PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Super-Critical CO_2 Geothermal Power Generation

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Keywords: EGS, Supercritical-CO_2, fracturing, permeability. Mineral deposit

ABSTRACT

In Japan, the development of renewable energies is expected against not only the global warming but also the disaster of nuclear power plant and an energy policy which showed a plan of the electricity generation for each energy in 2030 was announced. Geothermal energy is desired to install power generation more than 1.5GWe under this new policy, which is almost three times of the current installed capacity. The achievement of the political goal is, however, so high when conventional geothermal power generation is applied using natural geothermal resources. We are developing a new heat recovery technology in JOGMEC on the base of the supercritical CO_2($ScCO_2$) and EGS technology creating an artificial heat exchange layer in a high-temperature area. In $ScCO_2$ geothermal power generation, CO_2 in the supercritical state is used for two purposes.

The first is to create an artificial heat exchange surface (artificial reservoir), and the other is as a heat recovery medium. The first artificial reservoir creation utilises the property that supercritical substances, whether water or CO_2 have very low viscosity to penetrate fine cracks. In Japan's HDR technology development (Hijiori Project), which was carried out until the early 2000s, no damage was caused by induced earthquakes during the creation of the artificial reservoir, but in other countries the occurrence of earthquakes was a major problem. Since $ScCO_2$ forms fine cracks, it is expected to have the effect of suppressing induced earthquakes that occur during fracturing. For this use, basic experiments using rock samples have been completed, and small-scale field experiments are also being carried out. $ScCO_2$ is used as a working fluid.

Short circuit was formed and observed at Hijiori, which connected between the injection and production wells directly. $ScCO_2$ may be possible to prevent the occurrence of short circuits by changing the conditions of injection of $ScCO_2$ or by adding additives. The recovery rate, which shows the rate of reproduced fluid against the injected fluid, was less than 50% in the Hijiori project. $ScCO_2$ is also expected for the working fluid that escapes to react with the rocks and become solidified. Since much is unknown about the method of using $ScCO_2$ to extract geothermal fluids, basic experiments and studies are being conducted.

1. INTRODUCTION

Technologies of EGS (HDR), which creates an artificial reservoir, injects water from an injection well, and extracts steam and hot water from a production well, was studied and developed in Japan in the 1980s. NEDO (New Energy Development Organization, currently New Energy and Industrial Technology Development Organization) constructed a HDR site in Hijiori (Kuriyagawa, 1996) and CRIEPI(Central Research Institute of Electric Power Industry) also started a HDR experiment in Ogachi (Kaieda, et al., 2005), where they created artificial reservoirs and developed heat extraction technology. The location of these sites is shown in Figure 1. Research and technology development for some technologies were also carried out as a joint research project among three countries, Japan, the United States, and Germany. In NEDO's technology development, two artificial reservoir layers of different depths, shallow and deep, were created. The artificial reservoir was successfully formed, and individual circulation tests for each layer as well as simultaneous circulation tests for two layers were conducted.

Figure 1: Locations of old HDR sites (Hijiori and Ogachi), geothermal power plants (Matsukawa and Wasabizawa), CCS test site (Nagaoka) and core sample collection point (Honkomatsu Andesite)

During a circulation test that lasted about a year, a phenomenon occurred in which the amount of water from the production well increased and the water temperature decreased. This might be due to the progress of fracturing due to circulating fluid in the artificial reservoir, resulting in a short circuit path. The NEDO's HDR project was ended in 2003, due to the government's budget cuts for geothermal energy development. For this reason, it was not possible to design a whole system including the surface facilities such as turbine and generator.

Geothermal power generation in Japan began with the start of operation of the Matsukawa Geothermal Power Plant in 1966 (Figure 1), and the installed capacity of the power plant steadily increased until 2000 (Figure 2). Larger power plants with the install capacity exceeding that of 10MW were not constructed after 2000. The major reasons for the construction not progressing include not only the long time it would take to build, but also the lack of consent from nearby residents and hot spring operators who were concerned that their hot springs would dry up. EGS, which creates artificial reservoirs and extracts geothermal fluids after heat exchange in the reservoir, is expected to be less impact on hot springs than pumping up hot water vapor from natural reservoirs. The underground temperature distribution is a major factor in determining the location, and there is no need to assume the existence of groundwater. EGS has various advantages. Development of EGS (HDR) technology had been halted because there are several cases that the induced earthquakes, which caused by the injection of water into geological formations, could be felt by local residents around the EGS sites.

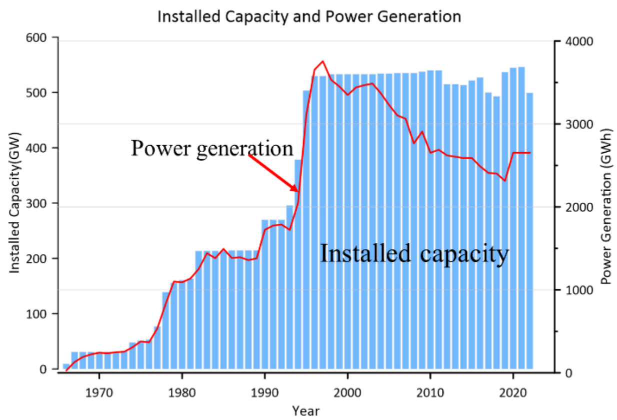

Figure 2: Annual change in installed capacity (Bar chart) and power generation (line chart) from the start of the first geothermal power plant in 1966 (Thermal and Nuclear Power Engineering Society, 2024)

The geothermal power generation has recently been reviewed as part of the government's carbon neutral policy as it emits less global warming gas. The basic energy plan as a future energy usage plan in Japan also encourage the geothermal development. Conventional geothermal development using natural geothermal resources is, however, lagging for various reasons. We have to process with technological development for geothermal power generation using artificial reservoirs.

This article provides an overview of the current JOGMEC (Japan Organization for Metals and Energy Security, former Japan Oil, Gas and Metals National Corporation) project named "EGS technology development using supercritical carbon dioxide" with the recent situation surrounding geothermal power generation and reflections on past technology development, such as the occurrence of short circuit paths. As EGS also uses a wide range of concepts such as closed cycle geothermal heat such as coaxial heat exchange and U-loops, well stimulation, and supercritical geothermal resources in addition to HDR technology, we will refer to HDR technology as EGS (HDR) in this article. In the EGS(HDR) technology development in JOGMEC, ScCO2 has two major roles. One is a fluid, which is injected into the reservoir from an injection well and is produced from a production well, used as a working fluid to circulate in an artificial reservoir. The other is a fracturing fluid to create an artificial reservoir by the fracturing. They are referred to as "working fluid" or "fracturing fluid" to differentiate between the two.

2. ENERGY PLAN

2.1 Japanese Basic Energy Plan (7th)

Japan is creating five scenarios to predict the power generation mix in 2040:

1. Scenario where innovative renewable energy technologies spread widely,
2. Scenario where hydrogen, ammonia, synthetic fuels, synthetic methane, etc., spread widely,
3. Scenario where the use of CCS (Carbon Capture and Storage) expands,
4. Scenario where the dissemination and utilisation of innovative technologies expand widely,
5. Scenario where the cost reduction of innovative technologies is insufficient, and the introduction progresses mainly based on existing technologies.

The proportion of electricity generated in each scenario in 2040 is debated, but renewable energy sources are expected to account for 22% to 24% of the total in each scenario. Geothermal power generation is also expected to supply around 1% of the total electricity supply (~150MW in installed capacity) in 2030, as the same as the previous supply and demand plan.
Subsection headings should be capitalized on the first letter.

2.2 Increase and expected increase of geothermal power generation

Figure 2 also shows the year changes in amount of electricity produced in the geothermal power plants in polygonal lines. Until the mid-1990s, as power plants were constructed, both installed capacity and electricity showed steady growth, but since then, power generation has continued to decline. Although the reasons of the decrease in power generation vary depending on each power plant, one of the reasons for the decline is a decrease in the temperature of the reservoir and a decrease in the amount of produced geothermal resources due to an over-intake of geothermal resources. The renewable potential of geothermal heat is ensured by the amount of heat extracted and the flow of fluid from the surroundings to replenish the amount extracted, but it is generally difficult to determine whether the amount extracted is within the range of renewable capacity.

This problem is, however, gradually being solved with the recent development of simulation technology. They can simulate the production and injection with their field model and find a suitable production and injection rate. The attenuation of the production at some geothermal power plants has been successful and this leads the stable electricity generation in recent three years. The Wasabisawa Geothermal Power Plant with an installed capacity of 46,199kW, which started operation in May 2019, also made a large contribution for the stability of the power generation (Figure 1）.

The master plan also shows how much current geothermal power generation is expected to increase by 2040. The estimation is based on the number of power generation facilities that are currently FIT/FIP certified, which can start generating power by 2040 is 25GW, and an increase of 50GW by continuing the current policy, and an increase of 857GW by implementing enhanced policies. (METI, 2024) (Figure 3).

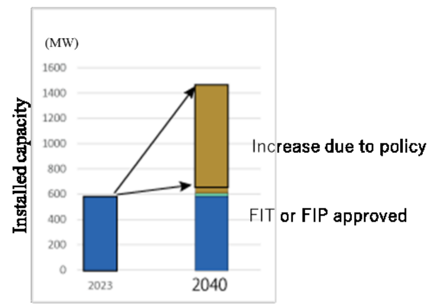

Figure 3: Expected increase in installed capacity

3. PROJECT

The idea of using $ScCO_2$ for HDR has been announced since around 2000 (e.g. Brown, 2000; Pruess, 2009). Efficient power generation is possible mainly due to the difference in molecular weight between water and CO_2. However, the chemical properties of CO_2 were not fully taken into. It is well known that CO_2 dissolves in water and produces an acidic fluid, and when CO_2 is injected into the ground, it can react with formation water or groundwater to make an acidic fluid that can dissolve rocks.

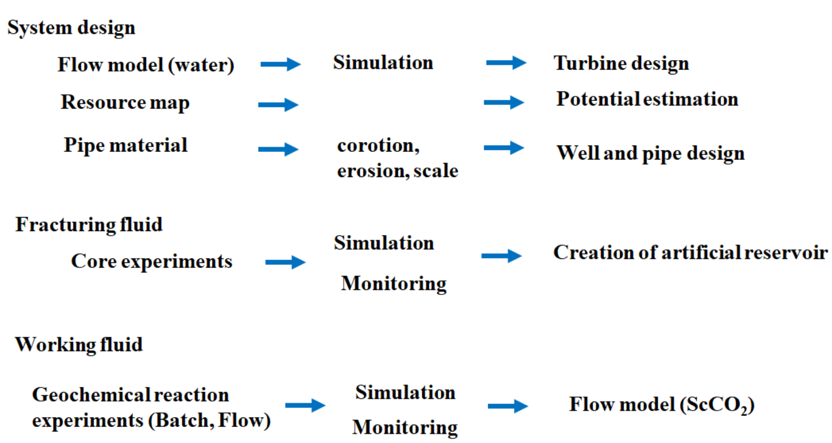

Figure 4: Individual development technologies and their targets

Mineral trapping where CO_2 is stored as carbonate minerals in subsurface is one of the feasible trapping mechanisms. Elements contained in coloured minerals such as Mg and Fe combine with hydrogen carbonate ions generated from CO_2 dissolved in water to form carbonate minerals that do not dissolve in water. It would take more than 100 years for CO_2 to be trapped in carbonate minerals, but RITE (personal communication) conducted a CO_2 aquifer storage experiment using an unused well in the Nagaoka oil field area and found that carbonate minerals were being produced in a 10-month injection experiment. Carbonate mineralisation should be happened more quickly in geothermal areas with high temperatures.

The JOGMEC project to use $ScCO_2$ in a geothermal power generation is broadly divided into three subprojects, the overall conceptual design, physical technology development, and geochemical technology development (Figure 4).

3.1 System Design

a) Turbine design
Design of a CO_2 turbine assuming the reservoir temperature and pressure. It is assumed that the working fluid (circulating fluid) is assumed to be $ScCO_2$ as we don't know the contents ratio of $ScCO_2$ in water. Depending on the ratio of CO_2 and water, a separation device might be required that extracts only CO_2.

b) Flow model
A dynamic flow model in which the working fluid is water and CO_2 and no geochemical reaction in the model (e.g., Nakao et al., 2023; Masaoka et al., 2023).

c) Flow model with geochemical reactions
The flow model will be constructed based on physical laws, and then we will include the chemical reaction between $ScCO_2$ and formation water. Simulations that combine flow and geochemical changes are also required. We will use TOUGHREACT for the simulator.

d) Resource map
The resource to be developed using the technologies in this project is in the area with the high temperature. We can estimate the underground temperature distribution from aeromagnetic data (Ohkubo, 2025) and create a resource quantity map assuming the possible drilling depth.

e) Selection of possible construction sites
A demonstration site will be selected among the possible high temperature site with regulations, environment, and supply of CO_2

f) Evaluation of economic efficiency
Taking into all factors for $ScCO_2$ EGS(HDR) technologies, economic efficiency will be evaluated.

3.2 Individual elemental technology (based on geomechanics)

a) Rock experiment at high temperature and pressure
Geothermal development using EGS (HDR) requires the creation of an artificial reservoir. Conventionally, fracturing was carried out with water, but in order to understand the advantages of using $ScCO_2$ as the fracturing fluid, rock experiments using $ScCO_2$ and water as the fracturing fluid were conducted for rock cores samples (Pramudyo et al., 2024; Takuma et al., 2024).

b) Fracture simulation based on rock experiments
Conducting simulations to adapt fracturing results in the experiments using $ScCO_2$ and estimating facture creation for an artificial geothermal reservoir.

c) Monitoring technology
Monitor the movement of $ScCO_2$ underground (Fiber Optics, gravity, electromagnetic, elastic wave methods)

3.3 Individual elemental technology (based on geochemistry)

a) Geochemical reaction experiment (batch type)
Batch experiments using fine rock sample and CO_2 water to estimate products after equilibrium (e.g. Satake et al., 2023).

b) Reaction experiment by flowing CO_2 through core-shaped rock sample
Investigate the reaction between rocks and CO_2 by continuously flowing CO_2 water through the core sample (e.g. Nishiyama et al., 2025).

c) Natural Analogue study
Understanding the behaviour of carbonate minerals by investigating similar examples in nature (e.g. Mao et al., 2025).

d) Simulation of geochemical reactions caused by CO_2 in the laboratory
Since experimental conditions such as rock types that can be observed in the laboratory are limited, modelling simulations are conducted to cover a wide range of experimental conditions (e.g. Shiga et al., 2023).

e) Technology to suppress scale formation in wells
Suppress the occurrence of the carbonate minerals as scale in production well

f) Material selection for pipes
Countermeasures against corrosion caused by $ScCO_2$

4. PRELIINARY RESULTS

Two preliminary results will be presented.

4.1 Rock fracturing experiment

To clarify the difference between fracturing with water and $ScCO_2$ as a fracturing fluid, the fracturing fluid is injected into a cylindrical rock sample (diameter 30 mm, length 25 mm) under confining pressure (30 MPa), axial pressure (100 Ma), and temperature (250°C). The changes in injection pressure and the occurrence of AE were observed (Takuma et al., 2024).

Table 1: Mechanical and hydraulic properties of Honkomatsu andesite (Takuma, et al., 2024)

Porosity (%)	5
Permeability (m^2)	1~4 $\times 10^{-18}$
Tensile strength (MPa)	10
Uniaxial compressive strength (MPa)	242
Young's modulus (GPa)	26
Poisson's ratio	0.3
Cohesion (MPa)	40
Internal friction angle (degree)	58

The experiment was conducted by shaping samples from substitute volcanic rocks such as basalt and andesite. Here, we will describe an experiment using Honkomatsu Andesite, which is a pyroxene andesite flowed during the eruption of Hakone Volcano（Figure 1). The physical properties of the andesite are shown in Table 1. A small diameter hole was created at the centre of the sample to a depth of about half of the sample, and fluid was injected into the hole. The sample is covered with a gasket to prevent the leak of the pressure (Figure 5). The injection pressure and the AE were observed.

When water was injected and the injection pressure reached to about 60 MPa, the AE energy suddenly increased and the fracture of the rock sample occurred. The surface of the core sample was identified using X-ray CT images after the experiment. The core, which was X-rayed after the water injection experiment, suggests that the fracture progressed in nearly one direction shown in Figure 6.

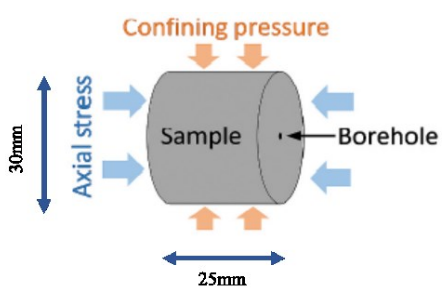

Figure 5: A rock sample for the fracturing experiment

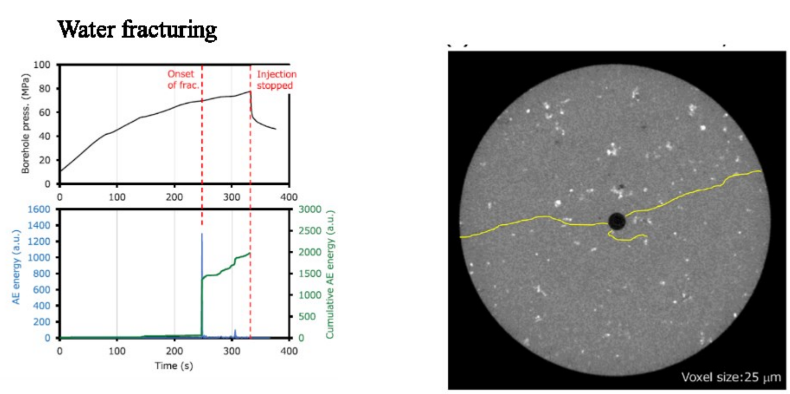

Figure 6: Changes in borehole pressure (upper left figure) and AE energy (lower left figure) with time in the water fracturing experiments and core X-ray CT image after the experiment (right figure) (after Takuma et al., 2024)

In the other hand, when $ScCO_2$ is injected, AE begins to be generated when the injection pressure becomes to be about 40 MPa, suggesting that the fractures occur near this pressure. Core X-ray CT images taken after this experiment showed the fractures were spreading in multiple directions with small sizes. Many and fine fracture surfaces are generated by using $ScCO_2$ as a fracturing fluid, and this may be due to the low viscosity coefficient of $ScCO_2$ shown in Figure 7.

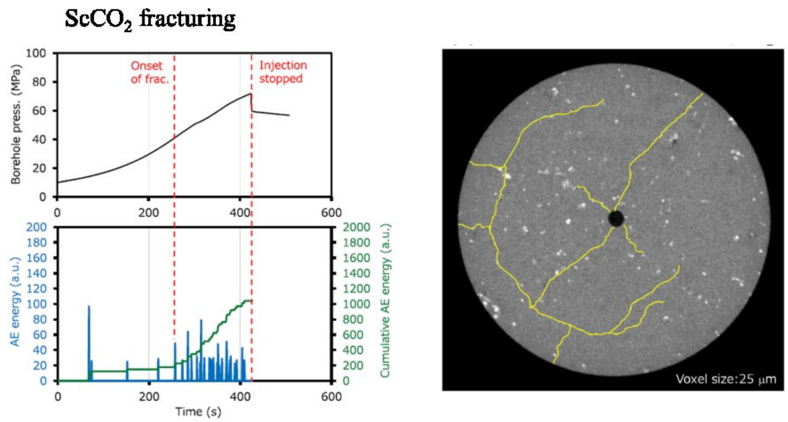

Figure 7: Changes in borehole pressure (upper left figure) and AE energy (lower left figure) with time in the $ScCO_2$ fracturing experiments and core X-ray CT image after the experiment (right figure) (after Takuma et al., 2024)

AE was also generated in experiments using $ScCO_2$ as the fracturing fluid, but the AE energy was quite low. The energy released during fracturing will be small and dispersed. Earthquakes induced during fracture are one of the factors restraining the development of EGS technology. The use of $ScCO_2$ as a fracturing fluid can reduce the risk of induced earthquakes during the creation of artificial reservoirs. Reducing the possibility of induced earthquakes will greatly contribute to the future development of EGS technology.

4.2 Rock geochemical reactions caused by $ScCO_2$ dissolved water

The project uses $ScCO_2$ as the working fluid, which transports thermal energy from reservoir to turbine with a power generator. Geochemical reactions between rock minerals and $ScCO_2$ (and $ScCO_2$ dissolved in water) will occur with the rocks in the reservoir. In JOGMEC's technology development, geochemical experiments are conducted using two methods. One method uses crushing rocks to observe the chemical equilibrium in a reactor and the other uses rock samples (cores) to observe changes with time. As not enough data is available yet, the results are preliminary and may change in the future.

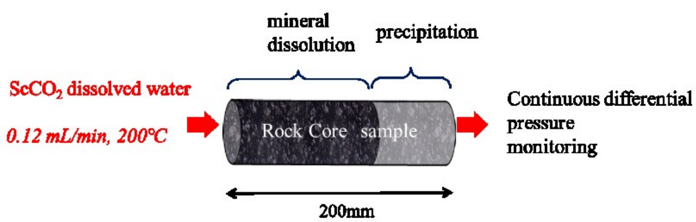

Figure 8: A rock sample for the fracturing experiment (Nishiyama et al., 2025)

Table 2: Mineral composition (Left Table) and whole-stone chemical composition (Right Table) of the rock samples

Oxides	Andesite	Basalt
SiO_2	61.13	51.89
TiO_2	0.8	1.63
Al_2O_3	16.72	16.17
$(Fe_2O_3)_{total}$	6.93	11.28
MnO	0.15	0.15
MgO	2.52	6.38
CaO	6.2	8.75
Na_2O	3.53	2.83
K_2O	1.69	0.45
P_2O_5	0.18	0.22
LOI	nd	0.25
	wt%	wt%

Minerals	Andesite	Basalt
feldspar	28.8	59.1
clinopyroxene	5.2	17
orthopyroxene	7.2	0
glass	10.5	14.6
olivine	0	2.5
opaque mineral	5.4	5.2
others	28.7	0
secondary minera	14.3	1.6
total	100	100
	wt%	wt%

Nishiyama et al. (2025) used core samples of natural basalt and andesite to inject $ScCO_2$ dissolved in water and observed changes in permeability (Figure 8). A rock sample is shaped into a cylinder, and a mixed fluid of $ScCO_2$ and water is flowed under a constant temperature and pressure. Continuous pressure measures are carried out between the fluid inlet and outlet. The experimental conditions are as shown in Table 2. Assuming that the flow within the rock sample follows Darcy's law, the permeability is calculated from the flow rate and the differential pressure. The viscosity coefficient takes a constant value and is 1.4 x 10^{-4} Pa s at 200°C and 10 MPa (Akinfiev and Diamond, 2009). Andesite and basalt were used as rock samples. The mineral composition and whole-stone chemical composition of the rock samples are shown in Table 2(Left Table) and Table 2(Right Table), respectively. Generally, andesite has more Si component and less Fe, Mg, and Ca components than basalt. The rock samples used in this study show this tendency.

Table 3: Conditions for the core flow experiment (Nishiyama et al., 2025)

temperature	**200℃**
pore pressure	**10 MPa**
lateral pressure	**14.5 MPa**
Distribution period	**42Days**
flow rate	**0.12 mL/min**
fluid	**CO_2 dissolved water （pH ~3.6）**

The andesite core sample after the $ScCO_2$ flow test became whitish overall, with intense whitening in some areas, suggesting that there happened dissolution of coloured minerals such as pyroxene and glass, or white secondary mineral precipitation. A change in mass is also measured. The core mass was 321.9g before the test, but it became 317.0g after the test with a decrease of 4.9g. This is presumed to be caused by dissolution of minerals. The experimental results are shown in Figure 9. The permeability of basalt continued to decrease throughout the observation period, but that of andesite decreased on the several days after the start of the circulation, but it began to increase and became triple from the initial permeability.

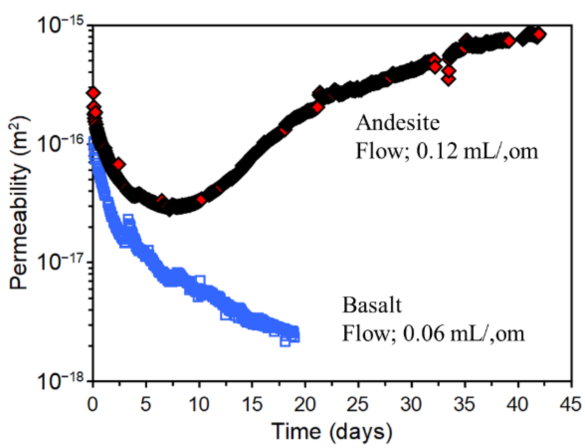

Figure 9: Temporal permeability changes for the flow experiment in basalt and andesite samples (Nishiyama et al., 2025)

There are different permeability changes due to geochemical reactions in andesite and basalt samples, suggesting that andesite may be less prone to clogging than basalt. Basalt contains many coloured minerals including Fe, Mg, and Ca components, which are the members of carbonate minerals. Carbonate minerals are precipitated by the injection of carbonated water. On the other hand, in andesite, carbonate minerals precipitate and block the flow path at the beginning of the experiment. The content of the carbonate component in andesite is lower than that in basalt, the carbonate minerals precipitate ends early, and the acidic flow of CO_2 water dissolves the minerals, creates the flow path, and increases the permeability. Due to the possibility of creating an artificial reservoir shell due to the formation of carbonate minerals, and the once the sell is created it works as cap rocks. $ScCO_2$ is one of the best flowing fluids in EGS(HDR) technology rather than water. The artificial geothermal reservoir in basalt layer has possibility to reduce the number of the path at the early stage of the circulation by creating the carbonate minerals. However, since the results are still based on limited samples and experimental conditions, we will increase the number of experimental examples and explore ways to reproduce the phenomenon through simulation. Through this, we will find a method to control the "short circuit" that occurred in past HDR projects by adjusting the $ScCO_2$ content of the circulating fluid.

5. CONCLUSION

Development of geothermal energy is of importance in the carbon neutral plan against the global warming. The conventional geothermal development explores underground natural geothermal reservoirs and takes out geothermal resources. The JOGMEC's new geothermal project, EGS technology development using supercritical carbon dioxide, bases on a different perspective than conventional geothermal development, which creates an artificial geothermal reservoir, controls injection waters, and generates electricity. The project is expected as the next generation technology of geothermal development.

Regarding the method of forming an artificial reservoir using $ScCO_2$ as a fluid for fracturing rocks, the injection of $ScCO_2$ is confirmed that the low-viscosity fluid permeates widely into the rock sample, causing smaller cracks to spread than the injection of water and is also confirmed that the generated elastic wave energy (AE energy) is lower than that generated by water fracturing. It will become widespread in the future that the creation of artificial reservoirs using $ScCO_2$ as a working fluid for rock crushing as an EGS technology.

In the CO_2 utilisation for working fluid CO_2 behaviour in aquifers is unclear. Although the similar technology for the underground storage of CO_2 is used in CCS projects, the temperature range is completely different. The time required for CO_2 mineralization is thought to be several hundred years or more in the CCS project, but carbonate minerals are creating even for a few months in CCS storage site. In the high temperature site mineralisation will be more active. It is necessary to accumulate more data on the geochemical reactions between CO_2 (+H_2O) and minerals within the reservoir.

The occurrence of induced felt earthquakes due to water injection has also been observed in EGS fields overseas in recent years (Evans et al., 2012) and is recognized as a significant environmental impact associated with EGS. The occurrence of induced felt earthquakes due to fluid injection underground has also been reported in the shale gas development field (Li et al., 2019), so this is an issue that needs to be resolved in the entire field of underground fluid resource development in the future.

Acknowledgement

The project is made up of the cooperation of more than 10 organizations, including companies, universities, and national research institutes. Funding will also come from METI grants. We would like to express our deep gratitude to each organization for their cooperation.

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