

## Super-Critical CO<sub>2</sub> Geothermal Power Generation

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### 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<sub>2</sub>(ScCO<sub>2</sub>) and EGS technology creating an artificial heat exchange layer in a high-temperature area. In ScCO<sub>2</sub> geothermal power generation, CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> is used as a working fluid.

Short circuit was formed and observed at Hijiori, which connected between the injection and production wells directly. ScCO<sub>2</sub> may be possible to prevent the occurrence of short circuits by changing the conditions of injection of ScCO<sub>2</sub> 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<sub>2</sub> is also expected for the working fluid that escapes to react with the rocks and become solidified. Since there are many unknown factors for the use ScCO<sub>2</sub> to extract geothermal fluids, basic experiments and studies are being conducted.

### 1. INTRODUCTION

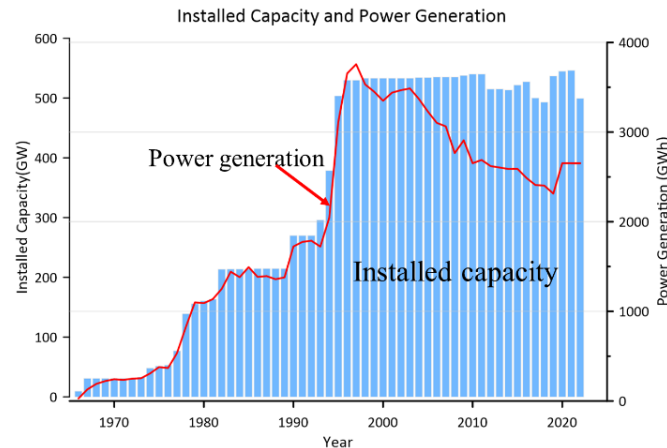
Technologies of EGS (HDR), which creates an artificial reservoir, injects water from an injection well, and extracts steam and hot water from a production well, was studied and developed in Japan in the 1980s. NEDO (New Energy Development Organization, currently New Energy and Industrial Technology Development 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 happened 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. For this reason, it became impossible 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, however, 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, which 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. EGS also uses a wide range of concepts such as closed cycle geothermal heat, coaxial heat exchange, U-loops, well stimulation, and supercritical geothermal resources in addition to HDR technology. We will discuss on the EGS technology based on HDR using  $\text{ScCO}_2$ . In the EGS(HDR) technology development in JOGMEC,  $\text{ScCO}_2$  has two major roles. One is a use of a working fluid, which is injected into the reservoir from an injection well and is produced from a production well to circulate in an artificial reservoir. The other is a fracturing fluid to create an artificial reservoir by the injection into the subsurface with a high pressure to make small fractures. They are referred to as "working fluid" or "fracturing fluid" to differentiate between the two.

## 2. ENERGY PLAN

### 2.1 Japanese Basic Energy Plan (7<sup>th</sup>)

Japan is creating five scenarios to predict the power generation using several energy sources in 2040 (METI, 2024):

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. 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, which is the same as the previous supply and demand plan.

## 2.2 Increase and expected increase of geothermal power generation

The polygonal lines in Figure 2 also shows the year changes of the energy production in the geothermal power plants. Until the mid-1990s, as power plants were constructed, both installed capacity and electricity production showed steady growth, but since then, power generation has continued to decline. Although the reasons of the decrease in power generation are different 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 heat of extracted flow and the flow of fluid from the surroundings to replenish, but it is generally difficult to estimate and 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 (Figure 1) 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.

The supply and demand plan by the Japanese government 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 (Figure 3).

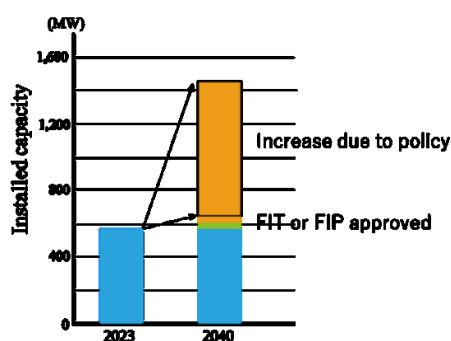


Figure 3: Expected increase in installed capacity

## 3. PROJECT

The idea of using  $\text{ScCO}_2$  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  $\text{CO}_2$ . However, the chemical properties of  $\text{CO}_2$  were not fully taken into in the previous papers. It is well known that  $\text{CO}_2$  dissolves in water and produces an acidic fluid. When  $\text{CO}_2$  is injected into the ground in HDR geothermal generation, it can react with formation water or groundwater to make an acidic fluid that can dissolve minerals in the rock.

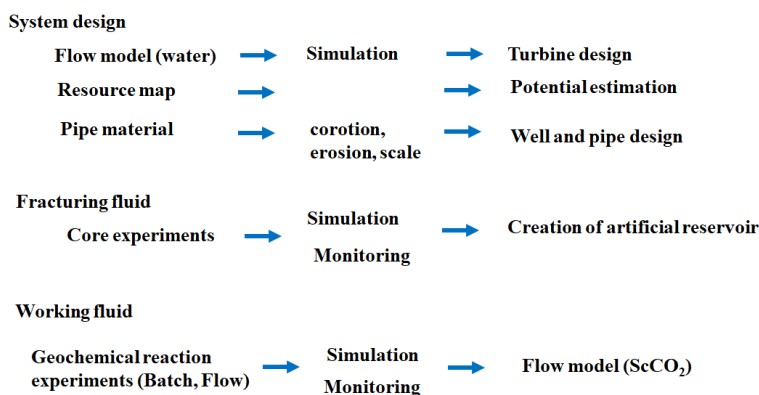


Figure 4: Individual development technologies and their targets

Mineral trapping where  $\text{CO}_2$  is stored as carbonate minerals in subsurface is one of the feasible trapping mechanisms at CCS technology. Elements contained in coloured minerals such as Mg and Fe combine with hydrogen carbonate ions generated from  $\text{CO}_2$  dissolved in water to form carbonate minerals that do not dissolve in water. It would take more than 100 years for  $\text{CO}_2$  to be trapped in carbonate minerals, but a CCS project conducted  $\text{CO}_2$  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 because of their high temperatures.

The JOGMEC project to use ScCO<sub>2</sub> in a geothermal power generation is broadly divided into three subprojects, which are the overall conceptual design, physical technology development, and geochemical technology development shown in Figure 4.

### 3.1 System Design

#### a) Turbine design

Design of a CO<sub>2</sub> turbine assuming the reservoir temperature and pressure. It is assumed that the working fluid is assumed to be pure ScCO<sub>2</sub> as we don't know the contents ratio of ScCO<sub>2</sub> in water. Depending on the ratio of CO<sub>2</sub> and water, a separation device might be required that extracts only ScCO<sub>2</sub>.

#### b) Flow model

A dynamic flow model in which the working fluid is water and ScCO<sub>2</sub> 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<sub>2</sub>, formation water and minerals in rocks. Simulations that combine flow and geochemical changes are also required. We will use TOUGHREACT (Spycher et al., 2022) 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<sub>2</sub>

#### f) Evaluation of economic efficiency

Taking into all factors for ScCO<sub>2</sub> EGS 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 requires the creation of an artificial reservoir. Conventionally, fracturing was carried out with water, but in order to understand the advantages of using ScCO<sub>2</sub> as the fracturing fluid, rock experiments using ScCO<sub>2</sub> and water as the fracturing fluid were conducted for rock cores samples (e.g. 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<sub>2</sub> and estimating fracture creation for an artificial geothermal reservoir.

#### c) Monitoring technology

Monitor the movement of ScCO<sub>2</sub> underground using fiber optics, gravity, electromagnetic, elastic wave and so on.

### 3.3 Individual elemental technology (based on geochemistry)

#### a) Geochemical reaction experiment (batch type)

Batch experiments using fine rock sample and CO<sub>2</sub> water to estimate products after equilibrium (e.g. Satake et al., 2023).

#### b) Reaction experiment by flowing CO<sub>2</sub> through core-shaped rock sample

Investigate the reaction between rocks and CO<sub>2</sub> by continuously flowing CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>

## 4. PRELIMINARY RESULTS

Two preliminary results are presented in this capture.

### 4.1 Rock fracturing experiment

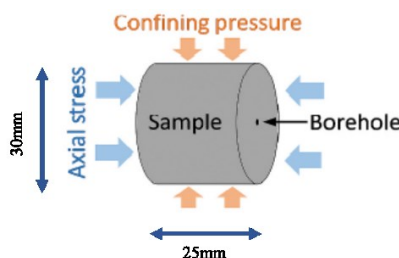
To clarify the difference between fracturing with water and ScCO<sub>2</sub> as a fracturing fluid, the fracturing fluid is injected into a cylindrical rock sample (diameter 30 mm, length 25 mm) under confining pressure (30 MPa), axial pressure (100 MPa), and temperature (250°C). The changes in injection pressure and the occurrence of AE were observed (Takuma et al., 2024).

**Table 1: Mechanical and hydraulic properties of Honkomatsu andesite**

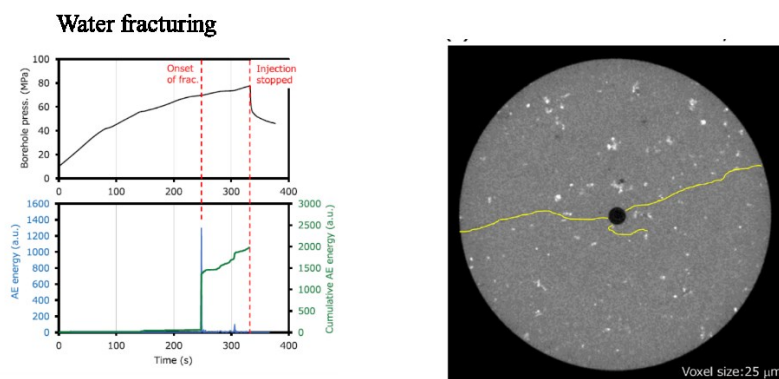
Porosity (%)	5
Permeability (m <sup>2</sup> )	$1\sim 4 \times 10^{-18}$
Tensile strength (MPa)	10
Uniaxial compressive strength (MPa)	242
Young's modulus (GPa)	26
Poisson's ratio	0.3
Cohesion (MPa)	40
Internal friction angle (degree)	58

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. The location of this rock sample is shown in 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 changes of the injection pressure and the production of AE were observed.

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

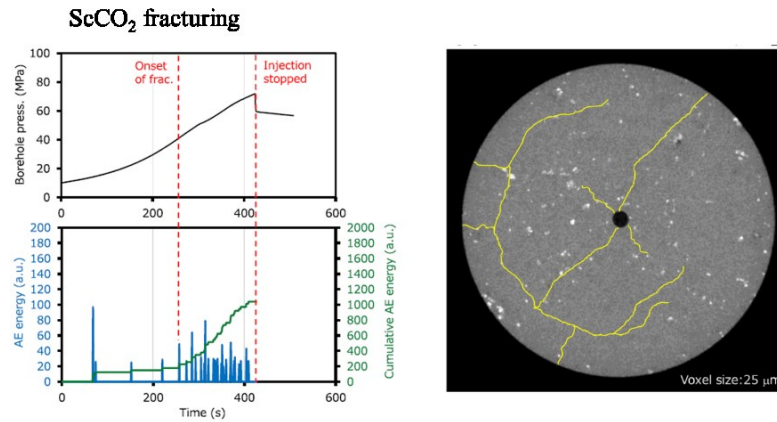


**Figure 5: A rock sample for the fracturing experiment**



**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)**

In the other hand, when ScCO<sub>2</sub> 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<sub>2</sub> as a fracturing fluid, and this may be due to the low viscosity coefficient of ScCO<sub>2</sub> shown in Figure 7.

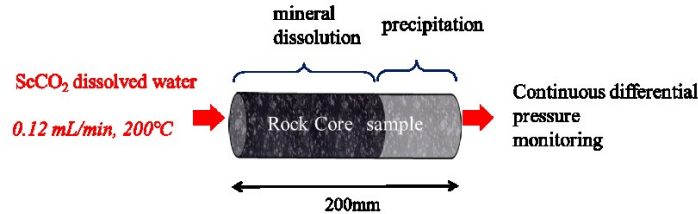


**Figure 7: Changes in borehole pressure (upper left figure) and AE energy (lower left figure) with time in the ScCO<sub>2</sub> fracturing experiments and core X-ray CT image after the experiment (right figure)**

AE was also generated in experiments using ScCO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> dissolved water**

The project uses ScCO<sub>2</sub> as the working fluid, which transports thermal energy from reservoir to turbine with a power generator. Geochemical reactions between rock minerals and ScCO<sub>2</sub> (and ScCO<sub>2</sub> dissolved in water) is expected at 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**

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

Oxides	Andesite	Basalt	Minerals	Andesite	Basalt
SiO <sub>2</sub>	61.13	51.89	feldspar	28.8	59.1
TiO <sub>2</sub>	0.8	1.63	clinopyroxene	5.2	17
Al <sub>2</sub> O <sub>3</sub>	16.72	16.17	orthopyroxene	7.2	0
(Fe <sub>2</sub> O <sub>3</sub> ) <sub>total</sub>	6.93	11.28	glass	10.5	14.6
MnO	0.15	0.15	olivine	0	2.5
MgO	2.52	6.38	opaque mineral	5.4	5.2
CaO	6.2	8.75	others	28.7	0
Na <sub>2</sub> O	3.53	2.83	secondary minera	14.3	1.6
K <sub>2</sub> O	1.69	0.45	total	100	100
P <sub>2</sub> O <sub>5</sub>	0.18	0.22		wt%	wt%
LOI	nd	0.25			
	wt%	wt%			

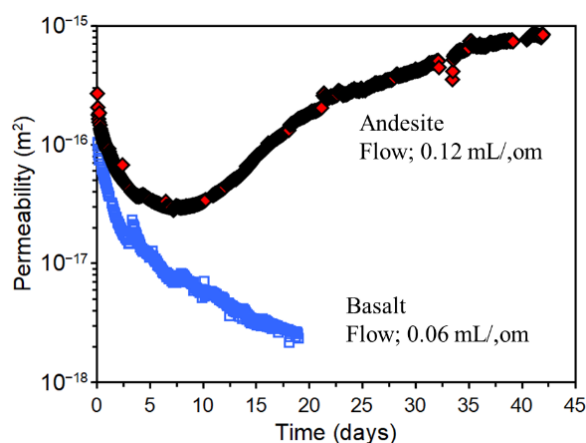
Nishiyama et al. (2025) used core samples of natural basalt and andesite to inject ScCO<sub>2</sub> dissolved in water and observed changes in permeability (Figure 8). A rock sample is shaped into a cylinder, and a mixed fluid of ScCO<sub>2</sub> and water is flowed under a constant temperature and pressure. Continuous pressure measures are carried out between the fluid inlet and outlet. The experimental conditions are 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  $1.4 \times 10^{-4}$  Pa s at 200°C and 10 MPa (Akinfiyev 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**

temperature	200°C
pore pressure	10 MPa
lateral pressure	14.5 MPa
Distribution period	42Days
flow rate	0.12 mL/min
fluid	CO <sub>2</sub> dissolved water (pH ~3.6)

The andesite core sample after the ScCO<sub>2</sub> 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**

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<sub>2</sub> 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 shell is created it works as cap rocks. ScCO<sub>2</sub> is one of the best flowing fluids rather than water in the EGS technology. 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<sub>2</sub> content of the circulating fluid.

## 5. CONCLUSION

Development of geothermal energy is of importance in the carbon neutral plan against the global warming. The geothermal energy is currently taken by the conventional geothermal development, which explores underground natural geothermal reservoirs and takes out geothermal resources. This geothermal energy development, however, is not progressing in Japan because of not only the long time necessary for the development 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 technology development bases on a different perspective than conventional geothermal development. The technology creates an artificial geothermal reservoir, controls injection waters, and generates electricity and is expected as the next generation technology of geothermal development. Regarding the method of forming an artificial reservoir using ScCO<sub>2</sub> as a fluid for fracturing rocks, the injection of ScCO<sub>2</sub> in the JOGMEC's new geothermal project 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<sub>2</sub> as a working fluid for rock crushing as an EGS technology.

In the CO<sub>2</sub> utilisation for working fluid CO<sub>2</sub> behaviour in aquifers is still unclear. Although the similar technology for the underground storage of CO<sub>2</sub> is used in CCS projects, the temperature range is completely different. The time required for CO<sub>2</sub> mineralisation is thought to be several hundred years or more in the CCS project. In the high temperature site mineralisation should be more active and mineralisation with reaction between ScCO<sub>2</sub> and minerals will be happened in shorter time scale in EGS site. It is necessary to accumulate more data on the geochemical reactions between CO<sub>2</sub> (+H<sub>2</sub>O) and minerals within the reservoir.

The occurrence of induced felt earthquakes due to water injection has also been observed in the overseas EGS sites (Evans et al., 2012) and is recognized as a significant environmental impact associated with EGS. The induced felt earthquakes due to fluid injection underground has also been reported in the shale gas development field (Li et al., 2019). The avoidance and suspension of the induced

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