Vol.9 No.2 September 2016

ISSN 1883-0978 (Print)
ISSN 1883-2318 (Online)

Synthesiology

English edition

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Special Issue of Geological Surveys

Synthesiology editorial board

2016

2

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Synthesiology is a journal that describes the objectives and social value of research activities that attempt to utilize the results in society, the specific scenarios and research procedures, and the process of synthesis and integration of elemental technologies. To allow the readers to see the value of the papers in a glance, the highlights of the papers characteristic to *Synthesiology* are extracted and presented by the Editorial Board.

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Development and utilization of geochemical reference materials
— Reliability improvement in the analysis of geological materials —
Takashi OKAI
This paper is a presentation of the history and the research scenario for providing more than 50 highly reliable geochemical reference materials over 50 years. The scenario was revised frequently and new research plans were created as the researchers looked at the changes in R&D and the ways in which reference materials are used, the changes in reference materials themselves due to the advancement of analysis devices, as well as changes in the world trends. Here, we can read the history in which the Geological Survey of Japan with its strengths has been leading the world in both the development and research of reference materials.

Three-dimensional urban geological map
— New style of geoinformation in an urban area —
Tsutomu NAKAZAWA *et al.*
This is a summary of the research result regarding a 3D geological ground map that was created for the purpose of utilizing geoinformation in hazard map compilation and urban planning to prevent and mitigate earthquake disasters. The display and modeling of a 3D geological ground map in the heavily populated urban areas have reached a very fine level, and future advancement is greatly expected. Also, multiple elemental technologies including the data collected by local governments are integrated to construct a framework that is useful and easy to use for society. It is a challenging topic that has potential to make contribution to society.

Constructing a system to explore shallow velocity structures using a miniature microtremor array
— Accumulating and utilizing large microtremor datasets —
Ikuo CHO *et al.*
Looking at the shallow ground where damages by strong motion and liquefaction are expected in an earthquake, this paper presents the technological development of a microtremor array that allows accurate exploration of the subsurface S wave velocity structure. This is an example of R&D in which the core technology, on which one of the authors have engaged in R&D over a long period of time and realized an array exploration method, underwent mutual complementation and strengthening through theoretical consideration and technological innovations and the timely response was made to the social demand to know the shakiness of the ground. It should be noted that the ripple effect on the general users is enormous.

Development of rock deformation techniques under high-pressure and high-temperature conditions
— Evaluation of long-term geological processes by a compressed timescale process model —
Koji MASUDA
By developing experimental technology and methods to reproduce past geological phenomena that occurred in deep underground in a laboratory setting and to accelerate rock deformation and fracture phenomena that progress in a thousand-year scale, an attempt was made to fulfill a social demand for a highly accurate earthquake forecasting model. The experimental apparatus was developed originally by introducing and integrating high-pressure and high-temperature technologies to a general pressure testing device. This is an excellent example where the research advanced by appropriately setting a research scenario that clearly defines the position and objective of the basic research.

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J-Stage
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Synthesiology - English edition Vol.9 No.2 (Sep. 2016)
Special Issue of Geological Surveys

Contents

Development and utilization of geochemical reference materials

— Reliability improvement in the analysis of geological materials —

Takashi OKAI

[Translation from *Synthesiology*, Vol.9, No.2, p.60–72 (2016)]

The Geological Survey of Japan has issued about 50 reference materials over the past 50 years. They have been used all over the world to improve the reliability in chemical analysis of geological materials. Geological samples of rocks, ores, minerals, soils, sediments, etc. generally contain various elements at high concentration levels. For accurate chemical analysis, it is necessary to use geochemical reference materials that contain major components at similar levels to the samples to be analyzed and predetermined concentration of target elements. In this paper, scenarios to develop geochemical reference materials for Japan and the rest of the world are described. Methods for selecting and grinding sample materials, the determination of reference values, and data sharing are also reported.

Keywords **:** reference material, geochemistry, chemical analysis, geological materials, sample grinding

1 Introduction (what are geochemical reference materials?)

The chemical analysis of elements, a part of the geological survey activities of the Geological Survey of Japan (GSJ), is an essential technique for examining geological characteristics and geologic history. For example, chemical analysis is essential in the utilization of mineral resources for exploration and formation analysis of ore deposits, the evaluation of their feasibility as resources, among others. As such, accurate chemical analyses are desired in the trading of actually mined ores. In addition, chemical analysis is necessary for environmental assessments, such as those considering contamination by specific elements and the ways these elements migrate. The geological materials that are the targets of a geological survey, such as rocks, ores, minerals, soils, and sediments, contain various elements in high concentration. For example, there are as many as 10 elements of relatively high contents that are referred to as major components of rock samples such as silicon, aluminum, iron, etc. These components of high concentration affect each other in chemical analysis; therefore, to chemically analyze specific elements accurately, the effects from other elements must be identified accurately. Therefore, for accurate chemical analysis, it is effective to use reference materials with similar major component contents (similar effects from high-content elements) and with the target element concentration determined. These reference materials for accurate chemical analysis of geological materials are called “geochemical reference materials,” and they are used as reference materials essential for the chemical analysis of geological materials around the world, such as for the development of methods of chemical analysis for geological materials, accuracy management for day-to-day analysis, and preparation of calibration curves to gauge instrumental analysis.

Generally, when analyzing the chemistry of geological materials, massive samples are ground into powders by using various crushers. Because natural rocks are aggregates of various minerals, from the perspective of the representativeness of the sample, a certain amount (hundreds of grams to several kilograms) of the sample is ground and homogenized, and a portion of these powders is sampled and analyzed for chemistry. Fundamentally, geochemical reference materials are obtained by grinding source rocks into powders and then storing these powders in bottles or other containers (Fig. 1).

The history of the development of geochemical reference materials began in 1949 when the U.S. Geological Survey (USGS) issued the G-1 (granite) and W-1 (diabase) reference materials. In Japan, the Geological Survey of Japan (GSJ) began developmental studies in 1964, and the first reference material, JG-1 (granodiorite), was issued in 1967. Thereafter, the responsibility was passed to the Research Institute of Geology and Geoinformation of GSJ, and about 50 types of reference materials have been prepared in the subsequent 50 years (Table 1). More than 10,000 units of these GSJ geochemical reference materials have been distributed

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Original manuscript received August 26, 2015, Revisions received October 6, 2015, Accepted October 16, 2015

Table 1. Geochemical reference materials published by GSJ

Volcanic rocks		**Sedimentary rocks**	
JA-1	Andesite (1982)	JLs-1	Limestone (1987)
JA-1a	Andesite (2002)	JCp-1	Coral (1999)
JA-2	Andesite (1985)	JCt-1	Giant Clam (2002)
JA-2a	Andesite (2013)	JDo-1	Dolomite (1987)
JA-3	Andesite (1986)	JSl-1	Slate (1988)
JB-1	Basalt (1968)	JSl-2	Slate (1989)
JB-1a	Basalt (1984)	JCh-1	Chert (1989)
JB-1b	Basalt (1996)		
JB-2	Basalt (1982)	**Sediments**	
JB-2a	Basalt (2004)	JLk-1	Lake sediment (1987)
JB-3	Basalt (1983)	JSd-1	Stream sediment (1988)
JB-3a	Basalt (2003)	JSd-2	Stream sediment (1989)
JF-1	Feldspar (1985)	JSd-3	Stream sediment (1989)
JF-2	Feldspar (1986)	JSd-4	Stream sediment (2005)
JG-1	Granodiorite (1967)	JSd-5	Stream sediment (2006)
JG-1a	Granodiorite (1984)	JMS-1	Marine sediment (1999)
JG-2	Granite (1985)	JMS-2	Marine sediment (2000)
JG-2a	Granite (2015)	JMS-3	Marine sediment (2007)
JG-3	Granodiorite (1986)		
JGb-1	Gabbro (1983)	**Coal fly ash and soil**	
JGb-2	Gabbro (1991)	JCFA-1	Coal fly ash (1995)
JH-1	Hornblende (1992)	JSO-1	Soil (1997)
JP-1	Dunite (1984)	JSO-3	Soil (2009)
JP-2	Dunite (2011)		
JR-1	Rhyolite (1982)	**Ores and minerals**	
JR-2	Rhyolite (1983)	JMn-1	Manganese nodule (1994)
JR-3	Rhyolite (1990)	JZn-1	Zinc ore (2000)
JSy-1	Syenite (1993)	JZn-2	Zinc ore (2008)
		JCu-1	Cupper ore (2001)

around the world and are contributing globally to improve the reliability of chemical analyses.

2 Background and history of development

2.1 Technological background and history of development during the 1940s

In traditional chemical analysis of geological materials, the wet method is used to separate elements (components) chemically, and gravimetric, volumetric, and colorimetric methods are used for quantification. This method is extremely accurate when such analysis is appropriate, but complex operations are required to separate and quantify elements; thus, the method requires experience and a large investment of time. Under such conditions, a method for the analysis of the major components of silicate rocks through spectroscopic analysis (emission analysis) using a DC arc was developed, and the era of instrumental analysis began. Compared to the traditional wet method, which requires experience and a large amount of time, instrumental analysis increased the efficiency of chemical analysis significantly. However, instrumental analysis is fundamentally a comparative analysis of physical quantities such as intensity or absorption of light, and it requires criteria. In addition, for samples with complex elemental compositions, such as geological materials, the effects of existing forms of elements and interference by other elements are significant, which caused some problems. To solve these problems, it is useful to create criteria from natural rocks having the same composition as the samples. Based on this idea, Fairbairn at the Massachusetts Institute of Technology (MIT) led the preparation of reference materials from volcanic rocks, and in 1949, the USGS published two references: G-1(Granite) as the representative reference for acidic rocks with high silicon dioxide content and W-1(Diabase) as the representative for basic rocks with less silicon dioxide.[1]

Fig. 1 Geochemical reference materials published by GSJ
From left: JA-1a, JB-2a, JB-3a, JZn-1, and JCu-1
Powdered samples are packed in bottles and distributed.

2.2 The world's first collaborative analysis and evaluation

These two samples were distributed to research institutions, including notable universities and geological surveys (GS) around the world, and collaborative analysis was conducted to decide the standard values for the reference. This was an important effort in the sense that it was the first international collaborative analysis of geological materials using common samples. The results of the collaborative analysis, which were reported by Fairbairn *et al*. in 1951,[2] were shocking. Despite the fact that those who participated in the collaborative analysis were top analysts with first-class techniques from the various countries, the results were not as consistent as predicted. The analytical results for silicon dioxide in G-1 and W-1 are shown in Fig. 2. The differences among the reported results were too large, so a standard value for instrumental analysis could not be decided. The cause for these large differences was that differences among analytical methods were too significant, which thus resulted in a new challenge: the improvement of analytical methods. Subsequently, studies to improve analytical methods were conducted around the world, and finally, in the early 1960s, the desired standard value (recommended value) was reported.[3][4][5] In addition to improvements in analytical methods for major components using the same samples, the development of analytical methods for trace components was actively pursued. The analysis of trace components is strongly affected by major components; however, because collaborative analysis had accurately determined the values of the major components, these samples became ideal materials for examination of trace component analysis worldwide. Furthermore, to establish a standard, many reported analytical values must be compiled. Statistical examinations of geological materials analysis have also been conducted, and these have contributed significantly to the chemical analysis of geological materials.

2.3 Early development of global reference materials

Various examinations and research development occurred as a result of work on these first two samples. As a result, to samples that were considered simply as standards for instrumental analysis, a new utility value, the development and evaluation of analytical methods and techniques (precision, accuracy, and level of expertise), was born. Thus, the necessity and utility of reference materials became widely acknowledged. The fact that the initial analytical values did not agree led to utility values of the reference materials. However, the first two samples were nearly exhausted because they had been used for ten years or more worldwide. Foreseeing this problem, in the 1960s, the USGS prepared six types of new samples, including G-2 (granite) to replace G-1, and reference materials were also being actively developed in many other countries. The list of the main countries (organizations) includes the USA (National Bureau of Standards, NBS), the UK (Bureau of Analyzed Samples, BAS), France (Centre de Recherches Petrographique et Geochimiques, CRPG), Canada (Nonmetallic Standards Committee Canadian Association for Applied Spectroscopy, CAAS), East Germany (Zentrales Geologisches Institut, ZGI), and Japan (GSJ) (names of organizations are as of the 1960s). The commonality among all of these organizations is that each used geological materials from its own country. Based on the list of reference materials related to geochemistry provided by Ando (1967),[1] reference materials that were issued at that time in the countries (by the organizations) listed above are summarized in Table 2. The table reveals the intentions of the various countries and organizations by the types of geological materials that were used as reference materials. The USGS focused on volcanic rocks, which are common in the bedrock of the USA, but NBS focused on materials that could be raw materials and products of the mining and manufacturing industries. Like the USGS, GSJ began their efforts with volcanic rocks.

Table 2. International geochemical reference materials in 1967

Excerpt from Ando (1967)[1] for samples published from major organization

Country	Organization	Samples
USA	USGS	andesite, basalt, diabase, dunite, granite, granodiorite, nepheline syenite, peridotite (in preparation)
	NBS	basalt, bauxite, refractory bricks, cement (five types), iron ore (two types), limestone, manganese ore, magnesite, petalite, phosphate ore, silica sand, tin ore, spodumene, zinc ore
UK	BAS	refractory bricks (two types), iron ore, manganese ore, slag (three types)
France	CRPG	basalt, biotite, granite (three types)
East Germany	ZGI	basalt, clay shale, granite, limestone
Canada	CAAS	syenite, sulfide ore
Japan	GSJ	granodiorite, basalt (in preparation)

3 Developmental scenario of GSJ

3.1 Basic concepts at the outset

3.1.1 Background and significance of creating reference materials in Japan

The most important significance of developing geochemical materials in Japan is “elucidating the chemical compositions of domestically produced rocks at the global research level.”[6] In the 1960s, when such studies began, instrumental analysis was not common, and the wet method was mainly used. It took time to obtain chemical data, and a single analytical value was extremely important and valuable. Despite this

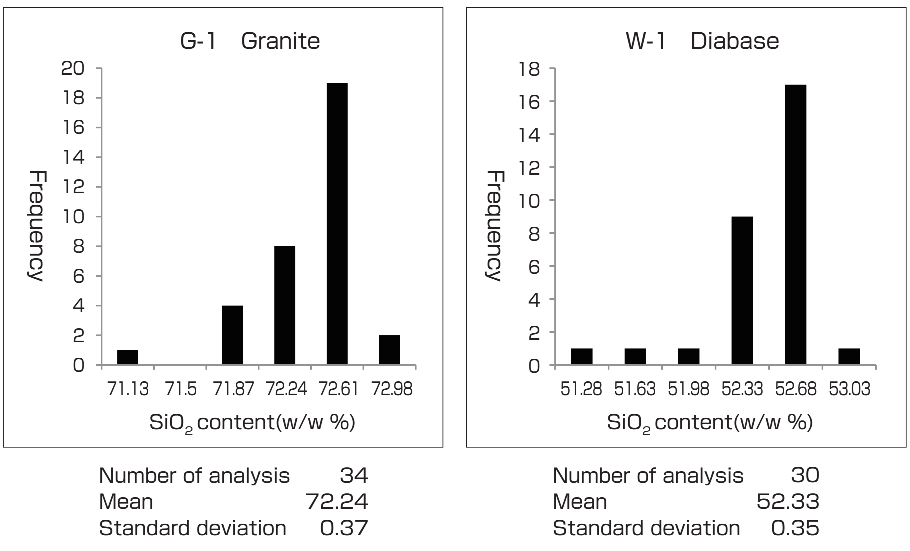

Fig. 2 F Silicon dioxide contents and histograms for G-1 and W-1 as reported in 1951 (prepared from Fairbairn *et al.* (1951)[2])

Peaks occur in areas greater than the mean value, showing scattering.

situation, the first samples, G-1 and W-1, were analyzed globally and a large amount of data was collected. The values were determined at a global research level. In addition, the number of geochemical reference materials was small at that time, and these materials were analyzed globally immediately after issuance. In other words, during that time, a large number of global-level analytical values could be obtained from reference materials based on rocks in Japan that were released to the research community. Based on the thinking of current reference material development, this may seem strange. However, in the initial stage, sample preparation and the assigning of values had large research and developmental importance, and these goals were established as the main target. In addition, the rocks that constitute a country (types and chemical compositions) are different for each country, and the necessity and priority of each rock type were also different; therefore, to prioritize the preparation of samples necessary for research and development domestically, it was desirable to make the samples in Japan. It was much easier to obtain materials produced within the country rather than having to import materials from foreign countries, and it was meaningful to promote their use in Japan and raise the standard of analytical techniques.

3.1.2 Basic concept

The first problem to be considered was the rock types for which reference materials should be prepared. The intentions of the manufacturing organization are normally reflected strongly in this selection. In reference to the preceding significance, the basic concept determined was that the first rock types to be prepared should be "rocks that represent Japan." This decision also had practical significance because the rocks that represent Japan were well represented in geological research documents (petrological descriptions, geological ages, chemical analyses, etc.) and many studies and analyses had been conducted. Consequently, these materials had many opportunities to be used for research, and the prepared reference materials would be used frequently; thus, good analytical values could be collected more easily and the use of the reference materials would be widespread.

3.1.3 Examination of underlying technologies and strengths of GSJ

The necessary technologies underlying the preparation of reference materials are roughly divided into sample selection, grinding methods, and standard value determination methods (described in Chapter 4). The advantages of GSJ for these underlying technologies and the development of reference materials are shown in Fig. 3. Understanding the need is the most important aspect for selecting samples, and reference materials are prepared by geochemical researchers who need them the most. In addition, because there were notable researchers in each field regarding various types of geological materials, an environment for making the best choices was established, and this included the perspective of using rocks that represent Japan. Because GSJ is the geological survey organization representing Japan, it was able to secure a variety of types of samples domestically. Rocks that represent Japan exist in significant abundance, so there was no problem securing necessary amounts of samples. In addition, the chemical analysis technology of GSJ that existed at the time was highly appraised worldwide, therefore, the initial analytical value (analyzed by GSJ) when reference materials were prepared and distributed was highly reliable and believed to contribute to the further utilization of reference materials.

3.2 Evaluation and development of reference materials

3.2.1 Japan's first geochemical reference materials

With the basic concept and the advantages of GSJ described above, the development of geochemical reference materials began in Japan in 1964 (research topic: "study of geochemical reference material"), and the first two reference materials, JG-1 (1967, granodiorite, Sori, Gunma Prefecture) and JB-1 (1968, basalt, Sasebo, Nagasaki Prefecture), were prepared.

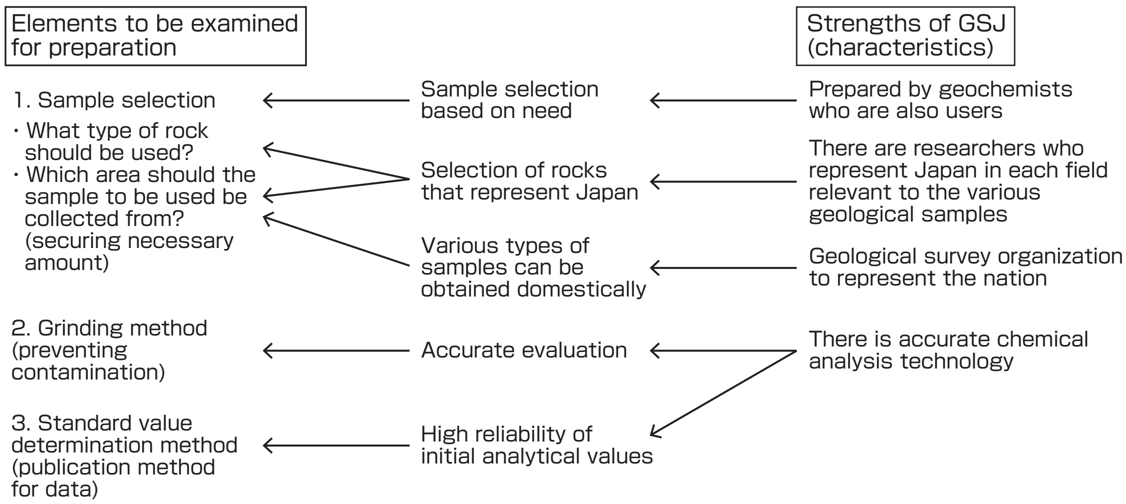

Fig. 3 Underlying technology for geochemical reference materials and strengths of GSJ

The most notable characteristic of these two samples is that contamination was strictly prevented. Geochemical reference materials are fundamentally prepared by grinding massive rocks into powders; therefore, a certain amount of contamination from the crusher cannot be avoided. The details are discussed in Chapter 4. The mixing in of iron, etc., from the steel crushers that were generally used in the 1960s was tolerated, and for those who were actually conducting chemical analyses, as long as the mixing was uniform and did not impact the decomposition of samples, it did not interfere with the utilization of the reference materials. However, from the perspective of elucidating the chemical composition of rocks that represent Japan, contamination needed to be minimized as much as possible; thus, sample rocks were crushed with mortar and pestle made of the same rock ("tomozuri" method). This process took a large amount of time and effort, but because of sufficient care, Japan attained the utmost trust in its reference materials from international organizations as the following comment shows: "The reference materials of Japan are prepared with extreme care and reflect the composition of original rocks directly." As a result, in addition to normal chemical analysis values, isotopic ratios and ages of rocks were reported, and physical constants such as elastic wave velocity and breaking strength[7] were reported from rock fragments. At the time, there was no other example of reporting on the physical constant of the reference materials for chemical analysis, and these results were highly appraised globally. By virtue of being globally utilized as such, the stock of both samples was exhausted and distribution was discontinued in the early 1980s. Therefore, in 1984, as re-prepared samples of JG-1 and JB-1, JG-1a and JB-1a were newly prepared by using the same source rock. It is impossible to make reference materials of identical elemental contents even when the same source rocks are used. Therefore, newer batches of reference materials were given subscripts, a, b, c, etc., to differentiate them.

3.2.2 High evaluation leads to project status

The success of the first two types of reference materials led to a significant change in the atmosphere of geochemical reference material development. The research effort for initial development in 1964 was part of basic research and its budget was limited. However, because of the high praise the work received, it became a project—special research "study of rock reference material preparation" of the Geological Survey—in 1981. After it became a special project, the rate of preparation increased, and in 1982, the third reference material, JA-1 (andesite, Mount Hakone), was prepared. Since then, two to three types of new reference materials have been prepared each year, and around 1990, 17 types of the first volcanic rock series (two of these are the re-prepared types mentioned above) were prepared, and these were followed by nine types of the sedimentary rock series. Thus, the goal of "rocks that represent Japan" was mostly completed. This achievement was highly praised as seen in the following comment: "GSJ's reference materials represent the most representative rocks of Japan, and their compositions are the same as the chemical compositions of the Japanese Islands." Appended figures and tables in the "*New Cyclopedia of Earth Sciences*," published in October 1996, presented the recommended values (standard values) of the main components of the 15 types of the volcanic rock series (excluding two types that were discontinued) and the nine types of the sedimentary rock series as the "major chemical composition of rock reference samples of the geological survey."[8] In this manner, the significance of reference material preparation at GSJ was acknowledged widely. In addition, the advanced analytical technology at GSJ contributed greatly to its success. At the time, reference materials were distributed with initial analytical values analyzed by GSJ that was the issuing organization. Subsequently, analytical data were collected to determine the standard values. With this method, it took some time for the standard values to be decided. As the reliability of the initial analytical values analyzed by GSJ was high, these initial values were used as standard values in many general analytical labs.

By 1990, the geochemical reference materials were distributed widely, and these materials were used regularly not only by initial research organizations but also by general analytical labs. Additionally, reference materials had been issued for many types of rocks. The list of geological reference materials summarized by Abbey in 1977[9] included 75 types issued by 16 organizations. In the list summarized by Potts in 1992,[10] the number of types had increased to 493 by 35 organizations, and new development for the project was being contemplated by GSJ.

3.3 Changes in distribution of reference materials and instrumental analysis

3.3.1 Changes in needs

In the early stage of reference material development, users were mostly universities and research organizations, which not only used reference materials but also participated in the decision on the values of reference materials. To present more accurate and precise standard values, they joined forces with the development organizations to prepare reference materials. However, as the development of reference materials became widespread and utilization by general analytical labs and researchers with less expertise in chemical analysis increased, most users simply used the pre-valued samples as reference materials rather than participating in value determination. The goal of developing analytical methods for research purposes did not change, but the original use of reference materials for accuracy management of analyses and preparation of calibration curves, etc., became mainstream. This was a natural progression of reference material development as it moved away from its initial stage and reached its mature stage leading to changes in the sample selection, standard value determination methods, and distribution methods.

3.3.2 Progress in analytical methods

Figure 4 shows the changes in the analytical methods that were used in the chemical analysis of geological materials. The initial instrumental analyses required large instruments, had high cost, and the analytical accuracy was insufficient. Therefore, except for trace elements with which quantitative analysis with the wet method is difficult, the most common method employed was the wet method. However, analytical equipment evolved rapidly with development in X-ray fluorescence analysis and atomic absorption spectrometry, and in the 1970s, instrumental analysis quickly became widespread. With the development in the 1980s of atomic emission spectrometry and mass spectrometry using inductively coupled plasma (ICP), the majority of chemical analyses were conducted through instrumental analysis. The wet method, which achieved high accuracy, remained as the official method of JIS and other organizations, but the main analysis methods had shifted toward instrumental analysis. The development and distribution of reference materials are strongly associated with the distribution of such general-purpose methods of instrumental analysis. For example, X-ray fluorescence analysis combines several geochemical reference materials to prepare a calibration curve for quantitative analysis, thus accurate quantitative analysis is impossible without geochemical reference materials. In the atomic absorption spectrometry and the ICP method, the use of the geochemical reference materials is essential for evaluating the effects from matrix and coexisting components and managing analytical accuracy. The development and progress of analytical instruments and the development and distribution of reference materials have evolved together.

4 Underlying technology for reference material development

4.1 Sample selection

4.1.1 Initial sample selection (rocks that represent Japan)

Based on the basic concept of rocks that represent Japan, volcanic rocks (silicate rocks) that constitute the Japanese Islands were prepared first. As the first two types of reference materials, JG-1(J for Japan and G for Granite), which is a granitic rock with high silicon dioxide content, and JB-1 (B for Basalt), which is a mafic basalt (high iron and magnesium) with relatively low silicon dioxide content, were selected. The next question was from which area the samples should be collected, and based on ample geological research materials, granodiorite from Sori, Gunma Prefecture, was chosen for JG-1, and alkaline basalt from Sasebo, Nagasaki Prefecture, was chosen for JB-1. For the actual sample collection, because rocks exposed at the surface are affected by weathering and pollution, fresh samples that had not been exposed to the atmosphere were sampled from quarries and rock pits (Fig. 5). For the preparation of reference materials, about 200 kg of a sample is needed. Specifically, for the first two types, about 400 kg of the source rock was sampled,

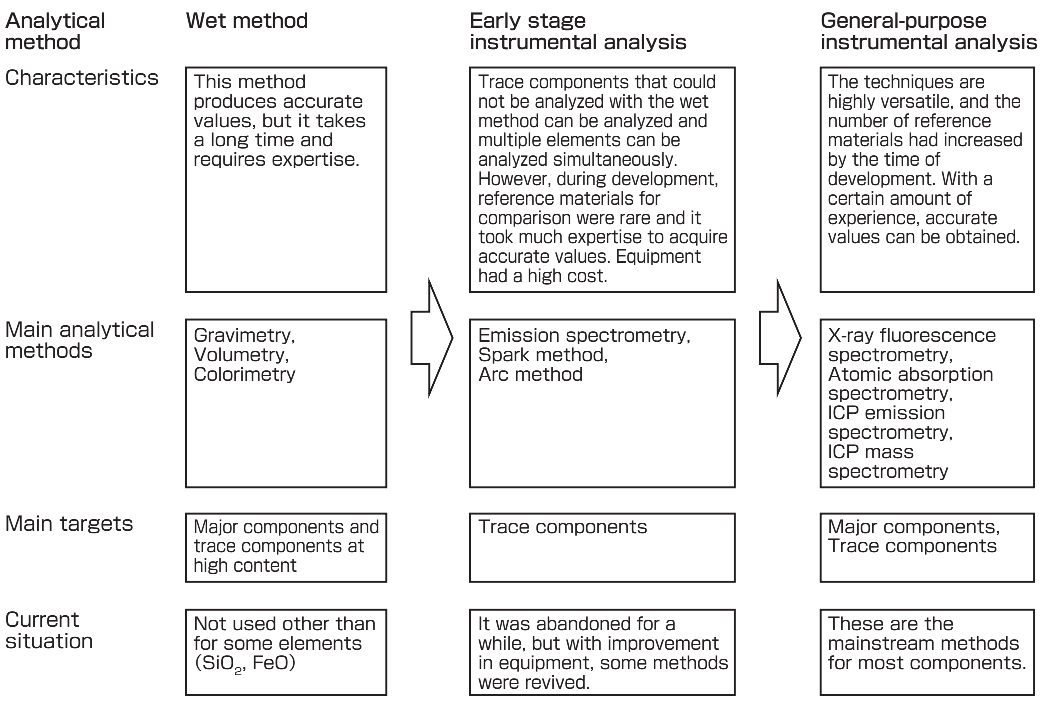

Fig. 4 Main chemical analysis techniques for geological materials and changes through time
Temporal changes in analytical methods are shown from left to right.

including some for future research. Such an amount of rock could be secured with relative ease at the selected locations.

As mentioned earlier, these two types of reference materials were highly praised and led to the creation of a project status for the work. Subsequently, representative rock types of Japan were prepared in the volcanic and sedimentary series, and for the very important granite (G), basalt (B), and andesite (A), three kinds of samples were prepared for each rock type, as shown in Table 1. Because each rock type is subdivided according to various characteristics even within the same general rock type, the whole geology was observed and reference materials were prepared from important sections. Using basalt as an example, the basalt produced in Japan can be divided roughly into three types according to the mineral and chemical compositions: alkaline basalt rich in sodium and potassium but poor in iron, tholeiitic basalt rich in calcium and iron but poor in sodium and calcium, and high-alumina basalt that falls between the previous two and is rich in aluminum. For each division, JB-1 (Sasebo, Nagasaki Prefecture), JB-2 (Izu Oshima Island), and JB-3 (Mount Fuji) were prepared, respectively.

4.1.2 Sample selection suitable for instrumental analysis and environmental analysis

Once the volcanic and sedimentary series were completed in the 1980s, sample selection based on geological classification changed to selection based on analytical chemistry. Specifically, as appropriate concentration in samples was desired in order to prepare calibration curves for instrumental analysis, such as atomic absorption spectrometry and ICP atomic emission spectrometry, by ranking previously prepared samples in their order of concentration of each component, samples were selected to fill the gaps, and the instrumental analysis series was prepared. A specific example is JSy-1 (syenite), which is rich in aluminum, sodium, and potassium. As there was no appropriate sample in Japan, a reference material was prepared by purchasing a source rock from Canada.

Around that time, environmental research became active globally, and the need to analyze environmental samples such as soils and sediments increased significantly. At laboratories that prepared geochemical reference materials, the "Geochemical Map" project—the mapping of elemental concentration—progressed simultaneously, and as reference materials for the river and marine sediments used to make geochemical maps were desired, preparation of the environmental analysis series began. A characteristic example is JCp-1 (coral). To reconstruct environmental information of the marine environment from the present to several hundreds of years ago, various elements in coral samples were analyzed at many laboratories. However, there was a problem in the reliability of the analytical results. Therefore, in response to requests from related projects, a coral reference material for general chemical analysis was prepared for the first time in the world.[11] It was used worldwide to improve analytical accuracy (improved reconstruction accuracy of environmental change) and for comparison of analytical results between laboratories (securing of reliability of analysis).

4.2 Grinding of samples

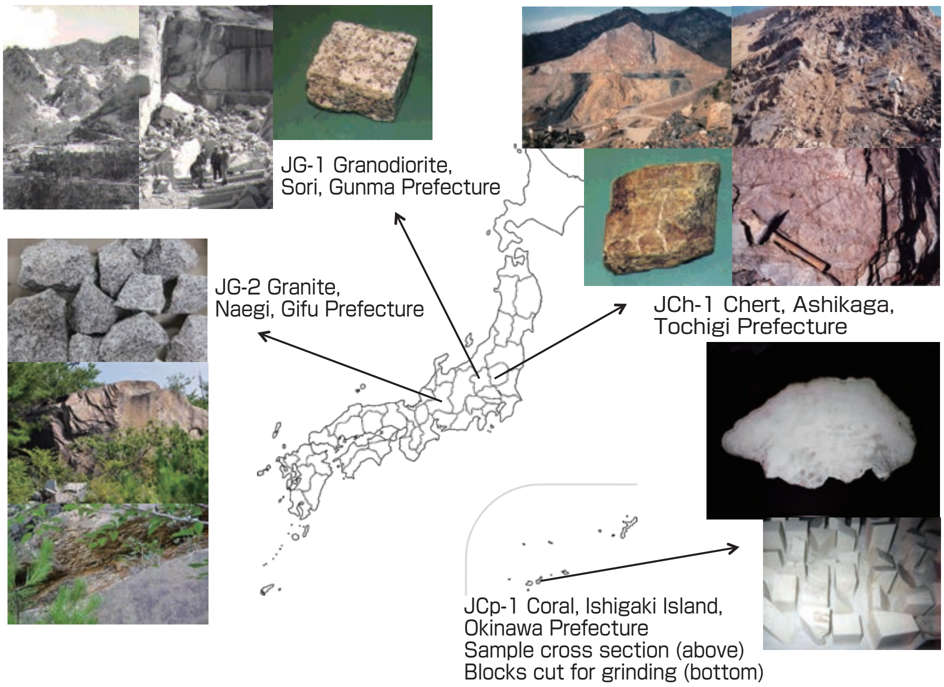

Fig. 5 Examples of sampled source rocks and sampling sites

4.2.1 Examination of grinding methods without contamination

The most important issue in grinding samples is contamination that may come from grinding equipment. Details of the examination process for grinding were summarized by Ando (1984),[6] so only an outline is provided here. During the development stage at GSJ, the biggest issue was contamination from the steel crushers. If the whole process was conducted with steel equipment, trace components such as manganese and nickel (contained in iron materials) in addition to iron would be likely contaminants, and in a grinding experiment at GSJ using silica stone, the contamination of iron could not be avoided. However, considering that samples are ground in units of 100s of kg, the use of a steel crusher is extremely efficient. When the USGS prepared G-1, a steel jaw crusher was used and the contamination of some iron was unavoidable. The South African metallurgical laboratory (National Institute for Metallurgy, NIM), which began development at the same time as Japan, has removed iron contamination from the steel jaw crusher using a magnet (magnetic separator) to prevent contamination. The disadvantage of this method is that it also removes magnetic minerals included in the original samples, such as magnetite, along with the iron contamination. As mentioned earlier, considering that the USGS method and the NIM method use the chemical analysis of elements as the standard, this problem is actually not a big issue. However, focusing on the basic concept of development at GSJ, because a method that contains contamination and removes specific substances can potentially change the original characteristics of samples and because it was deemed desirable to prepare reference materials retaining as much of the original characteristics as possible, a method that was not impacted by contamination was searched. The results led to “tomozuri,” in which samples are ground in a crusher made of the same material as the sample. An outline of this grinding process is shown in Fig. 6. For JG-1 and JB-1, a mortar and pestle was prepared using granite and basalt, respectively. Samples were first ground roughly in these mortars and pestles and then ground and mixed in a ceramic pot mill. Because samples are ground by hand using mortar and pestle, despite the lack of contamination, a large amount of effort and time is required. However, at the time, no other reference materials in the world were prepared with the care and attention given to this grinding process. Because of the extreme care used in the preparation of these samples, high praise was received, as mentioned earlier, and it contributed strongly to subsequent development of reference materials.

4.2.2 Efficient grinding method

In the 1980s, the preparation of reference materials received project status, and reference materials were prepared each year. At this point, it became difficult to expend the effort that was put into the first reference materials, and it became necessary to examine the efficiency of grinding. For the third reference material, JA-1 (andesite, Mount Hakone), coarse grinding was conducted using a mortar and pestle made of the same rock as JB-1 and pulverization was done using a ball mill with an alumina lining.[6] This method allowed the processing of much larger amounts of samples compared to using a pot mill, and as the alumina used as the lining is contained in rock samples at high concentration, it did not affect the samples easily by contamination. In addition, another effort was made: the ball used for

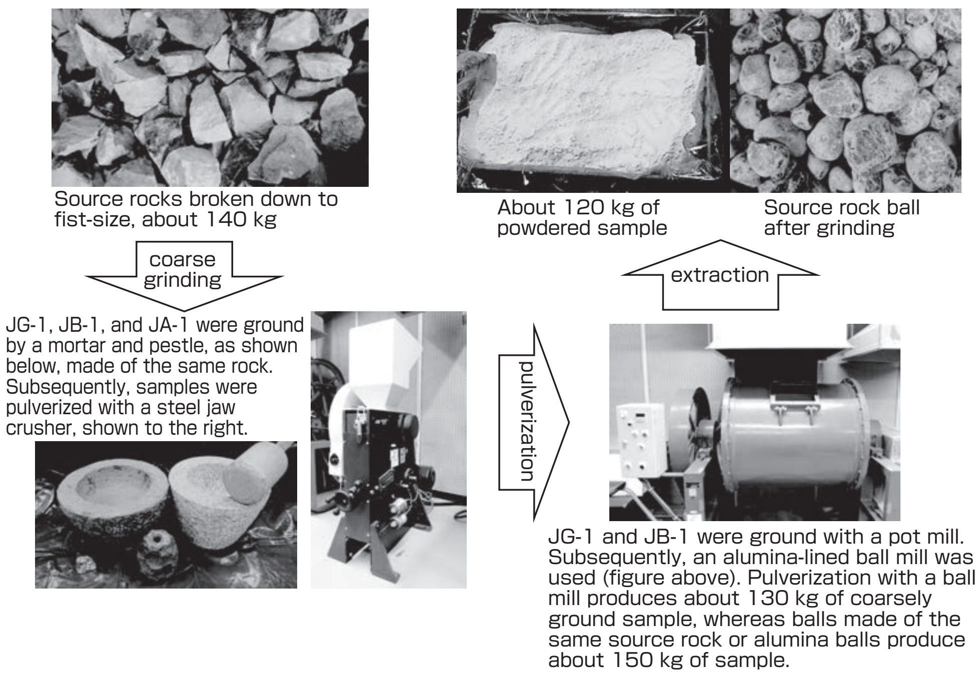

Fig. 6 Schematics of sample grinding process
Guideline to place 100 g and prepare 1,000 samples

Table 3. The major component contents of the JB-1 sample and the re-prepared sample

	JB-1 (1968)	JB-1a (1984)	JB-1b (1996)
	recommended values	recommended values	initial analytical values
(w/w %)			
SiO_2	52.37	52.41	51.11
Al_2O_3	14.53	14.45	14.38
T-Fe_2O_3	8.99	9.05	9.02
MnO	0.153	0.148	0.147
(μg/g)			
Co	38.2	38.6	40.3
Cr	425	392	439
Cu	55.1	56.7	55.5
Ni	133	139	148

T-：total, JB-1&JB-1a：Imai *et al.* (1995) [12],
JB-1b：Terashima *et al.* (1998)[13]

grinding was a fist-sized to egg-sized mass of the same rock (source rock ball). By grinding through "tomozuri," contamination was minimized. Afterwards, the mortar and pestle was considered too inefficient, and a steel jaw crusher became the mainstream tool for grinding (blade is made from manganese steel). Around this time, as a certain amount of iron and manganese were contained in samples and equipment was improved, the contamination from the jaw crusher ceased to be a problem. Currently, as shown in Fig. 6, after grinding with a steel jaw crusher, samples are pulverized in an alumina-lined ball mill with an alumina or source rock ball. When JG-1 and JB-1 were exhausted, the re-prepared samples JG-1a and JB-1a were prepared from the remaining samples collected at the time of initial reference preparation; they were ground by the current method. As JB-1b is a re-re-prepared sample of JB-1, the analytical values of major components in three samples of JB-1, 1a, and 1b were compared as an example (Table 3), and there was no sign of effects from the crusher.

4.3 Standard value determination method and publication of data

4.3.1 Standard value determination and publication of data during free distribution

Prepared samples were analyzed first by GSJ and then distributed worldwide with these initial analytical values, while additional analytical data were gathered. Basically, it was notified publicly through reviews of academic societies etc. that the samples had been prepared,[14][15] requests for distribution were gathered, and under the condition to send back analytical data of the sample, reference materials were distributed free of charge. There were two methods of distributing reference materials. One of these methods was used by GSJ: in return for free distribution, the reporting of analytical values was required, and the standard values were decided from the collected analytical values. The other method was to sell the reference materials with standard values assigned. Currently, the latter method is the mainstream method; however, at the time, only NBS (present-day NIST) and BAS used the latter method, and a majority of the organizations distributed reference materials via the first method. Only the latter fits the original definition of reference materials, and the former should be called a common analysis sample for research. However, based on the USGS's experience with G-1 and W-1, analytical values may change according to evolution of analytical methods. Although a majority of the elements are targets of analysis (research) of geological materials, it is difficult to assign a definite value to many of the elements from the beginning. Therefore, to collect analytical values of various elements in response to evolving analytical methods, the former method was more effective.

Reported analytical results were summarized and published in a journal for the first time in 1971.[16] At that point, all analytical values (24 for JG-1 and 17 for JB-1, including analytical methods and the name of the analysts), the overall mean, standard deviation, and the mean except value that exceeds ±2 σ from the mean were published. Subsequently, after a certain amount of analytical values had been collected, the reported analytical values were calculated statistically to obtain the standard value, and this standard value was published. However, as the number of analytical values increased, not all of the results could be published, and reports were limited to the mean value for each analytical method and the range of analytical values. In short, although it is called "standard value," its name also has changed through time. In the early stage, it was called "Consensus Mean (Value)," but afterwards, results with a sufficient number of analytical values and high reliability were called "Recommended Value." Results with a limited number of analytical values and low reliability were initially called "preferable data," but were later changed to "Reference Value." In addition, because of the nature of the method by which the standard value was decided based on collected analytical values after distribution, the standard value had the potential to change. Table 4 shows changes in the major component values of the JG-1 sample, which actually changed little.

4.3.2 Change in the distribution method and certified reference materials

Once geochemical reference materials became widely used, free distribution with the requirement of reporting of analytical values became difficult for general users, and the demand for the sale of reference materials without a requirement for reporting increased. In addition, global standardization by ISO started to affect geochemical reference materials in the late 1990s, and the production of certified reference materials, which are distributed with certified values (determined

Table 4. Changes in major component standard values for the JG-1 sample

Year	1971	1974	1988	1994
Name of standard value	consensus mean	consensus mean	consensus value	recommended value
(w/w %)				
SiO_2	72.24	72.28	72.30	72.30
TiO_2	0.26	0.27	0.26	0.26
Al_2O_3	14.21	14.23	14.20	14.20
T-Fe_2O_3	2.21	2.17	2.14	2.18
MnO	0.06	0.061	0.063	0.063
MgO	0.73	0.73	0.74	0.74
CaO	2.18	2.17	2.18	2.20
Na_2O	3.39	3.38	3.39	3.38
K_2O	3.96	3.96	3.97	3.98
P_2O_5	0.10	0.098	0.097	0.099

1971 : Ando *et al.* (1971)[16], 1974 : Ando *et al.* (1974)[17], 1988 : Ando *et al.* (1989)[18], 1994 : Imai *et al.* (1995)[12]

by a method with its accuracy verified), was considered. Under these circumstances, GSJ became an independent administrative agency from the national research institution in April of 2000, and, fundamentally, reference materials became available only by sale. In addition, based on its track record, GSJ was acknowledged globally as a main issuing (producing) organization of geochemical reference materials, and it also bore social responsibility to a certain degree. Therefore, for the sale of GSJ reference materials, it was determined that it would be best to follow the regulations of ISO and provide certified reference materials. Thus, GSJ initiated a completely opposite method of selling reference materials with a certificate. ISO certification as a reference material producer was acquired in 2007 through the ASNITE program of the International Accreditation Japan (IA Japan), the National Institute of Technology and Evaluation (NITE).[19] Currently, all newly prepared reference materials are certified reference materials (Fig. 7), and GSJ was awarded a Prize of the Minister of Education, Culture, Sports, Science and Technology (Department of Development) for the "Development of Certified Geochemical Reference Materials" in 2010.

4.3.3 Publication via database

In the beginning, the whole data of reported analytical values was published in academic journals and some other sources. However, as the number of analytical values increased, it became difficult to publish the whole data in paper format. Consequently, as the Internet became well established, a program of publishing research results widely in the form of a database (RIO-DB project) was begun at the former Agency of Industrial Science and Technology. Analytical data of geochemical reference materials could be processed statistically, and information such as samples, components (elements), analytical values, analytical methods, analysts, and literature (the date of publication) were digitized as a set. Thus, the database could be created with relative ease. For this reason, it was proposed as one of the first contents to be summarized under the RIO-DB project. This was an ideal method for GSJ because it was searching for a method by which as many analytical values as possible could be published. The database allows for publication of the whole

Contents of a certificate

Producer (issuer)
Sample name
Main usage
Certified value and reference value
Analytical method (measurement method)
Pretreatment of sample (decomposition method)
Determination method for certified value
Sample preparation method (preparation method)
Notes on usage and storage
Confirmation of homogeneity
Cooperation organizations
Issuing date and person in charge
Contact information
Etc.


独立行政法人　産業技術総合研究所
地質調査総合センター　地質情報研究部門
地球化学標準物質認証書
認証標準物質
National Institute of Advanced Industrial Science and Technology
AIST

GSJ CRM　JB-2a　玄武岩（伊豆大島三原山）
GSJ certified geochemical reference material JB-2a Basalt (Oshima volcano)

本標準物質は、玄武岩やそれに類似したマトリックスを持つ試料中の主・微量成分濃度の定量において、分析の精度管理及び分析方法や分析装置の妥当性の確認に用いることができる

認証値

成分	認証値(%)	分析方法(下記参照)
SiO_2	53.22 ± 0.21	1
TiO_2	1.18 ± 0.02	2
Al_2O_3	14.67 ± 0.08	2
全Fe_2O_3	14.18 ± 0.07	2, 3, 4
FeO	9.83 ± 0.12	4
MnO	0.214 ± 0.004	2, 3
MgO	4.56 ± 0.04	2, 3
CaO	9.79 ± 0.05	2, 3
Na_2O	2.03 ± 0.02	2, 3
K_2O	0.41 ± 0.01	2, 3
P_2O_5	0.095 ± 0.005	2, 5

参考値
認証成分以外のいくつかの成分について分析値の一例を参考値として以下に示す。

成分	参考分析値 (mg/kg)	分析方法 (下記参照)	成分	参考分析値 (mg/kg)	分析方法 (下記参照)	成分	参考分析値 (mg/kg)	分析方法 (下記参照)
Ba	219, 225	2, 2	Li	7.9, 7.84	3, 2	V	574, 575	2, 2
Co	40, 38.4	2, 2	Ni	14.5, 16.5	2, 2	Y	25.4	2
Cr	28, 27.7	2, 2	Rb	7.2	6	Zn	109, 107	2, 2
Cu	274, 269	2, 2	Sr	179, 179	2, 2	Zr	61.8	2

その他の成分の分析値についても順次「産総研地球化学標準試料ホームページ」上で公開するので参照されたい
http://www.aist.go.jp/RIODB/geostand/welcomej.html

分析方法
1）重量法と吸光光度法、ICP発光分光法、原子吸光法のいずれかの併用法
2）ICP発光分光分析法
3）フレーム原子吸光分析法
4）二クロム酸カリウム滴定法
5）吸光光度法
6）炎光法

Fig. 7 An example of a certificate
List of described items and a part of the certificate for JB-2a: Izu Oshima basalt

body of data and it can be utilized widely. The “Rock Reference Samples DataBase,” developed in this manner, was extremely popular, and it improved the convenience of using the reference materials, contributing to further distribution and development of RIO-DB. Currently, it is published as the “Geochemical Reference Samples DataBase” of the GSJ Database Collection (Gbank) (Fig. 8). GSJ is the only organization in the world that is publishing all reported data.

5 Summary and the future of geochemical reference materials

5.1 Summary of GSJ geochemical reference materials

To summarize the development of geochemical reference materials by GSJ, the goal of “elucidating the chemical compositions of domestically produced rocks at the global research level,” which was the initial intent, was sufficiently achieved by the preparation of the volcanic and sedimentary series and their evaluation. In addition, the development of reference materials came with responsibilities that change according to the age and the environment such as social responsibility as a producer of global reference materials, supplying reference materials needed by the age, and promoting widespread utilization and user services of reference materials. To these responsibilities, GSJ has responded accordingly through the following means: distribution of certified reference materials that follow the regulations of ISO, distribution of suitable reference materials for instrumental analysis and environmental analysis, and implementation of user support through the webpage (database). There were some imperfections, but GSJ fulfilled its role sufficiently. From the beginning of their development, GSJ geochemical reference materials have been used worldwide. About half of the present customers are in foreign countries. As an issuing organization representing Japan, it is a pride of GSJ to have developed reference materials that are used globally. In addition, as stated previously, reference materials have changed with the age. In the future, flexible responses to various types of changes will likely lead to success.

5.2 Geochemical reference materials in the future

How will geochemical reference materials change in the future? It is easy to predict expanding utilization and increasing importance of reference materials. In addition, it should be possible to predict some changes in the surrounding environment. First, the analysis of environmental samples will likely increase and so will demand for quality standards. Second, the number of analysts who can perform analysis using the wet method will decrease dramatically, and the number of technicians who work much like operators of instrumental analytical equipment will increase. Additionally, many analyses will be performed by automatic analysis and flow analysis, in which untreated raw samples are set in a device, the device automatically performs various processes with a push of a button, and analytical results are received as output. Analysis for existing forms of elements in samples also will likely increase.

As a result, the development of reference materials to satisfy

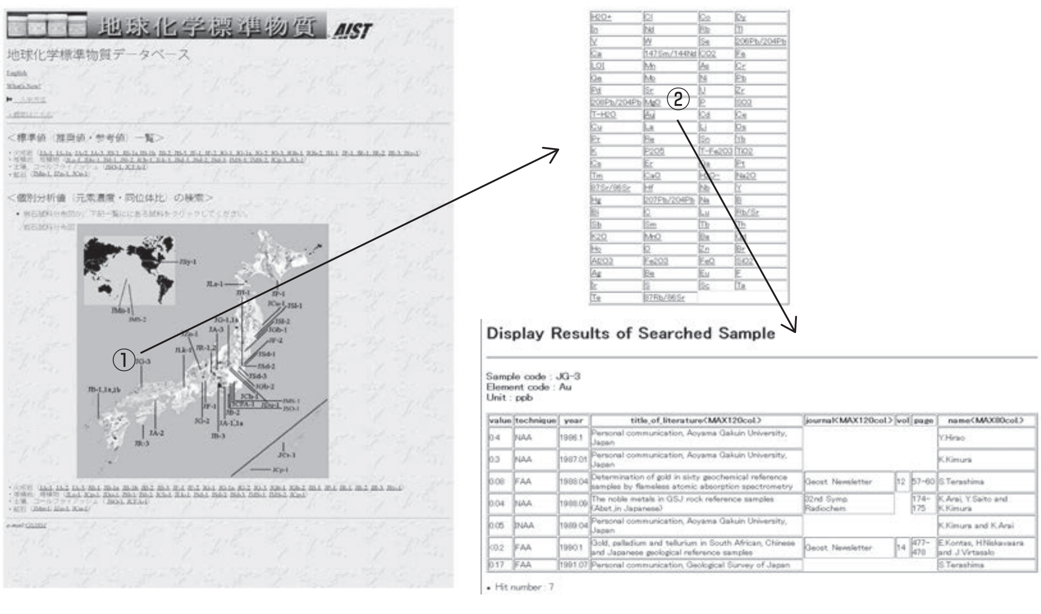

Fig. 8 Publication of geochemical reference materials database
Geochemical reference materials homepage
(https://gbank.gsj.jp/geostandards/welcome.html)
① When one clicks on the sample name for which he/she would like to see analytical data, the list of analytical components is displayed.
② When one clicks on the component name, the list of all reported analytical data is displayed.

the needs of environmental and morphological analysis will be desired. The largest problem with the development of such reference materials is the stability of the sample. This paper did not address stability, which is an important factor for reference materials. The reason for this omission is that rock samples are fundamentally stable and can be used almost indefinitely. JG-1 and JB-1 samples can still be used as reference materials from data analyzed more than 40 years ago. However, for samples suitable for environmental and morphological analysis, even if suitable reference materials were developed, the duration of their usage would be highly limited. For example, for the analysis of hexavalent chromium in contaminated soil samples (includes certain organics and water), much of hexavalent chromium would change to trivalent chromium after a certain period of time after grinding and packaging in a bottle. Thus, even if reference materials for analysis of hexavalent chromium could be prepared, their effective duration would be extremely short. In addition, the matrix of reference materials that will be demanded in environmental analysis is diverse, and the target components will also likely be diverse. Hence, in order to perform accurate analysis with the automatic analysis methods described earlier, it is necessary to develop reference materials suitable to this more diverse matrix in the shortest amount of time possible. The GSJ reference materials are prepared by grinding natural samples, and at least several years are required from conceptualization of development to supply. Hence, as the supply needed in the future would be impossible with such a short cycle and timeframe, the development of reference materials for which the necessary matrix and components are industrially synthesized is desired. It will be difficult to respond to this need by GSJ alone, and this technological development is extremely important not only for geochemistry but also for overall reference materials. Therefore, with the leadership of the National Metrology Institute of Japan (NMIJ), knowledge and technology in each area of the National Institute of Advanced Industrial Science and Technology (AIST) should be combined to more effectively address this issue.

5.3 Future plans for GSJ geochemical reference materials

The importance of the currently prepared geochemical reference materials will not change in the future. As mentioned earlier, because these references can be used indefinitely, mutual evaluation of analytical results 40 or more years old and current results is possible, and their supply as foundational reference materials needs to be maintained. Currently, samples prepared in the initial series are being exhausted; thus, there is a focused effort on re-preparation of samples in order to maintain the supply of reference materials. In addition, through recent research developments, elemental analyses of individual trace minerals that constitute the boundary of minerals are being attempted through localized analysis using lasers and ion probes. Reference materials vitrified by the melting of rocks (homogenized through vitrification) that can respond to such localized analysis are desired. Currently, only the USGS is able to provide the reference materials vitrified through the melting of rocks. It is necessary to closely examine this topic, including cooperation with the USGS.

Finally, in the development of reference materials, the most important concern in any situation is to maintain analytical technology that can provide accurate values (standard values). In the future, a variety of reference materials will be prepared, but the necessity of assigning an accurate value will not change. As mentioned earlier, as the number of experienced technicians decreases and the number of technicians who work as operators of instrumental analysis equipment increases, this is the most important issue for GSJ and AIST as research organizations that represent the nation.

Acknowledgments

Dr. Noboru Imai of the Research Institute of Geology and Geoinformation provided valuable documents along with much advice that were helpful for the writing of this paper. I extend my thanks and respect to Dr. Imai and all predecessors associated with geochemical reference materials.

References

[1] A. Ando: Geochemical standards, *Chishitu News*, 158, 23–27 (1967) (in Japanese).
[2] H. W. Fairbairn and others: A cooperative investigation of precision and accuracy in chemical, spectrochemical and model analysis of silicate rocks, *U. S. Geological Survey Bulletin*, 980, 1–71 (1951).
[3] R.E. Stevens, M. Fleischer, W.W. Niles, A. A. Chodos, R. H. Filby, R. K. Leininger, L. H. Ahrens and F. J. Flanagan: Second report on a cooperative investigation of the composition of two silicate rocks, *U. S. Geological Survey Bulletin*, 1113, 126 (1960).
[4] M. Fleischer and R.E. Stevens: Summary of new data on rock samples G-l and W-l, *Geochimica et Cosmochimica Acta*, 26, 525–543 (1962).
[5] C.O. Ingamells and N.H. Suhr: Chemical and spectrochemical analysis of standard silicate samples, *Geochimica et Cosmochimica Acta*, 27 (8), 897–910 (1963).
[6] A. Ando: Processing of reference rock powders, *Bunseki*, 116, 597–602 (1984) (in Japanese).
[7] S. Iizuka and K. Inami: Measurements of physical properties for geochemical rock standards GSJ JG-1 and JB-1, *Bull. Geol. Surv. Japan*, 27, 155–165 (1976) (in Japanese).
[8] The Association for the Geological Collaboration in Japan ed.: *New Cyclopedia of Earth Sciences*, appended figures and tables, Heibonsha Ltd., Tokyo, 71 (1996).
[9] S. Abbey: Studies in "standard samples" for use in the general analysis of silicate rocks and minerals, *Geological Survey of Canada Paper*, 77–34 (1977).
[10] P. J. Potts, A. G. Tindle and P. C. Webb: *Geochemical Reference Material Compositions*, Whittles Publishing, London, (1992).
[11] T. Okai, A. Suzuki, H. Kawahata, S. Terashima and N. Imai:

Preparation of new GSJ geochemical reference material Coral JCp-1, *Geostandards Newsletter*, 26, 95–99 (2002).
[12] N. Imai, S. Terashima, S. Itoh and A. Ando: 1994 compilation of analytical data for minor and trace elements in seventeen GSJ geochemical reference samples, "Igneous rock series", *Geostandards Newsletter*, 19, 135–213 (1995).
[13] S. Terashima, M. Taniguchi, M. Mikoshiba and N. Imai: Preparation of two new GSJ geochemical reference materials: basalt JB-1b and coal fly ash JCFA-1, *Geostandards Newsletter*, 22, 113–117 (1998).
[14] A. Ando: A new silicate rock standard, JG-1 issued from the Geological Survey of Japan, *Geochemical Journal*, 1, 155 (1967).
[15] H. Kurasawa: A new silicate rock standard, JB-1 issued from the Geological Survey of Japan, *Geochemical Journal*, 2, 185 (1968).
[16] A. Ando, H. Kurasawa, T. Ohmori and E. Takeda: 1971 compilation of data on rock standards JG-1 and JB-1 issued from the Geological Survey of Japan, *Geochemical Journal*, 5, 151–164 (1971).
[17] A. Ando, H. Kurasawa, T. Ohmori and E. Takeda: 1974 compilation of data on the GSJ geochemical reference samples JG-1 granodiorite and JB-1 basalt, *Geochemical Journal*, 8, 175–192 (1974).
[18] A. Ando, H. Kamioka, S. Terashima and S. Itoh: 1988 values for GSJ rock reference samples, "Igneous rock series", *Geochemical Journal*, 23, 143–148 (1989).
[19] T. Okai: GSJ certified geochemical reference materials, *Chishitu News*, 663, 61–63 (2009) (in Japanese).

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Discussions with Reviewers

1 General

Comment (Akira Ono, Special Emeritus Advisor AIST)

The Geological Survey of Japan has been researching and developing geochemical reference materials for about 50 years. This paper clearly describes the scenarios of developing and providing geochemical reference materials in order to support highly reliable chemical analysis of geological samples. It is quite interesting that during the 50 years of research and development, scenarios have been flexibly reviewed according to the user's needs for reference materials, which have been reflected in the subsequent research plans. It is also noteworthy that the geological reference materials, including the ideas unique to Japan, are being used worldwide.

This paper is structured in such a manner that it is easy to grasp for readers unfamiliar with this field, and will likely be used as a reference by many. I believe this is a paper well suited for publication in *Synthesiology*.

Comment (Chikao Kurimoto, AIST)

The Geological Survey of Japan (GSJ) and the Research Institute of Geology and Geoinformation of GSJ have published over 50 types of reliable reference materials during the past 50 years. The paper summarizes the significance, process, and results of studies by GSJ on the global trends in standard materials for geochemical reference and the development of these standard materials. In addition, the changes and future outlook of the standard materials with the advancement of analytical instruments have also been discussed. As such, this paper reviews the advances in geochemical reference materials in the last 50 years, and proposes future developments; and thus, I believe this paper is suitable for publication in *Synthesiology*.

2 Importance of the wet method

Question (Akira Ono)

Can I assume the following based on this paper? "The advantage of instrumental analysis is that it does not require labor and skills; however, analytical results are relative. Therefore, to calibrate the instruments, reference materials with absolute value for elemental concentration are necessary. In contrast, although the wet method requires labor and skills, its analytical results provide absolute value of elemental concentration. Therefore, the reference values of elemental concentration for reference materials are determined using the wet method."

If the above understanding is correct, in order to guarantee the reliability of analytical values (absolute value), the GSJ researchers also need to make technological advancement for the wet method to provide absolute value. What is your opinion on this issue? Is AIST still focusing on the wet method?

Answer (Takashi Okai)

In the early days of developing geochemical reference materials, values were determined using the wet method, as you have pointed out. However, now, as shown in Fig. 4, the values for silicon dioxide (SiO_2) and ferrous oxide (FeO) are determined using the wet method (gravimetric method for SiO_2 and titration method for FeO), and the values for other major components are obtained through general instrumental analyses, such as atomic absorption spectrometry and inductively coupled plasma atomic emission spectrometry. Studies have been conducted for the improvement of instruments and the assessment of the effect of other elements (such as interference). The precision of the quantitative analysis by these instrumental analyses has increased. With the adoption of official methods such as JIS, and the efforts of the NMIJ, the standard materials for each element have been prepared. The standard solution can now be prepared for the calibration curve with the certified reference materials for traceability. Furthermore, the values for standards are determined by collaborative analyses. However, sufficient precision in the wet method requires skills, and only a few institutions provide such skilled analyses.

Currently, no new wet method is being developed for geochemical reference materials, but the wet method has been used for chemical analysis of geological samples for a long time, and there have been many improvements. Therefore, it is a well-developed method. In the wet method, expertise, which is difficult to express in the procedure of an analytical method, can lead to differences. AIST has abundant expertise and is focusing on maintaining the technology for accurate wet method analysis. Specifically, in addition to passing on the skills to the younger generations, given the current situation where there are few institutions that are able to perform the wet method analysis, it would be important to share the information externally in order to sustain the use of the technology.

3 Relationship where the analytical methods and target materials compete in terms of accuracy

Comment (Akira Ono)

I thought it was interesting that in the early stages of development of the geochemical reference materials described in Subchapter 2.2, when common samples were collaboratively analyzed by major institutions around the world, the variability in data was much larger than expected. As a result, it led to a higher precision of the analytical method. The reviewer has the following proposition on this issue. What is the authors' opinion?

Analysis consists of methods and target materials. If a certain target material is analyzed with multiple analytical methods and the results vary, there are two possible causes for such variability. One is the variability existing in the analytical methods, including the reproducibility of the measurements. The other is the variability existing in the target material itself, which can be attributed to the heterogeneity in a sample or temporal changes in its characteristics. These two types of variability are observed together, and usually cannot be separated. However, if one type of variability is assumed to be significantly less than the other, the more significant cause for the variability can be clearly identified, and a clear way to reduce such variability can thus be conceived.

As discussed in Subchapter 2.2, the cause of variability in the analytical results could not be attributed to the variability of the targets, but was because of the variability of the analytical methods. This inference led to the beginning of new studies.

In contrast, to evaluate the variability of target materials, a much more stable analytical method must be used. We assume that instrumental analysis has a better resolution and stability compared to the wet method. As such, the analytical method and target compete with each other as far as accuracy is concerned. If one makes progress, the other follows until it surpasses its counterpart. In this manner, both make progress. The present case was an example of such a situation, which I found interesting.

I also feel that those taking part in the collaborative analysis without fear of varying results in a stage where the results were unpredictable (not being afraid of his/her own result being different from others) are worthy of praise for their courage and determination. This effort is considered to be of universal value till date.

Answer (Takashi Okai)

Regarding the variability of the results, I was amazed by the high technological level back then. In a collaborative analysis, when evaluating the variability of analytical methods and target materials that you commented on, little variation in the skills of the participating analysts needs to be ensured. When multiple analysts perform the same analytical method, if there is variability of analytical skills (or if overall skill level is low), the results will show variability beyond the fundamental variability expected in that analytical method. In such a case, if multiple analytical methods are compared, the variability of each analytical method becomes larger than the variability between the analytical methods, and the difference between each analytical method is masked. In the present study, the difference observed for silicon dioxide, as shown in Fig. 2, was due to a few procedure differences in the gravimetric methods rather than differences in the analytical methods. For such a minor difference in procedure to be identified as a difference caused by the analytical methods, each analyst had to have performed their analyses with extremely high precision. Therefore, it reaffirmed the extremely high level of analytical skills exhibited by institutions that took part in the collaborative study back then.

The competition between the analytical methods and the target materials was also inferred. In the response to discussion 2, I stated that these days the values for standard materials are mainly determined through instrumental analysis. Indeed, the development in instrumental analysis and standard materials impacted on each other, and in both cases, progress was made owing to the competition.

Participating in a collaborative study is a serious challenge; however, I think that pride as a skilled analyst was an important motivation (the possibility that one's own data may be the only outlier can put great pressure on an analyst). I believe it is important to guide the next generation until they attain such pride as analysts.

4 Underlying technologies and strengths of GSJ

Comment (Chikao Kurimoto)

In Section 3.1.3, the elemental technologies and strengths of GSJ have been discussed. Figure 3 shows their relationship. The content is correct, but if Fig. 3 could illustrate the relationship of the two and their impacts, their relationship would become clearer. It could clearly indicate the significance of this study and the elemental technologies and strengths of GSJ.

Answer (Takashi Okai)

As you have pointed out, the elemental technologies and strengths of GSJ have merely been listed. Therefore, along with the content of Section 3.1.3, I have inserted the impacts of strengths of GSJ on the examination of the elemental technologies between the two, and have connected these relationships using arrows. Thus, the findings of our study and the elemental technologies and strengths of GSJ were integrated.

5 GSJ geochemical reference materials

Comment (Chikao Kurimoto)

Subchapter 5.3, titled "Future plans for GSJ geochemical reference materials," is quite interesting. This paper summarizes the long-term progress in geochemical reference materials, which is a valuable indication of the future prospects. Therefore, comments on the fundamental policy and future plans of GSJ would have been beneficial for the readers. In future, I hope that there will be further discussions within GSJ based on this paper.

Answer (Takashi Okai)

At present, these are simply ideas that I have, and hence, I refer to them as "future plans." However, I hope to utilize them for future discussions.

Three-dimensional urban geological map

—New style of geoinformation in an urban area—

Tsutomu NAKAZAWA*, Susumu NONOGAKI and Yoshinori MIYACHI

[Translation from *Synthesiology*, Vol.9, No.2, p.73−85 (2016)]

Although geoinformation pertaining to urban areas is very important, paper-based geological maps do not adequately describe the subsurface geological conditions of urbanized plains. A three-dimensional geological map, available via the Internet, is expected to provide intelligible, highly reliable, and easily utilizable geoinformation for urban areas. In this case, a three-dimensional geological model needs to be constructed on the basis of reliable borehole data using an advanced modeling tool. We are now developing a prototype of a three-dimensional geological map of the northern part of Chiba Prefecture as a new form of urban geoinformation which contributes to estimating the risk of geological disasters.

Keywords **:** Geoinformation, three-dimensional geological model, borehole data, subsurface geology, geological map

1 Introduction

The 2011 Off the Pacific Coast of Tohoku Earthquake brought about serious tsunami damage, and also caused liquefaction of the ground occurred in some coastal and riverside areas in Chiba and other places.[1] In this earthquake, there were not much residential collapse caused by the seismic motion despite the magnitude of the earthquake, yet there was much damage of falling roof tiles in the Tohoku and Kanto regions. According to a study in the Tsukuba and Tsuchiura areas, the distribution of the damage was very distinctive.[2] Such damage depends on the epicenter, magnitude, and characteristic of the seismic wave such as the dominant frequency, but are also greatly affected by geological conditions of the area. The general public became aware to some extent of this fact through the mass media, and their interest in geology has increased. Also, geological survey is essential for civil engineering and construction works, and if one can obtain prior information of the geology on which the construction will take place, the planning and estimation of the geological survey can be done easily and the process of actual construction may go smoothly. However, the current methods of understanding the subsurface geological condition of the urban plain areas are not sufficient.

With this background, in the Phase II of Measurement Standards and Intellectual Infrastructure Plan of the Ministry of Economy, Trade and Industry (METI) for 2013, we decided to work on the organization of geoinformation of the urban areas through the integration of borehole data as our priority issue. In the "Special Committee on Measurement Standards and Intellectual Infrastructure," the "use of a new intellectual infrastructure that can be easily understood and is easy to use from the viewpoint of the users" was discussed, and it was proposed that a geoinformation organization considering secondary use[Term 1] would be promoted in the Intellectual Infrastructure Plan. Based on this plan, AIST set the data of the drilling surveys that it originally conducted as standards, conducted a wide range of strata correlation using the borehole data of public works and others disclosed by the local governments, and engaged in research for analyzing the 3D distribution of strata by computer processing for the urban areas. We are working on a method that allows anyone to browse and use such a 3D geological model on the web, as well as construction of a system that also allows browsing and use of the original borehole data used in 3D analysis. In this paper, we introduce our efforts on geoinformation organization for urban areas.

2 Awareness of the current situation

Recently, data of drilling surveys conducted in the public civil engineering and construction projects are being disclosed on the websites as database because there is increased awareness that geoinformation is important. Tokyo Metropolitan[3] and Chiba Prefecture[4] have disclosed their borehole data from an early stage, and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has started to disclose the borehole data of national projects.[5] A portal site that allows browsing such databases was developed by the National Research Institute for Earth Science and Disaster Prevention.[6] In accordance with the recent Government's open government data strategy, the local governments are also enthusiastic in disclosing borehole data. However, these borehole databases that have been prepared so far simply

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Original manuscript received August 31, 2015, Revisions received October 22, 2015, Accepted October 26, 2015

store data (although we greatly appreciate such information), and there is no case that shows geological interpretation such as subsurface geological structures in an easy to understand manner.

The borehole data is a point data that merely shows one part of the strata that are distributed spatially. The geology of the urban areas can be understood only when many borehole data are used to show the spatial distribution of the strata. However, such geological interpretation can only be done by someone with advanced expert knowledge, and it is necessary to organize standard data with which the strata can be compared. While the 1:50,000 geological maps published by AIST show such distribution of strata and geological structures based on the survey and research by geologists, in the case of the geological maps of the urban plains, there is a limit to expressing the subsurface geoinformation planimetrically because the landform is flat. Therefore, we created and inserted many geological cross-section diagrams compared to the maps of mountainous and hill zones (Fig. 1),[7]–[9] but there were limits to such paper-based map publication. Also, the disclosure of fundamental borehole data was limited to the major ones due to the limitations of space or disclosure conditions, and they are not sufficient. It is necessary to display highly reliable interpretation of subsurface geological structures in an easy to understand manner, and to allow people to browse and use the borehole data that is the basis of such interpretation, in terms of reproducibility of the research and promotion of secondary data use.

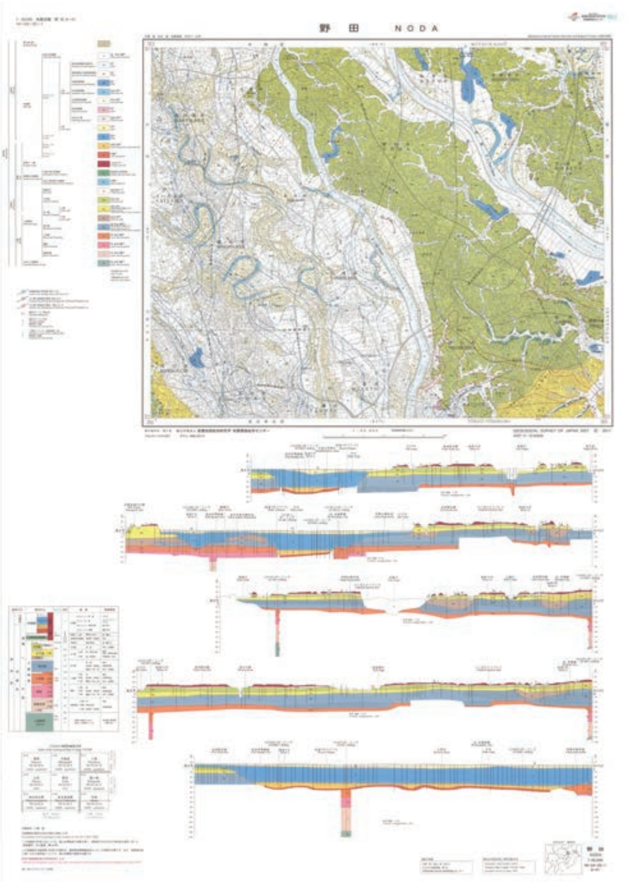

Fig. 1 Conventional style of geoinformation for urban areas

"Noda" sheet of 1:50,000 geological maps. Since the urban area in a plain has flat landform, there is little geoinformation that can be presented on a sheet map. Although this geological map contains several geological cross-section diagrams, there is a limit to how much can be printed on paper.

Recently, the computer processing technology has advanced, and delivery of various information over the Internet has become easy, and the Internet environment for the general public is widening. Assuming the delivery on the website, the degree of freedom of expression of the subsurface geological structure of urban plain areas will increase, and three-dimensional displays will be possible if necessary. It can be said that the organization of geoinformation that goes with the times is demanded.

3 Scenario and elemental technologies for the 3D geological maps

Considering the aforementioned awareness of the current situation, we started to study "3D geological maps" to be delivered on the web (Fig. 2) as urban geoinformation that is easy to understand, easy to use, and above all, highly reliable. Using as standard the data of drilling survey conducted originally by geologists, the borehole logs for public works disclosed by the local governments are correlated, and the 3D distribution of strata is analyzed by computer processing. A method is considered that allows a 3D geological model to be easily viewed on the web by anyone, and a system is constructed that allows browsing and use of the borehole data that is the original data used for 3D analysis. We thought this would enable the organization of geoinformation that is easy to understand, easy to use, and highly reliable. The scenario of the geoinformation for urban areas (Fig. 3) is composed mainly of six elemental technologies: use of the borehole data of public works of the local governments, basic drilling surveys, correlation of the strata, landform classification, 3D modeling technology, and data management and display technology. Our research group is working on the integration of these six elemental technologies taking into consideration the usability and reliability of geoinformation. Below is the explanation of the individual elemental technologies.

3.1 Use of the borehole data of the public works possessed by the local governments

The local governments conduct geological surveys when engaging in public works such as civil engineering and construction projects in their administrative areas. The main method of their geological surveys is drilling. The conducted drilling surveys are normally the standard penetration tests defined by the common specifications for geological survey work by the local governments (Table 1), and the

Table 1. Comparison of standard borehole data and borehole data of public works

	Standard borehole data	Borehole data of public works
Objective	Academic research Organization of reference data	Basic survey for civil engineering and construction work
Item	Geological data + engineering data Sedimentary facies Chronological data Volcanic ash layer Fossil Grain size Physical property data such as velocity logging etc.	Engineering data Rock and soil classification Observation Standard penetration test data Water level in borehole etc.
Drilling depth	About 40～120 m	About 10～60 m
Characteristic	Although there are not too many survey points, high precision information that serves as reference for strata comparisons	They are mainly of standard penetration test data and simple descriptions of strata, but there is accumulation of massive amount of data from the past

results are presented as borehole logs[10] according to the specifications of the Japan Construction Information Center (JACIC). When conducting the standard penetration tests, the samples available are not undisturbed all-core samples, and in many cases, the person entering the data is not a geological expert but a civil engineer or an on-site drilling operator, and therefore, the description of the strata is simple. Drilling surveys for civil engineering and construction work are basically terminated at the point when the depth of the stratum that is the support base of the structure is reached. Although the depth varies according to the geological conditions, many are about 10 to several tens of meters deep. Therefore, most construction borehole data are only to the depth of several tens of meters.

Recently, the massive borehole data of the civil engineering and construction work have been accumulated by the Government and local governments as mentioned before, and are being organized as electronic databases. Currently, the electronic borehole data format that has become a *de facto* standard is set by the MLIT.[11] This is the XML format of the JACIC specified borehole logs that includes the standard penetration test data explained earlier. Since the borehole data that are electronically delivered as geological survey reports to the local governments of prefectures or major cities are in this format, the electronically delivered borehole data can be stored in the database as they come, as long as the database is unified to this file format. Therefore, recently many databases store the borehole data in the JACIC spec XML format, but there are still databases with various data formats. In order to make secondary use easy, it is desirable to convert the data with other formats to the JACIC spec XML format to create the database. At any rate, to conduct the organization of borehole data and the use of borehole data for the geological structure analysis, it is necessary to gain the understanding and cooperation from the local governments for the geoinformation organization effort. Also, for the management and conversion of the local governments' borehole data to the standard format, it is important that AIST provide technical support if needed.

3.2 Drilling survey

The local governments have aggregated enormous amount of borehole data for public works from the past, and these may be great merit for geoinformation organization. On the other hand, since the main purpose of such data, as mentioned before, is the presentation of engineering data (standard penetration test data), they normally do not include the descriptions of volcanic ash layers or chronological data that are the basis of a wide range strata correlation (Table 1). The descriptions of strata are extremely simple, and the sedimentary structure, fossil occurrence, and detailed

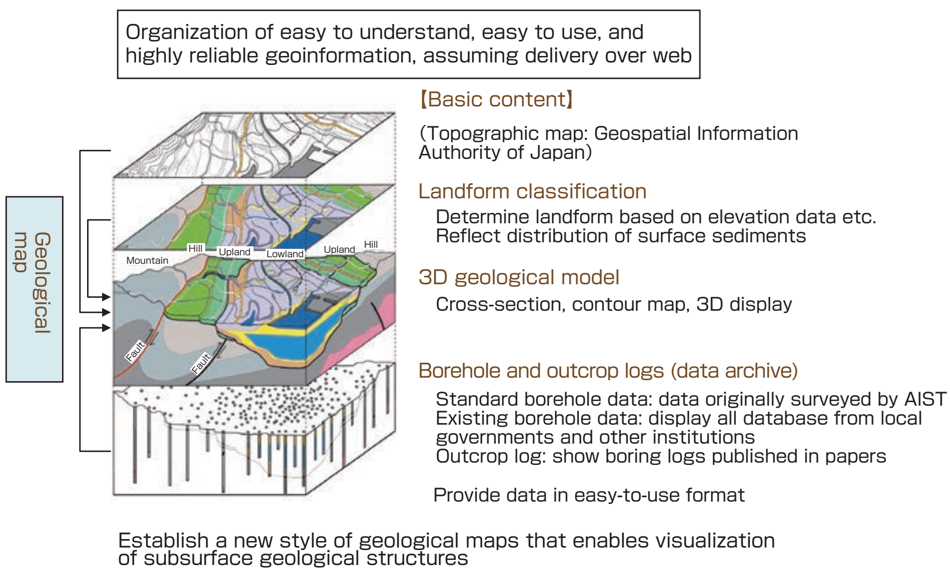

Fig. 2 Outline of 3D geological maps for urban areas

grain size variation that are recorded by geological experts are not included. While such borehole data may be fine for correlating strata within a small property that is the site of construction work, in many cases, the correlation of strata in a wide area that may stretch at prefectural levels are often difficult. However, this cannot be helped since wide range correlation of strata surpasses the original use of the borehole data format in the civil engineering and construction works.

Concerning such borehole data, if AIST can conduct drilling surveys in areas where the strata are thought to be schematically distributed, appropriately classify the strata based on these surveys, and accurately present the characteristics of each stratum, these will become the standard data, and the correlation of strata using the nearby borehole data from civil engineering and construction works can be done easily. We call such reference data the “standard borehole data” (Fig. 4).

Since standard penetration tests are conducted in regular civil engineering and construction works, in most cases, core sampling may not be done or only partially done if at all, and it is difficult to grasp the continuous change of the strata in the vertical direction. In our drilling survey, all-core sampling where the strata of all depths to be drilled will be sampled as cylindrical sediment core samples of approximately 10 cm in diameter is conducted. The survey depth is in most cases several tens of meters for the borehole data of civil engineering and construction work as mentioned before, while our drilling survey will completely cover the range and extends to about 100 m depth that is slightly deeper than the construction survey.

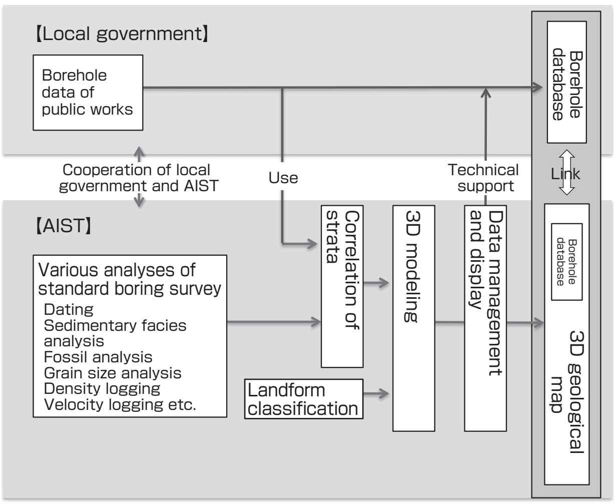

Fig. 3 Scenario for the creation of 3D geological maps for urban areas

The sampled sediment cores are split in half longitudinally, and sedimentary structures, fossil occurrences, volcanic ash layers, and others are descripted. Also, grain size analysis and radiometric dating are done, and depositional environments are interpreted from the contained fossils (Table 1). PS logging where the seismic wave velocities (P and S waves) of each stratum are measured, and also density logging using gamma rays are conducted (Table 1). Based on such surveys, the starata are appropriately classified in terms of stratigraphy[Term 2] and sedimentology,[Term 3] and the characteristic and age of each stratum are presented as comparative standards. Cases where highly reliable standard data based on strata research have been prepared by institutions in charge of geoinformation of urban areas are extremely rare, and it is possible for the Geological Survey of Japan to do so precisely because it is a group of geologists.

3.3 Correlation of strata

After organizing the standard borehole data, strata are compared with the existing borehole data based on the organized data. The spread of strata is grasped in this study. As mentioned earlier, a vast amount of existing borehole data has been accumulated. While it is a merit, the descriptions are simple compared to the standard borehole data, and personal differences in descriptions are large. In the

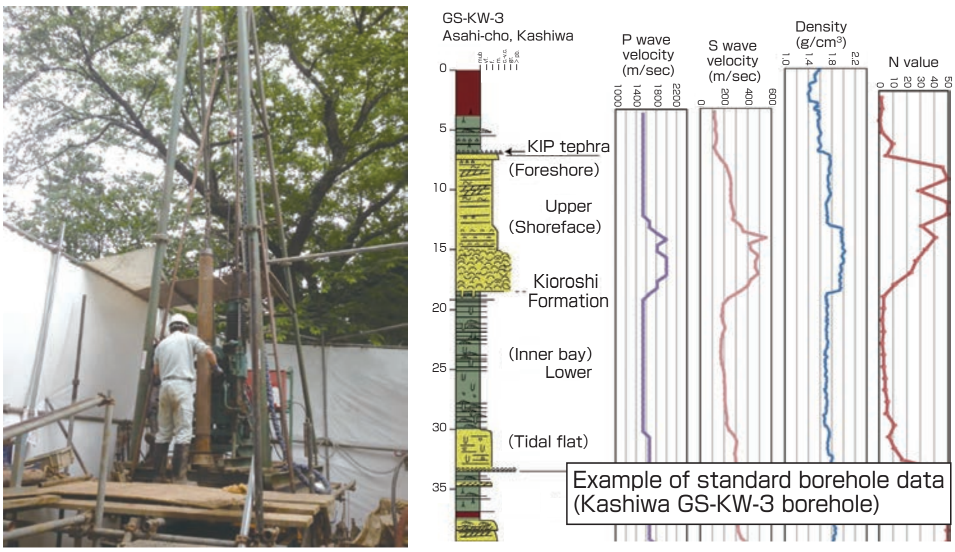

Fig. 4 Drilling survey and standard borehole data
The standard borehole data that will serve as the comparative index for existing borehole data is obtained through originally conducted drilling survey.

correlation of the strata, sedimentary facies, fossils, standard penetration test data, and others described in the existing borehole data are compared with the standard borehole data. The characteristic of the strata is understood by checking each data, and the boundaries of strata are traced. The standard and existing borehole data are in the relation of hub and satellite, and it is possible to increase the reliability of geoinformation by using both data appropriately.

The correlation of the borehole data must be conducted by researchers or engineers in geology who are experienced in strata observation and are able to understand strata characteristics. The actual correlation is done manually by placing the borehole logs on the computer screen using a borehole data analysis tool[12] developed by AIST. This analysis tool allows listing the location information (latitude, longitude, and elevation) of the correlated stratum boundary at the individual drill sites. This location information is used as basic data for 3D modeling.

3.4 Landform classification

Landform reflects the depositional process of the strata and their distribution. Therefore, for the surface (topmost) stratum, rather than determining the distribution only by borehole or outcrop data that is point data, a more accurate distribution can be learned by understanding the distribution of strata from the landform. The landform can be classified using topographical maps, a digital elevation model (DEM), aerial photographs, and others that are provided by the Geospatial Information Authority of Japan. Also, by comparing the old topographical maps or aerial photographs with the current ones, it is possible to know the distribution of the land reclaimed areas and the cut and fill of the developed plateaus and hills. For example, the old version of a topographical map, *jinsoku sokuzu* that was created in the Meiji Period[13] and the aerial photographs shot by the United States military immediately after WWII[14] are available. The results of the landform classification are shown in color on maps.

3.5 3D modeling technology

A 3D geological model is created by integrating the subsurface structure and landform information. For the subsurface structure, correlation of strata of multiple borehole data are conducted, and a 3D subsurface geological model is constructed by estimating the geological boundary surface from the elevation information of the boundary of each point. For the landform information, a landform classification map is created based on the topographical map, DEM, aerial photographs, and others. Finally, by integrating the classification categories of the 3D subsurface geological model and landform classification map, a 3D geological model is obtained (Fig. 5).

There are roughly two methods in the 3D geological modeling technology. One is a method in which a model is constructed manually based on the results of fieldwork by geologists. The other is a method in which a model is constructed by computer processing. In the manual method, the knowledge and experience of the geologists tend to be reflected and complex geological structures can be easily described. However, there are disadvantages that the 3D models may be completely different depending on the creator even if the same survey results are used, and that the 3D

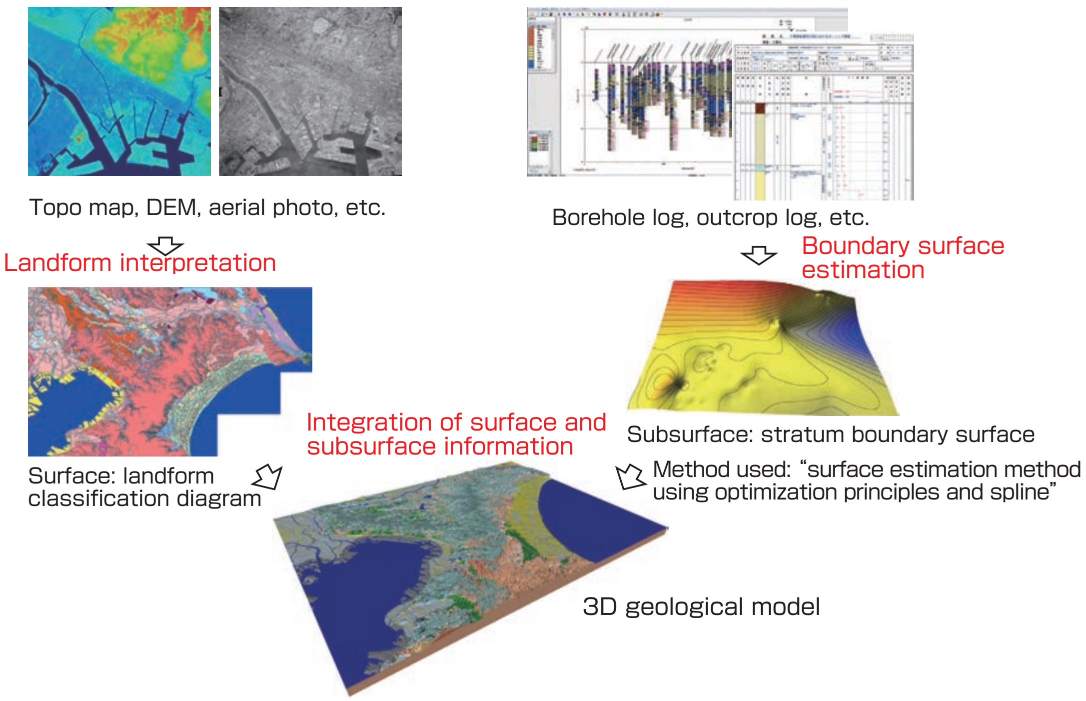

Fig. 5 Procedure of 3D modeling

model is necessarily reconstructed from step one when the model is revised. On the other hand, in the computer processing method, although only the geological structures supported by processing algorithms can be described, the same 3D model can be obtained by any person from the same survey results, and the 3D model can be revised and reconstructed immediately after adding data. The awareness among the geologists can be shared if one modeling method is used as a common base and the 3D model is revised and reconstructed every time. Considering the diffusion and secondary use of geoinformation by 3D models, it is desirable to maintain the reproducibility and upgradability of the model, rather than simply displaying the geological structures in an easy to understand manner. Therefore, in this research, 3D modeling is conducted mainly by computer processing.

When conducting 3D modeling by computer processing, a 3D model is constructed virtually using the logical model of geological structure[15] and the forms of the geological boundary surfaces. The forms of the boundary surfaces are expressed by DEM that is a dataset where the elevation value is arranged in a grid of equal intervals. In the 3D modeling of resource development fields where the main target is deep underground, the quantity of basic data is scarce compared to the scale of targeted geological structures due to the issue of survey costs. Therefore, it is important to determine the place with the highest possibility of the presence of the desired stratum, and in most cases, the DEM of the geological boundary surfaces is created using a stochastic method. On the other hand, for the shallow subsurface 3D modeling of urban areas, abundant elevation data for the geological boundary can be obtained by carefully analyzing the existing borehole data. Therefore, it is important to precisely calculate the surface form that satisfies the data. For this reason, we use a surface estimation method based on optimization principles and spline[Term 4] to create the DEM for the geological boundary surfaces.[16] This is a method that finds the smoothest surface among the feasible surfaces. Available data are the elevation data of the geological boundary and the strike-dip data unique to geology. The elevation data is obtained from the analysis of borehole data and the strike-dip data is obtained from field surveys. For the elevation data, not only the elevation value at the point where the geological boundary is observed, but also the one that indicates the uppermost or lowermost limit such as “the boundary runs above/below this point” can be used. Such characteristics are useful in the cases where the depth of the borehole data does not reach the targeted geological boundary or in the cases where the position of the boundary cannot be clearly indicated due to the absence of some parts of the borehole core. In this method, the DEM is constructed while adjusting the smoothness of surfaces and the goodness of fit to each data. By storing the DEM in machine readable ASCII format, it can be secondarily used in various analyses that utilize the geological boundary surfaces.

3.6 Data management and display technology

To have a 3D geological model used widely by the public, it is desirable to organize an environment where anyone can browse the 3D geological model easily. Therefore, we develop a web system in which the 3D geological model can be browsed by simple mouse operation (Fig. 6). From the perspective of maintaining the reliability of the 3D geological model, we make it possible to browse and search the borehole data used for the construction of the 3D geological model. Since the system is composed of free and open source software, it can be revised flexibly in the future. The 3D geological model is provided in three formats of 2D map, cross-section diagrams, and 3D diagrams to ensure usability

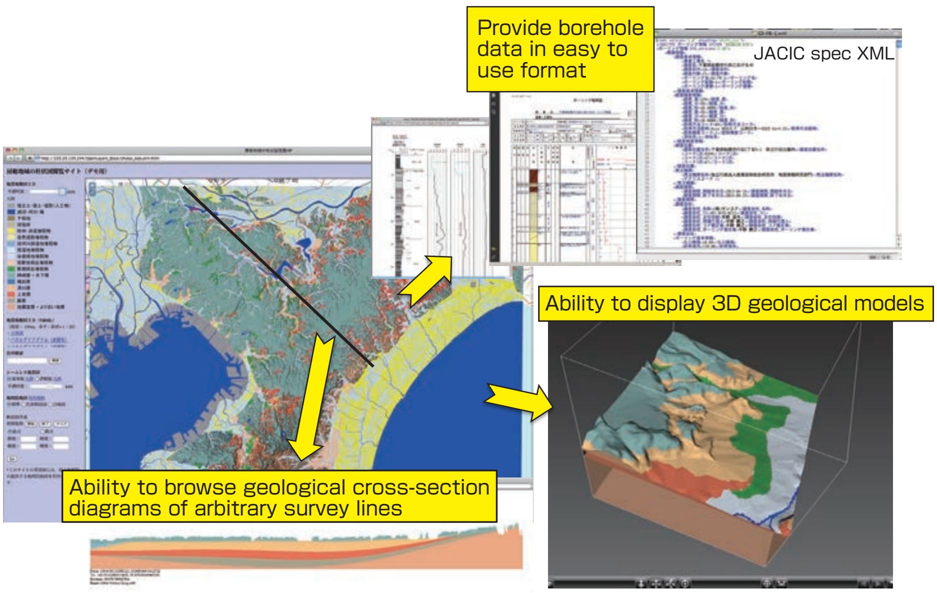

Fig. 6 Web system for browsing the 3D geological model and borehole data

by general users as well as researchers and engineers who are familiar with printed map sheets. For the display of the 2D map, high-speed map display technology using tiled images is used to provide better operability for users. This technology allows zoom in/out and moving by mouse operation. For the display of cross-section diagrams, a vertical geological cross-section between two points identified by clicking on a 2D map can be displayed. For the display of 3D diagrams, since web delivery of a whole area model is difficult due to the file size of 3D geological model data, the whole area is divided into lattices and a model for each smaller region is displayed. For the borehole data, by clicking on the data point, the metadata can be browsed. The metadata includes the link to JACIC XML and PDF. By constructing a database of metadata and by adding the function of setting the search range to the browser system, the metadata of borehole data can be searched from the browser system.

The borehole data for public works possessed by the local governments and the standard borehole data organized by AIST are important basic data that form the core of 3D modeling, and are essential information to maintain reliability of the 3D model. Therefore, we develop a system that allows the local governments to manage the borehole database in JACIC XML format (Fig. 7).[17] For the database, PostgreSQL,[Term 6] that is an RDBMS[Term 5] with high versatility, is used, and this system will be released free of charge. Through the use of such a system, it is expected that the borehole data that is the basic geoinformation of urban areas will be appropriately managed in many local governments.

4 Assumed utilization of a 3D geological map

Currently, in our group, the six elemental technologies discussed in the previous chapter are being integrated, and we are attempting to create a 3D geological map. Assumed utilization of such a 3D geological map is in making hazard maps for earthquakes, planning for urban infrastructures and industrial constructions, and in real estate transactions.

For the creation of an earthquake hazard map, the subsurface elastic wave velocity data (particularly S wave velocity data) and a shallow subsurface geological model are necessary.[18] However, existing borehole data that include S wave velocity data is rare. Since our drilling survey measures the S wave velocity, it can be used as the standard data for seismic motion simulation. Also, our 3D geological model created based on the standard borehole data is also expected to be used as geological model data when creating earthquake hazard maps (Fig. 8). Moreover, by understanding vibration characteristics such as specific dominant frequencies of the ground by microtremor measurement,[19] it is possible to create earthquake hazard maps that accurately take the geology into consideration. Therefore, our group conducts microtremor measurement along with the construction of the geological model, and we are considering classification of ground vibration characteristics according to geological conditions.

In planning urban infrastructures and industrial construction, it is extremely important to collect information beforehand on the presence of weak ground and at what depth the stratum that would be the support base of the structure is distributed. If this information can be known beforehand, the planning and estimates of the geological survey can be done easily. In the geological survey industry, efforts are spent on reducing the risks of delay of survey periods, design change, or increased project costs that may occur if the geological condition is different from the one assumed.[20] As a measure, the existing geoinformation should be actively used.[21] The existing borehole data of the urban areas and a 3D geological model appropriately interpreted from such data are thought to contribute to risk management through disclosure in an easy to use format (Fig. 8).

Since the 2011 Off the Pacific Coast of Tohoku Earthquake,

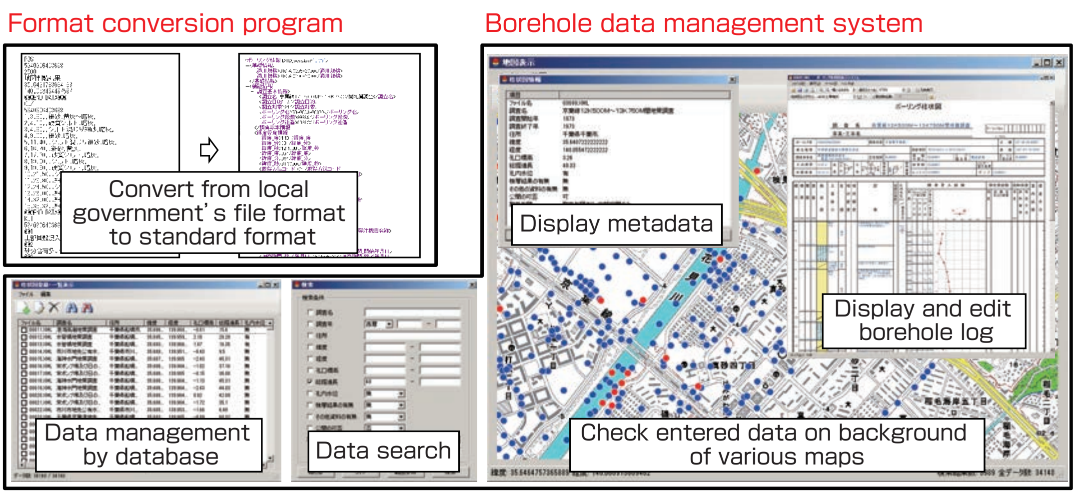

Fig. 7 Conversion program for the borehole data and its management system

interest in the geology and ground of the urban areas increased significantly among the general public. In real estate transactions, the provision of geoinformation is not an obligation, but with the serious liquefaction damage in the Tokyo Bay coastal area, it has been proposed that the geoinformation should be actively used in real estate transactions.[22] While there are concerns that the real estate appraisal value may change, we think it is necessary to nurture common awareness in society that the geoinformation is important public property, in order to raise the people's consciousness for disaster risks and to promote construction of cities resilient against disaster. The Science Council of Japan, in its proposal for sharing geoinformation,[23] states that it is indispensable that the information on subsurface geology is recognized as common property of the people, and that it is used effectively as basic information of our land. On the other hand, while the general public may be interested in the geology for building residences, it may be difficult to decipher the borehole data or geological maps for many people who do not have the geological expertise. This is the same for people in the real estate industry. To meet such needs, there are emerging consulting businesses that utilize the existing geoinformation. In such businesses, there are requests for geoinformation to be organized in a format that can be easily used. The 3D geological map on which we are working may satisfy such requests (Fig. 8).

5 Trial in the model region

In the scenario explained in Chapter 3, it is deemed possible to organize geoinformation of the urban areas. We have set the northern part of Chiba Prefecture as a testing area and are presently making a 3D geological map. The major reason that this region was selected is because the typical strata of the Kanto Plain is distributed, and because Chiba Prefecture is actively spending effort on the organization of geoinformation.

5.1 Geological topic of the model region

In the testing area, there are Pleistocene and Holocene strata that are representative deposits in the Kanto Plain, as well as landfill strata in the coastal lowlands.

The Pleistocene strata are exposed in uplands and commonly exhibit a large subsurface basin structure. The basin structure elucidates the history of the sedimentary basin, and also contributes to high-precision analysis of the subsurface water flow. Although the basin structure was estimated from the analysis of existing borehole data, there was hardly any stratigraphic research in the northern part of the Chiba area, and the accurate basic structure was unknown. Recently, stratigraphic research by our group is revealing the details of the basin structure centering around the Tokyo Bay coastal area.[24] It is important to accumulate the know-how for 3D analysis of the basin structure underneath the plain in the model region.

Beneath the present-day lowlands, there is a stratum formed 20,000 years ago or later called *Chuseki-so*. It is commonly known as soft muddy sediments filling old valleys. Recently, similar soft muddy sediments have been also found beneath uplands in the Kanto Plain.[25] Such muddy sediments are not

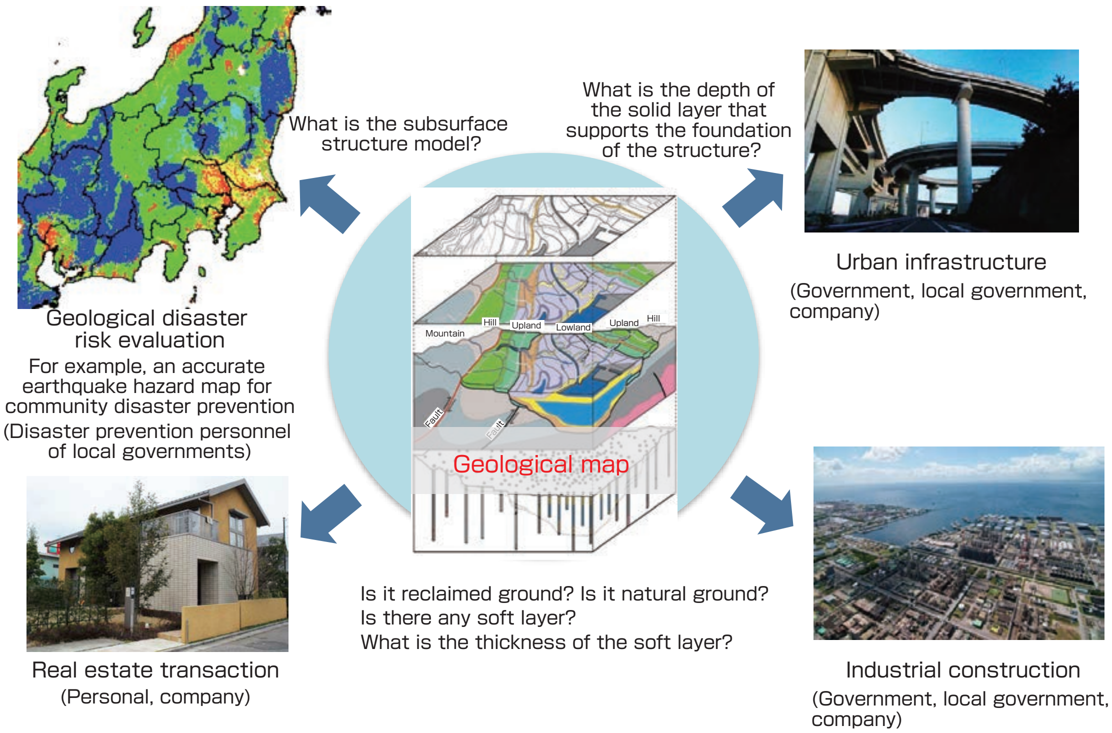

Fig. 8 Assumed ways of utilizing the 3D geological map

well known to exist beneath uplands, so this may be a blind spot of the urban ground. It is known that such valley filling sediments are distributed from east to west (from Kashiwa to Narita) in northern Chiba (Fig. 9), and it will be interesting to learn how the facies change, how the facies changes are reflected in the physical properties, and how this is expressed as differences in seismic motion.

The landfill layer is widely distributed along the coastline of the Tokyo Bay area of northern Chiba. Underneath the landfill layer, *Chuseki-so* exists in several strands of incised valleys. The landfill layer of this region caused serious liquefaction in the 2011 Off the Pacific Coast of Tohoku Earthquake, and in some areas, the urban infrastructure was paralyzed. In general, the stratum that is subject to liquefaction is the loosely packed sand layer saturated with underground water, and such a sand layer is commonly seen in the landfill layers of the coastal and riverside areas. The landfills in the Tokyo Bay area were made of sand and gravel dredged from offshore by a sand pump method.[26] They represent alternating layers of sand and mud, and may resemble a natural stratum at a glance, but it can be identified by detailed observation of the sedimentary structure and fossil occurrence in the core sample.[27] Also, in the case of the sand pump method, there is unevenness of the distribution of sand and mud in the landfill layers depending on the position of the pump outlet, and it is said that liquefaction is likely to occur in areas that are predominantly sand.[28] Through the series of drilling surveys that we conducted, it is possible to establish identification standards for the landfill layer by the sand pump method, and the pattern of unevenness of sand and mud in the landfill can be clarified through the analysis of borehole data and past aerial photographs. Moreover, soft muddy sediments (*Chuseki-so*) exist irregularly beneath the landfill layer, and the change in the thickness of the muddy sediments may be of effect on the liquefaction of the landfill layer on top.

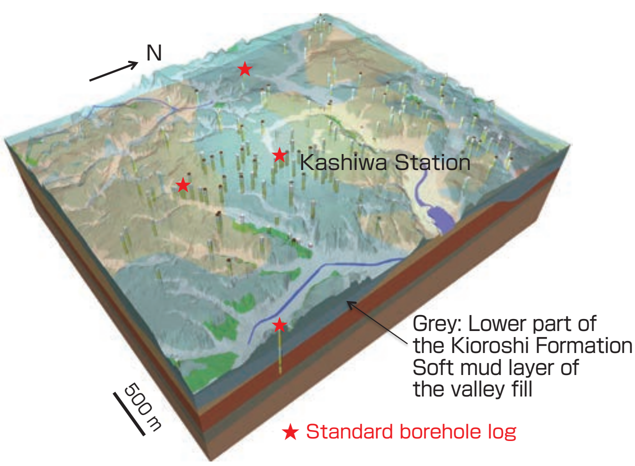

Fig. 9 3D geological model of the subsurface valley fill deposits around Kashiwa, Chiba Prefecture

5.2 Cooperation with the local governments

Currently, we are working on the management of borehole data and their analysis with the cooperation from the Chiba Prefectural Environmental Research Center. This Center has worked on research for geopollution, liquefaction, etc. It is also a pioneer in establishing a borehole database because it has gathered borehole data of public works in Chiba Prefecture and has disclosed them on the web since 1991. The "Chiba Information Bank for Geological Environments" managed by the Center provides borehole data for about 20,000 sites in Chiba. Since the data stored in this database is in an original format, we are attempting to convert them into the JACIC spec XML that is the current standard format (Fig. 7). We are working along with the researchers of the Center to convert to a database that stores in the JACIC spec XML format in the future. The specification of the aforementioned borehole data management system was decided while discussing with the researchers of the Center. Initially, the system that uses the web was considered, but as a result of meetings with the person in charge, we shifted to the specification that runs on stand-alone computers due to security concerns. Such demands became apparent after exchanging opinions with the local government, and it was a good opportunity to learn how extremely important it is to understand the situation of the local government. The Center has abundant experience in geological surveys, and has strong views that the organization of standard borehole data based on investigation of actual sediment core samples, as well as the collection of existing borehole data of public works, are extremely important for geological environment and disaster measures such as dispersal of soil contamination and liquefaction prediction. We are engaging in the topic together with such shared awareness.

5.3 Prototype of the 3D geological map

For the establishment of the algorithm for the 3D geological model creation of northern Chiba, we conducted practical research in the Kisarazu district of Chiba Prefecture that is a stratotype of the Pleistocene strata that comprises the Kanto Plain. First, we created the algorithm for constructing a 3D geological model based on the stratigraphy in the Kisarazu district described in the published 1:50,000 geological map, and a 3D geological model was constructed using the outcrop data same as the ones used to create the geological map. The created 3D geological model was compared digitally and visually with the published, hand-drawn geological map. As a result, this 3D geological model created by a logical method was found to have no problem stratigraphically, and have no human error compared to the conventional manual-work drawing. The geological boundary can be drawn precisely and faithfully to the data, and its practicality was demonstrated.[29] The algorithm constructed for the Kisarazu district that is a stratotype of the Pleistocene strata in the Kanto Plain is thought to be widely applicable to the entire Kanto Plain.

Using this algorithm, a temporary 3D geological model was created based on the standard borehole data of 14 points, outcrop logs at 355 points, and landform classification maps. We created the prototype of the 3D geological map that allows browsing of maps, arbitrary cross-section diagrams, 3D models, and borehole data using the aforementioned browsing system (Fig. 6).[30] We are aiming ultimately for geological maps that can be used at 1:25,000 scale that surpasses the basic scale (1:50,000) of the geological maps, by raising the precision of the geological model by increasing the standard borehole data to 20 points or more and using about 20,000 existing borehole data. Through such organization of the geological maps, it is expected that geological disaster risk evaluation will become possible at higher precision.

6 Conclusion

For the 3D geological map that is being attempted presently in the testing area, standard borehole data will be added in the future, and correlation of strata for the existing borehole data will be furthered to enhance the precision of the 3D geological model. The cross-section diagrams and 3D models will be revised for better operation and usability, and it is scheduled for disclosure in FY 2017. This result will be proposed as a new style of geoinformation for urban areas, and we hope this will initiate the expansion to other cities through the cooperation of the local governments. A guideline is considered that allows the local governments to create their own geological maps, and technical support will be provided where needed. By promoting the organization of geoinformation that is easy to understand, easy to use, and highly reliable for the urban areas, we hope the utilization of the geoinformation by the administration, companies, and general public will be further promoted.

Acknowledgements

In pursuing this research topic, we held various discussions to determine the direction of research with the following people from the start of the project: Measurement and Intellectual Infrastructure Division, METI; Research Planning Office for Geological Survey and Applied Geoscience (currently, Research Planning Office for Geological Survey of Japan), AIST; Geoinformation Center (currently, Geoinformation Service Center), AIST; executive personnel of the Research Institute of Geology and Geoinformation; Junko Komatsubara, Tomonori Naya, Ikuo Cho, and Kentaro Sakata of the Research Institute of Geology and Geoinformation who participated in this research topic; and the people of the Geological Environment Laboratory, Chiba Prefectural Environmental Research Center. We are grateful to all those involved.

Terminologies

Term 1. Secondary use: According to the “Guide for the promotion of disclosure and secondary use of ground information” (June 2013) of the Ministry of Internal Affairs and Communications, secondary use of ground information is defined as “the use or provision of ground information (such as borehole data) supplied by administrative organizations and others, by forming them into information that can be easily used or by adding other information.” Primary use is defined as “the use by the administrative institutions and others that possess the ground information mainly for their internal use.” In the open government data strategy, it is written that “the public data possessed by the Government, independent administrative bodies, local governments, or others should be disclosed in the machine readable data format, and should be subject to rules that allow secondary use including for commercial purposes.”

Term 2. Stratigraphy: A discipline that clarifies the layering order of the strata from fossils, measured age, and strata characteristics.

Term 3. Sedimentology: A discipline that clarifies the process and mechanism by which the sedimentary layers are formed from the properties of the deposits.

Term 4. Spline: A piecewise polynomial function in which the target region is broken down into multiple segments and the polynomial equation is set for each segment. It is excellent for fitting curves and curved surfaces with complex shapes.

Term 5. RDBMS (relational database management system): A general term for the software for managing relational databases. In RDBMS, comparison, joining, extraction, and others of the data are done while the data are managed in a table format.

Term 6. PostgreSQL: Open source RBDMS that can be used for various purposes, free of fee, license, secondary distribution, and others. SQL is used for database operation.

References

[1] K. Wakamatsu and S. Senna: Tohoku Chiho Taiheiyo-oki Jishin (Higashi Nihon Dai Shinsai) ni yoru ekijoka to kako no ekijoka rireki [Liquefaction in the 2011 Off the Pacific Coast of Tohoku Earthquake (Great East Japan Earthquake) and past history of liquefaction], *Chishitsu To Chosa*, 2013

(4), 138, 6–11 (2013) (in Japanese).

[2] S. Okada, T. Komatsubara, T. Nakazawa, Y. Nakamura, K. Sakata and T. Naya: Distribution of tiled-roof damage around Tsukuba and Tsuchiura Cities using Google Earth images by the 2011 Off the Pacific Coast of Tohoku Earthquake, *J. Seismological Soc. Japan*, Second Series, 64 (4), 257–264 (2012) (in Japanese).

[3] Civil Engineering Support and Training Center, Tokyo Metropolitan Government: Tokyo no jiban GIS-ban (GIS version of the ground in Tokyo), http://doboku.metro.tokyo.jp/start/03-jyouhou/geo-web/00-index.html, accessed 2015-08-27 (in Japanese).

[4] Chiba Information Bank for Geological Environments: Chiba Information Map (Geological Columns), https://www.pref.chiba.lg.jp/suiho/chishitsu.html, accessed 2015-08-26 (in Japanese).

[5] Ministry of Land, Infrastructure, Transport and Tourism: Kokudo jiban joho kensaku site KuniJiban (National ground information search site "KuniJiban"), http://www.kunijiban.pwri.go.jp/jp/index.html, accessed 2015-08-27 (in Japanese).

[6] National Research Institute for Earth Science and Disaster Prevention: Geo-Station, http://www.geo-stn.bosai.go.jp/jps/index.html, accessed 2015-08-27 (in Japanese).

[7] T. Nakazawa and H. Endo: Geology of the Omiya District, 1:50,000 Geological Map of Japan, Geological Survey of Japan (2002) (in Japanese).

[8] T. Nakazawa and S. Tanabe: Geology of the Noda District, 1:50,000 Geological Map of Japan, Geological Survey of Japan (2011) (in Japanese).

[9] T. Naya and M. Yasuhara: Geology of the Konosu District, 1:50,000 Geological Map of Japan, Geological Survey of Japan (2014) (in Japanese).

[10] Japan Construction Information Center Foundation: Boring chujozu sakusei yoryo (an) kaisetsusho [Manual (draft) of creating the borehole logs] (1999) (in Japanese).

[11] Ministry of Land, Infrastructure, Transport and Tourism: Chishitsu doshitsu chosa seika denshi nohin yoryo (an) fuzoku shiryo [Appendix of the electronic delivery method of geological and soil survey results (draft)] (2008), http://www.cals-ed.go.jp/mg/wp-content/uploads/boring62.pdf, accessed 2015-10-02 (in Japanese).

[12] K. Kimura: Boring data shori system no kokai—Kokudo kiban joho toshite no boring data no rikatsuyo o mezashite (Disclosure of the borehole data processing system—For the utilization of borehole data as basic national land information), *AIST Today*, 11 (1), 19 (2011) (in Japanese).

[13] National Institute for Agro-Environmental Sciences: Rekishiteki nogyo kankyo etsuran system (Browsing system for historical agricultural environment), http://habs.dc.affrc.go.jp, accessed 2015-10-02 (in Japanese).

[14] Geospatial Information Authority of Japan: Chizu kuchu shashin etsuran service (Browsing service for maps and aerial photographs), http://mapps.gsi.go.jp/maplibSearch.do#1, accessed 2015-10-02 (in Japanese).

[15] K. Shiono, S. Masumoto and M. Sakamoto: Characterization of 3D distribution of sedimentary layers and geomapping algorithm—Logical model of geologic structure, *Geoinformatics*, 9 (3), 121–134 (1998) (in Japanese).

[16] S. Nonogaki, S. Masumoto and K. Shiono: Gridding of geological surfaces based on equality-inequality constraints from elevation data and trend data, *International Journal of Geoinformatics*, 8 (4), 49–60 (2012).

[17] S. Nonogaki and T. Nakazawa: Development of management system for borehole logs in JACIC format, *Research Institute of Geology and Geoinformation Sokuho*, 68, 53–59 (2015) (in Japanese).

[18] Director General for Disaster Management, Cabinet Office: Jishin bosai map sakusei gijutsu shiryo (Technical resource materials for compilation of earthquake disaster prevention maps), http://www.bousai.go.jp/kohou/oshirase/h17/pdf/050513siryou.pdf (2005) (in Japanese).

[19] I. Cho and S. Senna: Constructing a system to explore shallow velocity structures using a miniature microtremor array—Accumulating and utilizing large microtremor datasets, *Synthesiology*, 9 (2), 86–96 (2016) (in Japanese).

[20] Chishitsu Risk Gakkai and Japan Geotechnical Consultants Association (eds.): *Chishitsu Risk Management Nyumon* (Introduction to Geological Risk Management), Ohmsha (2010) (in Japanese).

[21] A. Iwamatsu: Applying geo-information to geological risk mitigation, *Proceedings of 4th Symposium on Sediment Disasters*, 09, http://committees.jsce.or.jp/seibu_s01/system/files/04vip-iwamatu.pdf (2008) (in Japanese).

[22] M. Honma: Utilization plan for geological data in real estate transactions and recovery status from liquefaction damage in Urayasu City, *GSJ Chishitsu News*, 2 (12), 357–360 (2013) (in Japanese).

[23] Science Council of Japan: Teigen chishitsu jiban joho no kyoyuka ni mukete—Anzen anshin na shakai kochiku no tameno chishitsu jiban joho ni kansuru hoseibi (Proposal for sharing of geological ground information—Legal consideration for geological ground information to construct a safe and secure society) (2013), http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-22-t168-1.pdf, accessed 2015-10-02 (in Japanese).

[24] T. Naya, K. Sakata, H. Nakazato, J. Komatsubara and T. Nakazawa: Stratigraphy of Shimosa Group at the coastal area of Tokyo Bay in the northwestern region of Chiba Prefecture, central Japan, *Abstracts, 121st Annual Meeting of the Geological Society of Japan*, 52 (2014) (in Japanese).

[25] T. Nakazawa, R. Nakashima, T. Ueki, S. Tanabe, H. Oshima and S. Horiuchi: Sequence stratigraphy of the Pleistocene Kioroshi Formation, Shimosa Group beneath the Omiya Upland, central Kanto Plain, central Japan, *Journal of the Geological Society of Japan*, 112, 349–368 (2006) (in Japanese).

[26] O. Kazaoka: Tonegawa karyu teichi and Tokyo Wan umetatechi (Lowlands of Tonegawa downstream and landfill area of Tokyo Bay), *Urban Kubota*, 40, 5–13 (2003) (in Japanese).

[27] J. Komatsubara, R. Nakashima and T. Naya: Sedimentary facies and depositional environments of the Pleistocene to Holocene incised valley fills in Funabashi city, Chiba prefecture, *Abstracts, 121st Annual Meeting of the Geological Society of Japan*, 53 (2014) (in Japanese).

[28] O. Kazaoka, M. Sato, T. Kusuda, K. Kamura, T. Kazato, A. Kagawa, M. Morisaki, K. Satoh, K. Furuno, Y. Sakai, A. Kato and H. Nirei: Liquefaction fluidization on the boundary between artificial loose sand and soft mud reclaimed land around Tokyo Bay, *Proceedings of the 10th Symposium on Geo-Environments and Geo-Technics*, 33–38 (2000) (in Japanese).

[29] S. Nonogaki and T. Nakazawa: Three-dimensional geological modeling of the Kisarazu District based on logical procedures, *Geoinformatics*, 26, 3–13 (2015) (in Japanese).

[30] S. Nonogaki, T. Nakazawa and H. Nakazato: Development of browsing system for two- and three-dimensional geological data, *Proc. GIS-IDEAS 2014*, 236–241 (2015).

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Discussions with Reviewers

1 Overall

Comment (Akira Kageyama, Research Support Advisor, AIST)

This paper is a summary of the results of the trial that was conducted for the purpose of supplying geoinformation not only for two-dimensional but also for three-dimensional geological maps, to use in earthquake hazard assessment and urban planning. It discusses the process by which several elemental technologies were integrated, including the data possessed by the local governments. Since the research was started with consideration of ease of use, the social usefulness is high. In terms of technology, the paper can be highly evaluated since it carefully considers the modeling technology for estimating the three dimensional geological conditions that are difficult to study directly. From these points, we conclude that this paper is appropriate for publication in *Synthesiology*.

Comment (Chikao Kurimoto, AIST)

This paper proposes 3D geological maps of urban areas where the population is concentrated, and introduces the research results useful for the creation of hazard maps while collaborating with local governments. Such perspective is meaningful for urban areas where disaster prevention and mitigation are grave concerns, and this result is expected to have major impact on society. Also, the attitude of constructing a highly precise yet easy-to-use system through the development of modeling technology matches the social demand. This paper is based on geological surveys, but also goes on to the organization of geoinformation, handling and advancing the digital information, and implementation in society through collaboration with local governments. I think it sufficiently matches the objective of *Synthesiology*.

2 Primary and secondary uses

Comment (Chikao Kurimoto)

The primary use and secondary use mentioned in Chapter 1 "Introduction" are very important. I think the readers will better understand if you have a section on terminology.

Answer (Tsutomu Nakazawa)

I added a footnote for secondary use (and primary use).

3 Composition of the explanations for the scenario and elemental technologies

Comment (Akira Kageyama, Chikao Kurimoto)

You discuss the scenario for achieving the goal in the beginning of Chapter 3 and Fig. 3, but I think it will be easier to understand if you unify Figs. 2 and 3 (this doesn't mean you should join the two figures into one). For example, suggestion 1: if the "landform and land use information" and "geoinformation on the surface" shown in Fig. 2 are used in 3D modeling, you should mention them also in Fig. 3. Suggestion 2: you can explain that Fig. 3 is a diagram that shows the details of how to conduct the integration of data and information for the borehole data and outcrop log of Fig. 2.

Also, what about explaining that you have worked on the integration of six elemental technologies while considering the usability and reliability in the appropriate part of Chapter 3, and then explain the individual elemental technologies?

Answer (Tsutomu Nakazawa)

Since the information about the surface layer in Fig. 2, or the landform classification, is one of the important elemental technologies, we added the landform classification in the elemental technologies of Fig. 3, and added a section in the text for its explanation.

We also added the point that we are working on the integration of six elemental technologies in the preface of Chapter 3, and we also added that we are working on the trial creation of a 3D geological map by integrating the six elemental technologies at the beginning of Chapter 4.

4 Standard borehole data and borehole data of public works

Comment (Akira Kageyama)

You explain the differences between the two in Subchapter 3.2 and I think this is important. Therefore, how about showing the differences between the two data in a table? By directly comparing the objective and measurement data, I think it will make the scenario for the whole research easier to understand, that is, although borehole data for public works and others are useful, they are not sufficient as they are.

It is the understanding of the Reviewer that the process of comparing, contrasting, and refining the borehole data possessed by the local governments against the results of the standard boring survey is the comparison of the strata in Subchapter 3.3. If so, I think the standard boring survey has the “hub function” while the local governments’ borehole data have the “satellite function.” Do you agree?

Answer (Tsutomu Nakazawa)

We newly created Table 1 that compares the characteristics of the standard borehole data and the borehole data of public works. The two data are in the relation of hub to satellite, as you indicated, and we added the explanation that the reliability of geoinformation can be increased by using the two data.

5 3D modeling technology

Question & Comment (Akira Kageyama, Chikao Kurimoto)

I think the terminology should be unified for the discussion in Subchapter 3.3 and Fig. 5. For example, the terms, “3D geological model,” “3D geological ground model,” “landform classification diagram,” and “landform categorization diagram” are mentioned.

In Paragraph 2, Subchapter 3.5, it is described that there is a possibility that a completely different 3D model may be produced depending on the person in charge of manual work. Isn’t there need for making some sort of guideline that can produce a uniform model or interpretation? For example, the computer modeling method that you developed can be set as a common base, and then a gradual shift can be made to the system of adding on knowledge and experience of the experts as metadata.

Answer (Tsutomu Nakazawa, Susumu Nonogaki)

For terminology, we reviewed the descriptions, and call the 3D model for subsurface geology only as the “3D subsurface geological model,” and the model integrated with surface information as the “3D geological model.” The “landform classification” and “landform categorization” were unified into “landform classification map.”

As you indicated, at this point, we are not working on obtaining a uniform model and interpretation, but we think it is important. The fact that the 3D model by computer processing is useful in sharing common awareness among experts was added to the paper.

6 Discussion in Chapter 4

Question (Akira Kageyama)

(1) How many drilling surveys did you do for the establishment of reference data (standard borehole data) at Noda and Kashiwa? To obtain a certain level of reliability, how many drilling surveys are necessary? Also, while this may depend on the content of the local governments’ borehole data, how much supplementary effect can be expected in constructing the total system? If you would provide some information on these, I think it will be a rough guide (including costs) when expanding the project to various regions of Japan in the future.

(2) For the utilization in real estate transactions, it is expected that there will be requests for not disclosing 3D geological maps because it may reduce the appraisal value of real estate. In the case of landslide damage that occurred in Asa-minami, Hiroshima Prefecture, it has been reported that the disaster increased because the disclosure of the hazard map was withheld. In such situations, from the viewpoint of increasing the risk response capability of society (community) by raising the understanding among interested parties, what are the authors’ thoughts on this (of course, the authors or AIST cannot undertake responsibility)?

Answer (Tsutomu Nakazawa)

(1) In the northern Chiba area that is the testing area, we ultimately plan to conduct about 20 sites of drilling surveys for establishing reference borehole data and use about 20,000 existing borehole data from public works. By doing so, we aim for geological maps of 1:25,000 that surpasses the 1:50,000 which is the basic scale of the conventional geological maps. We believe the goal can be achieved. We added this point to Subchapter 5.3. About half of the standard drilling survey sites in this research mainly target the irregularly distributed valley fill deposits. While it is desirable to have as many standard borehole data as possible, the geological structure can be estimated with surveys at lesser density in areas where the strata are distributed flatly and evenly. In contrast, in areas with complex strata, more surveys will be necessary. This means that the density of the drilling survey differs greatly according to the geological characteristics of that region.

(2) As you indicate, I think there are concerns for the shift in appraisal value of a real estate if the geoinformation is added to real estate transactions. There may be both increase and decrease of the appraisal value. In either case, it is important for society to work on constructing a safe city by understanding the real geological and ground characteristics, and I think it is important to have people share the awareness that geoinformation is an important public asset for taking measures against disaster risks. We added this point to the paper, along with the citation of the proposal by the Science Council of Japan.

7 Creation of the 3D geological map, future prospect, and ripple effect

Comment (Chikao Kurimoto)

You cite Fig. 6 and explain the results of the prototype of the 3D geological map. I understand that this will lead to a “new style of geoinformation for urban areas” in future research. I think the readers will gain better understanding if you summarize the prospect of future research and its ripple effect.

Answer (Tsutomu Nakazawa)

The prototype of the 3D geological map is expected to increase the precision of geological disaster risk evaluation, and we believe the ripple effect on society is great. This point was added. Also, to clarify the future research prospect and the expected ripple effect, we summarized in Chapter 6 that we shall aim for the establishment of a new style of geoinformation for urban areas and the construction of 3D geological maps in the model region.

Constructing a system to explore shallow velocity structures using a miniature microtremor array

— Accumulating and utilizing large microtremor datasets —

Ikuo CHO[1*] and Shigeki SENNA[2]**

[Translation from *Synthesiology*, Vol.9, No.2, p.86–96 (2016)]

Our final goal is to provide quantitative information on subsurface S-wave velocity structures in response to a variety of social needs regarding geological and soil matters. Since S-wave velocity is a physical property directly related to site amplification and ground stiffness, it is expected to contribute to, for example, improving accuracy of seismic zoning for the mitigation of earthquake disasters. Currently, we are constructing a system for observation and analysis of microtremors to explore S-wave velocities within the depth range from several to tens of meters on the basis of 15-minute observations with a miniature seismic array having a radius of 0.6 m. The simplicity and objectivity of our system affords automization and quality control, with an expected capacity to acquire large amounts of microtremor data.

Keywords **:** Microtremor survey method, array observation, Rayleigh wave, S-wave velocity, soil-structure model, seismometer

1 Introduction

While devastating tsunami damage occurred by the 2011 off the Pacific coast of Tohoku Earthquake, there were also considerable damage by strong motion and liquefaction. The damage differed according to the soundness of the ground. The S-wave[Term 1] velocity of the ground is important information to learn about shakiness by earthquakes, and it is also useful in disaster prevention. As one of the methods to estimate the S-wave velocity, minute oscillations of the ground called microtremors can be used as data.

The microtremor array exploration method is a method for estimating the S-wave velocity structure from several tens of meters to several kilometers underground. This involves array observation of microtremors [Fig. 1(a)] over several hours by laying out the seismographs on the ground surface at several tens of meters to several kilometers scale. This is a nondestructive exploration where it is not necessary to excavate the ground as in logging.[Term 2] Since the collected data is for microtremors that are present everywhere and anytime, the advantages are that it is lower in cost than the seismic wave exploration that uses artificial seismic sources[Term 3] and it can be applied easily in urban areas.

The authors are constructing a system for microtremor array exploration that specializes in shallow ground, and in which the observation and analysis are thoroughly simplified (hereinafter, this will be called the "new system"). In the new system, an array with a radius of 0.6 m composed of one seismometer in the center point of a circle and three seismometers evenly placed around the circumference (in total, four seismometers) is used [Fig. 1(b), Fig. 2]. This array is used to observe microtremors for about 15 min to estimate the S-wave velocities of shallow ground to the depths from several meters to several tens of meters. Assuming the observers to be general users (such as university labs or high school geology clubs) who are not experts on subsurface structure exploration, one-touch operated measurement equipment is adopted. After measurement, the microtremor data obtained are transmitted wirelessly to a server, and are automatically analyzed. The users are sent analysis results, and the measurement and analysis data are stored in a database in the server. Our aim is comprehensive provision of

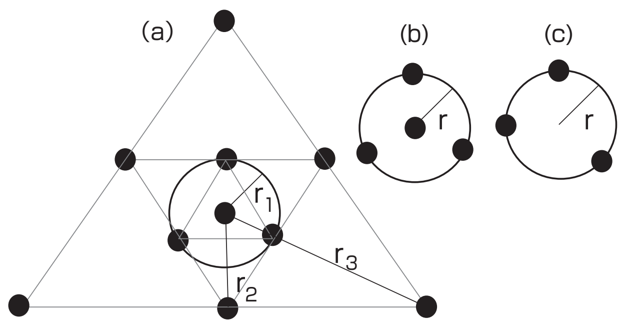

Fig. 1 Microtremor array
The "r" is the array radius, and black dots show the seismometers. In the conventional microtremor array exploration, the array radii range from several tens of meters to several kilometers [array (a)]. The new system will basically use 0.6 m radius [array (b)], and a radius of 5 m [array (c)] may be used supplementarily.

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Original manuscript received September 1, 2015, Revisions received November 30, 2015, Accepted December 2, 2015

this series of maneuvers. The array used in the new system is much smaller than the one used in conventional microtremor array exploration, and hereafter we call this a miniature array in this article.

The new system is an advanced version of an existing system called "i-bidou" that was created by a research group of Senna, one of the authors of this article.[1] The i-bidou is composed of a series of maneuvers including execution of single-point measurement[Term 4] using a microtremor measurement kit,[2] data transfer to a server, calculation of the spectral ratios of horizontal-to-vertical components of microtremors (H/V spectrum[Term 4]), forecasting seismic intensity during an earthquake, and delivery of these analysis results. An H/V spectrum of microtremors is said to represent the oscillating characteristics of the ground. The new system is positioned as a system that allows high precision analysis of the wave propagation velocity as well as the oscillating characteristics of the ground, by replacing the single-point measurement of i-bidou with the miniature array.

The goal of the authors is to provide information of the subsurface S-wave velocity that is of high density, high resolution, and quantitative as much as possible, in response to the various social demands related to surface geology such as earthquake disaster mitigation. To do so, it is necessary to collect, analyze, and accumulate massive amount of microtremor data, and we are attempting this using the new system. While not so much as the single-point measurement, measurement using the miniature array is still extremely simple. Therefore, by repeatedly performing measurement many times at different measurement points, the spatial changes of the S-wave velocity structure can be imaged easily. As mentioned at the beginning of this chapter, S-wave velocity is a material property that is directly linked to the shaking and stiffness of the ground, and may contribute to achieving high precision of seismic zoning[Term 5] to mitigate earthquake damage. That is, the ground surface shaking characteristics, which are currently estimated from the geomorphological classification[Term 5] from the perspective of resolution, will be evaluated from the actual data such as S-wave velocities and ground oscillation characteristics, and the forecasting precision for earthquake shaking may dramatically improve. It also contributes to the evaluation of ground disasters such as liquefaction and helps determine the locational conditions of construction and civil engineering structures. Wide-ranging social value and ripple effect are expected of the results of this research.

Fig. 2 Measurement using a miniature array with a radius of 0.6 m [Fig. 1(b)]

First, conventional microtremor array exploration and the positioning of this research will be explained (Chapter 2). Next, the core concept for the new system will be explained (Chapter 3), and the development process is discussed from a synthesiological perspective (Chapter 4). Subchapters 4.1 and 4.2 correspond to the charges of Cho and Senna, respectively. Finally, the future issues will be discussed (Chapter 5).

2 Conventional microtremor array exploration and the positioning of this research

Microtremors are minute oscillations that cannot be detected by the human body, and are caused by wind, waves, industrial activities, and other various sources of oscillations. They are superposition of P-waves and S-waves (body waves) as well as Rayleigh waves and Love waves (surface waves).[Term 1] Since the body waves are attenuated in high degree, they are dominant only near the oscill1ation source. As a result, the wave field of microtremors is composed of multiple surface waves that generally arrive from various directions. Based on the theory of elasticity, the body of such microtremors can be easily assumed, but the verification by measurement data was done only after 1950s–1960s.[3]–[5]

After the nature of microtremors was clarified, research to establish a method for measuring the vertical component of microtremors by arrays was conducted[6][7] by extracting the propagation velocities of Rayleigh waves (phase velocity), and estimating the subsurface S-wave structure from the dispersion characteristics (the property where propagation velocity differs by frequency). This is the research for "microtremor array exploration."

In the latter half of the 1990s, the microtremor exploration was put to practical use to estimate the deep velocity structure as part of the subsurface structure survey by the Government and local governments.[8][9] Roughly explained, the estimation of the deep velocity structure is the evaluation of the foundation of S-wave velocity of 3 km/s called the seismic basement that appears at a depth of several kilometers in the cases

Table 1. Microtremor exploration methods

Item	The conventional microtremor exploration method	New system
Microtremor array layout and size	Arrays in star-shaped layout that combine four-point arrays [Fig. 1(a)]. The array radii are about several tens of meters to 1,000 ~ 2,000 m.	Basically, four-point arrays with radius of 0.6 m [Fig. 1(b)]. Three-point irregular arrays with 5 m radius [Fig. 1(c)] are used optionally.
Measurement time	Several hours. Nighttime measurement when long-period microtremors become dominant is appropriate.	15 min. Daytime observation when short-period microtremors become dominant is appropriate.
Analyzable wavelength range	The analyzable minimum wavelength is two times the array radius, and the maximum wavelength is about several times to a dozen times.	The analyzable minimum wavelength is two times the array radius, and the maximum wavelength is about several tens of times to over 100 times if the condition is good.
Exploration depth	Several tens of meters ~ a few thousands of meters	Several meters ~ several tens of meters

of the Kanto Plain and the Osaka Plain, and a manual has been created for such measurement.[10][11] Specifically, the arrays [Fig. 1(a)] of large and small scale with radii of several tens of meters to about 1,000 meters are laid out, and the microtremors, whose oscillation sources are natural waves or wind, are measured overnight (in practice, 1 to 2 h or 3 h or more according to the radius of the array) (Table 1). The phase velocity of Rayleigh waves at a frequency of 0.1~10 sec is extracted from the microtremor data obtained, and the information for the seismic basement depth that may reach the depth of several kilometers is obtained.

The wavelength range analyzable with one array is dependent on the array size, and it is said to be approximately from twice to several times or dozen times the array radius.[11] Since the maximum depth of exploration is dependent on the maximum wavelength of the analyzable waves, to obtain data at a wide wavelength range that covers the target depth, it is necessary to make measurements using multiple arrays with different radii. For example, Fig. 3 is the dispersion characteristic (called dispersion curve) obtained by measuring microtremors with six types of triangle arrays (arrays of radii of 50 m and 100 m, 250 m and 500 m, and 1,000 m and 2,000 m; these are shown in blue, green, and red, respectively) where Fig. 1(a) are combined multiple times. For example, the 2 Hz phase velocity (blue line) was obtained using an array with 50 m radius, while 0.2 Hz phase velocity (red line) was obtained using an array with 2 km radius. The wavelengths were 125 m and 10 km, respectively, while the depth scale was several tens of meters and several kilometers, respectively. The dispersion curves of the phase velocity obtained for each array were connected to create one dispersion curve, and this is deemed as the data representing the subsurface velocity structure at the measurement points with depths of several tens of meters to several kilometers.

However, as shown in the figure, often data obtained with different radii do not connect well. Whether the dispersion curves from arrays of different sizes connect smoothly or not is the index for the reliability of data. If the connections of the analysis results of arrays are extremely poor, re-measurement must be considered. The reason for conducting array measurements of multiple sizes is not only to cover the range of exploration depth, but also to evaluate the reliability of the results.

We shall address this issue further. In the microtremor array analysis, it is assumed that the sources of microtremors are generally located sufficiently far from the array. However in practice, rarely is this assumption met. If the microtremor array of several tens of meters is laid out in the urban area, it is unavoidable that the industrial activities such as traffic vibrations will be included within the array. As a result, these add up as unforeseen record components, or noise, add

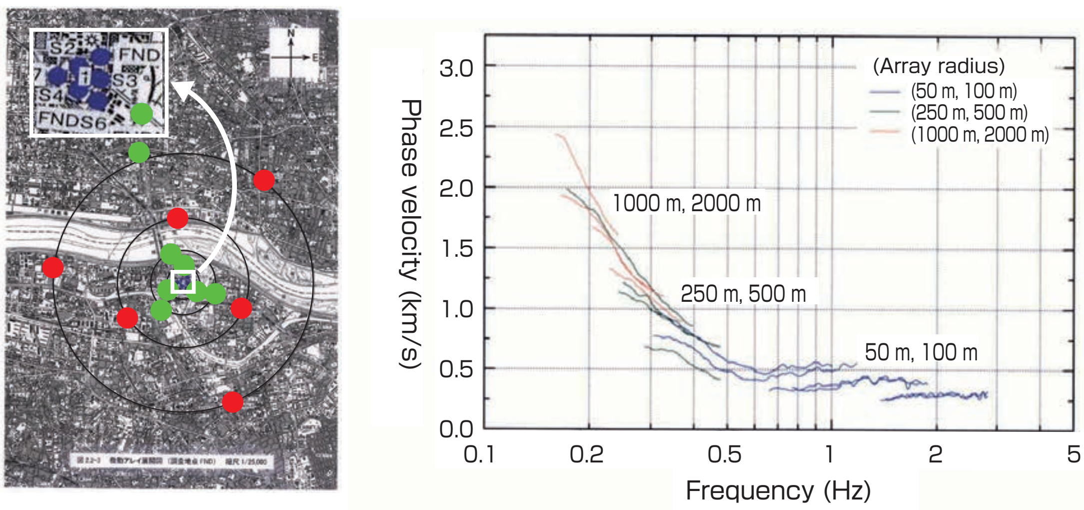

Fig. 3 Microtremor arrays in conventional exploration (left) and an example of the dispersion curve obtained for each array (right) (after Report [12] of the Tokyo Metropolitan Government)
In many cases, the data obtained from arrays with different radii do not connect entirely.

bias to the dispersion curve of each array, and may result in poor connection of the final dispersion curve. This is a fairly serious problem that accompanies the microtremor array exploration. However, there was no model to quantify this problem, no quantitative investigation was conducted, and the matter was left to the field such as re-measurement.

Against a background where much of the framework of microtremor array exploration was based on experience, Cho, one of the authors, has been working on the basic theory of microtremor array exploration since the 2000s. In the middle of the 2000s, theoretical construction to understand the limitations and potential of the microtremor array exploration was attempted.[13]–[19] The idea for a "miniature array" specialized in shallow velocity structure to analyze wavelengths hundred times or more of the array size was born during that time.

On the other hand, Senna worked on modeling deep velocity structure using conventional microtremor array exploration by developing a highly mobile microtremor measurement kit,[2] and organized systematic mass microtremor measurement through the development of a single-point microtremor measurement and analysis system called "i-bidou" (Chapter 1). The two researchers became aware of each other's research around 2011, and started collaboration while dividing their work into the development of the theory of data processing and the development of a measurement system. That is, the idea for a miniature array was already formed at that point, and since i-bidou was already in operation, they aimed to create a new system [a shallow structure (of several meters to several tens of meters) exploration system using a miniature microtremor array] by conducting R&D to fuse the two (Fig. 4, Fig. 5, Table 1).[20][21]

In terms of synthesiology, it is an attempt to obtain information for shallow velocity structures precisely and easily by improving one of the components of the existing integrated system called i-bidou. The i-bidou has an internal processing capability where the S-wave velocity structure is modeled from an existing geological model of the area around measurement points and an H/V spectral data. However, due to the characteristic of the data, an S-wave velocity structure model cannot be constrained so tightly, and it was positioned only as a middle process to evaluate a seismic intensity during an earthquake, rather than an exploration system. In the new system, the existing i-bidou measurement is set as the core technology, and not only ground oscillation characteristics but also the propagation velocity of waves unique to the site can be obtained as actual data, and therefore, fundamental improvement in precision is possible. When the new system is completed, it will be a new exploration device to realize mass exploration at a precision level of local exploration. While quantitative evaluation of the practicality is necessary in the future, the range of application will become extremely wide. In terms of synthesiology, it may be an example where improvement of one component of an existing integrated system can be an innovation.

3 Development policy assuming usage by general users

Senna, one of the authors, assumed the use by general users (non-experts of microtremor analysis) in the development of the microtremor equipment including i-bidou, and took the approach of comprehensively providing a series of maneuvers from measurement and analysis to display of results. The following is the explanation of the system.

The shallow (of several meters to several tens of meters) velocity structures that are targets of our study are also interesting to the general public from the perspectives of house location or disaster prevention of towns. Since the velocity structures at this depth change locally, damage that occurs to a neighbor's house may not necessarily happen

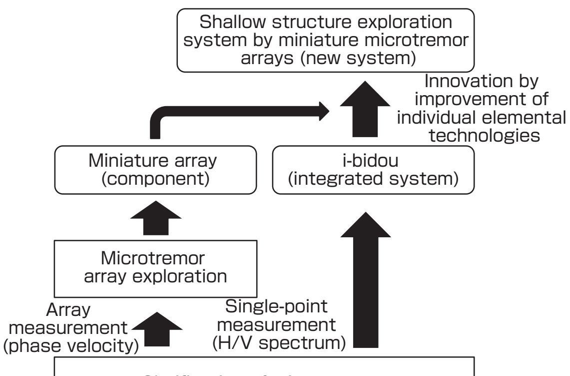

Fig. 4 Conceptual diagram of the microtremor research based on synthesiological perspective

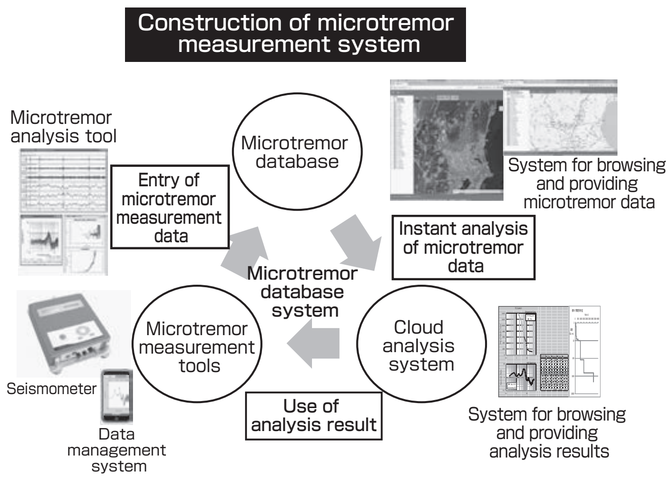

Fig. 5 Conceptual diagram of microtremor system configuration

to one's house despite the small difference in location. Therefore, in some cases, it is necessary to collect data at a several meters pitch (for example, Subchapter 4.3).

However, such high resolution is difficult to realize in a wide-area survey such as earthquake disaster mitigation projects of the Government and local governments. On the other hand, a pinpoint survey is less likely to benefit the majority. Therefore, Senna considered building self-reliant tools where the users, such as local universities who are interested in their communities, can collect data on their own and are able to view the analyses and results. It is estimated that there are more potential users who wish to use such tools than the microtremor experts. Although such users' interests may be limited to their own regions, if users from many areas participate, and if the data obtained can be centrally aggregated in a database, wide-region data can be obtained. The general users are provided with lectures and rented measuring equipment to fulfill their needs. If a structure that allows accumulation of data could be built, it may benefit all parties involved.

To realize such an approach, it is necessary to develop measuring equipment that can be easily operated and managed by general users. It is necessary to conduct objective quality control and automation of data processing. To prevent scattering of data and to ensure continuous accumulation, it is also necessary to develop database related technologies at the same time. Thus, the idea (Fig. 5) for developing such elements in a well-balanced manner and to comprehensively provide equipment and services was born.

The above development policy was also applied to the new system, and care was taken to not lose the ease of measurement of i-bidou when using the miniature array (Sections 4.1.1 and 4.2.2). Also overall ease of use is maintained by quality control based on the theory developed together with the miniature array, automation of data processing to visualization (Section 4.1.1), and delivery of analysis results in quasi-real-time (Section 4.2.3). The users can even obtain two-dimensional cross-sections of shallow S-wave velocity structures that are directly related to earthquakes and ground disaster, as easily as with the existing i-bidou (Subchapter 4.3).

4 Components of the new system

4.1 Theoretical development

4.1.1 Miniature array analysis (measure: extension of analysis limit of long wavelengths)

In the case of the i-bidou developed earlier, the ease of measurement was emphasized for the purpose of mass measurement (Chapter 3). Since such emphasis applies to this research as well, we wish to conduct array measurement without compromising the ease of single-point measurement. Therefore, one of the goals was to lay out the array behind a car parked on the roadside (Fig. 2), and we decided to use a four-point array with a radius of 0.6 m (Fig. 1(b)).

As long as the standard is based on the conventional microtremor array exploration (Chapter 2), the wavelengths that can be analyzed by a miniature array of a radius of 0.6m are about 1.2 to 12 m, and exploration up to several tens of meters depth is expected to be difficult. However, if the array is small, it is possible to exclude the oscillation sources within the array (Chapter 2), and taking measures such as setting them at a distance from the noise sources (e.g., construction sites) can be done easily. Therefore it is expected that the noise problem that inhibits the analysis of long wavelength ranges will be decreased and relatively longer wavelengths compared to the array size can be analyzed. Also, combining with various analysis methods developed by the authors,[14]–[17] it will be possible to correct the noise effect by evaluating the SN ratio,[Term 6] and it may be possible to analyze long wavelengths that are over 100 times the array radius. Also, based on the spectral estimation theory, it is estimated that sufficiently stable analysis can be done in measurement time of about 15 min.

The authors considered such theoretical schemes, conducted experiments at numerous sites using the actual equipment,[2] and verified its practicality. Specifically, the time needed from arrival to pullout from the site was kept to about 30 min, and it was shown that dispersion characteristics of phase velocity in the wavelength bands of targeted several tens of meters to 100 m or more in some cases could be obtained.[20]

4.1.2 Reading of the phase velocity (measure: evaluation of analysis limit)

As mentioned in Chapter 2, in conventional microtremor array exploration, arrays of multiple sizes are used from two perspectives: (i) to cover the wavelength range corresponding to the targeted depth range, and (ii) to maintain the reliability of the dispersion curve. However, in the new system, we wish to emphasize the ease of measurement, and the measurement should be basically done with a miniature array of a radius of 0.6 m (Fig. 1(b)). In the case of the miniature array, because it has originally limited the depth scale and has succeeded to extend the analytical limit of long wavelengths (Section 4.1.1), (i) is cleared. Therefore, the issue is how to achieve (ii).

To tackle this issue, the authors took the approach of presenting the analytical limit of phase velocity by evaluating the SN ratio and then evaluating the reliability.[20] If the reliability of the analysis results obtained is high, measurement can be terminated by one measurement using miniature arrays. If the reliability is low, measurement using a three-point irregular array at a larger size can be conducted additionally (next section).

When the feasibility of this idea was investigated using real data, it was found that the expected results as demonstrated by theory could be obtained (refer to Reference [20] for technical details). Let us look at Fig. 6 for an explanation. The figure is the dispersion curve of phase velocity obtained by a miniature array of a radius of 0.6 m. The purple triangle shows the phase velocity that has been corrected for noise effect and the blue cross shows one that has not been corrected. Normally for the dispersion curve, the phase velocity increases as the frequency decreases (called normal dispersion), and this is in reflection of the fact that S-wave velocity increases with the increase of depth. In the dispersion curve of the same figure, the phase velocities suddenly increase at 7.5 Hz or less. On the other hand, the phase velocities increase as the frequency increases above 7.5 Hz, and the trend called reverse dispersion is seen. This reflects the fact that there is a high velocity layer near the surface. In fact, there is a clay layer with extremely slow S-wave velocity embedded at a depth of about 5 m around the measurement point in the figure, and it is known that the S-wave velocity is faster near the surface.

Figure 6 shows the lines that correspond to the wavelengths of 25 m (red), 40 m (purple), and 100 m (green), as the reference indices that show up to which depth the data can be obtained using the miniature array. The intersection points of the dispersion curve and these lines represent the frequencies and phase velocities that correspond to each wavelength. It can be seen from this figure that the phase velocities of slightly less than the wavelength of 100 m are obtained if the noise is not corrected, and phase velocities of wavelengths surpassing 100 m are obtained if corrected for noise. Here, by visual inspection of the noise-corrected results (shown by crosses), the phase velocity surpassing the wavelength of 100 m is identified. A wavelength of 100 m is about 167 times the radius of the array. The adequacy of this visual inspection was verified by separately executing with an array of a radius of about 5 m.

Up to now, the performance of the miniature array has been described while explaining how to read the figure. However, what we wish to present in Fig. 6 is the evaluation of reliability based on the analytical limit of the phase velocity. In the figure, the upper limit for analysis is shown as a yellow broken line. This is the limit for analysis that is set strictly based on the developed technology, which separates the microtremor record into the components of surface waves (signals) crossing the array and the components of noise unrelated to such signals. If the upper limit is sufficiently high compared to the estimated value of phase velocity, it can be judged that the estimated value of phase velocity is safe to use. In the figure, the long wavelengths are automatically read up to the phase velocity surpassing the wavelength of 40 m (yellow square), based on this upper limit for analysis. That is, in this case, the objective quality control of the analysis result was done based on the data from the miniature array only, and it was automatically determined that the data up to at least the wavelength of 40 m can be “used.” Of course, this information is provided regardless of whether the recipients are experts or non-experts.

In this way, we came to be able to obtain the phase velocity of the Rayleigh waves as new data to determine S-wave velocity by using miniature arrays. This is the core of sophisticating i-bidou. Objective quality control, automation of the analysis, and therefore, the use by general users are made possible by the theoretical development allowing the data-based evaluation of the upper limits for analysis.

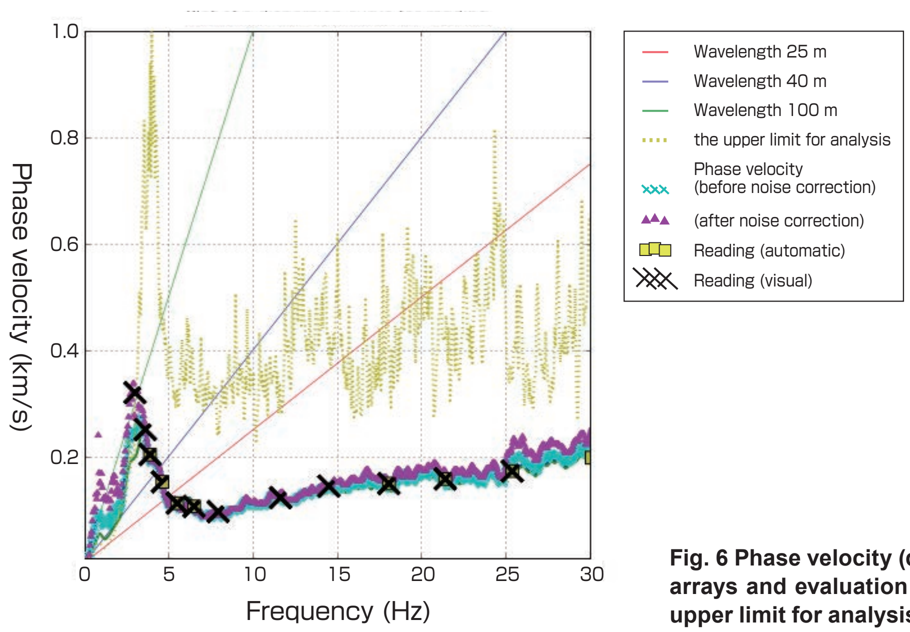

Fig. 6 Phase velocity (dispersion curve) by miniature arrays and evaluation of automatic reading and the upper limit for analysis

4.1.3 Three-point irregular array analysis (measure: evaluation of irregular array layout)

In cases where the analysis results of a miniature array with a radius of 0.6 m are of low quality, arrays with a larger size are used to supplement the data. Here, arrays larger by one order (radii of several meters) are considered. However, arrays of this size do not fit behind a car parked on the roadside. Conventionally, arrays of Fig. 1(b) where the seismometers are laid out at equal intervals on a circle are used, but due to the problem of roads and buildings in the urban areas, one cannot expect the arrays to be laid out neatly.

As a measure for this, we considered using three-point irregular arrays [Fig. 1(c)] of a radius of about 5 m as supplementary arrays. In conventional microtremor array exploration, data processing is done assuming that arrays are laid out at equal intervals, and it is difficult to apply such three-point irregular arrays. However, the authors have already proposed a data processing method in cases of unequal intervals, and have theoretically evaluated the effect on the analysis results.[13] In this research, using an actual equipment,[2] field experiments were repeatedly conducted by combining miniature arrays and three-point irregular arrays of several meters size, and the applicability to the new system was studied. As a result, it was shown that the supplementary data that fulfill the objective could be obtained by applying this idea, and that it is sufficiently practical without much difference in measurement time and amount of labor.[22]

4.1.4 Estimation of velocity structure (measure: use of simplified analysis)

What we ultimately want is the S-wave velocity structure of the ground. To model the velocity structure, nearby logging data and wide-area geological structures are referenced as initial models, and in many cases, iterative inversion analyses are conducted to optimize a model to fit the phase velocity obtained in array measurement.

However, expert knowledge is necessary to create the initial models, and this does not match the demands for automatic processing and instant delivery of analysis results. Therefore, here, a simple conversion method is adopted, where the dispersion curve that is expressed as frequency versus phase velocity is converted to the relationship between wavelength and phase velocity, and this is deemed as the relationship between depth and S-wave velocity through appropriate scaling.[22] A method where the phase velocity that corresponds to the wavelength of 40 m is deemed as the average S-wave velocity from the surface to a depth of 30 m is also used concurrently.[23]

This falls within the range of a standard preliminary analysis, but we believe that analysis results in a sufficiently satisfying range can be obtained (for example, Subchapter 4.3) when considering the balance between supply and demand. However, currently, we are also investigating the possibility of some advanced inversion methods such as a simultaneous inversion[24] of the H/V spectrum and the dispersion curve.

4.1.5 Automation of the data analysis (measure: optimization of the parameter)

From the perspective of use by general users, all processes including the selection of analysis intervals[19] and reading of phase velocity (Fig. 6)[25][26] should be automated. This doubles the measures for maintaining objectivity in reading, time reduction, and human error countering. The design also allows visual checking of the results of automated processing afterwards, and re-reading.

In the estimation of velocity structures, the analysis results for each measurement point are presented, but in many cases the interpretation is shaky with only those results. It will be very effective in supplementing the interpretation if there is a two-dimensional velocity cross-section made by connecting together the results of multiple measurement points. Therefore, we created a tool that automatically draws the S-wave velocity cross-section simply by setting the cross-section line on the map (Subchapter 4.3).

4.1.6 Quality control of the raw data and analysis results (measure: creation of index)

In cases where there are problems in the raw data due to lack of data, failure to synchronize time on GPS, poor installation environment, or others, the decision of whether to conduct re-measurement can be made on the spot, by presenting these facts in quasi-real-time. In cases where the quality of the analysis results is low (such as when exploration does not reach the target depth due to low SN ratio since the microtremor intensity is low, etc.), deciding to conduct additional measurement by three-point irregular arrays becomes possible. To avoid overinterpretation of the analysis results, it is necessary to conduct thorough quality control. The index for quality control will be presented by combining the maximum amplitude of waveform, spectral density, SN ratio, and other quantities. Details are currently being investigated.

4.2 Development of the measurement system

4.2.1 Development of the seismometer (measure: maintaining mobility, robustness, stability, and simplicity)

The seismometer used in the microtremor array exploration must have small individual differences in response characteristics, and they must be particularly uniform in phase characteristics. Also, to obtain high quality data in regions with small microtremor levels, it is important to have low self-noise. Considering the possibility that they may be used for microtremor arrays of several hundred meters size, a wide-frequency-range seismometer that has time synchronization by GPS and analyzability of the low frequency ranges is necessary. Considering the possibility for use in single-point measurement of the H/V spectrum, sensors that can detect ground motions in the horizontal direction as well as the vertical direction are necessary.

To maintain mobility, the conditions set are as follows: the device must be small, lightweight, and the content can be stored in a single box; there must be no maneuvers of wiring and clamp removal on site; it must have short recharge time and the power source must last throughout the day of measurement; and the recording can be started stably soon after turning the power on. It is also important to minimize the exposure of the terminals in addition to being drip-proof and vibration resistant for transport by vehicles.

To fulfill these requirements, Senna *et al*.[2] developed a seismometer that is highly sensitive, that has wide dynamic range, low noise, and high bias temperature stability. In the development of this seismometer, attention was especially paid to the amplitude resolution and SN ratio of the recording device. It has been demonstrated that this equipment can be applied to miniature arrays.[20]

4.2.2 Development of the data transfer system (measure: handling of lacking data)

In order to conduct mass measurement with microtremor arrays and to smoothly manage the analysis results, it is necessary that the procedures from the measurement to result evaluation be few in number and simple. Particularly, from the measurement data collection to analysis, much time must be spent on preparatory work, such as data check, data format conversion, organizing photographs, and others. However, if it becomes possible to gather data easily on site and store them in a database, vast amount of measurement data can be managed easily, and mass measurement management becomes possible along with the simple measurement equipment described earlier.

To achieve this objective, it is necessary to create a mechanism where the series of maneuvers from data organization on site to analysis (data entry of location information, photographs, measurement data, chronological information, analysis results, etc.) can be done easily, and thereby reducing human error. Specifically, we focused on the construction of a mechanism where data can be sent, received, aggregated stably through a standard format from multiple units of measurement equipment, and the data can be shared through the database system and analysis software.

To solve this issue, we created a system composed of one master equipment and a corresponding slave equipment, where individual seismometers automatically determine the positions, with added function of aggregating data to the master equipment. We employed the ACT protocol[Term 7] that has redundancy, so the data can be sent and received from the master equipment to the terminals such as PCs and tablets without loss of data.[27]

4.2.3 Delivery of the analysis result (measure: maintaining quickness)

The data entered in the database must be automatically quality controlled and analyzed, and the S-wave velocity (soil structure model) from the analysis results must be delivered and be checkable on WEBGIS and others along with the map information. For the observer to check quality control and analysis results on site, it is necessary to be able to analyze and browse the results of the data sent to the database in near real-time.

To realize the above, the construction of application for smart phones and the construction of a “cloud analysis system” that analyzes and quality controls microtremor data at high speed are issues to be tackled. For the smart phone application, the functions of i-bidou[1] are used to enable reception of data in real time, checking of waveforms and spectrum, and conducting data quality control such as simplified SN ratio management of the microtremors. In cloud analysis, detailed analysis of the entered data and quality control is done.[20] Using this cloud system, about five to ten times increase in speed can be achieved. It is known that the current i-bidou can deliver results within several minutes.[27] This high speed will be incorporated in the new system (a shallow structure exploration system using miniature arrays).

4.2.4 Database related (measure: definition of the format)

The format of the database is considered to enable efficient browsing and utilization of raw and analysis data of microtremors. Specifically, an XML[Term 8] format is defined for microtremor measurement data, and raw measurement data and analysis result data will be stored in several formats that allow high degree of general use.

4.3 Integration of the components

Arranging the components of Subchapter 4.1 in order enables the development policy of Chapter 3 to be realized. The level of completion can be measured by the general users’ convenience or inconvenience, the basic policy of development, as well as by the reliability of the results. Since the usability and reliability tend to have a trade-off relationship, here, we shall deem that the goal of usability has been achieved when the general users are able to obtain the results easily, and the development will be terminated at that point. The reliability of the new system will be evaluated by comparing the data obtained with the verification data. Then, it will become a product with a given “range of application.”

Currently, we are in the process of development, but we are gaining a certain degree of progress. Figure 7 illustrates this as an example. This is the S-wave velocity cross-section obtained when we had geology researchers (non-experts of microtremor exploration), who wished to evaluate the subsurface velocity structure of the grounds of Urayasu High School in Chiba Prefecture to study the liquefaction phenomenon, use the new system in a trial. This result was used in a conference presentation by Sato *et al*.[29] After receiving a simple lecture on miniature array measurement, the researchers drew two measurement lines of 40 m and 120 m on the grounds of the high school, and repeated miniature array measurement at about 5 m intervals. About 20 min were spent per point, or a total of 12 hours. However, the total measurement time for the shorter measurement line was less than 2 hours.

Since the data transfer system (Section 4.2.2) and the analysis result delivery (Section 4.2.3) were incomplete, we received the measurement data when the equipment was returned. Figure 7 shows the complete automated process from data analysis to drawing for the 120 m measurement line. From the survey for the landfill work of 1965-1971 as well as from hand-operated auger boring,[Term 2] it is known that the topmost part of the grounds of Urayasu High School is 3 m of landfill layer that is composed of a sand layer and a silt layer in the east and west of the center of the measurement line.[30] In the part up to 10 m of depth of the velocity cross-section in the figure, clear difference is shown at about 45 m horizontal axis.

5 In the future

We believe about 70 % of our goal has been completed. It is necessary to work on the components that have not been addressed (data transfer system and analysis result delivery) and parts that can be refined (such as an estimation method for ground structures).

Currently, there is a plan for measurement using miniature arrays at 1 to 2 km grid for the entire Kanto Plain area, and it has been partially conducted.[30] We wish to utilize this data to discern the limitations and possibilities of the new system and to consider future development.

The research group to which Cho, one of the authors, belongs is working on the high resolution geological ground maps.[31] We are considering the application of this new system and adding the quantitative evaluation using the microtremor data.

Terminologies

Term 1. S-waves: A type of seismic wave. The seismic waves that travel through materials internally are called body waves, and they can be separated into P- and S-waves according to the relationship of directions of propagation and particle motion. The seismic waves that travel on material surfaces are called surface waves, and can be separated into Rayleigh and Love waves according to the relationship of directions of propagation and particle motion.

Term 2. Logging: Measurement of the subsurface geology and ground conditions using boreholes. Boring is the term used for the act of digging a cylindrical hole in the ground or for the hole itself. Hand-operated auger boring is boring using hand drills.

Term 3. Artificial seismic source: Vibrations caused by explosion, pounding, or a vibrator (truck-mounted device) that are instigated near the surface to artificially generate seismic waves. The exploration

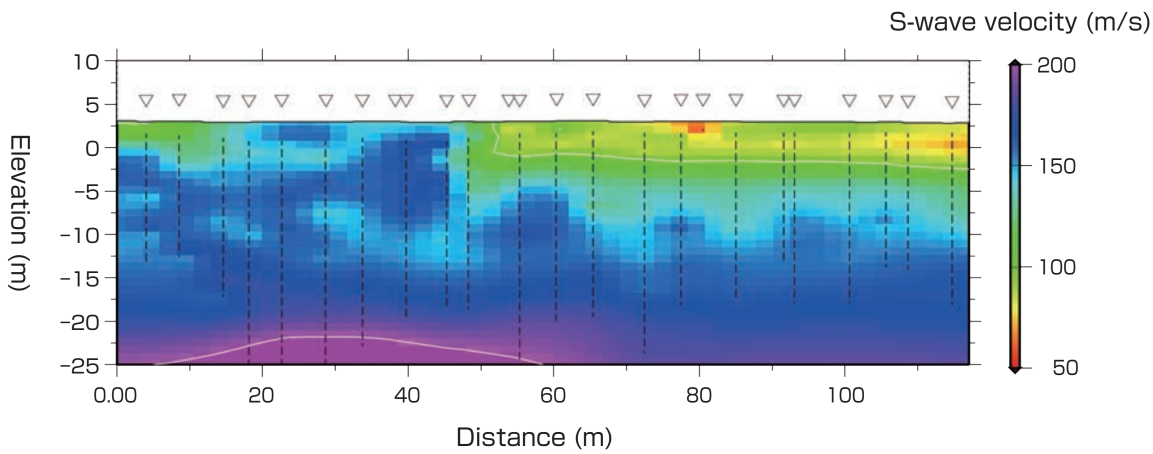

Fig. 7 S-wave velocity cross-section by miniature array exploration conducted on the Urayasu High School grounds
The right and left part of the cross-section diagram corresponds to the south-east and north-west directions, respectively. The legend of the cross-section shows the S-wave velocity with unit m/s. The triangles in the cross-section diagram show the positions of miniature arrays, and the dashed lines show the range of depth where the velocity structure data exist. Generic Mapping Tool[28] was used for drawing.

conducted using seismic waves generated by artificial seismic sources is called the seismic wave exploration.

Term 4. Single-point measurement: Measurement conducted using one seismometer. H/V spectrum is the spectral ratio of ground motion in the horizontal and vertical directions obtained in single-point measurement.

Term 5. Seismic zoning: A map expression of the seismic hazard and damage of buildings, taking into consideration the ground conditions. The ground conditions include the geomorphological classification that are small-scale undulations that may be difficult to be shown clearly on 1:50,000 scale topographic maps.

Term 6. SN ratio: Ratio of the intensities of signal strength to background noise.

Term 7. ACT protocol: Autonomous cooperative data transfer (ACT) protocol was developed to stably transfer data for the Metropolitan Seismic Observation network (MeSO-net). Protocol is a set of rules and procedures to mutually transfer information.

Term 8. XML: General-use data descriptive language suitable for handling various data on the internet.

References

[1] S. Senna, H. Azuma, Y. Murui and H. Fujiwara: Development of microtremor survey observation system 'i-bidou' etc., *Proceeding of the SEGJ Conference 124*, 346–348 (2011) (in Japanese).

[2] S. Senna, S. Adachi, H. Ando, T. Araki, K. Iisawa and H. Fujiwara: Development of microtremor survey observation system, *Proceeding of the SEGJ Conference 115*, 227–229 (2006) (in Japanese).

[3] K. Aki: Space and time spectra of stationary stochastic waves, with special reference to microtremors, *Bull. Earthquake Res. Inst.*, 35, 415–457 (1957).

[4] M. N. Toksöz and R. T. Lacoss: Microseisms: Mode structure and sources, *Science*, 159, 872–873 (1968).

[5] R. A. Haubrich and K. McCamy: Microseisms: Coastal and pelagic sources, *Review of Geophysics*, 7, 539–571 (1969).

[6] H. Okada and N. Sakajiri: Estimates of an S wave velocity distribution using long-period microtremors, *Geophysical Bulletin of Hokkaido University*, 42, 119–143 (1983) (in Japanese).

[7] H. Okada, T. Matsushima, T. Moriya and T. Sasatani: An exploration technique using long-period microtremors for determination of deep geological structures under urbanized areas, *BUTSURI-TANSA*, 43, 402–417 (1990) (in Japanese).

[8] Chiba Prefectural Government: 1998 Chiba Prefecture subsurface structural survey (1999) (in Japanese).

[9] Yokohama City: 1998 subsurface structural survey for the Kanto Plain (Yokohama City area) (1999) (in Japanese).

[10] H. Okada: *The Microtremor Survey Method, Geophysical Monograph Series, 12*, Society of Exploration Geophysicists, Tulsa (2003).

[11] Standardization Committee of the Society of Exploration Geophysicists of Japan: Applications manual of geophysical methods to engineering and environmental problems, 111–126 (2008) (in Japanese).

[12] Tokyo Metropolitan Government: Report of survey results of subcontracted microtremor array exploration in 23 wards (no. 1) (2004) (in Japanese).

[13] I. Cho, T. Tada and Y. Shinozaki: A new method to determine phase velocities of Rayleigh waves from microseisms, *Geophysics*, 69 (6), 1535–1551 (2004).

[14] I. Cho, T. Tada and Y. Shinozaki: A generic formulation for microtremor exploration methods using three-component records from a circular array, *Geophys. J. Int.*, 165 (1), 236–258 (2006).

[15] I. Cho, T. Tada and Y. Shinozaki: Centerless circular array method: Inferring phase velocities of Rayleigh waves in broad wavelength ranges using microtremor records, *J. Geophys. Res.*, 111, B09315, doi:10.1029/2005JB004235 (2006).

[16] I. Cho, T. Tada and Y. Shinozaki: A new method of microtremor exploration using miniature seismic arrays—Quick estimation of average shear velocities of the shallow soil, *BUTSURI-TANSA*, 61 (6), 457–468 (2008) (in Japanese).

[17] T. Tada, I. Cho and Y. Shinozaki: Beyond the SPAC method: Exploiting the wealth of circular-array methods for microtremor exploration, *Bull. Seism. Soc. Am.*, 97 (6), 2080–2095, doi:10.1785/0120070058 (2007).

[18] T. Tada, I. Cho and Y. Shinozaki: New circular-array microtremor techniques to infer Love-wave phase velocities, *Bull. Seism. Soc. Am.*, 99 (5), 2912–2926, doi:10.1785/0120090014 (2009).

[19] T. Tada, I. Cho and Y. Shinozaki: Analysis of Love-wave components of microtremors, *Proc. 7th International Conference on Urban Earthquake Engineering*, 115–124 (2010).

[20] I. Cho, S. Senna and H. Fujiwara: Miniature array analysis of microtremors, *Geophysics*, 78 (1), KS13–KS23, 10.1190/GEO2012-0248.1 (2013).

[21] S. Senna, I. Cho and H. Fujiwara: Sophistication of microtremor methods to survey shallow structures, *Summaries of technical papers of Annual Meeting (Kinki), Architectural Institute of Japan 2014*, 355–356 (2014) (in Japanese).

[22] I. Cho: On the generalization of the SPAC method and the development of a CCA method, *Abstracts, Japan Geoscience Union Meeting* (2014) (in Japanese).

[23] K. Konno and S. Kataoka: An estimating method for the average S-wave velocity of ground from the phase velocity of Rayleigh wave, *Journal of JSCE*, No. 647/I-51, 415–423 (2000) (in Japanese).

[24] H. Arai and K. Tokimatsu: S-wave velocity profiling by joint inversion of microtremor dispersion curve and horizontal-to-vertical (H/V) spectrum, *Bull. Seism. Soc. Am.*, 95 (5), 1766–1778, doi:10.1785/0120040243 (2005).

[25] I. Cho, S. Senna and H. Fujiwara: Sophistication of microtremor methods to survey shallow structures, Part I: Development of automatic reading algorithms, *Abstracts, Japan Geoscience Union Meeting* (2014) (in Japanese).

[26] S. Senna, I. Cho, and H. Fujiwara: Sophistication of microtremor methods to survey shallow structures, Part2: Application of automatic reading algorithms, *Abstracts, Japan Geoscience Union Meeting* (2014) (in Japanese).

[27] S. Senna: Sophistication of the cloud type microtremor observation system, *Abstracts, Japan Geoscience Union Meeting (CD-ROM)* (2015) (in Japanese).

[28] P. Wessel and W. H. F. Smith: New, improved version of the Generic Mapping Tools released, *EOS Trans. AGU*, 79 (47),

579 (1998).
[29] S. Sato, M. Higashi, S. Higuchi, A. Inada, A. Ito, H. Iwamoto, S. Kamikaseda, K. Kawasaki, K. Kusunoki, S. Shinada, K. Suenaga, T. Watanabe, S. Senna and H. Fujiwara: Geological interpretation of a liquefied area by 'i-bidou': A case study in the Urayasu area, Japan (2), *Abstracts, Japan Geoscience Union Meeting* (2014) (in Japanese).
[30] H. Iwamoto, M. Higashi, S. Higuchi, A. Inada, A. Ito, S. Kamikaseda, K. Kawasaki, K. Kusunoki, S. Sato, S. Shinada, K. Suenaga and T. Wabanabe: Ground damage on manmade land caused by the 2011 Off the Pacific Coast of Tohoku Earthquake—The characteristics of dredged silt formed reclamation, *Abstracts, 119th Annual Meeting of the Geological Society of Japan* (2012) (in Japanese).
[31] S. Senna, H. Matsuyama, K. Jin, J. Wakai, T. Maeda and H. Fujiwara: Estimation of velocity structure and modeling the subsurface structure of Kanto area based on microtremor array observation, *Proceedings of the SEGJ Conference 133* (2015) (in Japanese).
[32] T. Nakazawa, S. Nonogaki and Y. Miyachi: Three-dimensional urban geological map—New style of geoinformation in an urban area, *Synthesiology*, 9 (2), 73–85 (2016) (in Japanese).

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Discussions with Reviewers

1 Overall

Comment (Akira Kageyama, Research Support Adviser, AIST; Chikao Kurimoto, AIST)

The microtremor array exploration method allows estimation of the S-wave velocity structure at several tens of meters to several kilometers underground, as well as assesses the shakiness by earthquakes. In this paper, the target is specified to shallow ground, and the goal is set to clarifying the subsurface S-wave velocity structure at high density, high resolution, and quantitatively, for the urban areas in which damage due to strong motion and liquefaction are expected. The authors appropriately present the progress of their research along a steady scenario, including correct response to social demands, theoretical development of miniature microtremor array analysis, application to existing microtremor array technology, development of an automatic analysis system, and actual trial by general users. Therefore, we consider this paper appropriate for publication in *Synthesiology*. Also, this paper shows that a system can be given an innovative function by advancing the core technology with a new idea, in a system that is composed of multiple elemental technologies. It can be said that it proposes a new synthesis method for papers of *Synthesiology*.

2 Outline

Comment (Akira Kageyama, Chikao Kurimoto)

Please state, "How the results of this research is useful to society." Also, you give as the goal of research, "to provide information for subsurface S-wave velocity structure," but I think the readers can deepen their understanding if you also address the ripple effect of this research.

Answer (Ikuo Cho)

The subsurface S-wave velocity structure is directly linked to the "shakiness or stiffness of the ground." If this information can be obtained at high density and high resolution, it will lead to "dramatic improvement of the forecasting precision of earthquake shaking." I explained this point in the beginning.

3 Composition of the paper and its significance in synthesiology

Comment (Akira Kageyama)

The technology described in this paper is development of new technology including the theoretical investigation specifically for earthquake disaster prevention and mitigation, by enhancing the exploration precision of surface geology, using as a fundamental system the microtremor array exploration that one of the authors has been researching and putting to practical use for many years. It is an attempt for complementarity and strengthening of the fundamental system using new technology, and provides a new type of paper configuration for *Synthesiology*. Please keep this in mind and review the composition of the whole paper.

Answer (Ikuo Cho)

As you indicated, we wrote this paper as an example where the problem that could not be solved with conventional technology was solved by partial improvement of an existing system. To clarify this point, in the final paragraph of Chapter 2, we emphasized that the precision of the new system could be improved essentially by obtaining wave propagation velocity of the ground, not just the ground oscillation characteristics, and that the improvement of one component of the existing integrated system can be an innovation. Also, in the final paragraph of Chapter 3 and the final paragraph of Section 4.1.2, we organized the technological development points such as the simplification of measurement, quality control, complete automation from data processing to visualization, quasi-real-time delivery, and others.

4 Advantage of S-wave velocity measurement

Comment (Akira Kageyama)

You discuss the velocity structure of S-waves, but can you more specifically address how you can provide merit to society with this technology? For example, you discuss "high precision of earthquake zoning," but I think it will be easier to understand if you explain what the user can understand from this and how it will serve as material for making decisions.

Answer (Ikuo Cho)

We explained that the forecasting precision of earthquake shaking could be improved by using the actual data of ground oscillation and material properties that were only estimated based on a geomorphological classification.

5 Figure 4

Comment (Chikao Kurimoto)

Figure 4 contains the components of this research, and I think you should show the scenario of the paper using this figure.

Answer (Ikuo Cho)

The important point is the development from "microtremor array exploration" to "miniature arrays," and we think this process is the major synthesiological point of this paper. Therefore, the paper is composed around this process. In the paper, the "shallow velocity structure exploration system using a miniature microtremor array" is called the "new system."

6 Three-point irregular array of Section 4.1.3

Question (Akira Kageyama)

In Paragraph 2, Section 4.1.3, you write, "such application of three-point irregular arrays is impossible in the conventional microtremor array exploration." Is this because the data processing method for uneven intervals were not studied or developed? If so, is it correct to say that although the authors were preparing a measurement data processing method assuming equal interval layout of the array in the conventional microtremor array exploration, the authors returned to the "basic question" and newly developed and evaluated the data processing method for irregular array layout, and demonstrated that it was practical?

Answer (Ikuo Cho)

Yes, it is correct. Based on your question, we added "the data processing is done assuming that the arrays are laid out in equal intervals in the conventional microtremor array exploration," and supplemented our insufficient explanation.

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

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

Koji MASUDA

[Translation from *Synthesiology*, Vol.9, No.2, p.97–107 (2016)]

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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Original manuscript received January 29, 2016, Revisions received March 11, 2016, Accepted March 12, 2016

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]

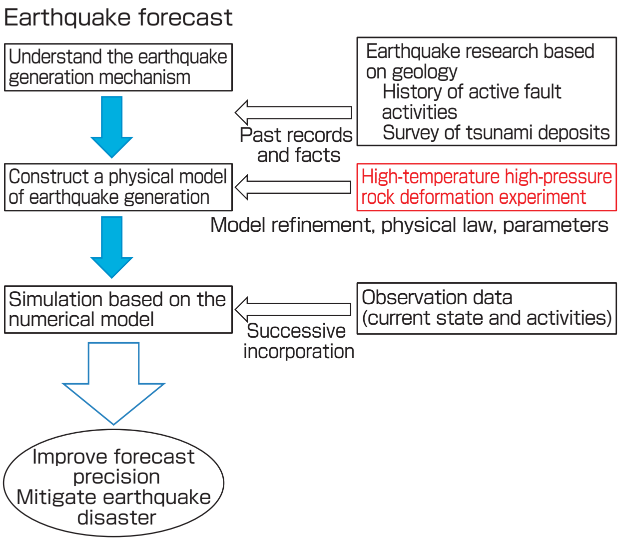

Fig. 1 Flow chart of earthquake forecast research and the position of high-temperature and high-pressure rock deformation experiments in the overall research scheme

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

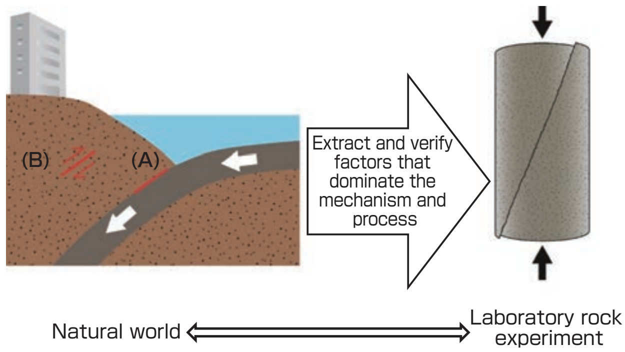

Fig. 2 Fault zones in the natural world and faulting in a laboratory rock experiment

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

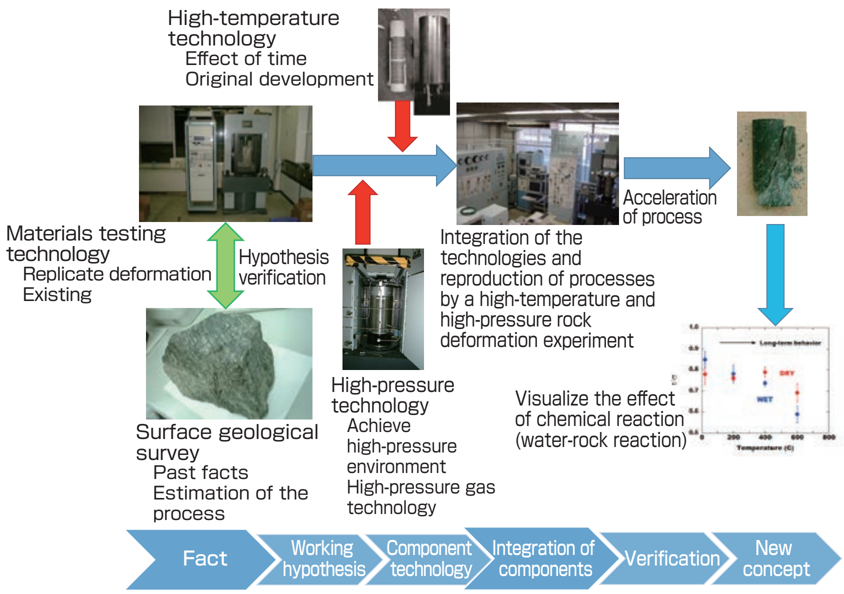

Fig. 3 Relationships among the component technologies and the overall flow of the research

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.

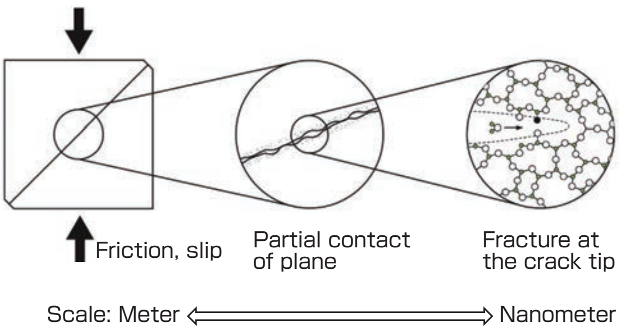

Fig. 5 Schematic diagram of friction and fractures
On a spatial scale of centimeters to meters, friction can be understood as a force resisting slip along a flat plane. However, at a small spatial scale of millimeters or less, the two surfaces on either side of the plane can be seen to not be in continuous 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

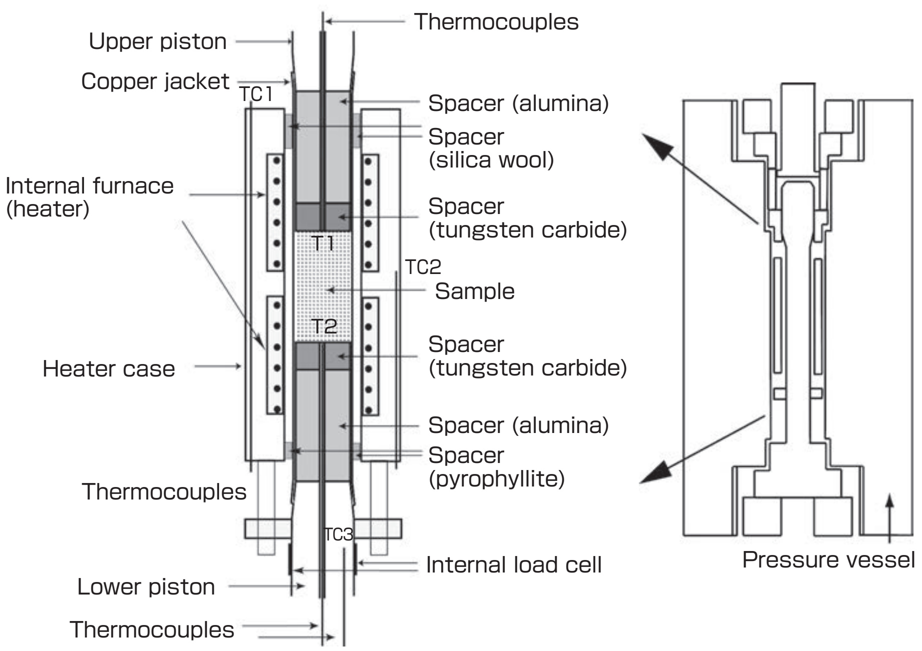

Fig. 7 Schematic diagram of the pressure vessel[19]

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 ºC; 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 ºC) 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 ºC or less).

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

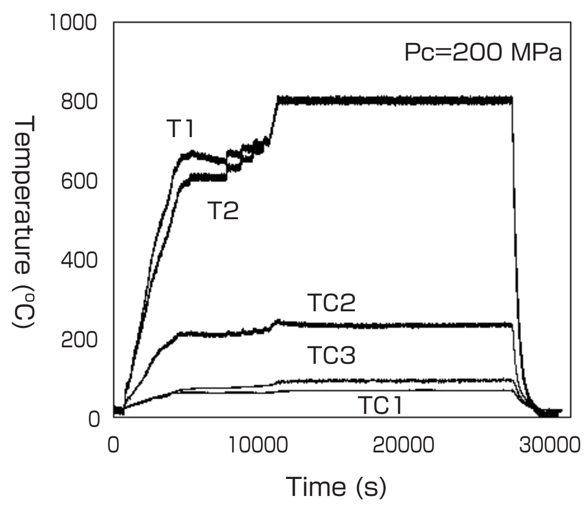

Fig. 10 Performance test results of the developed heater[19]
Both the top (T1) and bottom (T2) of the sample inside the pressure vessel are maintained at a constant temperature. The interior wall of the pressure vessel (TC1 and TC2) and the location of the internal load cell (TC3) are maintained at 300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

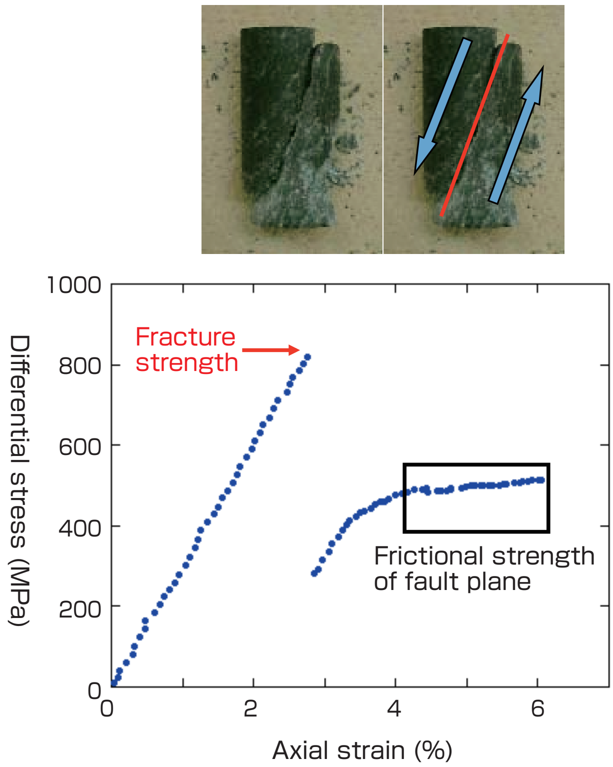

Fig. 11 Photograph of a sample after the experiment and the resulting stress-strain curve[18]
The fracture strength of the rock and the frictional strength of the fault were measured. When the differential stress reached the fracture strength, a fracture plane formed in the rock sample. The differential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

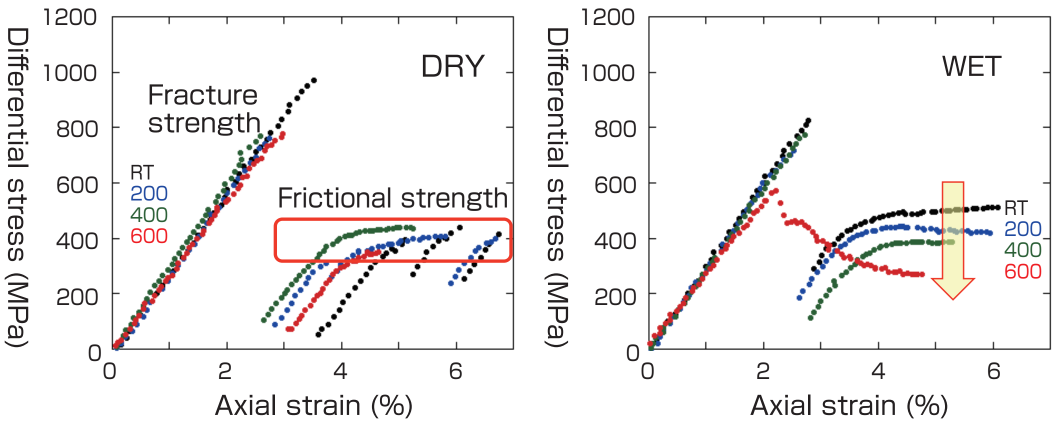

Fig. 12 Measurement results[18]
Under the dry condition (DRY), frictional strength was almost constant (area inside the red frame) and independent of temperature, but under the wet condition (WET), the strength level decreased (shown by arrow) as the temperature rose. Measurement results in (left) the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

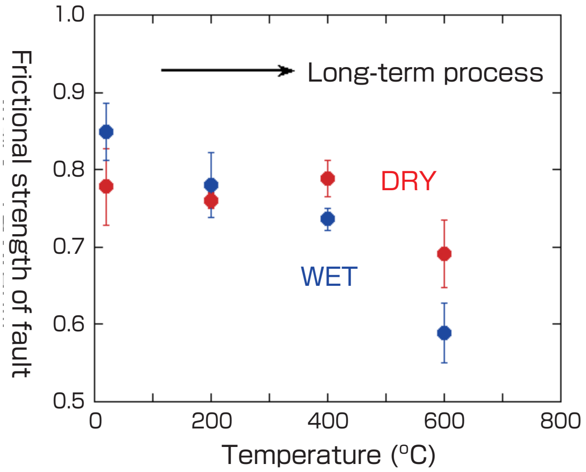

Fig. 13 Temperature dependency of the frictional strength of the fault plane in rock samples[18]

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.

Acknowledgements

This research was conducted with the help of many colleagues. I am particularly grateful to Koichiro Fujimoto, Takashi Arai, Miki Takahashi, Keigo Kitamura, Kazuo Mizoguchi, and Norio Shigematsu. The internal heater was developed with the help of Kenichi Iryo and Akira Ogura (currently, Pre-Tech Co., Ltd.).

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).

Editorial Policy

Synthesiology Editorial Board

Objective of the journal

The objective of *Synthesiology* is to publish papers that address the integration of scientific knowledge or how to combine individual elemental technologies and scientific findings to enable the utilization in society of research and development efforts. The authors of the papers are researchers and engineers, and the papers are documents that describe, using "scientific words", the process and the product of research which tries to introduce the results of research to society. In conventional academic journals, papers describe scientific findings and technological results as facts (i.e. factual knowledge), but in *Synthesiology*, papers are the description of "the knowledge of what ought to be done" to make use of the findings and results for society. Our aim is to establish methodology for utilizing scientific research result and to seek general principles for this activity by accumulating this knowledge in a journal form. Also, we hope that the readers of *Synthesiology* will obtain ways and directions to transfer their research results to society.

Content of paper

The content of the research paper should be the description of the result and the process of research and development aimed to be delivered to society. The paper should state the goal of research, and what values the goal will create for society (Items 1 and 2, described in the Table). Then, the process (the scenario) of how to select the elemental technologies, necessary to achieve the goal, how to integrate them, should be described. There should also be a description of what new elemental technologies are required to solve a certain social issue, and how these technologies are selected and integrated (Item 3). We expect that the contents will reveal specific knowledge only available to researchers actually involved in the research. That is, rather than describing the combination of elemental technologies as consequences, the description should include the reasons why the elemental technologies are selected, and the reasons why new methods are introduced (Item 4). For example, the reasons may be: because the manufacturing method in the laboratory was insufficient for industrial application; applicability was not broad enough to stimulate sufficient user demand rather than improved accuracy; or because there are limits due to current regulations. The academic details of the individual elemental technology should be provided by citing published papers, and only the important points can be described. There should be description of how these elemental technologies are related to each other, what are the problems that must be resolved in the integration process, and how they are solved (Item 5). Finally, there should be descriptions of how closely the goals are achieved by the products and the results obtained in research and development, and what subjects are left to be accomplished in the future (Item 6).

Subject of research and development

Since the journal aims to seek methodology for utilizing the products of research and development, there are no limitations on the field of research and development. Rather, the aim is to discover general principles regardless of field, by gathering papers on wide-ranging fields of science and technology. Therefore, it is necessary for authors to offer description that can be understood by researchers who are not specialists, but the content should be of sufficient quality that is acceptable to fellow researchers.

Research and development are not limited to those areas for which the products have already been introduced into society, but research and development conducted for the purpose of future delivery to society should also be included.

For innovations that have been introduced to society, commercial success is not a requirement. Notwithstanding there should be descriptions of the process of how the technologies are integrated taking into account the introduction to society, rather than describing merely the practical realization process.

Peer review

There shall be a peer review process for *Synthesiology*, as in other conventional academic journals. However, peer review process of *Synthesiology* is different from other journals. While conventional academic journals emphasize evidential matters such as correctness of proof or the reproducibility of results, this journal emphasizes the rationality of integration of elemental technologies, the clarity of criteria for selecting elemental technologies, and overall efficacy and adequacy (peer review criteria is described in the Table).

In general, the quality of papers published in academic journals is determined by a peer review process. The peer review of this journal evaluates whether the process and rationale necessary for introducing the product of research and development to society are described sufficiently well.

In other words, the role of the peer reviewers is to see whether the facts necessary to be known to understand the process of introducing the research finding to society are written out; peer reviewers will judge the adequacy of the description of what readers want to know as reader representatives.

In ordinary academic journals, peer reviewers are anonymous for reasons of fairness and the process is kept secret. That is because fairness is considered important in maintaining the quality in established academic journals that describe factual knowledge. On the other hand, the format, content, manner of text, and criteria have not been established for papers that describe the knowledge of "what ought to be done." Therefore, the peer review process for this journal will not be kept secret but will be open. Important discussions pertaining to the content of a paper, may arise in the process of exchanges with the peer reviewers and they will also be published. Moreover, the vision or desires of the author that cannot be included in the main text will be presented in the exchanges. The quality of the journal will be guaranteed by making the peer review process transparent and by disclosing the review process that leads to publication.

Disclosure of the peer review process is expected to indicate what points authors should focus upon when they contribute to this journal. The names of peer reviewers will be published since the papers are completed by the joint effort of the authors and reviewers in the establishment of the new paper format for *Synthesiology*.

References

As mentioned before, the description of individual elemental technology should be presented as citation of papers published in other academic journals. Also, for elemental technologies that are comprehensively combined, papers that describe advantages and disadvantages of each elemental technology can be used as references. After many papers are accumulated through this journal, authors are recommended to cite papers published in this journal that present similar procedure about the selection of elemental technologies and the introduction to society. This will contribute in establishing a general principle of methodology.

Types of articles published

Synthesiology should be composed of general overviews such as opening statements, research papers, and editorials. The Editorial Board, in principle, should commission overviews. Research papers are description of content and the process of research and development conducted by the researchers themselves, and will be published after the peer review process is complete. Editorials are expository articles for science and technology that aim to increase utilization by society, and can be any content that will be useful to readers of *Synthesiology*. Overviews and editorials will be examined by the Editorial Board as to whether their content is suitable for the journal. Entries of research papers and editorials are accepted from Japan and overseas. Manuscripts may be written in Japanese or English.

Required items and peer review criteria (January 2008)

	Item	Requirement	Peer Review Criteria
1	Research goal	Describe research goal ("product" or researcher's vision).	Research goal is described clearly.
2	Relationship of research goal and the society	Describe relationship of research goal and the society, or its value for the society.	Relationship of research goal and the society is rationally described.
3	Scenario	Describe the scenario or hypothesis to achieve research goal with "scientific words".	Scenario or hypothesis is rationally described.
4	Selection of elemental technology(ies)	Describe the elemental technology(ies) selected to achieve the research goal. Also describe why the particular elemental technology(ies) was/were selected.	Elemental technology(ies) is/are clearly described. Reason for selecting the elemental technology(ies) is rationally described.
5	Relationship and integration of elemental technologies	Describe how the selected elemental technologies are related to each other, and how the research goal was achieved by composing and integrating the elements, with "scientific words".	Mutual relationship and integration of elemental technologies are rationally described with "scientific words".
6	Evaluation of result and future development	Provide self-evaluation on the degree of achievement of research goal. Indicate future research development based on the presented research.	Degree of achievement of research goal and future research direction are objectively and rationally described.
7	Originality	Do not describe the same content published previously in other research papers.	There is no description of the same content published in other research papers.

Instructions for Authors

"Synthesiology" Editorial Board
Established December 26, 2007
Revised June 18, 2008
Revised October 24, 2008
Revised March 23, 2009
Revised August 5, 2010
Revised February 16, 2012
Revised April 17, 2013
Revised May 9, 2014
Revised April 1, 2015
Revised October 1, 2015

1 Types of articles submitted and their explanations

The articles of *Synthesiology* include the following types:
• Research papers, commentaries, roundtable talks, and readers' forums
Of these, the submitted manuscripts of research papers and commentaries undergo review processes before publication. The roundtable talks are organized, prepared, and published by the Editorial Board. The readers' forums carry writings submitted by the readers, and the articles are published after the Editorial Board reviews and approves. All articles must be written so they can be readily understood by the readers from diverse research fields and technological backgrounds. The explanations of the article types are as follows.

① Research papers
A research paper rationally describes the concept and the design of R&D (this is called the scenario), whose objective is to utilize the research results in society, as well as the processes and the research results, based on the author's experiences and analyses of the R&D that was actually conducted. Although the paper requires the author's originality for its scenario and the selection and integration of elemental technologies, whether the research result has been (or is being) already implemented in society at that time is not a requirement for the submission. The submitted manuscript is reviewed by several reviewers, and the author completes the final draft based on the discussions with the reviewers. Views may be exchanged between the reviewers and authors through direct contact (including telephone conversations, e-mails, and others), if the Editorial Board considers such exchange necessary.

② Commentaries
Commentaries describe the thoughts, statements, or trends and analyses on how to utilize or spread the results of R&D to society. Although the originality of the statements is not required, the commentaries should not be the same or similar to any articles published in the past. The submitted manuscripts will be reviewed by the Editorial Board. The authors will be contacted if corrections or revisions are necessary, and the authors complete the final draft based on the Board members' comments.

③ Roundtable talks
Roundtable talks are articles of the discussions or interviews that are organized by the Editorial Board. The manuscripts are written from the transcripts of statements and discussions of the roundtable participants. Supplementary comments may be added after the roundtable talks, if necessary.

④ Readers' forums
The readers' forums include the readers' comments or thoughts on the articles published in *Synthesiology*, or articles containing information useful to the readers in line with the intent of the journal. The forum articles may be in free format, with 1,200 Japanese characters or less. The Editorial Board will decide whether the articles will be published.

2 Qualification of contributors

There are no limitations regarding author affiliation or discipline as long as the content of the submitted article meets the editorial policy of *Synthesiology*, except authorship should be clearly stated. (It should be clearly stated that all authors have made essential contributions to the paper.)

3 Manuscripts

3.1 General

3.1.1 Articles may be submitted in Japanese or English.
Accepted articles will be published in *Synthesiology* (ISSN 1882-6229) in the language they were submitted. All articles will also be published in *Synthesiology - English edition* (ISSN 1883-0978). The English edition will be distributed throughout the world approximately four months after the original *Synthesiology* issue is published. Articles written in English will be published in English in both the original *Synthesiology* as well as the English edition. Authors who write articles for *Synthesiology* in Japanese will be asked to provide English translations for the English edition of the journal within 2 months after the original edition is published.
3.1.2 Research papers should comply with the structure and format stated below, and editorials should also comply with the same structure and format except subtitles and abstracts are unnecessary.
3.1.3 Research papers should only be original papers (new literary work).
3.1.4 Research papers should comply with various guidelines of

research ethics

3.2 Structure

3.2.1 The manuscript should include a title (including subtitle), abstract, the name(s) of author(s), institution/contact, main text, and keywords (about 5 words).
3.2.2 Title, abstract, name of author(s), keywords, and institution/contact shall be provided in Japanese and English.
3.2.3 The manuscript shall be prepared using word processors or similar devices, and printed on A4-size portrait (vertical) sheets of paper. The length of the manuscript shall be, about 6 printed pages including figures, tables, and photographs.
3.2.4 Research papers and editorials shall have front covers and the category of the articles (research paper or editorial) shall be stated clearly on the cover sheets.
3.2.5 The title should be about 10–20 Japanese characters (5–10 English words), and readily understandable for a diverse readership background. Research papers shall have subtitles of about 15–25 Japanese characters (7–15 English words) to help recognition by specialists.
3.2.6 The abstract should include the thoughts behind the integration of technological elements and the reason for their selection as well as the scenario for utilizing the research results in society.
3.2.7 The abstract should be 300 Japanese characters or less (125 English words). The Japanese abstract may be omitted in the English edition.
3.2.8 The main text should be about 9,000 Japanese characters (3,400 English words).
3.2.9 The article submitted should be accompanied by profiles of all authors, of about 200 Japanese characters (75 English words) for each author. The essential contribution of each author to the paper should also be included. Confirm that all persons who have made essential contributions to the paper are included.
3.2.10 Discussion with reviewers regarding the research paper content shall be done openly with names of reviewers disclosed, and the Editorial Board will edit the highlights of the review process to about 3,000 Japanese characters (1,200 English words) or a maximum of 2 pages. The edited discussion will be attached to the main body of the paper as part of the article.
3.2.11 If there are reprinted figures, graphs or citations from other papers, prior permission for citation must be obtained and should be clearly stated in the paper, and the sources should be listed in the reference list. A copy of the permission should be sent to the Publishing Secretariat. All verbatim quotations should be placed in quotation marks or marked clearly within the paper.

3.3 Format

3.3.1 The headings for chapters should be 1, 2, 3…, for subchapters, 1.1, 1.2, 1.3…, for sections, 1.1.1, 1.1.2, 1.1.3, for subsections, 1.1.1.1, 1.1.1.2, 1.1.1.3.
3.3.2 The chapters, subchapters, and sections should be enumerated. There should be one line space before each paragraph.
3.3.3 Figures, tables, and photographs should be enumerated. They should each have a title and an explanation (about 20–40 Japanese characters or 10–20 English words), and their positions in the text should be clearly indicated.
3.3.4 For figures, image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be in black and white.
3.3.5 For photographs, image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be in black and white.
3.3.6 References should be listed in order of citation in the main text.

Journal—[No.] Author(s): Title of article, Title of journal (italic), Volume (Issue), Starting page–Ending page (Year of publication).

Book—[No.] Author(s): Title of book (italic), Starting page–Ending page, Publisher, Place of Publication (Year of publication).

Website—[No.] Author(s) name (updating year): Title of a web page, Name of a website (The name of a website is possible to be omitted when it is the same as an author name), URL, Access date.

4 Submission

One printed copy or electronic file (Word file) of manuscript with a checklist attached should be submitted to the following address:

Synthesiology Editorial Board
c/o Public Relations Information Office, Planning Headquarters, National Institute of Advanced Industrial Science and Technology(AIST)
Tsukuba Central 1, 1-1-1 Umezono, Tsukuba 305-8560
E-mail: synthesiology-ml@aist.go.jp
The submitted article will not be returned.

5 Proofreading

Proofreading by author(s) of articles after typesetting is complete will be done once. In principle, only correction of printing errors are allowed in the proofreading stage.

6 Responsibility

The author(s) will be solely responsible for the content of the contributed article.

7 Copyright

The copyright of the articles published in "*Synthesiology*" and "*Synthesiology English edition*" shall belong to the National Institute of Advanced Industrial Science and Technology(AIST).

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Letter from the editor

We deliver four papers in this issue that focuses on "geological surveys." The subject of "geological surveys" is subsurface geoinformation. The Japanese Archipelago is located on one of the most geologically active mobile belts in the world, and many geological disasters such as earthquakes, volcano eruptions, and landslides occur. Also, subsurface geoinformation is essential for land development, environmental protection, and infrastructure construction. Although geoinformation is very important, it is impossible to directly see beneath the ground, and the Government must organize its geoinformation as a national effort to build a safe and wealthy nation.

Unlike other research fields, "geological surveys" do not directly lead to industrial promotion or product development. However, the quality and availability of geoinformation are important as knowledge that links directly to the safety of society and sustainable development, from the perspectives of land development, environmental protection, infrastructure construction, and measures against geological disasters. There is a term *jitsugaku* or practical science, which is an academic discipline whose objective is actual practice, and geology is such a discipline that is closely linked to society. Therefore, from this perspective, we collected the papers on "geological surveys."

In the paper on geochemical reference materials, the development of reference materials and AIST's superior position as a research institute of geology are presented. In the paper on a 3D geological map, a new proposal is made to society on earthquake disaster prevention and mitigation. In the paper on microtremor arrays, timely response is given to the social demand to know the shakiness of the ground. Since the analysis using this microtremor array is dependent on the accuracy of the 3D geological ground map, we would like the readers to pay attention to the relationship between the two papers. In the paper on high-temperature and high-pressure rock deformation experiments, the main point is the research scenario for future earthquake forecasting. I think the readers will be able to deepen their understanding of the research on earthquake forecasting if the papers are read alongside other papers on earthquakes, active faults, and tsunamis.

A wide range of research is conducted in "geological surveys," and I hope we can introduce more papers from diverse aspects at the next opportunity.

(Chikao KURIMOTO, Executive Editor)

Aim of *Synthesiology*

— Utilizing the fruits of research for social prosperity —

There is a wide gap between scientific achievement and its utilization by society. The history of modern science is replete with results that have taken life-times to reach fruition. This disparity has been called the *valley of death*, or the *nightmare stage*. Bridging this difference requires scientists and engineers who understand the potential value to society of their achievements. Despite many previous attempts, a systematic dissemination of the links between scientific achievement and social wealth has not yet been realized.

The unique aim of the journal *Synthesiology* is its focus on the utilization of knowledge for the creation of social wealth, as distinct from the accumulated facts on which that wealth is engendered. Each published paper identifies and integrates component technologies that create value to society. The methods employed and the steps taken toward implementation are also presented.

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URL: http://www.aist.go.jp/aist_e/research_results/publications/synthesiology_e

Synthesiology - English edition Vol. 9 No. 2, Sep. 2016
Edited by *Synthesiology* Editorial Board
Published by National Institute of Advanced Industrial Science and Technology (AIST)

Synthesiology Vol.9 No.2 September 2016
-English edition

Highlights of the Papers in *Synthesiology*

"Synthesiology-English edition" is a translated version of "Synthesiology," which is published quarterly, ISSN 1882-6229, by AIST. Papers or articles published in "Synthesiology-English edition" appear approximately four months after the publication of the original "Synthesiology."

AIST11-A00005-21 Published by AIST

Synthesiology-English edition 2 2016

National Institute of Advanced Industrial Science and Technology (AIST)