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ABSTRACT:

The Matsushiro basin, Nagano city, Central Japan, is a unique natural analogue site of the CO₂ storage and leakage through fault. From May 1966 to February 1967, ten million tons of CO₂-bearing water discharged through surface ruptures and springs midst an earthquake swarm. The swarm began in August 1965 and the active period lasted two years followed by three-year relatively silent term. The location of water and CO₂ discharge was concentrated in a narrow strip along the main focal fault. Weak seismic activities, CO₂ bearing hot spa, and bubbles in rice paddy are observed, so the low intensity activities seem to continue. The fault is a left-lateral strike-slip fault striking NW-SE. Surface upheaval up to 90 cm and lateral motion corresponding to the strike-slip fault were observed. Based on this and additional geophysical evidence, some past studies adopted the idea that the upward water migration in the fault played a major role in the occurrence of the earthquake through the dilatancy mechanism. In this model, the earthquakes are assumed to follow the preceding hydrological and hydraulic phenomena such as water migration to the fractures in rock mass, reducing effective stress, and shear failures with increasing permeability. The authors anticipate that also CO₂ played some vital roles in the phenomena observed at Matsushiro, and we could learn the CO₂ behaviour in the underground condition. We assume that the fault and CO₂ bearing water interacted through chemo-physical (precipitation/dissolution of carbonate and phase change) and mechanical (CO₂ pressure induced stress and permeability change in the fault) processes, and affected the flow characters, seismicity, and the initiation and termination of the activities. For the investigation, geochemical surveys were carried out in the area to characterize present day surface CO₂ flux. Geochemical and geomechanical modelling are being conducted for the quantitative understanding of the mechanisms. Also, water production test and coring are being conducted using shallow borehole to better understand how surface geology and hydrogeology affect the CO₂ migration. The result of this study will be used to better understand CO₂ migration in fault systems, combined with knowledge from other natural analogues.

Natural Analogue Study for Geological Sequestration of CO₂ at the Matsushiro Earthquake Fault Zone, Japan: CO₂ Seepage Mechanism

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Introduction

Studies of natural analogues are very useful for identifying key mechanisms and processes relevant to long-term stability and seepage mechanisms associated with CO₂ geological sequestration. Recent science reports on the safety of CO₂ geologic sequestration, identifies faults and their dynamic behavior as the major potential paths and cause of CO₂ seepage, respectively. Because the dynamics and long-term behavior of faults are difficult to characterize by laboratory tests, studies of natural analogues provide valuable knowledge about potential fault behavior during deep injection of CO₂.

In mid-1965, a swarm of earthquakes began in the Matsushiro area of Nagano city, Central Japan. The most active period lasted until 1967, followed by a five-year period of lower activity until 1970. During the earthquake swarm, a large volume of CO₂-saturated water discharged at the ground surface through surface ruptures in the epicenter region. The earthquake swarm was well observed and documented, and many scientists investigated the mechanism behind the tremors.

The Matsushiro earthquake swarm is a promising natural analogue to study the interaction of CO₂ bearing fluid flow and solid deformations. Thus, we have initiated a joint project using state-of-the-art coupled processes modelling and CO₂ flux measurement. In this paper, we briefly describe the Matsushiro earthquake swarm, one hypothesis of the mechanisms (leading to/causing) the swarm, and our research plan to investigate and try to verify such a hypothesis.

This study is carried with a grant of the Ministry of Economy, Trade and Industry of Japan. This paper describes the whole project and the scope of the geomechanical modelling. The scope of geochemical study is described by Todaka et al. [2006a, submitted] in GHGT-8.

Matsushiro earthquake swarm

During the five-year term of the swarm, between 1965 to 1970, approximately 60,000 earthquakes were felt while an additional ten times, i.e. about 600,000, unfelt tremors were recorded [JMA, 1968]. The total energy released was M6.4, and the energy of the maximum single earthquake was M5.4. During the swarm, ten million tons of CO₂ bearing water discharged at the surface through newly created surface ruptures.

The distribution of the surface ruptures and horizontal displacements of the ground surface showed movements along a left lateral, NW-SE oriented, strike slip fault, which is centered near the swarm epicenter. Also, up to 90 cm of uplift was measured. One probable cause of the swarm is water intrusion from great depth and associated dilatancy reactivated the fault system (Nur 1974, Kisslinger, 1975). Nakamura [1971] defined this mechanism as “water eruption”. Shimizu [1971] reported about CO₂ dissolved in the water.

We hypothesize that the water intrusion was the main cause of the earthquake swarm, and chemical and mechanical interactions of CO₂ with the formations played key roles controlling the eruption of water and CO₂ at the surface. Hence, we are studying how CO₂ migration depends on the dynamic behaviour within the deep formations. Specifically, we are studying how the dynamic fault behavior affects the trapping mechanisms for CO₂, and how potential breaches of cap formations along faults and the overlying fault system may control CO₂ up-flow. A schematic view of the assumed CO₂ path is shown in **Figure 1**.

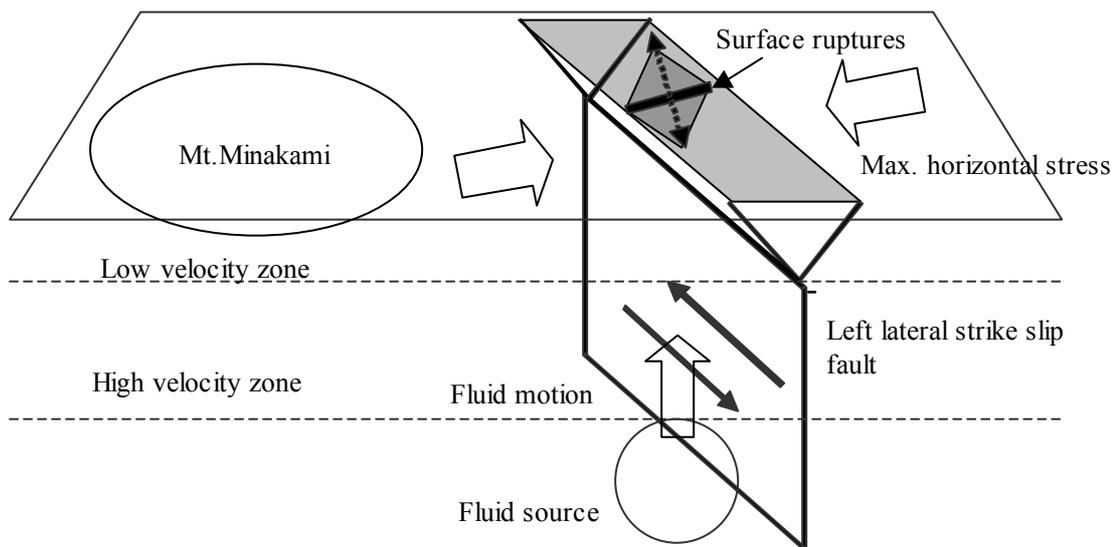


Figure 1. Schematic of the assumption of fluid intrusion and fault motion of Matsushiro earthquake swarm.

Investigation methodology

To investigate and try to verify the hypothesized mechanism for CO₂ release, and to investigate at what conditions such phenomena could occur at a CO₂ injection site, we plan to 1) synthesize existing data for the Matsushiro site, 2) conduct new CO₂ flux measurements at

the site, and 3) perform state-of-the-art coupled processes modelling, including both geomechanics and geochemistry. New soil gas and CO₂ flux measurements will be conducted in the area to identify the present path and magnitude of the CO₂ flow. Geochemical modeling with the TOUGH-REACT reactive transport simulator Xu et al. [2004] is used to analyze fluid flow, including phase transition of CO₂ and chemical reaction of carbonic acid and rocks. The coupled CO₂ fluid flow and mechanical processes, including fault motion and associated permeability changes, are modelled using the TOUGH-FLAC coupled reservoir-geomechanical simulator [Rutqvist et al., 2002]. The study structure is shown in **Figure 2**.

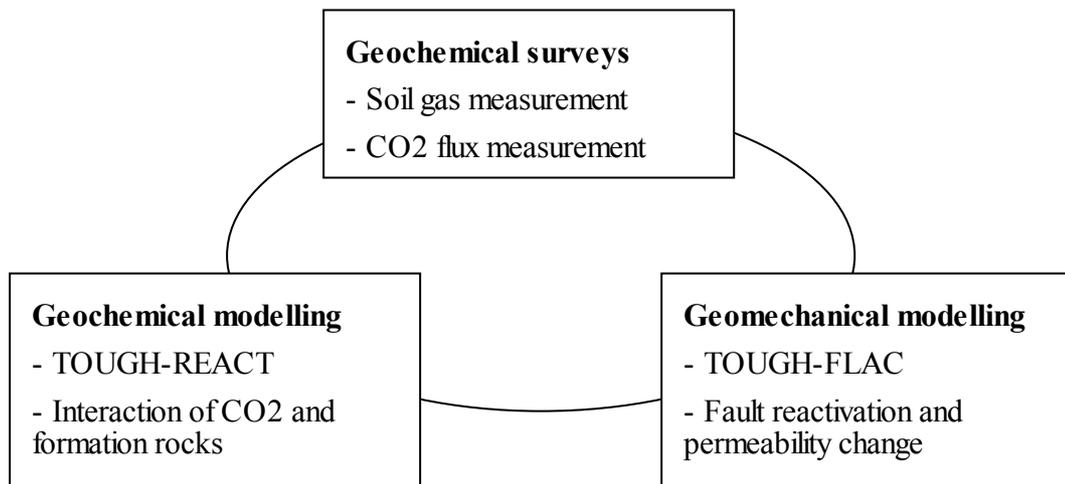


Figure 2. Plan for the natural analogue study of the Matsushiro site.

Conclusions

The Matsushiro site has been identified as a promising natural analogue for studies of fault - fluid interaction related to CO₂ injection, including both mechanical and chemical interactions. The combination of geochemical surveys, geochemical and geomechanical modelling, as well as comparison with other natural analogue sites are expected to add knowledge about the fluid seepage through a faulted rock system. Also, simulation models employed here will be tools for assessing the risk of CO₂ seepage and designing CO₂ storage facilities. The outcomes of the study will be valuable for establishing risk assessment and management guidelines for CO₂ seepage through faults.

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Earthquake related fluid migrations: Mechanism, historical records and lessons learnt

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Introduction

In the image of public, earthquake is regarded as a potential cause of rapid or catastrophic seepage of stored CO₂ in sequestration sites. In fact, there are some cases of earthquake related fluid migration to the surface, but there is no report of human causality. Here, some of such cases are described, and possible mechanisms of them are discussed. Such knowledge is useful for the site selection of CCS program.

Mechanism and historical record of fluid motion/fluid pressure change due to earthquakes

Direct relation of gas migration and seismic fault motion

Fluid pressure increase causes the reduction of effective stress. In the condition of high shear stress, this process works as the reduction of frictions and cause the subsequent shear failure. In the seismic active zone, the stress condition is “critical” in which small stress change easily cause the failure. On the other hand, fault motion (both opening and shear displacement) changes, basically increasing, permeability, and can create or enhance fluid flow path. Also, large and rapid deformation of the formation can cause pore pressure surge because pressure diffusion in low permeable rock is a slow process than earthquake.

A well-known case of the interaction of fluid and earthquake happened in Rocky Mountain Arsenal near Denver Co. when wasted fluid was injected in deep well [Evans 1966]. For the geophysical researches, similar process was intentionally caused by water injection to faults in Rangely oil field (CO, USA), Matsushiro (Nagano, Japan), and Nojima fault (Hyogo, Japan). This process, Micro Seismic, is also used for the monitoring of injected fluid motion for the monitoring of EOR (Enhanced Oil Recovery) operation.

Miller et al.[2004] reported a case of relatively big aftershocks following the main shock in Apennine Mts, Italy in 1997. They found that the focal points of the aftershocks correspond to the migration of CO₂ in major faults.

In the above cases, no fluid release to the surface was observed. In Matsushiro, however, vast volume of CO₂ dissolved water appeared on surface during the Matsushiro earthquake swarm (1965-1967) [Nakamura 1971].

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Stress change due to earthquake

Earthquake is a process of stress release from the critical state. However, redistribution of the stress can make stress concentration and pore pressure change at some places due to the heterogeneity of the earth crust (Fig.1). In fact, change of ground water level, spring water production rate and noble gas concentration in the ground water in pre- and post-seismic periods have been studied for the earthquake prediction purpose.

Seismic wave induced pore pressure

According to the theory of dynamic poroelasticity by Biot [1956], P-wave contains the pore-pressure component. When displacement is large, also S-wave can cause pore pressure through dilatancy mechanism (Fig.2). Pore pressure measurement at some underground oil storage sites and a mine showed co-seismic pore pressure change [Sasaki et al. 1999, Hasegawa et al. 1999]. The level of the pore pressure change is not great, but not negligible level when the stress condition is critical.

Surface deformation

Deformation of earth crust by earthquake is largest at the surface because of the amplification of free surface. In fact, damage of underground structures caused by major earthquakes is less significant than surface structures. When the stored gas is in shallow depth, surface deformation and failure such as creation of cracks, land slide, liquefaction etc. lead the local failure of seal mechanism. In Chitose, Hokkaido, Japan, natural gas erupted at several places just after the M8.0 Tokachi-oki earthquake in 2003, although the epicentre is 220km far from this place. The area is known as high gas flux region, and gas flow is observed in many places in the regular condition [Kanoko and Inokari, 2005]. The origin of the gas is deep underground, but some volume of gas is usually stored in shallow formation and move to surface gradually. After the earthquake both surface condition and stress state change in this area cause the rapid release of natural gas.

Lessons learnt

Earthquakes surely affect the stability of the stored CO₂. However, their risk depends on the mechanical condition of the storage site, and is not common. Only when the stress and pore pressure has been already critical, the failure of the seal mechanism occurs, and the earthquakes work as triggers. Also the observation of natural phenomena suggest that the CO₂ discharge is a temporal phenomena, and the fluid flow is decreasing to the normal level, because excess pore pressure is released, and fluid flow usually reduce the fault permeability by the fine particle migration and other mechanisms. Therefore, catastrophic seepage by the earthquake is not likely.

For the safety CO₂ storage, information of faults and natural fractures is important. Also the stress state is how close to the critical condition is the key knowledge of safety assessment. The microseismic survey during injection stage can give useful information about this.

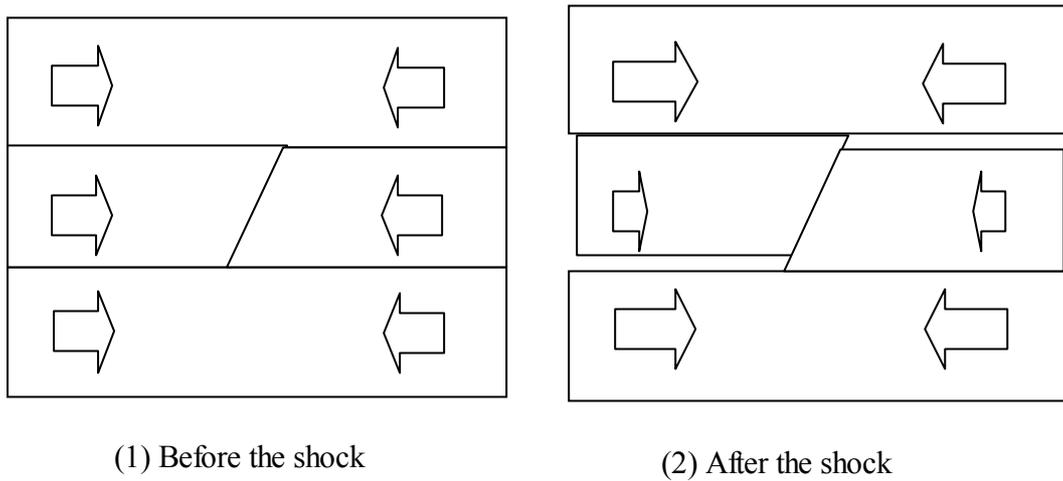


Fig.1 Stress re-distribution after an earthquake

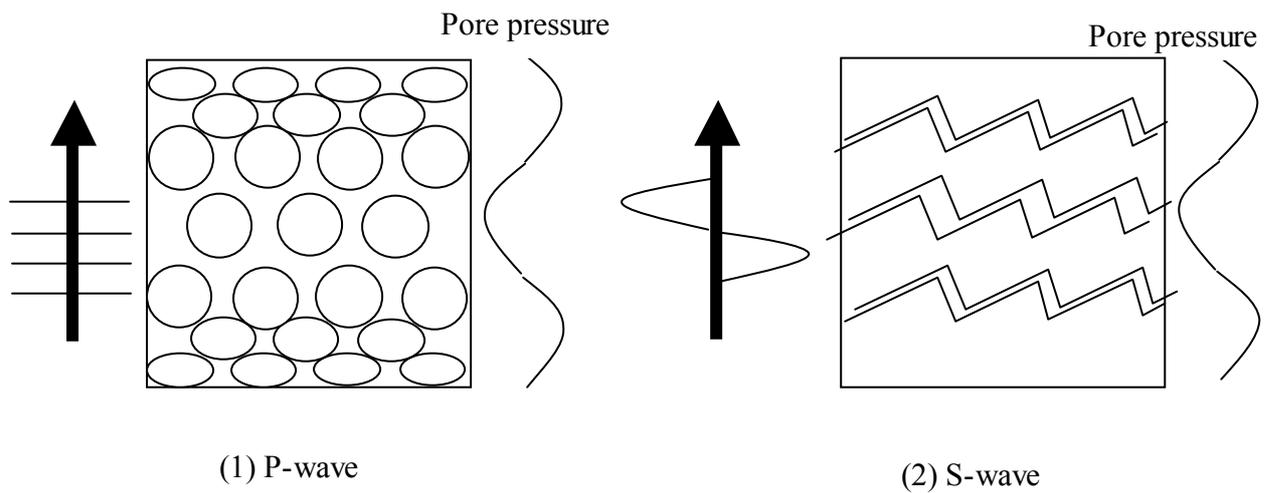


Fig.2 Wave motion and induced pore pressure

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Natural Analogue Study for Geological Sequestration of CO₂ in the Matsushiro Field, Japan: Geochemical Modeling

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Introduction

Two fluid paths in the geological formation are considered as potentially considerable risk of CO₂ leakage. One is an abandoned well and the other is a fault zone or open fracture. To better understand environmental effect and manage the risk associated with CO₂ storage, we study mechanism and conditions of leakage through the fault zone based on natural analogues. The Matsushiro field in central Japan is selected to understand hydrogeochemical and geomechanical effects due to CO₂ leakage. It is a famous place as the Matsushiro Earthquake Swarm between 1965 and 1968. During this period, huge amount of water and CO₂ discharged from the fissures (Figure 1). We are conducting soil gas (CO₂) survey and CO₂ flux monitoring in the Matsushiro field. CO₂ flux will be monitored for one year at some measurement points of high soil gas concentration. Soil gas concentration and CO₂ flux between present and the active period of earthquake swarm will be compared to validate geomechanical and geochemical models.

This study is carried out as a part of Monitoring and Modeling Studies for “Environmental Effect and Risk Management Study for Carbon Dioxide Geologic Sequestration using Natural Analogues”, sponsored by Ministry of Economy, Trade and Industry of Japan. This paper describes the scope of the geochemical study. The whole project and the geomechanical modeling are described by Yamamoto et al. [2006a and 2006b, submitted] in GHGT-8.

Methodology

In this paper, reactive geochemical transport simulations using the code TOUGHREACT [Xu et al., 2004] were carried out to study the natural analogue of geochemical changes caused by the Matsushiro Earthquake Swarm. The numerical simulation tool TOUGHREACT was developed by introducing reactive chemistry into the framework of the existing multi-phase fluid and heat flow code TOUGH2 [Pruess et al., 1999].

Problem Setup

Field description: The earthquake swarm had been extremely active for 3 years from 1965 (Figure 2). A vast amount of groundwater and CO₂ gas discharged from the surface fissures

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for the active period. Changes in water chemistry from wells and fissures are measured for the active period. Figure 3 shows an example of change in the chloride concentration of the hot spring water from the shallow well (Well No.1 of Ichiyokan). In the periods I and II in Figure 3, chloride concentration and water discharge showed only small changes. The discharges of water and CO₂ gas began to increase from September, 1966. It is consistent with the peak of seismic activity in the period III. Chloride concentration of the hot spring water increased rapidly after the peak of seismic activity in the period III. It might be mixed with the ascended deep brine. From 1967 to present time, seismic activity rapidly decreases but chloride concentration is almost constant.

Such chemical changes would be caused by mainly mixing of the deep brine with high concentration of dissolved CO₂ gas, based on the relationship between chloride and bromine. Okusawa and Tsukahara [2002] considered that changes in sodium and calcium concentrations are due to water-rock interaction as well as water mixing.

Conceptual model: Figure 4 shows conceptual model of CO₂ leakage in the active period of the Matsushiro Earthquake Swarm. The deep brine (Cl: 11,000 mg/l at a depth of 1,800m) with high concentration of dissolved CO₂ would be upwelling along the fault zone. CO₂ would be degassing from the brine due to water pressure decrease as original deep brine flows up. The pH would increase when CO₂ degasses and calcite might precipitate in the fault zone like calcite scaling in the geothermal production wells. According to Okusawa and Tsukahara [2002], there might be some aquifers. The deep brine with degassed CO₂ ascending from the fault zone would partly flow laterally in each aquifer and mix with groundwater with lower concentration of chloride.



Figure 1. Photo shows water and CO₂ discharged from fissure zone in the Matsushiro field [Nakamura and Tsuneishi, 1967].

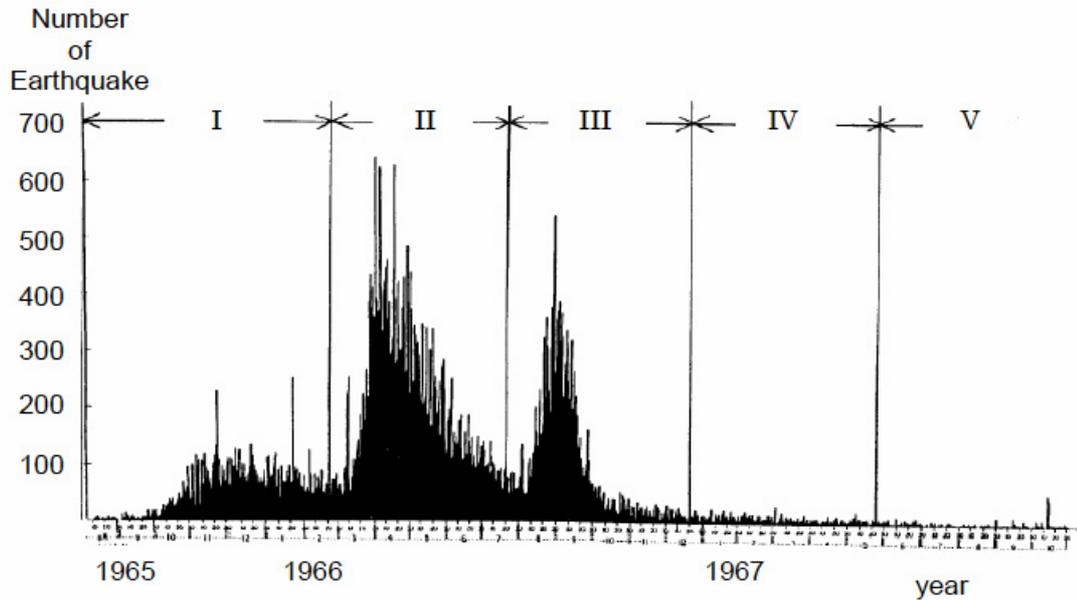


Figure 2. Number of felt earthquakes in the period from 1965 to 1968 [JMA, 1968].

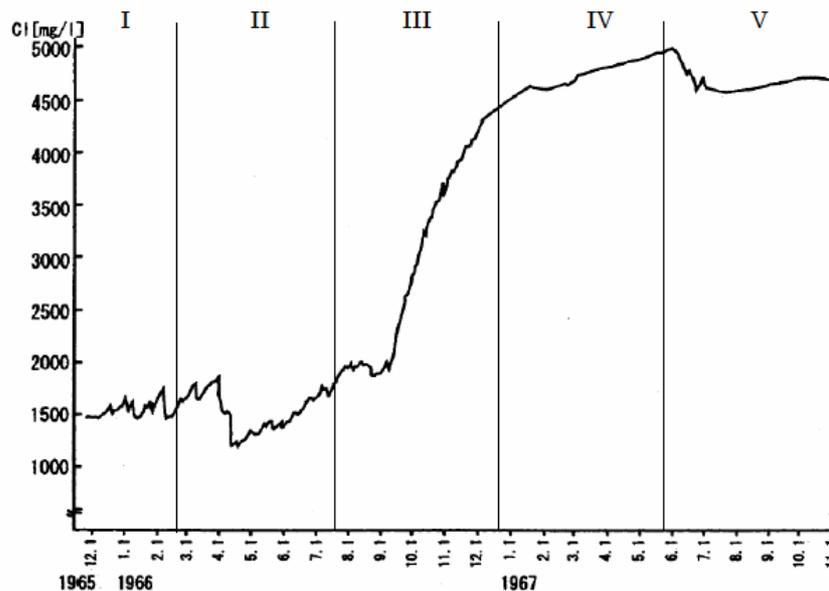


Figure 3. Change in chloride concentration of hot spring water for the active period (Okusawa and Tsukahara [1992]).

Simulation: Using the historical data such as discharge rate, chemical compositions of water and seismic activity, we plan to make a numerical model to reproduce the geochemical behavior during the swarm earthquakes. To evaluate geochemical effect of degassing brine upwelling along fault zone, one-dimensional (1-D) model using Multiple Interacting Continua (MINC) method will be carried out. The upwelling zone from surface to 1,800 m depth was

modeled. The 1-D model was intended to explore the general geochemical behavior when the brine is upwelling. A linear temperature gradient from 10°C to 98°C is assumed in the non-isothermal flow model.

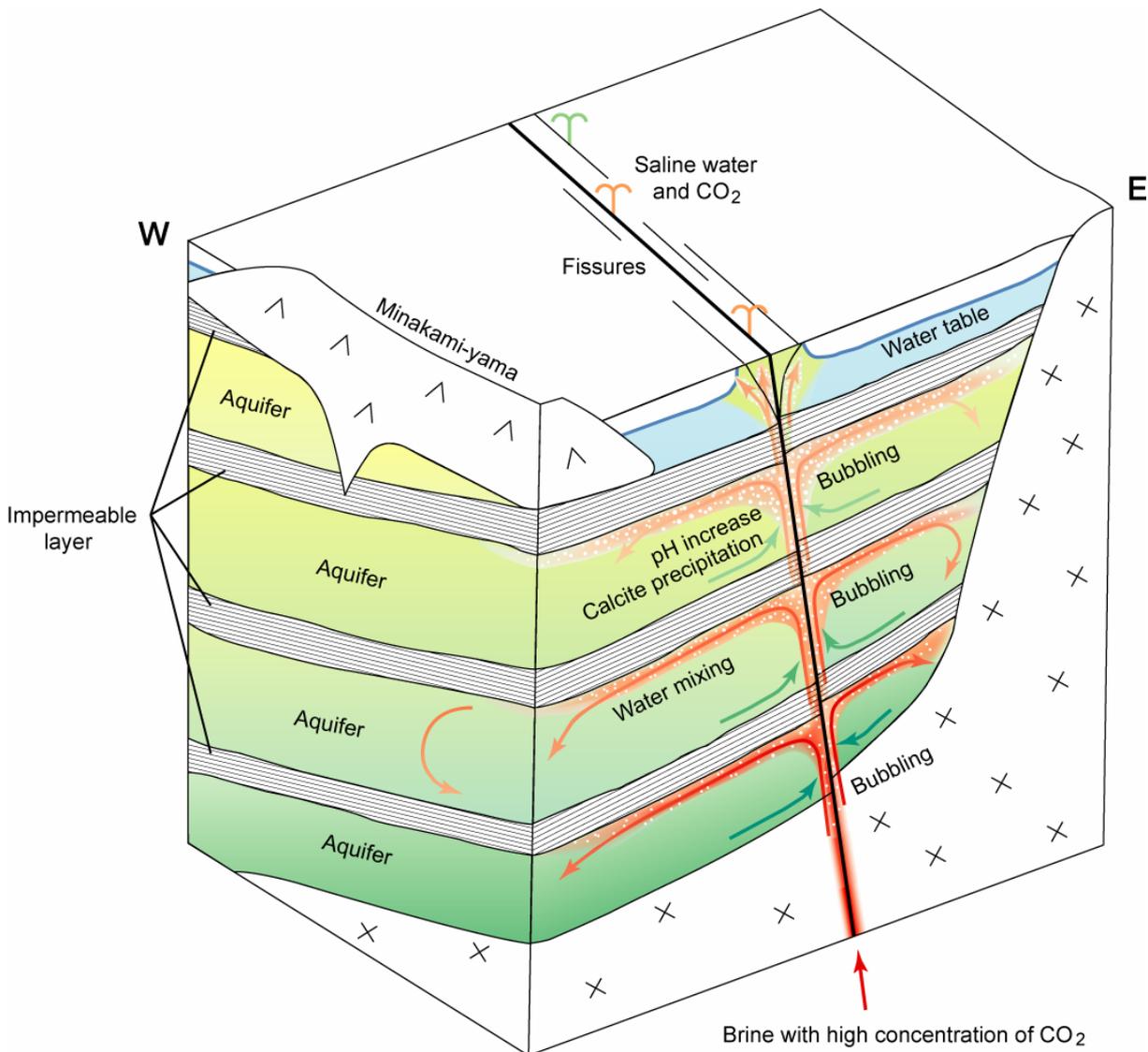


Figure 4. Conceptual model of CO₂ leakage by Matsushiro Earthquake Swarm.

Future simulations

A reactive fluid flow and geochemical transport numerical model will be developed to evaluate CO₂ leakage along the fracture zone using natural analogue of CO₂ leakage caused by the Matsushiro Earthquake Swarm in this study. In the next step, we plan a 2-D simulation and finally perform a predictive simulation if the injected CO₂ leaks along the fracture zone, using the EOS module including transitions from super- to subcritical conditions, and boiling of liquid CO₂. Then, we will evaluate environmental effect by CO₂ leakage from the geochemical point of view.

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