sediments on the rock and well surface.

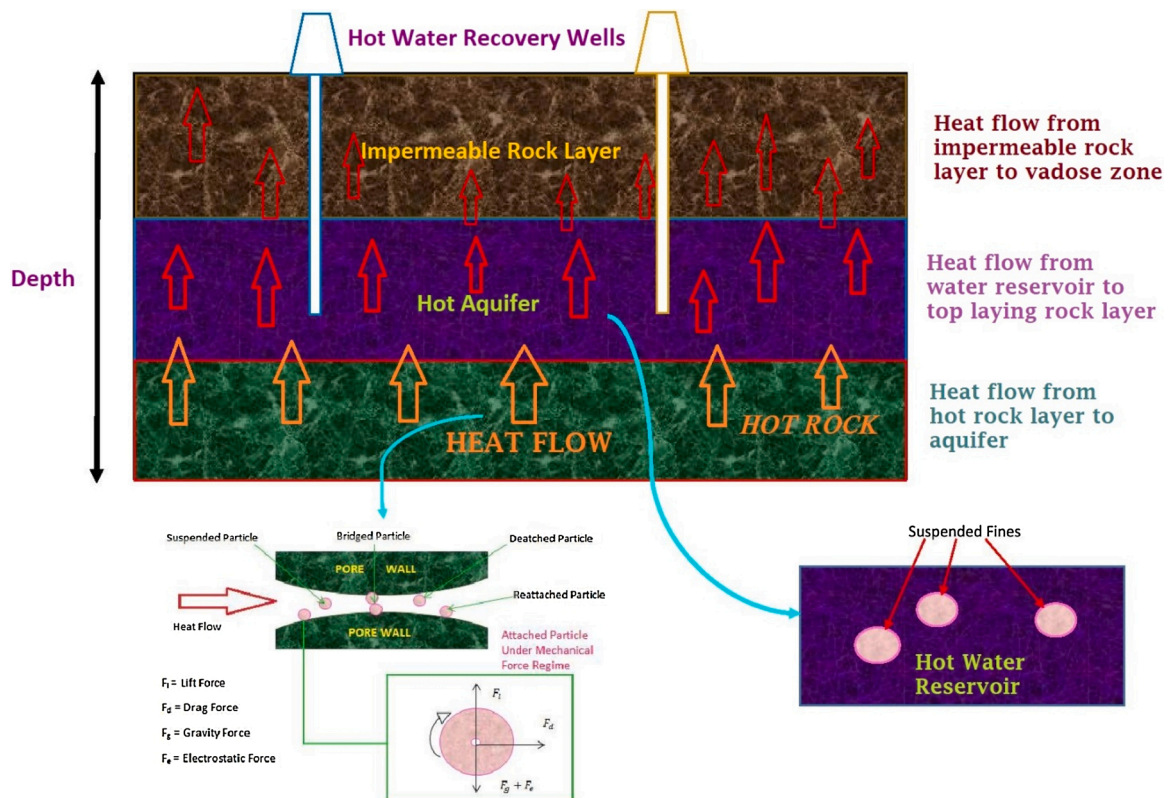


Fig. 12. Schematic diagram of fines transport and behavior in a hot aqueous sedimentary subsurface environment.

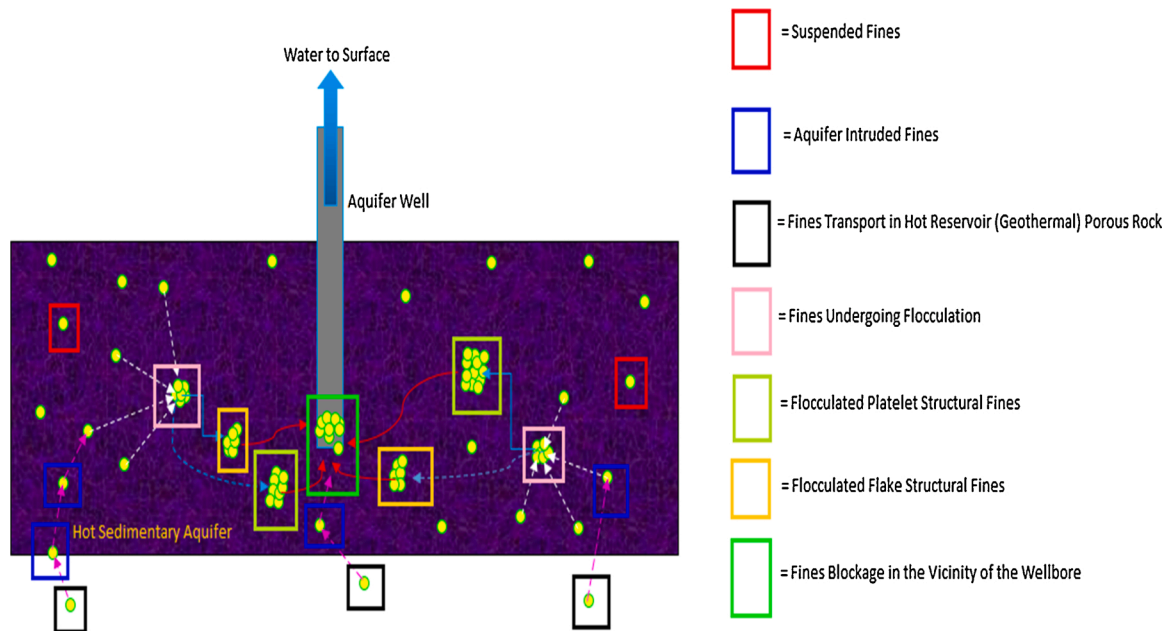


Fig. 13. Schematic diagram indicating the mechanism of kaolinite clay fines flocculation in hot sedimentary aquifer.

Already, it has been mentioned that the fines geometry plays a crucial role in reducing the permeability of the porous medium and this is mainly due to size exclusion that is the difference between the size of the fine particle and the area of the pore—throat (rock-grain) intersection (Bedrikovetsky, 2008; Santos and Bedrikovetsky, 2006). Additionally, fines straining also known as pore-straining (in the pore-throat regions) is a major cause of permeability decline and the fluid flow restriction and this straining mechanism are absolutely attributed to differences in the particle and pore-throat size distribution (Gomes et al., 2017). Moreover, Zbik et al. (2008), reported that during dewatering of slurry streams and mineral slurry disposal the clay minerals are becoming a serious problem since they form a colloid and flocculate. The latter has a major impact on the transport characteristics of the fluid because the flocculated clay minerals retain water and stem the fluid movement. On the whole, it is clear that clay minerals that undergo flocculation could result in a severe permeability damage and well productivity deterioration.

Finally, You et al. (2019), conducted a laboratory based experimental and analytical modelling of fines migration in geothermal reservoirs. The authors initially noted that temperature variation in the rock core weakens the detachment force and strengthens the lift and drag forces to migrate in the porous rock and is subsequently, captured in the pore-throat. It was observed from their modelling results that kaolinite and illite/chlorite clay fines migration and straining induced the permeability decrease and these fines were carried by the flow rate velocity. Furthermore, during water flow the ionic strength velocity perturbs the torque balance of fine particles and produces a maximum fines retention in the porous rock core. Also, the salinity alteration triggers the instant fines mobilization and straining. The authors developed an analytical model and acquired laboratory data that was able to predict the well productivity capacity or well impedance (extent of reservoir fluid production or decline). This data has been historically matched with well discharge in the Salamander geothermal field, Australia, which showed good agreement.

5. Conclusions

This paper has successfully explicated the importance of subsurface clay fines penetration and suspension in the aquifer. The hot sedimentary aquifer associated with formation damage has been critically

analyzed through experimental and mathematical models. Thus the following conclusions can be drawn based on the laboratory modelling:

- 1) Firstly, an experimental investigation was conducted to analyze the feasibility of fines suspension flow in a hot porous sandstone rock. A sandstone core was placed in an oven and heated at the temperatures 125 °C, 150 °C, and 175 °C. A Three sets of suspension flow experiments were performed at these temperatures conditions. There is also an observation of steam at these temperature regimes.
- 2) A steady increase of water saturation in the sandstone core was noted for an increasing injection time. The higher saturation rate was observed at the temperature of 175 °C and it is stated that when the temperature increases the water saturation rate also increases rapidly. Additionally, at these temperatures, the water saturation increases the heat transfer coefficient and simultaneously, increasing injection time increases the rate of enthalpy.
- 3) It was observed that increasing PVI increases the concentration of fines. In this case higher temperature also (175 °C) contributes to the high degree of fines concentration. This is due to the fact that the fines are highly excited at higher temperatures. After some time, there is an observation of a permeability decline in the sandstone core due to fine suspension and straining. A huge loss in permeability was recorded at 175 °C, which falls steadily. But, on the other hand, the pressure over the core increases rapidly for increasing PVI and at 5 PVI the pressure starts to stabilize. This increase and stabilization is due to the surrounding temperature and internal stress exerted by fines and water saturation.
- 4) Mainly, it was observed that the water discharge rate decreases for increasing water injection time of a fine suspension. Besides, the water discharge rate increases with increasing water injection time. In this scenario an increased temperature also contributes in the rise and fall of the water discharge rate. Then the experimental models were tested against the statistical model multiple linear regression, which revealed good agreement and the R^2 values were found to be 0.97 and 0.95, showing that the model is valid.
- 5) The intruded fines in the aquifer underwent flocculation that ultimately impaired the well and FESEM images revealed that the kaolinite fines are with platelet and flake geometries. Also, a flocculated and plugged kaolinite was seen in the microstructural images. Altogether, this will obstruct and damage the permeability of

the sedimentary formation containing the hot water resource and result in a declining well production. Therefore, a laboratory based examination was performed successfully and this paper may have contributed to the existing literature/research gap on fines migration in aquifers and in our future work, we expect to perform numerical modeling.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.geothermics.2020.101975>.

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