Development of rock deformation techniques under high-pressure and high-temperature conditions

— Evaluation of long-term geological processes by a compressed timescale process model —

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The reliability of earthquake forecast information is important for disaster mitigation in our society. A physical model of the earthquake generation process was constructed to improve the reliability of earthquake forecast information. We proposed a model based on the information extracted from geological surveys. Our model was evaluated using experimental techniques in the laboratory. During the experimental study, we considered two disparities between laboratory and natural conditions, which were differences in environmental conditions and timescale. A new experimental rock deformation technique was developed that unifies previous and newly developed techniques. Long-term geological processes were evaluated by a process model operating over a compressed timescale.

Keywords **:** Earthquake, geological survey, rock mechanics, high-temperature and high-pressure, disaster mitigation

1 Introduction

We, the members of the earthquake research community, wish to contribute to making society resilient to disasters. The final goal of the study of earthquakes is to help mitigate disasters caused by earthquakes through scientific results. Although disasters cannot be prevented, society can prepare appropriately for them. When information and forecasts that are accurate and geologically and physically reliable are quickly transmitted, they become basic information useful to society to prepare for disasters. Forecasts must be delivered not as mere hypotheses; rather, they must be based on verified results and delivered in the words of science. Although uncertainty is inherent in earthquake forecasts arising from data and models,[1] the AIST research team aims to improve earthquake forecasts by building an earthquake forecast model with high precision. To construct a highly precise earthquake occurrence model, it is necessary to first develop a geologically and physically reliable model of the various processes that must take place for an earthquake to occur. In this paper, I report techniques and methods developed to verify such a model.

In overview, earthquake research includes various research methods, such as geological surveys, observations of phenomena such as seismic waves and groundwater, computer simulations, and laboratory experiments. All of these various types of earthquake studies supplement each other to help us better understand earthquakes.[2][3] For example, research is being conducted to forecast the occurrence period and scale of future mega-earthquakes by clarifying the occurrence period and scale of past mega-earthquakes by studying the past activity (the activity history) of active faults and tsunami deposits.[4][5] Other studies being conducted at AIST aim to swiftly detect abnormalities in observations obtained by constant monitoring of crustal changes (minute movements and changes near the Earth's surface) and earthquake occurrences in the Japanese islands using the latest observation technology.[6] The objective of this study was to clarify earthquake occurrence mechanisms and underground rock behavior, because it is impossible to understand how earthquakes occur unless these are clarified. This study is an attempt to refine the earthquake forecast model by clarifying earthquake occurrence models and scenarios. Figure 1 is a flow chart that summarizes the various components of research that contribute to earthquake forecasting and shows the role and position of high-temperature and high-pressure rock experiments in the overall research scheme.[7][8] In this paper, I report experimental technologies and methods used to accelerate geological phenomena that normally progress on a thousand-year timescale in a laboratory, and I show how rock experiments conducted with those technologies and methods can be used to verify an earthquake forecast model.

An earthquake occurs when a fault moves beneath the earth’s surface. When a rock fractures underground, the fracture is accompanied by rapid movement (displacement) along a certain plane (the fault plane). Although in the natural world, an earthquake is a complex phenomenon, rock experiments have an important role in determining the dominant factors

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composing the fracture process mechanism, in constructing a physical model of the process, and in verifying the model. A laboratory experiment does not re-create in miniature fault movement that occurs in the natural world, so it is important when designing laboratory rock experiments to determine how natural and laboratory conditions differ (Fig. 2). For example, they differ with respect to size, timescale, and structure. The size difference is the difference in spatial scale at which the process occurs. Do processes that occur in rock samples in the laboratory exactly reproduce the wide-ranging fault movement and deformation/fracture processes that occur in nature? Experimental results have shown that the fracture strength of a rock differs according to the size of the sample. In natural fault movements, it is known that some properties of the movement are dependent on the fault size and others are not. While it may be relatively straightforward to replicate and study properties that do not depend on spatial size in the laboratory, the size-dependent properties must also be studied to determine how they change with size; then, to interpret the natural processes, the laboratory results must be extrapolated to the natural scale. The friction law on which current computer simulations of earthquakes are based was determined mainly from rock experiments conducted in the laboratory, but it has been clearly shown that the frictional properties of rocks differ depending on the area (spatial size) of the contact surface.[9]

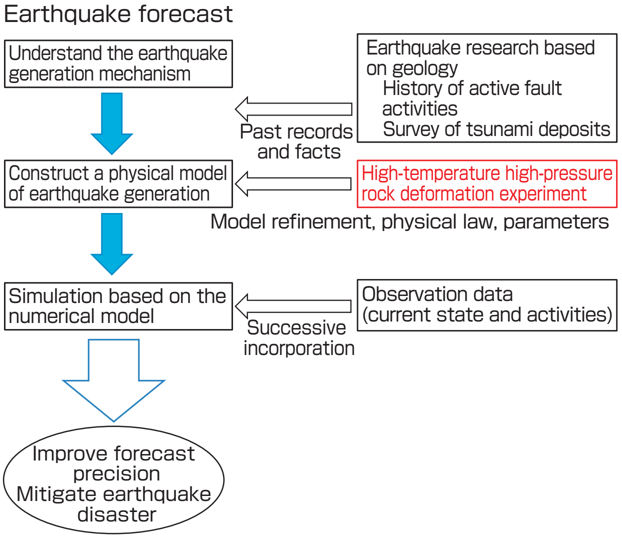

Fig. 1 Flow chart of earthquake forecast research and the position of high-temperature and high-pressure rock deformation experiments in the overall research scheme

To forecast earthquake occurrences, it is necessary to correctly understand the earthquake occurrence mechanism, to construct a physical model of earthquake occurrence, to develop a numerical model of earthquake processes, including those leading up to earthquake occurrences, and to replicate them in a computer simulation. High-temperature and high-pressure rock deformation experiments contribute to the refinement of the earthquake occurrence model by providing knowledge that can be used to determine the constitutive equation and its parameters, as well as by verifying the physical model.

Another important difference is the difference in timescale between the natural world and the laboratory. In the natural world, earthquake-related processes normally progress extremely slowly. Because the occurrence interval of earthquakes that cause major disasters is several hundred to a thousand years, we cannot replicate the progression of the processes involved at the same speed. In this paper, I report an example of an experiment in which these processes are accelerated. Also, the natural materials of a fault zone are not uniform; both the materials and their structural features are complex. What plays the main role in fault movements? For example, in a fault zone composed of several types of materials, does one material dominate the overall fault movement? Where does the movement occur? The properties of the material that occupies the most space in terms of volume percent does not necessarily dominate the fault movement process. If slip or movement occurs dominantly in a particular fault zone stratum, then the properties of that stratum, though it may account for a low percentage of the materials in the fault zone, must be investigated carefully to learn how and why the fault movement occurs. Thus, the aim of rock experiments in the laboratory is not to imitate the natural world, but to extract and investigate the essential mechanism of fault movement.

2 History of the development of rock experimental technology

For the rock experiments in the laboratory, von Karman first developed a deformation testing device using hydrostatic pressure in the 1910s; Griggs succeeded in developing a modern experimental apparatus for rock deformation experiments in the 1930s; and researchers such as Handin

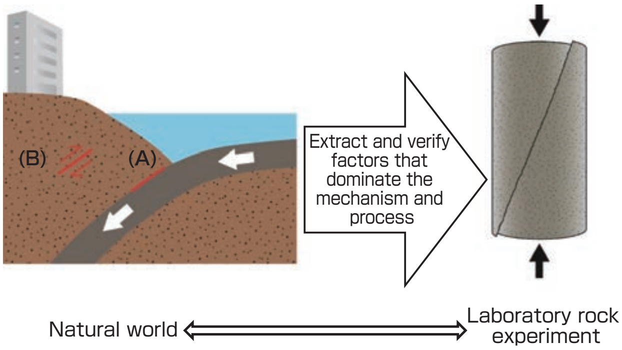

Fig. 2 Fault zones in the natural world and faulting in a laboratory rock experiment

Left: Occurrence zones of a subduction zone earthquake (A) and an inland earthquake (B) caused by plate subduction. The arrows show the direction of fault slip. Inland earthquakes are also caused by other types of slip such as normal faults and lateral faults.

Right: A cylindrical rock sample used to reproduce faulting in a laboratory experiment. Rather than trying to exactly replicate fault movement in the laboratory, the important aims of a rock experiment are to determine the factors that dominate the processes and mechanisms of natural fault movements, to construct a physical model on the basis of these factors, and to verify the model.

and Heard of the Shell Technology Center in Houston, USA, subsequently developed the technology further.[10] At present, rock experiments continue to be conducted in oil company laboratories, or with funding from oil companies, in relation to the development of shale gas. At the Geological Survey of Japan in the 1960s, Hoshino *et al.* designed several original devices for experimental deformation of rocks based on an apparatus used in the United States and produced prolific experimental data.[11] An experimental apparatus that used gas pressure was developed in the 1960s by Paterson at the Australian National University; this device was sold throughout the world through a spin-off company and was used widely in both Europe and the United States.[12] In the late 1990s, I considered purchasing this apparatus and went to Australia, where Paterson showed me the factory where the apparatus was made. However, because it was very troublesome at that time to arrange for an inspection and obtain clearance for the import of an apparatus using high-pressure gas, I did not purchase the apparatus. Instead, we, the AIST research team, developed a custom experimental system by integrating our own original technology with existing technology.

Recently, samples of actual fault rocks have been retrieved from deep underground by deep drilling projects that penetrated a fault zone. By measuring the physical properties of such samples in the laboratory, understanding of the large-scale slip that occurred in the shallow part of the fault zone during the 2011 off the Pacific coast of Tohoku Earthquake has been enhanced.[13] Currently, the most important challenge in the field of rock experimentation is to find and generalize the physical laws that govern various fault behaviors, to extract the parameters of a constitutive equation, and to fuse these findings with research on earthquake simulation by numerical models. To construct such a model, an accurate understanding of earthquake occurrence processes is mandatory. This paper reports on technologies and methods that have been developed in the effort to meet this challenge.

3 Issues in reproducing earthquake processes

An earthquake occurs when a fault beneath the Earth's surface moves. Therefore, to construct an earthquake occurrence model, it is necessary to first clarify the fault processes and movements that occur deep underground during an earthquake. We try to clarify fault movement processes by investigating the conditions under which a fault starts to move or an earthquake begins to occur, as well as the forces on the fault that result in the fault movement, by reproducing in the laboratory fault movements that occur deep underground. To reproduce processes that occur deep underground in the laboratory, technologies need to be developed to address the difference in environmental conditions and the difference in timescale between the natural world and the laboratory.

Temperature and pressure conditions are different deep underground than they are at the ground surface. To reproduce the conditions that prevail underground in the laboratory, it is necessary to develop experimental technologies to reproduce a high-pressure and high-temperature environment and also control for water content. Such an environment can be reproduced by first putting the material to be tested in the experiment into a sealed high-temperature and high-pressure vessel and then applying force to deform the material. This can be achieved by adding a pressure vessel that controls the sample environment to an apparatus based on existing technology in the materials science field.

The timescale of many natural phenomena is long; it is impossible to observe even one cycle of a phenomenon such as the occurrence of a mega-earthquake on the human timescale. The progression of the mega-earthquake processes, which is our research subject, is very slow, much longer than a human lifespan. For example, subduction-zone earthquakes such as a magnitude 8 class Nankai Trough earthquake occur at intervals of several hundred years, and a magnitude 9 class mega-earthquake such as the 2011 off the Pacific coast of Tohoku Earthquake occurs at thousand-year intervals. Earthquakes that occur on active inland faults in the Japanese islands may occur at intervals of more than a thousand years. This means that if one wishes to observe the processes occurring during one earthquake cycle, one needs several hundred to a thousand years or more. Here, we apply thermodynamics considerations.[14] From a microscale viewpoint, the progression speed of a process that occurs deep underground is thought to be regulated by the speed of chemical reactions, as will be discussed in the next chapter. Therefore, to observe and investigate in a laboratory setting the progression of a process that progresses extremely slowly deep underground, the progression must be sped up. To do this, it is necessary to develop a high-temperature technology to accelerate the speed of chemical reactions by producing higher temperatures than those that exist in the underground environment where the fault movement actually takes place. We developed our own high-temperature technology for this purpose.

4 Scenario for achieving our research aim and the integration of component technologies

Figure 3 shows the overall research flow and the component technologies used in this research. First, a working hypothesis is developed based on observations. The working hypothesis is verified by using methods and techniques that integrate specially developed technologies with existing technology. In this chapter, the component technologies are explained, and in Chapter 5, new concepts resulting from our research are presented.

4.1 Surface geological survey: using the geological record to construct a working hypothesis

First, to construct a working hypothesis, processes that contribute to the phenomenon being investigated are inferred. To estimate a phenomenon occurring deep underground, strata that were previously located deep underground but are now exposed at the surface are surveyed and observed (Fig. 4). In some regions, ridges have formed, or a previously buried stratum has risen over a long period of time, and at such places, it is possible to observe at the surface rocks that were deep underground in the past. What is manifested at the surface is the result of processes such as deformation and fracture that occurred deep underground in the past. By carefully observing and analyzing such materials, that is, rocks and minerals and their structures, the processes that occurred in the past can be inferred. However, although the geology records the past, these records are only snapshots of the results of past processes; their evolution over time and the amount of time that has elapsed cannot be finely read by a geological survey. Therefore, it is necessary to construct a model and a working hypothesis from the physical and geological evidence about what processes occurred to produce the observed results. This research involves developing procedures for reproducing the processes read from the geological record and verifying the resulting model.

Since the great earthquakes that cause major disasters repeat about every thousand years, changes must occur over

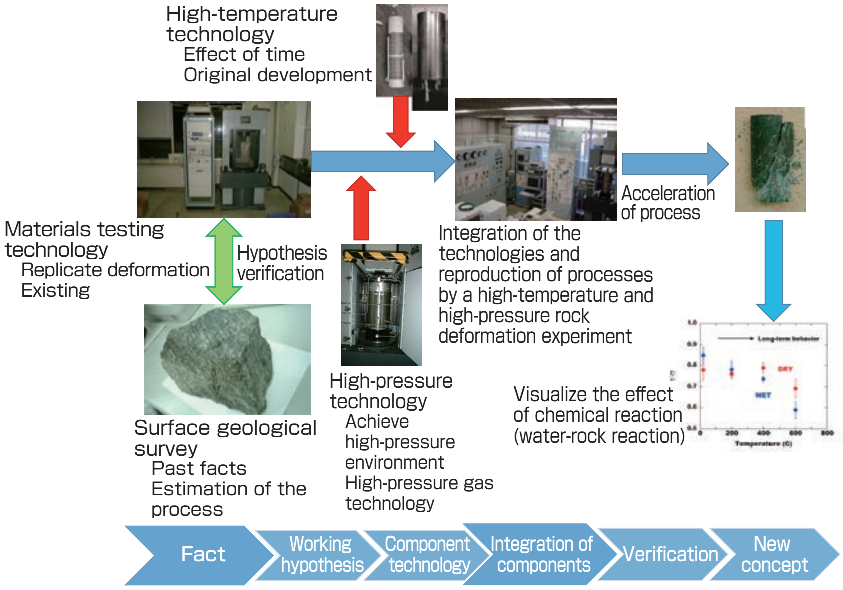

Fig. 3 Relationships among the component technologies and the overall flow of the research

Fig. 4 Surface geological survey

A stratum that was deep underground in the past but is currently exposed at the surface (outcrop) is being surveyed. The photographs show an outcrop along the median tectonic line (Nagano Prefecture). The rocks, which were deformed while they were deep underground, are being sampled. Processes that might have occurred in the past are inferred by observing and analyzing rocks and strata that record the results of processes that occurred a long time ago while the rocks were deep underground.

a timespan of about a thousand years, and the processes causing those changes must take place over this extremely long period of time. These processes slowly change the fault strength and deform the rocks. When water is present, chemical interactions between water and rocks must occur in the high-temperature and high-pressure environment deep underground. Although fault movement is imaged as a “slip,” isn’t friction really a micro-fracture occurring at the point where the surfaces on either side of the fault plane are in contact? Don't chemical reactions occur between rocks and water that affect the fracture process in this microscopic domain? We proposed a working hypothesis that such processes are important, namely, that friction really consists of micro-fractures caused by chemical reactions between rocks and water in the area of contact, specifically at the tip of asperities of the fault plane (Fig. 5). A rock fractures when a stress that surpasses its strength is applied, and the fracture progresses at the tips of cracks within the rock. According to this reasoning, a fracture or a change in state will not occur if the applied stress does not reach the fracture strength, nor will the crack continue to grow. However, cracks and fractures are known to slowly progress even in environments where the stress is less than the fracture strength. This phenomenon is called stress corrosion, and it is explained by a mechanism in which the rock materials or other substances react with water or other components in the surrounding environment and their strength decreases.[15][16]

4.2 Materials testing technology

Slow deformation and slip are thought to occur deep underground when force (crustal stress) is applied to rocks and faults. Therefore, to reproduce processes occurring deep underground, we measure the deformation and slip that occur when we apply force to rock materials. The method and technique used here are the same as those used in materials testing. Figure 6 shows an apparatus used in this research that was originally designed for materials testing. When this testing apparatus was acquired by AIST (Geological Survey of Japan) in the 1980s, it was used mainly to test the fracture toughness of rocks. For our earthquake research, we brought this apparatus, which had been lying unused since the project for which it had been acquired had been completed, back into service. The basic function of this apparatus is to apply upward and downward forces on materials (in this case, rocks) to deform and fracture them. A control unit (on the left in Fig. 6) controls the upward and downward movement of the piston that applies force to the sample in the materials testing device (on the right in the figure). A servo-controller causes the position of the piston, and thus the load applied to the sample material, to change at a constant velocity or according to some pre-set function (such as a sine function), and the changes in the position and load are measured. We replaced the original analog control unit with the latest digital control technology. This materials testing apparatus was used as the basic framework of our device for measuring the deformation and fracturing of rock samples and the force applied to the samples.

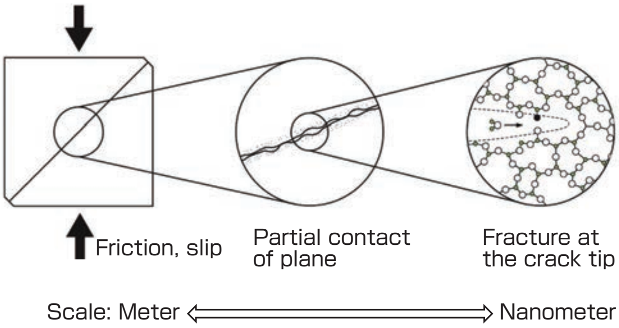

Fig. 5 Schematic diagram of friction and fractures
On a spatial scale of centimeters to meters, friction can be understood as a force resisting slip along a flat plane. However, at a small spatial scale of millimeters or less, the two surfaces on either side of the plane can be seen to not be in continuous contact, but only in partial contact. Micro-fractures occur where asperities on each surface contact the other surface. Such fracture processes in the contact area are the essence of the friction phenomenon. At a nanoscale, micro-fractures at the tips of the asperities progress slowly when water is present by means of chemical reactions.

4.3 High-pressure technology

Because the aim of this endeavor was not merely to conduct materials testing of rocks but to investigate how processes differ between the high-temperature and high-pressure conditions that prevail deep underground and those in the laboratory environment, we developed technologies to reproduce high-temperature and high-pressure conditions in which we could perform deformation experiments.

To produce a high-temperature and high-pressure environment in the laboratory, a solid or a fluid is used as the pressure medium, which is sealed inside a pressure vessel (sealed container). The pressure inside the vessel (confining pressure) is increased as the interior volume is decreased by inserting a

Fig. 6 Materials testing apparatus used for materials science investigations
Rocks were used as the test samples. Changes were made to this device in this study.

piston or by injecting more pressure medium from the outside. A higher pressure can be achieved when a solid material is used as the pressure medium than when a fluid is used. When solid materials such as talc, NaCl, or pyrophyllite are used as the pressure medium, they are enclosed in the vessel and the pressure is increased by a piston to create a high-pressure and high-temperature environment. However, when a solid medium is used, the pressure values cannot be measured accurately and the deformation of the sample under pressure cannot be measured with precision, so this method is not suitable for rock deformation experiments. Therefore, a fluid (liquid or gas) is used as the pressure medium in most rock deformation experiments. In reproducing high-pressure and high-temperature conditions with a liquid pressure medium, the maximum achievable temperature is about 500 ºC, even if silicon oil, a liquid with special properties, is used as the pressure medium. As it will be explained in the next section, it is necessary to achieve a higher temperature than 500 °C in this research; therefore, we used an inert gas (argon gas) as the pressure medium. Gas is an ideal pressure medium for applying a uniform pressure (hydrostatic pressure). However, when gas is used, particular attention must be paid to possible leakage. Also, because gas has a large compression ratio (i.e., the ratio of the volume change to the pressure change is large), a pump system that can deliver large volumes of gas is necessary to obtain high pressure. Moreover, because the change in volume is large, special care must be taken when operating the device. The characteristics and proper handling of high-pressure gas must be understood, and all safety regulations must be followed in compliance with the law.

A high-pressure experimental apparatus using gas as the pressure medium was developed later in Japan as compared with in other countries. The first gas-pressure testing device was designed and manufactured at Kyoto University around 2000. We obtained permission to use the technology developed at Kyoto University, and manufactured the second device in Japan.[17] The maximum pressure (confining pressure) achievable by these devices was 200 megapascals (MPa). As shown in Fig. 7, not only can this system apply pressure (confining pressure) to rock samples inside the pressure vessel, it can also deliver fluid (liquid or gas) directly to the sample from the outside, circulate the fluid, and control the pressure (pore fluid pressure) to a maximum of 200 MPa. We were thus able to conduct deformation and friction experiments with cylindrical rock samples with a maximum diameter of 20 mm and a length of 40 mm under such conditions.

To accurately measure the load applied to the sample inside the pressure vessel, we developed an internal load cell.[10][12][17] Normally, to measure the load applied to the sample, the load applied to the piston is measured outside the pressure vessel. However, because friction due to the O-ring used as the seal between the piston and the pressure vessel affects the load measurement, it is better to measure the load applied to the

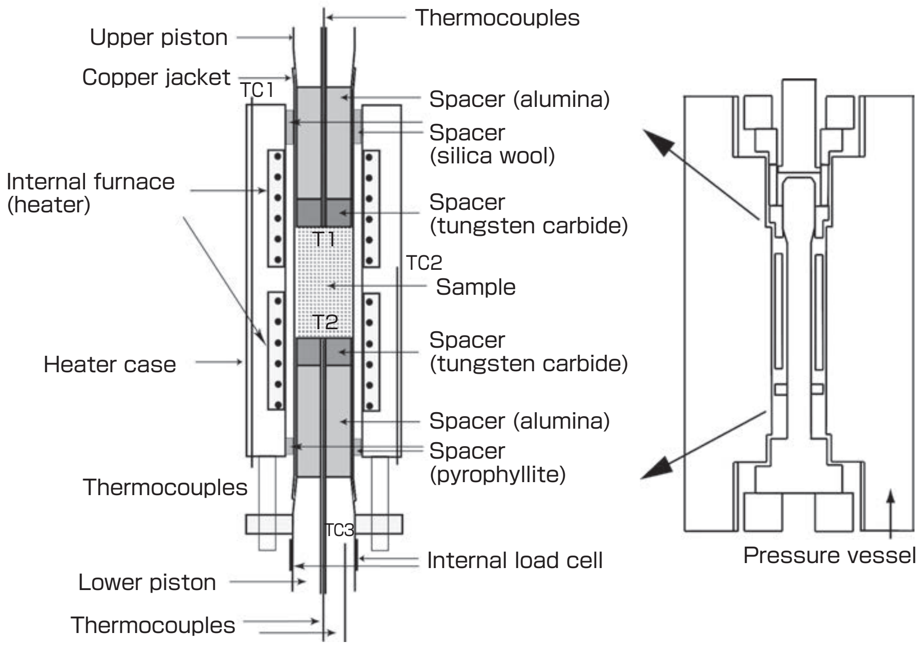

Fig. 7 Schematic diagram of the pressure vessel[19]

Left: Cross section of the sample assembly. The pressure (pore pressure) can be controlled and the fluid can be circulated by delivering fluid directly to the sample from the outside. The locations of the temperature measurements with the thermocouples are indicated by T1, T2, TC1, TC2, and TC3. T1 and T2 are the top and bottom surfaces of the cylindrical sample. TC1 and TC2 are located near the interior walls of the pressure vessel, and TC3 is the location of the internal load cell. Right: Diagram showing the structure of the pressure vessel.

sample directly, inside the pressure vessel. The performance of our device is superior at controlling the axial load, confining pressure, and pore pressure compared with gas pressure testing devices developed overseas.

By putting the rock samples in a high-pressure vessel (Fig. 8) and using a high-pressure gas as the pressure medium, it became possible to replicate environmental conditions at a depth of about 10 km. At 10 km below the ground surface, the pressure is about 200–300 MPa and the temperature is about 300 ºC. However, if we only reproduce the same pressure and temperature conditions as those underground, then we would have to wait about a thousand years to observe one cycle of the processes associated with a mega-earthquake. What technological developments are necessary to solve this problem?

4.4 High-temperature technology

According to our working hypothesis, chemical reactions play a major role in the processes that dominate the long-term changes that occur deep underground. The rate at which chemical reactions occur is generally related to temperature, as expressed in Equation (1).

$$\mathrm{Rate} = \mathrm{A}\exp\left(-\frac{H}{RT}\right) \qquad (1)$$

Here, A is a constant, H is the activation energy, R is a gas constant, and T is absolute temperature. Therefore, it should be possible to speed up the reaction to a rate observable in the laboratory by raising the temperature to increase the reaction rate. In this way, it should be possible to investigate in the laboratory a phenomenon that progresses slowly deep underground.[14] Because the results would be meaningless if the sample were to partially melt or if the dominant deformation process is changed when the temperature is raised, we determined the temperature range within which the same mechanism would be maintained before we set the temperature at which to conduct the experiment.[18] In fact, to speed up the reaction necessitates the development of a technology capable of achieving higher temperatures than the actual high-temperature, high-pressure conditions found in nature, and we developed the necessary technology. Here, we created a technology capable of achieving a high temperature of about 800 ºC at pressures up to 200 MPa. Specifically, we designed a heater for installation in the pressure vessel.[19]

The temperature of samples inside a pressure vessel can be raised by means of exterior or interior heating. In exterior heating, the entire pressure vessel is heated, but restrictions are imposed by the time needed for raising and lowering the temperature, and the temperature cannot surpass that at which the material of which the pressure vessel is made loses its integrity. In interior heating, the heating mechanism is placed inside the pressure vessel, and the sample inside the pressure vessel can be raised to temperatures surpassing the temperature limitations of the exterior heating method. In principle, interior heating is simple; a heating coil needs to be designed. However, for technological reasons, it took two years to develop a suitable heater. The developed heater (left side of Fig. 9) consists of the two independent parts (two heating coils), and power is supplied from the outside separately to the top and bottom coils. To keep the temperature distribution of the sample uniform, the power supplied to the top and bottom coils is controlled by a

Fig. 8 The pressure vessel, which contains the sample, to be installed in the materials testing device

Pressure (confining pressure) is applied to the rock sample in the pressure vessel during the test to replicate the conditions underground.

Fig. 9 The heater (electric heating element) developed at AIST

A temperature higher than the actual underground temperature can be achieved under high pressure. Left: Heater. Two heating coils are wrapped around a ceramic tube. Right: Exterior appearance of the heater.

feedback mechanism in which the output of the thermocouple that measures the temperature of the top or bottom part of the sample is used as the control signal for the corresponding coil. Similar devices developed overseas use a triple-zone system, but we found that a uniform temperature distribution of the sample can be obtained with the double-zone system.[19]

As shown by a schematic diagram of the interior of the pressure vessel (Fig. 7, right side), the sample and the heaters are installed in an extremely tight space. The rock sample at the center of the pressure vessel must reach an extremely high temperature, but the pressure vessel, because it is made of metal, will undergo plastic deformation if its temperature reaches 800 °C; such deformation would be extremely dangerous because of the high pressure inside the pressure vessel. A technological constraint, therefore, is that only the center part of the very tight interior space can be heated to a high temperature; the interior wall of the vessel cannot overheat. This problem was solved by packing an insulating material between the heater body and the heater case, as well as by the arrangement of the insulating material (shown in Fig. 9). A workable design was achieved through repeated trial-and-error with the help of a private company. The performance test results for the resulting heater (Fig. 10) confirmed that the sample could be maintained at an evenly distributed high temperature (800 °C) while the temperature of the interior wall of the pressure vessel and the measuring device (the interior load meter) were maintained within a safe range (300 °C or less).

4.5 Integration of the technologies and reproduction of processes by a high-temperature and high-pressure rock deformation experiment

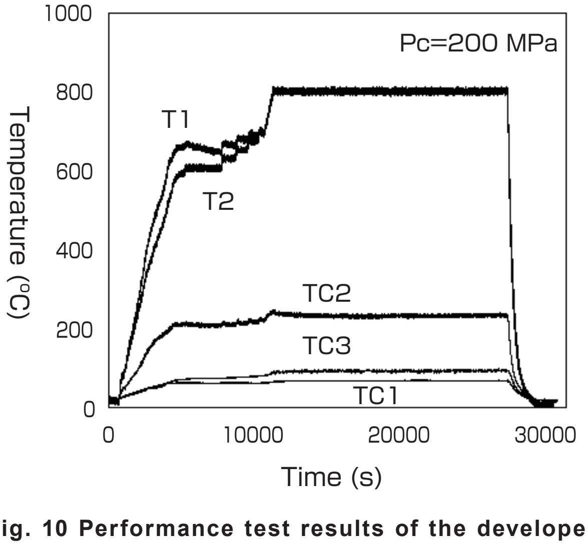

Fig. 10 Performance test results of the developed heater[19]
Both the top (T1) and bottom (T2) of the sample inside the pressure vessel are maintained at a constant temperature. The interior wall of the pressure vessel (TC1 and TC2) and the location of the internal load cell (TC3) are maintained at 300 °C or less.

The integration of technologies newly developed at AIST with existing technologies made it possible to conduct rock deformation experiments under high-temperature and high-pressure conditions. By means of such experiments, the mechanisms of fault movement were investigated and the working hypothesis developed on the basis of geological survey observations was tested (Fig. 3). In general, for rocks located deep underground, it is necessary to consider a non-hydrostatic pressure system where various types of pressure are applied from various directions. However, to investigate deformation and fracture, only the differential stress accompanying plate movement needs to be considered as the crustal stress under pressure (hydrostatic pressure), and it can be represented by compression under hydrostatic pressure. Such pressure conditions were reproduced by our experimental device. To accurately measure rock deformation under high-temperature and high-pressure conditions, it was necessary to use gas (high-pressure gas) as the pressure medium. The maximum achievable pressure was 200 MPa. Although the performance of our device is one of the highest of any device of this kind in the world, it can only reproduce conditions at depths of up to about 10 km.

5 Proposal of a new concept

We present as an example the results of an academic study carried out by using the technologies and method developed in this research.[18] In the field of seismology, it is known from geological and geophysical observations that the friction strength of faults in the natural world is weaker than the friction strength of rocks measured in the laboratory. Also, the rock strength changes depending on the rate of deformation, and it also changes with time, as seen by the creep phenomenon. These observations indicate that the properties of rocks, particularly their fracture strength and friction strength, are time dependent. It is important to understand the time dependency of rock properties to clarify earthquake occurrence mechanisms.

The occurrence cycles of large earthquakes have long periods of several hundred to a thousand years. Therefore, although direct observation of processes causing long-term changes in fault strength by geophysical monitoring methods is not possible, the friction strength of rocks is also thought to undergo long-term changes. Therefore, we explained the time dependency of friction strength by a model according to which the long-term weakening of fault friction strength is due in essence to the development of micro-fractures and the slow progression of cracks at the tips of asperities where surfaces on either side of the fault plane are in contact, and we conducted an experiment to verify this model. This model assumes that long-term weakening of fault strength is dominantly caused by chemical reactions that progress in the presence of water. Therefore, if such reactions are the effective mechanism, then it should be possible to observe the effect of water on the long-term weakening of fault strength in the laboratory. We studied the effect of water on the friction strength of a fault under temperature conditions higher than those actually found deep underground where the fault movement was assumed to occur by conducting compression fracture experiments with cylindrical rock samples (Fig. 11). The rock samples were mylonite[Term 1] sampled from the Hatagawa fracture zone, Fukushima Prefecture. This rock had been deformed and fractured while it was deep underground, and the cylindrical sample was cut such that its long axis was oriented at an angle of 30 degrees to the planar structure[Term 2] of the rock. When compression stress was applied axially to the sample, a fault plane formed parallel to the planar structure. With continued compression, the fault plane slipped and the frictional strength could be measured. Two types of experiment were conducted under constant pressure: one without water (dry condition) and the other with water (wet condition). Each experiment was performed at four temperatures: room temperature, 200 ºC, 400 ºC, and 600 ºC.

The results showed that frictional strength hardly changed even under high-temperature conditions in a waterless environment, but the frictional strength decreased as the temperature increased under the wet condition (Fig. 12). Because the pressure conditions were the same, the data suggest that the strength decrease was due to chemical reactions and not to the physical mechanism known as the effective pressure law, which attributes the strength

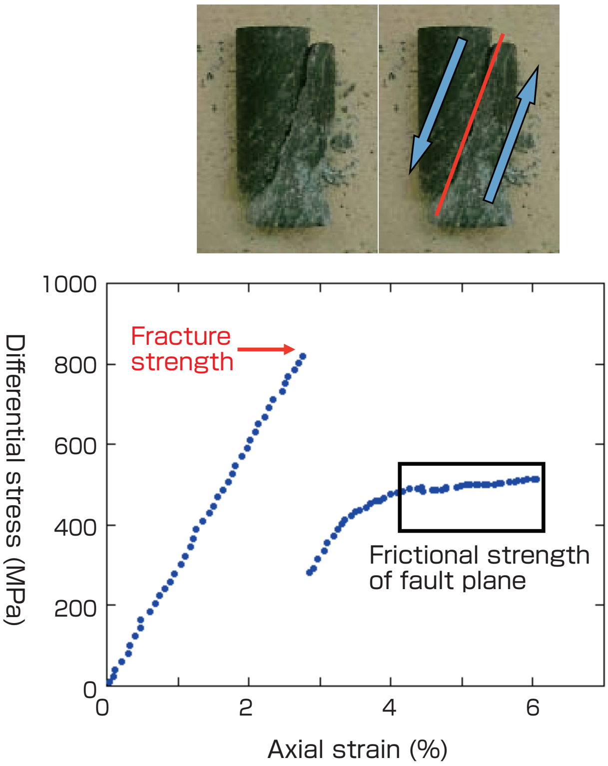

Fig. 11 Photograph of a sample after the experiment and the resulting stress-strain curve[18]
The fracture strength of the rock and the frictional strength of the fault were measured. When the differential stress reached the fracture strength, a fracture plane formed in the rock sample. The differential stress needed to cause the fracture plane to slip is used to calculate the frictional strength.

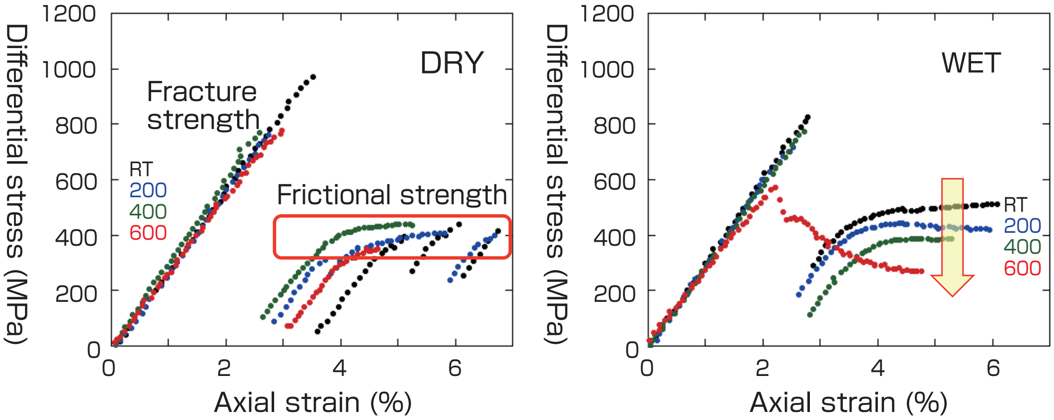

Fig. 12 Measurement results[18]
Under the dry condition (DRY), frictional strength was almost constant (area inside the red frame) and independent of temperature, but under the wet condition (WET), the strength level decreased (shown by arrow) as the temperature rose. Measurement results in (left) the absence of water (DRY) and in (right) the presence of water (WET).

decrease to an increase in the pore water pressure. Under the assumption that the processes of this phenomenon, which in nature progress slowly, are dependent on chemical reactions, we obtained results that support the inference that the speed of progression can be increased by raising the temperature to increase the rate of the chemical reactions. In fact, the results showed that higher temperatures allowed long-term processes to be observed (Fig. 13).

This study clarified the mechanism whereby fault strength is decreased over a long time period. The fault strength decreases and eventually becomes lower than the present crustal stress; when this point is reached and a fracture is triggered, an earthquake occurs. Through the modeling of this process, simulations of earthquake occurrences can be refined. In earthquake forecast studies, to be able to conduct simulations with a numerical model, it is first necessary to construct a physical model based on an accurate understanding of the mechanism of earthquake occurrence. Our results demonstrated an important mechanism leading to the occurrence of an earthquake, a phenomenon that cannot be directly observed on a human timescale. By quantitatively evaluating the mechanism and incorporating the results into a numerical model, we can construct a refined earthquake occurrence model. In the future, it will be necessary to develop a constitutive equation for earthquake occurrence in a mathematical form that can be incorporated into a numerical model and to determine the necessary parameter values and their dependency on environmental conditions such as temperature and pressure. By increasing the precision of earthquake forecasts, we expect to be able to deliver more accurate information to society.

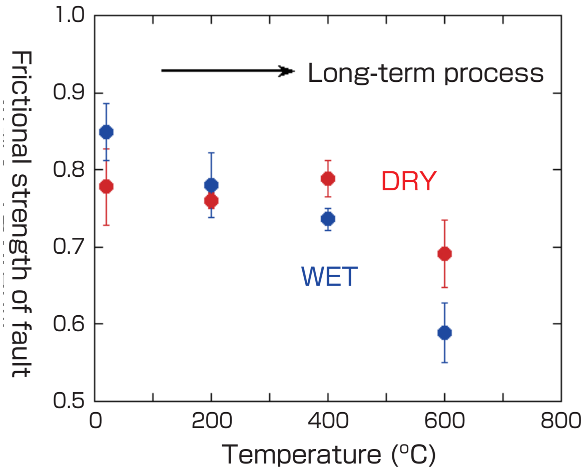

Fig. 13 Temperature dependency of the frictional strength of the fault plane in rock samples[18]

By subjecting the sample to higher temperature conditions than those experienced underground, the processes occurring in the area of contact along the fault plane were accelerated, allowing processes that normally occur over a long period of time to be observed. The measurement results show that the frictional strength decreased in the wet condition (WET) compared with that in the dry condition (DRY).

6 Future issues and prospect

To verify earthquake forecast models, we developed technologies and methods for accelerating and investigating geological phenomena that ordinarily occur on a thousand-year timescale in a laboratory rock experiment. Here, we combined existing methods and technologies with newly developed technologies and incorporated them into our research scheme (Fig. 3). We have provided the core technology to some universities in Japan.

Although our research is still in the data collection stage at this point, we were able to investigate and publish a new concept about time-dependent fault strength. Therefore, we have taken one step toward understanding earthquake phenomena.

The next step is to obtain data and develop a model that can be used in computer simulations to provide physical and geological evidence for future earthquake forecasts. We hope to work toward constructing a model to make accurate forecasts possible.

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Terminologies

Term 1. Mylonite: Rocks that have been ductilely deformed and formed in the high-temperature zone of deep faults (ductile shear zone).

Term 2. Planar structure: A two-dimensional rock element. The term also applies to structures formed by deformation processes.

References

[1] K. Yamaoka: *Nankai Trough Jishin* (Nankai Trough Earthquake), Iwanami Shoten (2016) (in Japanese).
[2] Seismology in Japan: Present state and seeds for the 21st century, *Jishin*, 2 (61), Special Edition (2009) (in Japanese).
[3] C. Scholz: *The Mechanics of Earthquakes and Faulting (Second Edition)*, Cambridge Univ. Press (2002).
[4] T. Yoshioka: Evaluation of earthquake occurrence from active faults—Evaluation of rupture probabilities of active faults using the Cascade Earthquake Model based on behavioral segmentation, *Synthesiology*, 2 (3), 194–200 (2009) (in Japanese) [*Synthesiology English edition*, 2 (3), 177–183 (2009)].
[5] Y. Okamura: Reconstruction of the 869 Jogan tsunami and lessons of the 2011 Tohoku earthquake—Significance of

ancient earthquake studies and problems in announcing study results to society, *Synthesiology*, 5 (4), 234–242 (2012) (in Japanese) [*Synthesiology English edition*, 5 (4), 241–250 (2012)].

[6] N. Koizumi: Earthquake prediction research based on observation of groundwater— Earthquake forecasting based on crustal deformation estimated from groundwater level change, *Synthesiology*, 6 (1), 24–33 (2013) (in Japanese) [*Synthesiology English edition*, 6 (1), 27–37 (2013)].

[7] A. Hasegawa, H. Sato and T. Nishimura: *Jishingaku* (Seismology), Kyoritsu Shuppan (2015) (in Japanese).

[8] N. Hirata: *Shuto Chokka Jishin* (Epicentral Earthquake in Tokyo Metropolitan Area), Iwanami Shoten (2016) (in Japanese).

[9] F. Yamashita, E. Fukuyama, K. Mizoguchi, S. Takizawa, S. Xu and H. Kawakata: Scale dependence of rock friction at high work rate, *Nature*, 528, 254–257 (2015).

[10] T. E. Tullis and J. Tullis: Experimental rock deformation techniques, Mineral and Rock Deformation: Laboratory Studies, The Paterson Volume, B. E. Hobbs and H. C. Heard eds, *Geophysical Monograph*, 36, 297–324 (1986).

[11] K. Hoshino: Experimental apparatus of rock deformation under high pressure, *Journal of the Japanese Association of Petroleum Technologists*, 44 (3), 161–165 (1979) (in Japanese).

[12] M. S. Paterson: A high-pressure, high-temperature apparatus for rock deformation, *Int. J. Rock Mech. Min. Sci.*, 7, 517–526 (1970).

[13] K. Ujiie, H. Tanaka, T. Saito, A. Tsutsumi, J. Mori, J. Kameda, E. Brodsky, F. Chester, N. Eguchi, S. Toczko, Expedition 343 and 343T Scientists: Low coseismic shear stress on the Tohoku-Oki megathrust determined from laboratory experiments, *Science*, 342, 1211–1214 (2013).

[14] M. S. Paterson: Rock deformation experimentation, The Brittle-Ductile Transition in Rocks, The Heard Volume, A. G. Duba, W. B. Durham, J. W. Handin and H. F. Wang, eds, *Geophysical Monograph*, 56, 187–194 (1990).

[15] S. W. Freiman: Effects of chemical environments on slow crack growth in glasses and ceramics, *J. Geophys. Res.*, 89, 4072–4076 (1984).

[16] K. Masuda: Effects of water on rock strength in a brittle regime, *J. Struct. Geol.*, 23, 1635–1657 (2001).

[17] K. Masuda, K. Fujimoto and T. Arai: A new gas-medium, high-pressure and high-temperature deformation apparatus at AIST, Japan, *Earth Planets Space*, 54, 1091–1094 (2002).

[18] K. Masuda, T. Arai, K. Fujimoto, M. Takahashi and N. Shigematsu: Effect of water on weakening preceding rupture of laboratory-scale faults: Implications for long-term weakening of crustal faults, *Geophys. Res. Lett.*, 39, L01307, doi:10.1029/2011GL050493 (2012).

[19] K. Masuda, K. Iryo and A. Ogura: Internal furnace for the gas-medium high-pressure and high-temperature apparatus at the Geological Survey of Japan/AIST, *Japanese Journal of Structural Geology*, 49, 73–76 (2006) (in Japanese).

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Discussions with Reviewers

1 Overall

Comment (Chikao Kurimoto, AIST)

Japan is positioned in one of the world's most active belts of crustal movement and thus experiences frequent geological disasters. There is a demand to build a society that is resistant against earthquake disasters, and research on earthquake forecasting is essential. This paper addresses the challenging topic of how rock experiments are used to reproduce geological phenomena that occurred deep underground in the past and to verify an earthquake forecast model. This work integrates advanced technological developments and investigations of geological phenomena to understand the differences in spatial scale, structural conditions, and time between the laboratory and the natural world and presents a clear research scenario, and I think the paper is appropriate for publication in *Synthesiology.*

Comment (Toshimi Shimizu, AIST)

This research addresses experimental techniques and methods to accelerate and investigate rock deformation and fracture processes that progress on a thousand-year scale in the natural world. The work has been developed through the introduction and integration of original high-pressure and high-temperature technologies with a compression testing apparatus that has been used for general materials testing. It is extremely interesting that the effectiveness of this method was demonstrated by a laboratory experiment showing the adequacy of the hypothesis that when water is present, fault friction strength weakens over a long period of time. This paper is a case study that contributes social value by constructing a high-precision earthquake forecast model, and I think the content is appropriate for *Synthesiology.*

2 Refinement of the earthquake forecast model

Comment (Toshimi Shimizu)

As a goal of this study, you mention the construction of a high-precision earthquake forecast model. I understand that the analysis of rock behavior and property changes based on accelerated tests under high temperature and high pressure can be helpful in investigations of earthquake occurrence mechanisms. However, I think that it is rather difficult to understand how the outcomes of this research can directly or indirectly help the general public prepare appropriately for an earthquake disaster. On the other hand, research on forecasting the timing and scale of mega-earthquakes in the future based on surveys of active fault history and tsunami deposits, as well as research on quickly detecting abnormalities through continuous monitoring of crustal changes, can be easily understood by the general public, perhaps largely because of frequent media exposure. Therefore, although you already address this issue in Paragraph 2 of the Introduction, I think the readers' understanding will increase if you include a diagram showing the various research (technological) components of earthquake research and the role of each component in earthquake forecasting; in particular, the diagram should show where refinement of the forecast model through high-temperature and high-pressure rock deformation experiments fits in the overall research scheme, and how they can contribute to better earthquake forecasts.

Answer (Koji Masuda)

I added Fig. 1, which summarizes the current flow of the earthquake forecast research, based on information in existing textbooks. I also added my own thoughts on the position of various research components and of rock experiments in particular in this research flow.

3 Research scenario

Comment (Chikao Kurimoto)

I think that a diagram that organizes the working hypothesis and the development and integration of the component technologies into the research scenario leading to the proposal of the new concept would deepen the readers' understanding.

Answer (Koji Masuda)

I combined photographs of actual rock samples and the experimental apparatus to show the research scenario in Fig. 3. I arranged the photographs to enhance the readers' understanding of how the whole research effort contributes to earthquake forecasts.

4 History of research and overseas technological advances

Question (Toshimi Shimizu)

You give us an explanation of the history of the rock deformation experimental devices, but what is the current situation overseas? If the same rock samples were used, can you tell us what the advantages would be if analyses were performed with the devices developed by other countries? Shale gas, which is an unconventional source of natural gas that is in the news right now, can be collected from shale strata, but are the oil companies still interested in and working on rock experiments? Related to this, please tell us about international collaborations or frameworks, if any exist, and about any work on the international standardization of rock deformation experiments.

Answer (Koji Masuda)

There aren't many different features or advantages of the devices developed by other countries that should be particularly described with respect to their basic performance and capabilities. Nor is there any particular organization that promotes international collaboration. This is in contrast to worldwide collaboration with regard to the observation of earthquakes and tsunamis.

As I wrote in the history section of this paper, the people of Shell Technology Center in Houston, USA, carried out research and developed a device for rock experiments during the early stages of shale gas research. Rock experiments are being actively conducted at oil companies currently. However, the shale gas that these companies are interested in developing is found at a much shallower depth than that at which many earthquakes we are interested in occur, and technologically speaking, devices developed specifically for earthquake research are better able to reproduce the necessary high-temperature and high-pressure conditions.

5 Mechanism of earthquake occurrence and rock deformation

Comment (Toshimi Shimizu)

I understand that an earthquake is a fracture phenomenon that occurs when a force applied to the buried bedrock surpasses the fracture strength of the rock. On the other hand, earthquakes are often discussed at macro-scale in terms of the release of stress between the plates with thicknesses of tens of kilometers that cover the surface of the earth. For general readers, discussions of the causes of earthquakes involve everything from nanometer- to micrometer-scale rock fractures to macro-scale stress release by tectonic plates, and this scale gap gives rise to confusion. In this research, since the objective is the reproduction of fault movement occurring deep underground and the clarification of fault movement processes, I suggest you prepare a diagram that enhances the readers' understanding of the spatial scale, for example, by combining Figs. 2 and 5 into a single diagram and adding a scale, such as kilometers, meters, micrometers, nanometers, and so on, to each diagram, as well as adding explanatory text for technical terms such as friction, slip, fracture, water molecule, mineral crystals, and others.

Answer (Koji Masuda)

The objective of Fig. 2 is to show the essential reason why a rock experiment is conducted in the first place. Here, it is not merely a downscaling of fault movement, and spatial scale is not the issue. With this figure, I wanted to emphasize that rock experiments are performed to determine the essence of this natural phenomenon and to extract and verify the factors involved. I modified the diagram and caption to make this point easier to understand. On the other hand, Fig. 5 is a diagram that shows how, by shifting the spatial scale, an investigation of fault movement becomes an investigation of micro-mechanisms. I modified the diagram and its explanation to clarify and improve the readers' understanding of the spatial scale argument.

6 Proposal of a new concept

Comment (Chikao Kurimoto)

You mention a contribution to the refinement of simulations of earthquake occurrences and the transmission of accurate information to society. In view of the latest related research trends, can you describe the present position and contribution of this research, as well as its prospective contribution, to such simulations?

Answer (Koji Masuda)

In this study, we demonstrated an important mechanism that explains earthquake occurrence processes that cannot be directly observed at a normal timescale. I stated in Chapter 5 that, in the future, these processes must be incorporated into a numerical model, and the necessary parameter values and their dependence on environmental characteristics such as temperature and pressure must be clarified.

7 Materials testing device

Question (Toshimi Shimizu)

In tests of materials such as plastics, ceramics, metals, wood, and concrete, diverse forces in addition to compression are applied, such as tension, bending, and torsion, and mechanical characteristics such as strength, elasticity, and hardness are measured up until fracture occurs. In contrast, for rocks in a deep underground environment, it is necessary to consider a non-hydrostatic pressure system in which various types of pressure are applied from various directions, and I imagine that various types of controls are necessary to apply such pressure. Therefore, can you tell us what the major performance differences, measurement limits, and other differences are compared with a general-use materials testing device, aside from the high-temperature and high-pressure conditions (and the control of the water content)?

Answer (Koji Masuda)

I added a response to this question to Subchapter 4.5. The underground stress state is basically represented by compression under pressure (hydrostatic pressure). Also, I explained that one limitation of this testing device is that the maximum achievable pressure (200 MPa) is constrained by the use of a high-pressure gas as the pressure medium (because high pressures and high temperatures cannot be achieved and the deformation cannot be measured precisely otherwise).