Vol.11 No.2 December 2018

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

Synthesiology

English edition

1:50,000 quadrangle geological mapping project in Japan

Traditional craftwork that can be washed with a dishwasher, "nanocomposite *tamamushi-nuri*"

Additive manufacturing of ceramic components

Earth science in safety regulations of radioactive waste disposal

Synthesiology Editorial Board

2018 2

Highlights of the Papers in *Synthesiology*

Synthesiology is a journal that describes the objectives, specific scenarios, and procedures of research activities that attempt to utilize the results in society, in particular, the process of synthesis and integration of elemental technologies for practical application. To allow the readers to see the value of the papers in a glance, the highlights of the papers that characterize *Synthesiology* have been extracted.

***Synthesiology* Editorial Board**

Research paper: 1:50,000 quadrangle geological mapping project in Japan
—Overall and individual scenarios of mapping project—
Kazuhiro Miyazaki
This paper overviews the process by which geological mapping projects in Japan have provided benefits to support society and economy including natural resource development, infrastructure development, industrial location, and disaster mitigation, ever since the Geological Survey of Japan was established in 1882. In the latter half of the paper, field surveys and analytic laboratory research are discussed as elemental technologies for producing geological maps with high precision and reliability, and explains the scenarios on how they are integrated, using specific examples.

Research paper: Traditional craftwork that can be washed with a dishwasher, "nanocomposite *tamamushi-nuri*"
—Expansion from exhibits to daily necessities—
Takeo Ebina *et al.*
This is a valuable case study in which new value was offered to society by overcoming weaknesses and limitations of a conventional product by fusing traditional craftsmanship and advanced science and engineering. The paper describes a sequence of events through which a new characteristic of dishwasher safe was developed for lacquerware and the results. Specifically, a protective layer was made by preparing nanometer size organic clay and dispersing it in polymer solution, to significantly improve scratch resistance that is a common weakness of lacquerware, while maintaining the unique appearance of "*tamamushi-nuri*." The joint effort by Tohoku Kogei Co., Ltd. and AIST is a success story that may provide hints to other fields

Report: Additive manufacturing of ceramic components
—Towards innovation of ceramic industry—
Tatsuki Ohji
The world share of Japan's ceramic field is declining in recent years as emerging countries improve their technological ability. This report focuses on additive manufacturing (AM) that is technology for creating ceramic products of complex shapes and uneven thickness that was difficult to achieve with conventional technology. This is expected to bring about innovation. The report explains the R&D methodology by which the solutions are obtained through selection and integration of elemental technologies and also the characteristics of prototypes, in the Strategic Innovation Program (SIP) conducted through industry-academia-government collaboration.

Commentary: Earth science in safety regulations of radioactive waste disposal
—Translation of scientific research to site selection criteria—
Kazumasa Ito
To safely dispose and manage radioactive waste that is generated by nuclear power generation, it is necessary to have regulatory standards and examination guides that are overseen by the Nuclear Regulation Authority. In so doing, it is essential to have comprehensive knowledge of geology and earth sciences including volcanic activities, fault activities, uplift and erosion phenomena, and underground hydrothermal behavior over several hundred thousand years, considering the half-life of radioactive materials. In this article, some examples utilizing the results of AIST's geological research for intermediate-depth diposal (at depth of 100 m, for low level radioactive waste) are introduced, and then geological research topics are extracted needed to discuss the geological disposal (at depth of 300 m or more) for high-level radioactive waste (such as spent nuclear fuel) to which stricter regulatory standards must be applied. The article also proposes the necessity of communication among the institutions to smoothly transfer knowledge acquired through research.

Electronic journal
URL
http://www.aist.go.jp/aist_e/research_results/publications/synthesiology_e/
J-Stage
https://www.jstage.jst.go.jp/browse/syntheng

Synthesiology – English edition Vol.11 No.2 (Dec. 2018)

Contents

1:50,000 quadrangle geological mapping project in Japan

—Overall and individual scenarios of mapping project—

Kazuhiro MIYAZAKI

[Translation from *Synthesiology*, Vol.11, No.2, p.55−68 (2018)]

The Geological Survey of Japan started a geological mapping project in Japan in 1882. This paper summarizes the historical transition of the strategy of the geological mapping project, which coincides with the transition of the overall scenarios of the mapping project in Japan. Each geological map has an individual scenario on which integration of research elements is conducted. Each individual scenario depends on local geology. 1:50,000 quadrangle geological map is the most basic one developed in the Geological Survey of Japan, and I discuss the mapping project in terms of the overall and individual scenarios.

Keywords **:** 1:50,000 quadrangle geological map, 1:200,000 quadrangle geological map, 75,000 quadrangle geological map

1 Introduction

Geological maps graphically show geological strata and rocks that exist near the ground surface, through categorization by lithologic characteristics, formation condition, formation age, and others. The geological maps show information about the land on which we live. The Japanese Islands on which we live is positioned in the subduction zone that is the most active spot on earth. The Japanese Islands and the east rim of the Eurasian continent have been at the subduction zone for over 500 million years. Geological phenomena that may directly or indirectly be threatening including fault activity, volcanic activity, landslides, erosion, uplifts, underground water flow, soil deposition, and others continue to occur. Records of phenomena that occur in a short time scale such as earthquakes, eruptions, and landslides, as well as phenomena that occur in a time scale of several 10 million to 100 million years such as orogeny are all recorded in the geological strata and rocks beneath our feet. Moreover, there are places where rocks, which record phenomena that occurred deep within the crust or mantle which we normally cannot see directly, are exposed at a large scale of several 10 km or more on the surface. As a result, a wide variety of strata and rocks are present beneath our feet. Knowledge of such strata and rocks are essential in advancing industry, for utilizing them directly or as foundation of construction. In fact, geological maps have been created to explore mineral resources in Japan starting in the Meiji Period and continuing to the postwar recovery period, excluding the brief period during WWII. From the rapid economic growth in the Showa Period to present, the geological maps have been produced as basic information for land development, conservation, as well as natural disaster mitigation.

In this paper, I shall first describe the role of geological maps in society, provide overview of the history of the quadrangle geological map[Term 1] project at the old Geological Survey of Japan (GSJ) and the new GSJ (AIST-GSJ after reorganization to AIST), and present the changes in the total plan of the mapping project. The overall plan of the quadrangle geological mapping project and the production process of 1:50,000 quadrangle geological maps can be rephrased as the general scenario and individual scenarios of the mapping project. In the first half of this paper, I shall address the general scenario through the changes in the plan of the quadrangle geological mapping project since the Meiji Period, and in the latter half, I shall introduce the individual scenarios for the production of 1:50,000 quadrangle geological maps. Finally, I shall discuss the roles of the general and individual scenarios in the 1:50,000 mapping project of the future.

2 Role of geological maps in society

The geological maps are used in various situations in society. When they are used as basic resource in major civil engineering works, construction companies use them to reduce expenses and shorten survey time, as they can grasp the geological overview of an area when selecting construction sites, based on the geological information from geological maps. The legend of the 1:50,000 geological maps is used as an industry standard for categorization of the strata and rocks in specific construction projects conducted by construction companies or subcontractors.[1] Large-scale terrestrial resource development has presently become rare in Japan, but there are cases where it was determined that exploration of oil or natural gas was worthwhile for an area for which a new 1:50,000 quadrangle geological

Research Institute of Geology and Geoinformation, Geological Survey of Japan, AIST Tsukuba Central 7, 1-1-1 Higashi, Tsukuba 305-8561, Japan E-mail: kazu-miyazaki@aist.go.jp

Original manuscript received January 25, 2018, Revisions received March 26, 2018, Accepted March 28, 2018

map was published with its detailed geology, and this led to the geological reconnaissance survey and geophysical exploration of several hundred million to several billion yen scale.[1] This demonstrates that highly reliable 1:50,000 quadrangle geological maps are important in current Japan as basic data for resource exploration. The 1:200,000 Seamless Digital Geological Map of Japan produced based on the 1:50,000 and 1:200,000 quadrangle geological maps are also used as data to determine the metrological condition, uplift, and landslide susceptibility in the deep-seated landslide frequency estimation map for Japan.[1]

Quadrangle geological maps are produced as public assets by the governments in many countries. However, rarely is the value of maps explicitly declared even when geological maps are used widely as basic material for planning regional infrastructure construction, selection of industrial facility location, resource development, or disaster mitigation. In the United States where the National Geologic Mapping Act was established in 1992, the budget of the geological map production program reached 64 million dollars in 2005, and the social value of geological maps was estimated to back up the budget proposal.[2] In this estimate, two cases of use were mentioned. They were for locating waste disposal sites and for construction of arterial transportation roads. In both cases, an economical method was used to evaluate whether old geological maps or new ones could reduce the risks. The geological maps used for the evaluation were the 1:500,000 geological maps for Virginia produced in 1963, and the 1:100,000 geological maps for Loudoun County, Virginia made by the US Geological Survey (USGS) in 1992 (Fig. 1). In the case of waste disposal site construction, water permeability of the area was estimated from geological features to determine the places where construction should be restricted due to water permeation (Fig. 2). Water permeability of a certain region calculated from geological maps has uncertainty corresponding to statistical distribution. The uncertainty of permeability can be reduced if geological maps with high quality (high quality is defined as a state in which the geology of a certain area is determined to be accurate and detailed) and high precision (has high positional accuracy of faults and lithofacies boundaries) are used. The distance from faults was added as a restricting condition of site location. From the property value of the restricted site area and the probability of contamination determined from such data, predicted loss that was avoided by restricting locations was estimated. On the other hand, in the case of arterial road construction, shear strength was estimated from regional geology, and the areas where measures must be taken to prevent landslides and areas where no such measures was needed were determined (Fig. 3). In road construction, by avoiding the places where landslide measures were needed, the cost of predicted preventative measures that could be saved was estimated from the probability of slope failure occurring by road construction and the cost of preventative measures. In both cases, uncertainties exist for values of water permeability and shear strength that were estimated from the geological maps. As mentioned earlier, if the geological maps for the area are of high quality and high precision, the uncertainty can be kept low. Therefore, the cost of benefit was calculated by subtracting the cost of producing the new geological maps from the difference between the predicted cost of preventative measures and the predicted loss that could be avoided by using the new and the old geological maps. The amount was predicted to be from 1.12 million dollars to 3.5 million dollars for the above two cases. Of course, the benefit will increase further if

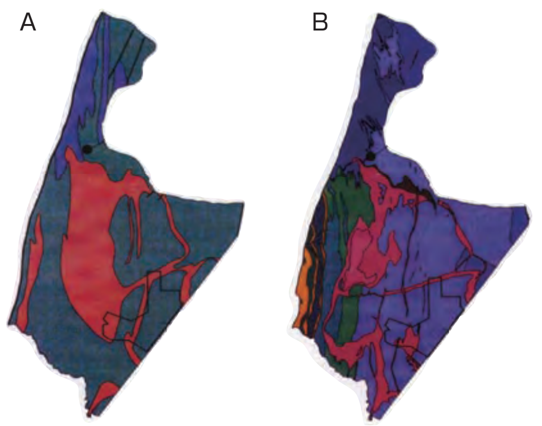


Fig. 1 Geological map of eastern Loudoun County, VirginiaH

A. Part of the geological map of Virginia, 1963 (Mineral Resources Department, Virginia). Green = sedimentary rock (sandstone and shale are not differentiated). Pink = igneous rock (diabase and gabbro are not differentiated). Blue = conglomerate (coarse sedimentary rock).

B. Part of USGS geological map of Loudoun County, Virginia, 1992 (preliminary version, open-file report). Green and blue colors = sedimentary rocks (sandstone, silt, conglomerate); pink and orange colors = igneous rock (diabase and basalt); dark blue = limestone conglomerate (Fig. 3, Introduction, Reference [2]). Compared to A, the lithofacies are more finely categorized in B.

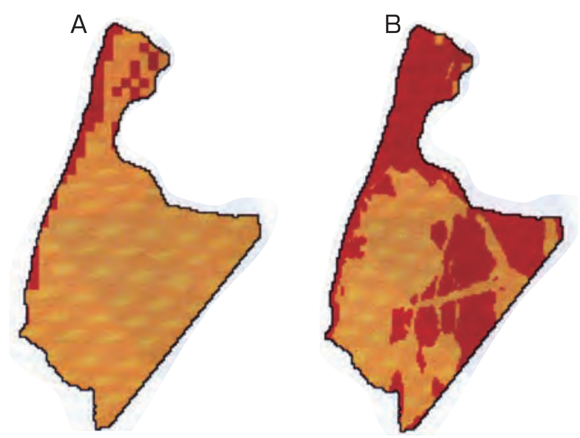


Fig. 2 A is the geological map of Virginia in 1963, and B is the distribution of cells that are not suitable as locations for waste disposal sites based on the USGS geological map of Loudoun County, Virginia, 1992.

Yellow = location is not restricted. Red = location is restricted (Fig. 4, Introduction, Reference [2]).

the geological maps are used for purposes other than waste disposal site or arterial road construction. What is important here is that geological maps of high quality and precision can provide large benefit to society. In the following chapters, I shall describe the history of geological mapping, the 1:50,000 quadrangle geological mapping project, and the process of producing high quality and high precision 1:50,000 quadrangle geological maps.

3 General scenario of quadrangle geological mapping project

3.1 1:200,000 detailed geological maps

The creation of geological maps in Japan started in the Meiji Period. The Division of Geology, Bureau of Geography, Ministry of Interior was established in 1878 (Meiji 11), or the year following the Seinan War (Satsuma Rebellion). In 1879 (Meiji 12), a written opinion was addressed to Hirofumi Ito, Secretary of Interior, on how geological survey was beneficial to agriculture, mining, metallurgy, and civil engineering, and how the development of underground resources was important for Japan.[3] Regarding geological surveys of other countries, the British Geological Survey was established in 1835 and USGS in 1879, and the importance of geological maps was recognized internationally as basic infrastructure information. The Geological Survey of Japan (GSJ) was established in 1882 (Meiji 15). GSJ immediately started the production of geological maps in Japan. There are two major types of geological maps created by the old GSJ and the current GSJ-AIST. One is the geological maps created by conducting geological field surveys and laboratory research, and this is represented by the current 1:50,000 quadrangle geological maps. The other is the geological maps created by mainly compiling existing materials, and this is represented by the 1:200,000 quadrangle geological maps

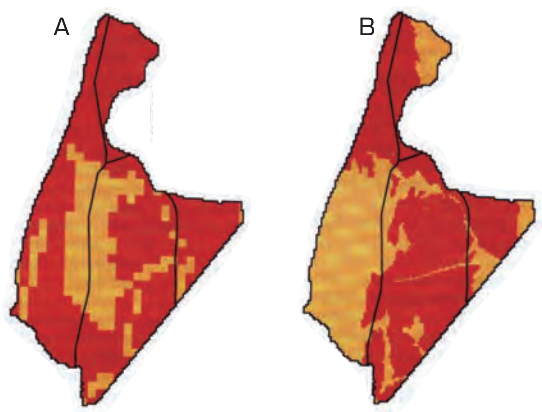


Fig. 3 Distribution of cells that require measures to prevent landslides that may be caused by construction of arterial road

A. Based on the geological map of Virginia, 1963.

B. Based on the USGS geological map for Loudoun County, Virginia, 1992. Yellow = preventative measures unnecessary. Red = preventative measures necessary. Black line = planned route for arterial road (Fig. 5, Introduction, Reference [2]).

published currently by GSJ-AIST (Fig. 4). The geological maps created by compilation are produced after some of the geological maps produced by original geological surveys are published to some extent (Fig. 4).

We shall look at the transition of the geological maps produced by original geological surveys in the Meiji Period to early Showa Period. As written in the letter proposing the establishment of a geological survey institution, there was recognition that geological surveys and geological maps produced as a result are important as basic infrastructure information for Japan to develop as a modern nation. The specific plan proposed in 1879 (Meiji 12) for executing geological surveys in Japan was to create 98 quads of 1:200,000 quadrangle geological maps (these early maps will be called 1:200,000 detailed geological maps to avoid confusion with the currently published 1:200,000 quadrangle geological maps) in about 12 years.[4] The plan for the survey of 1:200,000 detailed geological maps was to create 1:400,000 reconnaissance geological maps, 1:200,000 detailed geological maps and reports, as well as 1:100,000 soil maps and reports.[4] Five quads of reconnaissance maps were planned and Hokkaido was excluded. The Tohoku regional map was first published in 1886 (Meiji 19), maps of western and southwestern regions were published in 1894 (Meiji 27), and five quads were published in total. However, the Tohoku regional map that was published first was inferior in terms of locational precision compared to other maps. Therefore, re-survey began in 1895 (Meiji 28), and a second edition was published in 1901 (Meiji 34).[4] The above maps are called 1:400,000 reconnaissance geological maps (Fig. 4).

The 1:200,000 detailed geological maps were created after conducting original geological surveys. Note that it is positioned differently from the modern 1:200,000 quadrangle geological maps that are created mainly by compilation. The 1:200,000 detailed geological map “Izu,” the first in the series, was published in 1884 (Meiji 17), and the final in the series, “Suruga,” or the 98th map, was completed in 1919 (Taisho 8). It required 40 years from the proposal in 1879 (Meiji 12) to completion. Since the period in the initial proposal was 12 years, much more time was needed than planned. However, one 1:200,000 detailed geological map covered an area equivalent to 12 quads of 1:50,000 quadrangle geological maps that are currently produced, and about four months (about 120 days) of field survey were spent per quad.[4] The 1:200,000 detailed geological maps were the first maps to cover entire Japan through original geological field surveys. One can imagine that field surveys by our predecessors during the Meiji and Taisho periods must have been difficult. It can be considered that the first stage of geological maps of the Japanese Islands by field survey was completed.

3.2 1:75,000 quadrangle geological map

The completion of the 1:200,000 detailed geological maps for entire Japan was a major feat. However, in 1907 (Meiji 40) when the director and others of GSJ looked at the projects of geological survey institutions around the world, they became aware that the geological maps in larger scales were necessary. Therefore, plans were proposed in 1914 (Taisho 3) for 1:75,000 quadrangle geological maps. The 1:75,000 maps were equivalent to the area covered by three sheets of the current 1:50,000 quadrangle geological maps. The plan was to produce them by field surveys of four months (about 120 days).[4] Incidentally over a month of survey is needed for one 1:50,000 quadrangle geological map. The initial ambitious plan was to divide Japan into 324 quadrangles, survey about eight quads per year, and spend 40 years for completion.[4] The production of the 1:75,000 quadrangle geological maps was actually started in 1917 (Taisho 6). If it went according to the plan, the maps would have been completed by about 1957. Although there was an austerity measure imposed by the government until early Showa, importance was placed on the geological map survey.[3] However, the geological map survey was halted in 1943 (Showa 18) when Japan was at war.[3] This was the first time the survey was interrupted since the establishment of GSJ. The survey for 1:75,000 quadrangle geological maps, which was the main work of GSJ, was restarted in 1946 (Showa 21) after the war.[3] However, the "Onikobe" map published in 1958 (Showa 33) became the last 1:75,000 quadrangle geological map. The 1:75,000 quadrangle geological maps that were planned to cover entire Japan were terminated after 83 quads were produced. Nevertheless, there was strong demand for a mapping project from the point of view of land conservation and industrial promotion after the devastation of WWII, and people were aware that production of geological maps that were the foundation of social development was important.[4] The role of providing geological maps of Japan was carried over to the 1:50,000 quadrangle geological maps that will be discussed later.

3.3 1:50,000 quadrangle geological maps in old GSJ

The aforementioned 1:75,000 quadrangle geological mapping project was switched over to the 1:50,000 quadrangle geological mapping project started in 1949 (Showa 24) and is continued to present. This decision was made because the scale of the topological maps of the Geospatial Information Authority of Japan (GSI; the former Geographical Survey Institute), the base maps, was 1:50,000. There was consideration for the user's convenience, as well as need for locational precision during survey when comparing with the topological maps.[3] How did this change affect the goal of covering entire Japan? By simple calculation, larger the scale increases the number of maps necessary for total coverage to three times. Assuming that the time required to produce one quad is the same, the 40-year plan becomes a 120-year plan. In addition, since more detailed categorization of geological strata and rocks is required, more time is necessary including time for increased laboratory research. That means, switching from the 1:75,000 to 1:50,000 quadrangle geological mapping project changes not only the scale, but the general scenario of the mapping project, and coverage of entire Japan cannot be done in 100 years or less. Then, what general scenario has been employed up to

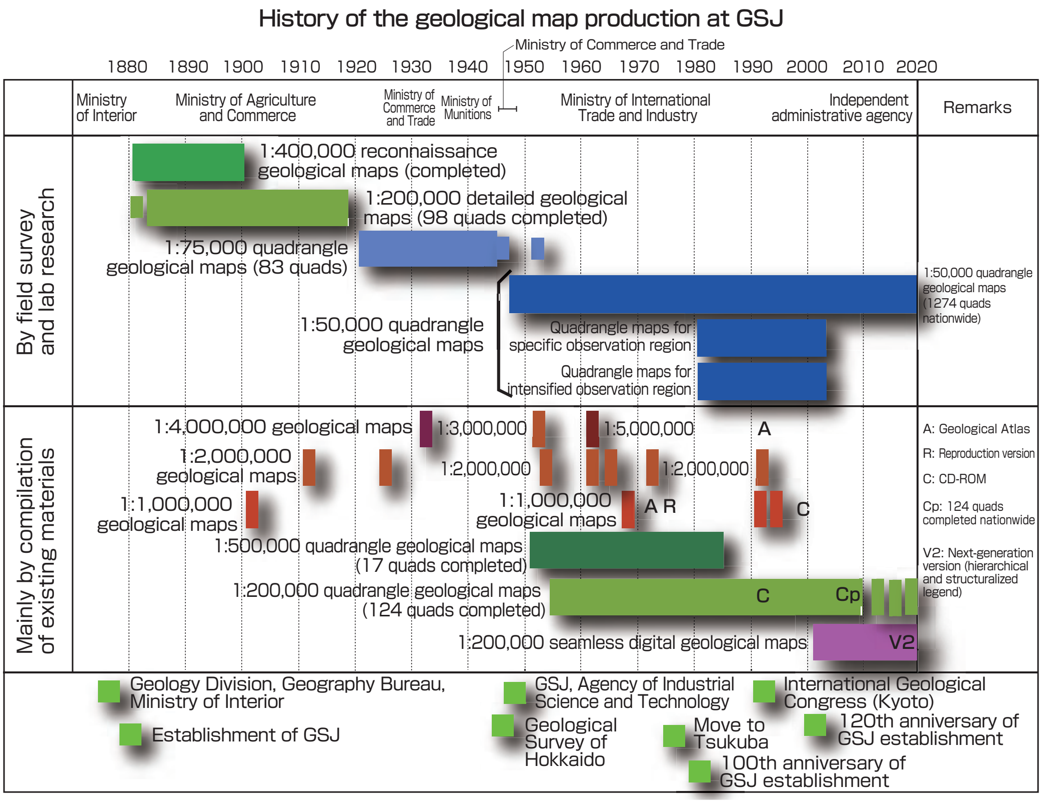


Fig. 4 History of geological maps at Geological Survey of Japan (GSJ)

now to produce the 1:50,000 quadrangle geological maps?

757.5 quads have been created up to present (as of 2017) of the 1:50,000 quadrangle geological maps, but there are large fluctuations in the number of publications per year (Fig. 5). Initially, when the 1:50,000 quadrangle geological mapping project started, surveys were actively done mainly in Hokkaido. This was because concentrated effort was spent in this area in cooperation with research institutes (such as Geological Survey of Hokkaido) outside GSJ to obtain energy resources (particularly coal).[5] That is, during the postwar recovery period, geological map production of Hokkaido was conducted by GSJ, the Geological Survey of Hokkaido, and the Hokkaido Development Agency. The survey for 1:50,000 quadrangle geological maps subcontracted to the Hokkaido Development Agency was started in 1951 (Showa 26). GSJ designated the mapping project as special research in 1954 (Showa 29), and several mapping surveys were started. That is, there was concentrated effort in the Hokkaido region for 1:50,000 quadrangle geological mapping. The concentrated geological mapping project in the Hokkaido region continued until about 1963 (Showa 38), and after that, mapping was continued as an ordinary research project, and the number of quads published decreased dramatically. This period of reduction overlapped with the period when many other special projects of research were started.[4] Due to the increased number of special research, the number of researchers participating in geological mapping surveys decreased, and this in turn, inflicted the relative decrease of budget for ordinary research.[4]

Slump in the number of publication continued for a while. The number of publication of geological maps increased in 1979 (Showa 54) when the special geological mapping project started as special research of GSJ (Fig. 5). The special geological mapping project was a plan to quickly create 1:50,000 quadrangle geological maps of “specified observation regions for earthquake forecast,” for which eight regions were designated. The eight regions were as follows: 1) eastern Hokkaido, 2) western Akita and northwestern Yamagata, 3) eastern Miyagi and eastern Fukushima, 4) southwestern Niigata and northern Nagano, 5) western Nagano and eastern Gifu, 6) Nagoya, Kyoto, and Kobe region, 7) eastern Shimane, and 8) Iyo-nada and Hyuga-nada area (Fig. 6). Although limited to specific regions, the general scenario of concentrating and producing the geological maps within a certain period was rebooted. Concerning 1:50,000 quadrangle geological maps during this period, about 250 days of field surveys were spent for one quad. There were 265 1:50,000 quads in the eight designated regions, and 132 quads were not yet drawn in 1979 (Showa 54). In the special geological mapping project, 42 quads were produced in the First Plan (1979–1984), 35 quads in the Second Plan (1985–1989), and 34 quads in the Third Plan (1990–1994). During the 16 years up to the Third Plan, 111 quads were produced, and the mapping of 1:50,000 quadrangle geological maps of the eight regions reached 90 % of its completion. The Fourth Plan (1994–2000) and the Fifth Plan (1999–2005) were also proposed, but when the plan was carried over to GSJ-AIST in 2001, the distinction between the special and ordinary mapping projects became unclear. Looking at the area of the special geological maps, it can be seen that the production rate of the 1:50,000 quadrangle geological maps in this region was extremely high (Fig. 6). The specific geological mapping project was a general scenario for a geological mapping project in a top-down manner. The maps to be produced were determined by the top, and the field survey period per quad was limited to one to three years. Although this project was unpopular among individual researchers, it resulted in the production of geological maps according to the scheduled plan.

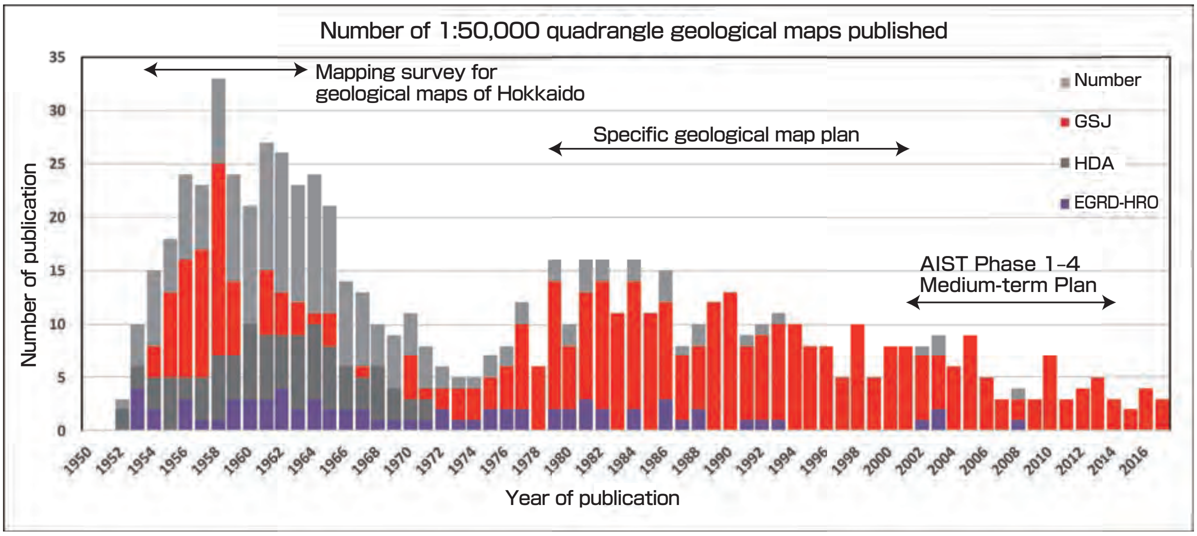


Fig. 5 Transition of publication of 1:5,000,000 quadrangle geological maps

GSJ: Geological Survey of Japan. HDA: Hokkaido Development Agency. EGRD-HRO: Environmental and Geological Research Department, Hokkaido Research Organization (former Geological Survey of Hokkaido).

3.4 1:50,000 quadrangle geological map after reorganization to AIST

After reorganization to AIST, there was no general scenario for the 1:50,000 quadrangle geological mapping project like the special geological maps that explicitly concentrated mapping in specific regions. Although there are important regions for 1:50,000 quadrangle geological maps, the current situation is similar to the 1970s when ordinary geological mapping was done. However, it is not true that there was absolutely no general scenario for the geological mapping project after the organization became AIST. In the general scenario of the government's Intellectual Infrastructure Plan or AIST Phase 1–2 Medium-Term Plan (2001–2009), the national coverage of the 1:200,000 quadrangle geological maps that was started in 1954 (Showa 29) was approaching completion, and this was the scenario that drove the whole mapping project. In 2010, the national coverage of the 1:200,000 quadrangle geological maps was achieved after 56 years.[6] During the AIST Phase 1–2 Medium-Term Plan (2001–2009), 34 quads of 1:200,000 quadrangle geological maps were published including the revisions. Unlike the 1:200,000 detailed geological maps completed before the war, the 1:200,000 quadrangle geological maps contained the advances in geological understanding of postwar Japan (Fig. 7). Moreover, in AIST Phase 3 Medium-Term Plan (2010–2014), the geology of the Japanese Islands was updated to the latest information in all 124 quads of the 1:200,000 quadrangle geological maps, and the Seamless Digital Geological Map (Next-Generation Seamless Digital Geological Map) that has a unified, hierarchical, structured legend was completed. After experimental publication, the Seamless Digital Geological Map was officially released in FY 2017. This completed the framework for systematically organizing the geological maps by roles, including the provision of open data of geological information by Seamless Digital Geological Map, national coverage of geological maps by 1:200,000 quadrangle geological maps, and the establishment of regional standards in which the representative geology of the Japanese Islands is manifest in the 1:50,000 quadrangle geological maps (Fig. 8). In considering the general scenario of future geological maps, the 1:50,000 quadrangle geological mapping project that is the basis of all geological maps is important. Before discussing this, the scenarios for producing individual 1:50,000 quadrangle geological maps will be described. These are considered separate scenarios, and they are related to maintaining the quality of geological maps. Also, new findings obtained from individual geological map research are published as research papers, and the intellectual curiosity of the individual researchers drives the mapping project (Fig. 8).

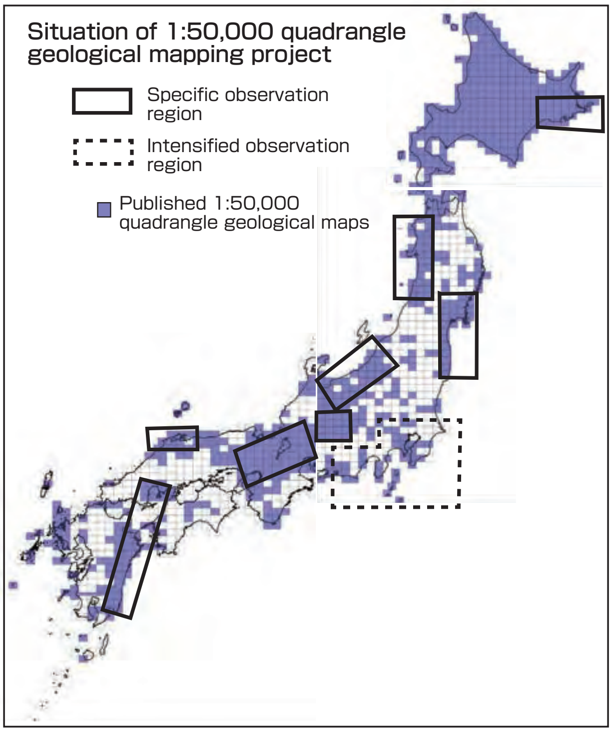


Fig. 6 Situation of 1:50,000 quadrangle geological maps (as of 2013)

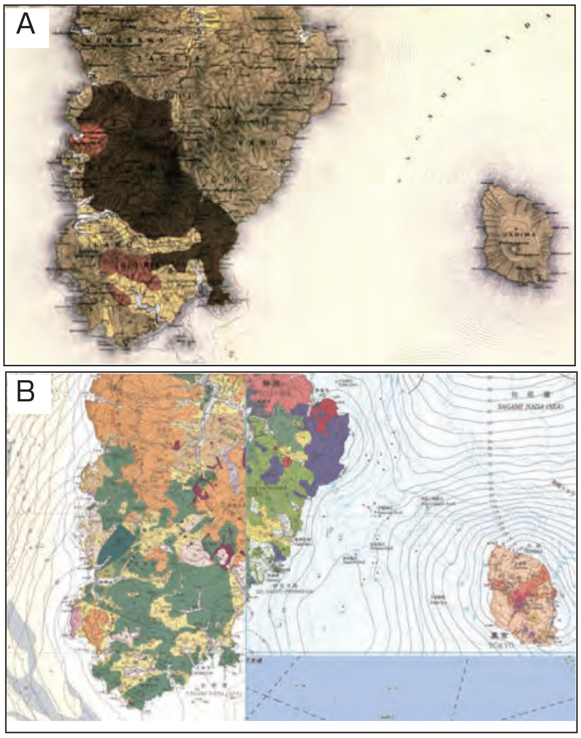


Fig. 7 Comparison of 1:200,000 detailed geological map and 1:200,000 quadrangle geological map

A. 1:200,000 detailed geological map "Izu" published in 1884. B. Mosaic version of the 1:200,000 quadrangle geological map "Shizuoka and Omaezaki (ver. 2)" published in 2010 and the 1:200,000 quadrangle geological map "Yokosuka (ver. 2)" published in 2015, using Geo Map Navi. In the current 1:200,000 quadrangle geological map, strata and rock categorizations are more detailed and accurate, due to the accumulation of 120 years of geological findings since the publication of 1:200,000 detailed geological map "Izu."

4 Individual scenarios and elements for producing 1:50,000 quadrangle geological maps

4.1 Outline of individual scenarios

The history of the geological mapping project and transition of the general scenario after the Meiji Period were described in the previous chapters. Now, we shall look at the elements for producing the individual 1:50,000 quadrangle geological maps, and how such elements are integrated in the scenario for producing the geological maps.

The elements for producing the 1:50,000 quadrangle geological maps can be roughly divided into geological field surveys and laboratory experiments (Fig. 9). In the geological field survey, outcrop observation, route survey, and forming of geological columnar sections and cross-sections of routes are done to estimate the geological structure. Such steady work is done for a number of routes. The estimated geological structure is rewritten as new geological survey results are obtained. The geological structures may be complex due to folding and fault activities of the crustal movements after the formation of target strata and rocks. There are many cases in which a geological structure model that was estimated after a few route surveys conducted earlier is completely overthrown. In field surveys, hypotheses concerning geological structures are set up, and these are verified and corrected by field surveys. This work is conducted repeatedly (Fig. 9(1) and Fig. 10). This work is the most time consuming in geological map production. By repeating verification by field surveys, it is possible to create a geological map with high precision, where the lithofacies boundaries and fault positions can be estimated even in valleys and ridges where

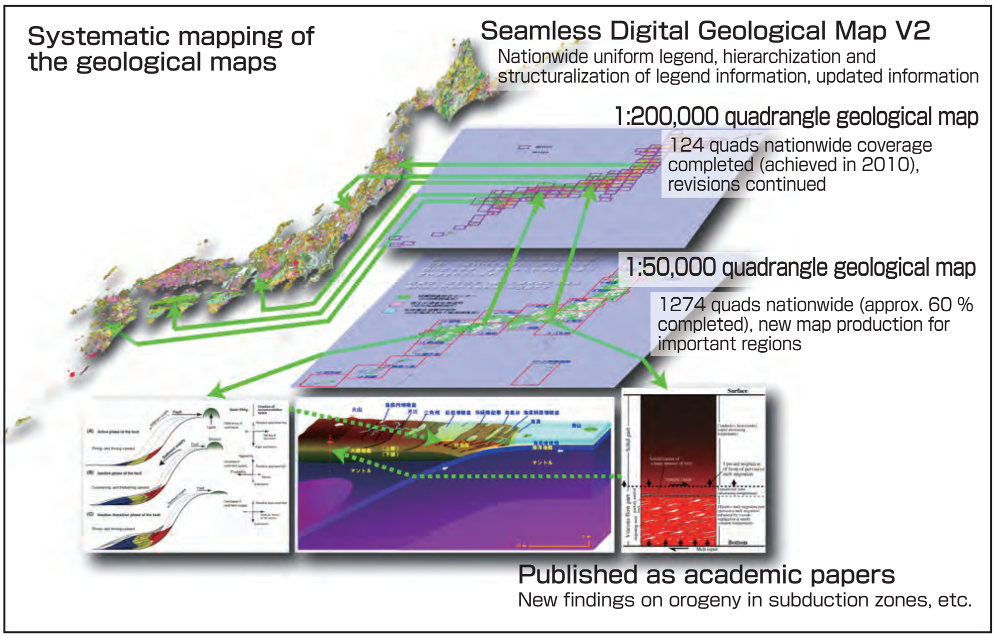


Fig. 8 Systematic mapping project for quadrangle geological maps at GSJ-AIST

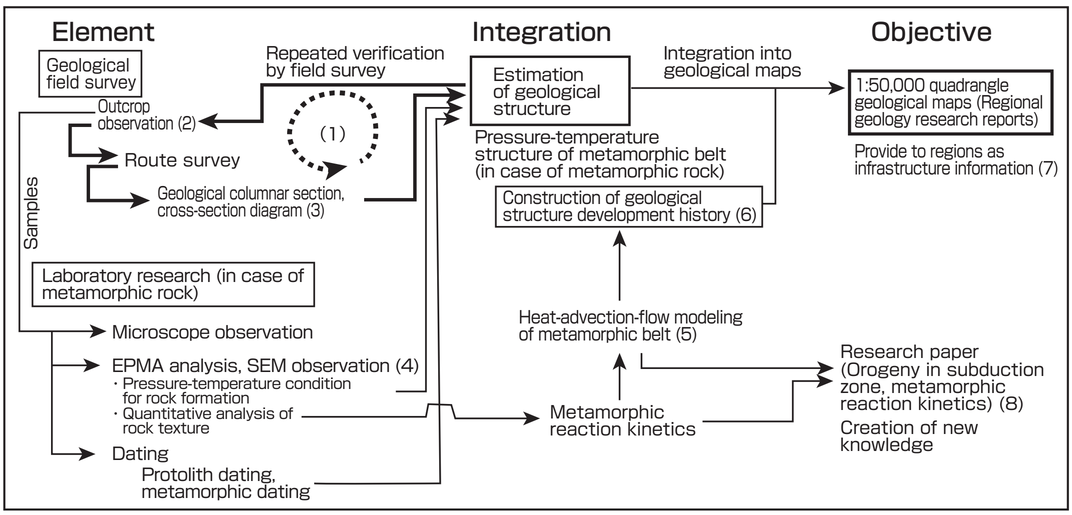


Fig. 9 Elements and scenario of 1:50,000 quadrangle geological map production

surveys have not been done (Fig. 10). To maintain accuracy of the categorization of strata and rocks that are present within a geological map quadrangle, laboratory studies for the samples collected in field surveys are necessary. This is because environment and locations of strata and rock formation cannot be obtained only by naked-eye observation in the field, and the age in which they were formed may become clear by laboratory research. The results of lab research are fed back to the field survey, and this enables the production of geological maps with high precision.

4.2 Elements of 1:50,000 quadrangle geological map production (in a case of geological map for metamorphic rock region)

In looking at the elements and integration of 1:50,000 quadrangle geological map production, in many cases, it is difficult to speak in general terms. The reason is because methodology of lab research may differ greatly by target geology. Therefore, we shall look at the details, taking the example of 1:50,000 quadrangle geological map "Goyu" that is in the Toyohashi, Tokai region[7] (Fig. 11). The author was in charge of metamorphic rock in these maps. The

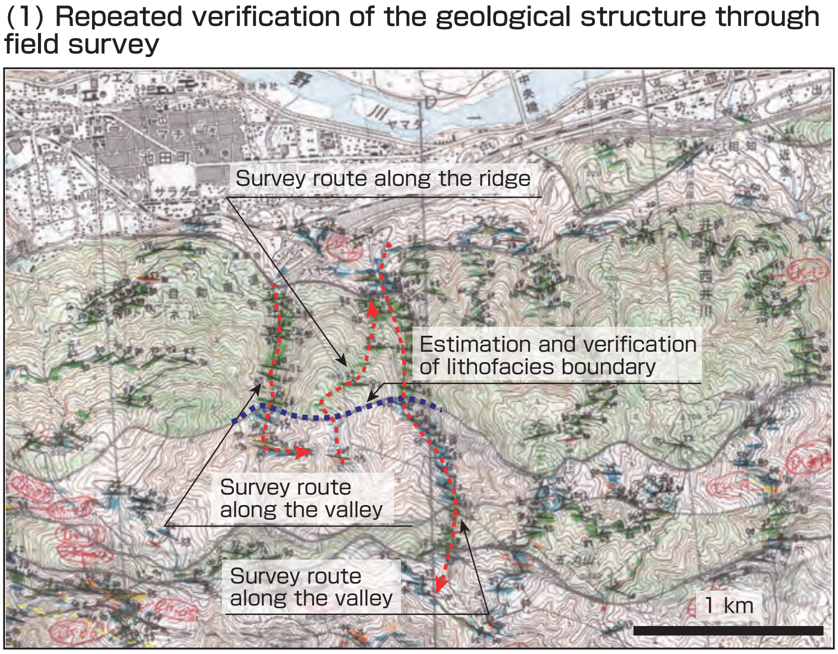


Fig. 10 Repeated verification of geological structure through field survey

Number in the title corresponds to the number in Fig. 9. The figure shows part of a route map of a certain region in a 1:50,000 quadrangle geological map that is currently being produced. In the route map, different types of observed lithofacies are colored with different colors. The strike and dip of schist are also drawn into the map. Writings in red designate the places where the rock samples were collected.

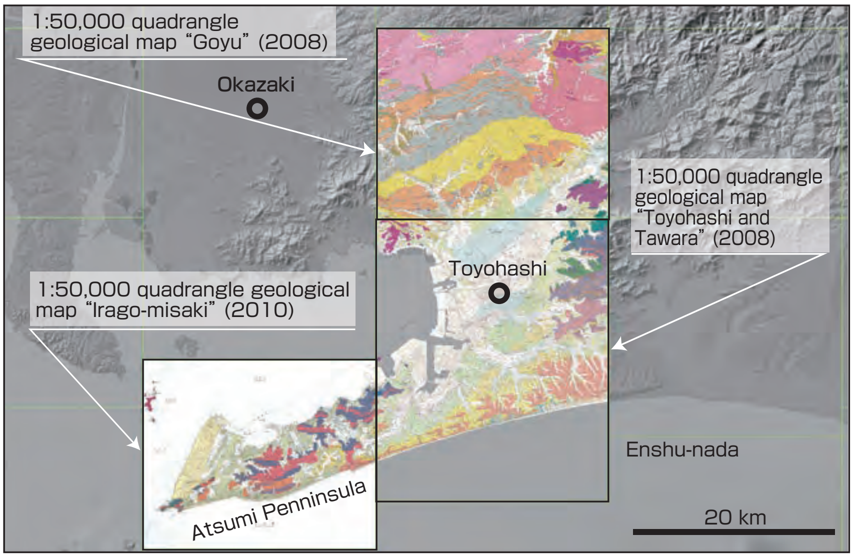


Fig. 11 1:50,000 quadrangle geological map of Toyohashi region[7][11][12]

lab research of metamorphic rock and metamorphic rock regions consists mainly of petrology, structural petrology, and dating using radioactive elements. On the other hand, the lab research of sedimentary rock regions consists of biostratigraphy and sedimentology. Therefore, the analysis methods also differ greatly.

There are roughly two types of metamorphic rock distributed widely in the Japanese Islands. One is the high-pressure metamorphic rock formed near the subduction zone where the oceanic plate sinks beneath the continental plate. Some of this metamorphic rock is formed at depth of 100 km and pressure of 2 GPa or more, and then rises near the surface. The other is the high-temperature metamorphic rock that is formed deep in the volcanic arc. This type of metamorphic rock is formed at depth of 20 to 30 km at temperature of 800 ºC or higher. This is a condition at which partial melting of rock occurs. Around Toyohashi, these two types of metamorphic rock are in contact through the median tectonic line. Taking the example of 1:50,000 quadrangle geological map "Goyu,"[7] I shall explain the production of a geological map for the Ryoke metamorphic rock that is a high-temperature type. The Ryoke metamorphic rock is a continuous belt of metamorphic rock that runs about 1000 km east-west in the central part of southwestern Japan, and the underground of the Pacific Belt is composed almost entirely of Ryoke metamorphic rock and the closely related Ryoke granite.

The characteristic of metamorphic rock is that there is a protolith from which it is formed. The protolith can turn into sedimentary rock, igneous rock, or metamorphic rock. When surveying the metamorphic rock in the "Goyu" region, it is necessary to carefully record the protolith and the changes in lithofacies that result from the metamorphic effects on the protolith (Fig. 9(2) and Fig. 12). Most of the protolith of the Ryoke metamorphic rock is the accretionary prism of the Jurassic period, and one can observe the outcrops where bedded chert, siliceous shale, and mudstone are in layers in the northern half of the map (Fig. 12). On the other hand, the southern half of the map has different lithofacies. In the southern side, there is a mixture of migmatite, which is rock composed of solidified magma, and metamorphic rock at several cm to several m scale. When observed carefully, the metamorphic rock part seems to be rock that may be the remains of partially melted mudstone. There are also bedded chert, but upon close observation, it can be seen that the quartz particles that compose the chert is significantly

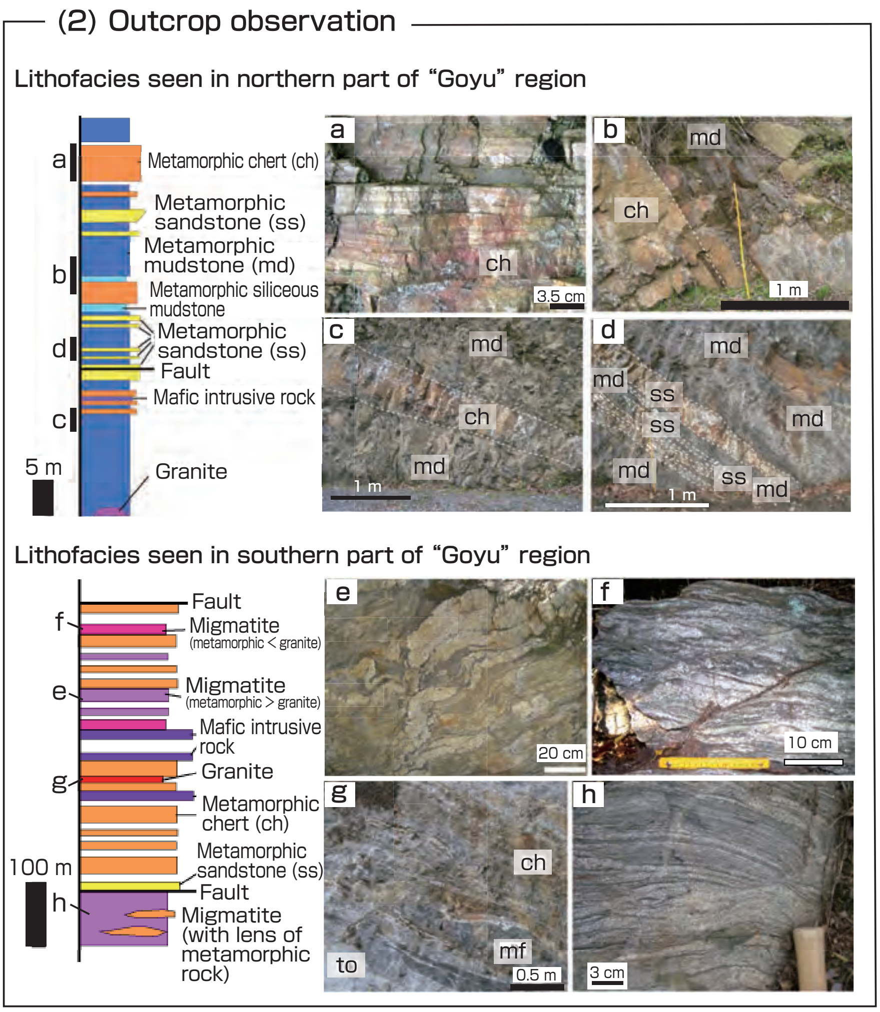


Fig. 12 Example of outcrop observation in field survey (quadrangle geological map "Goyu")[7]
Number in the title corresponds to the number in Fig. 9.
a-d Lithofacies seen in the biotite zone in the northern part of "Goyu" region. a outcrop of metamorphic chert (ch); b metamorphic siliceous shale sandwiched between metamorphic chert in the left side of outcrop, and right side is metamorphic mudstone (md); c metamorphic chert (ch) between metamorphic mudstone (md); d lens-shaped metamorphic sandstone (ss) in metamorphic mudstone (md).
e-h Lithofacies seen in the garnet cordierite zone in the southern part of "Goyu" region. e migmatite with high amount of metamorphic-rock-like part (mesozome); f migmatite with lots of granite-like parts; g gneissose tonalite (to) (granites in a wide sense) parallelly intruding schist of metamorphic chert (ch) and mafic intrusive rock (mf); h migmatite whose protolith is metamorphic sandstone.

coarser compared to the ones in the north. Why did such difference in lithofacies occur? Can a reasonable explanation be provided? There are cases where conclusion cannot be obtained by outcrop observation only. In metamorphic rock research, the samples are taken back to the lab for further observation.

In the field survey for the metamorphic rock region, the lithofacies are categorized according to the types of protoliths, and the samples (thin slices) collected at the outcrop are identified by polarizing microscope observation. Then, the metamorphic zone diagram that reflects the temperature and pressure conditions during metamorphosis through paragenesis is created. The integrated histogram for each survey route is created to estimate the overall geological structure and temperature structure (Fig. 9(3) and Fig. 13).

In the laboratory research for metamorphic rock, quantitative temperature and pressure estimation is done in addition to the estimation of general temperature and pressure structure. To do so, chemical composition analysis of the minerals in the collected metamorphic rock samples is necessary (Fig. 9(4) and Fig. 14). The pressure-temperature estimate is done from the element partition between two or more coexisting minerals. After the 1960s, thermobarometers using element partition coefficients between various minerals have been devised. Currently, there are programs that calculate composition and quantity ratio of minerals and liquid in the pressure-temperature condition in which the metamorphic rock was formed from the composition of the mineral component and chemical composition of the rocks, satisfying the minimal free energy condition. It seems that nothing has been left undone for the development of an estimation method of metamorphic rock formation condition using a thermodynamic equilibrium state between minerals. On the other hand, it is certain that the thermodynamic analysis method of metamorphic rock greatly contributed to the quantification of the orogenic belt formation model.

4.3 Integration of individual elements into geological maps

In the “Goyu” map, an interesting point was found when the results obtained by field survey and the results obtained by lab research were integrated. In the estimate using the geothermobarometer conducted in the lab, the value whereby pressure values were converted into depth and

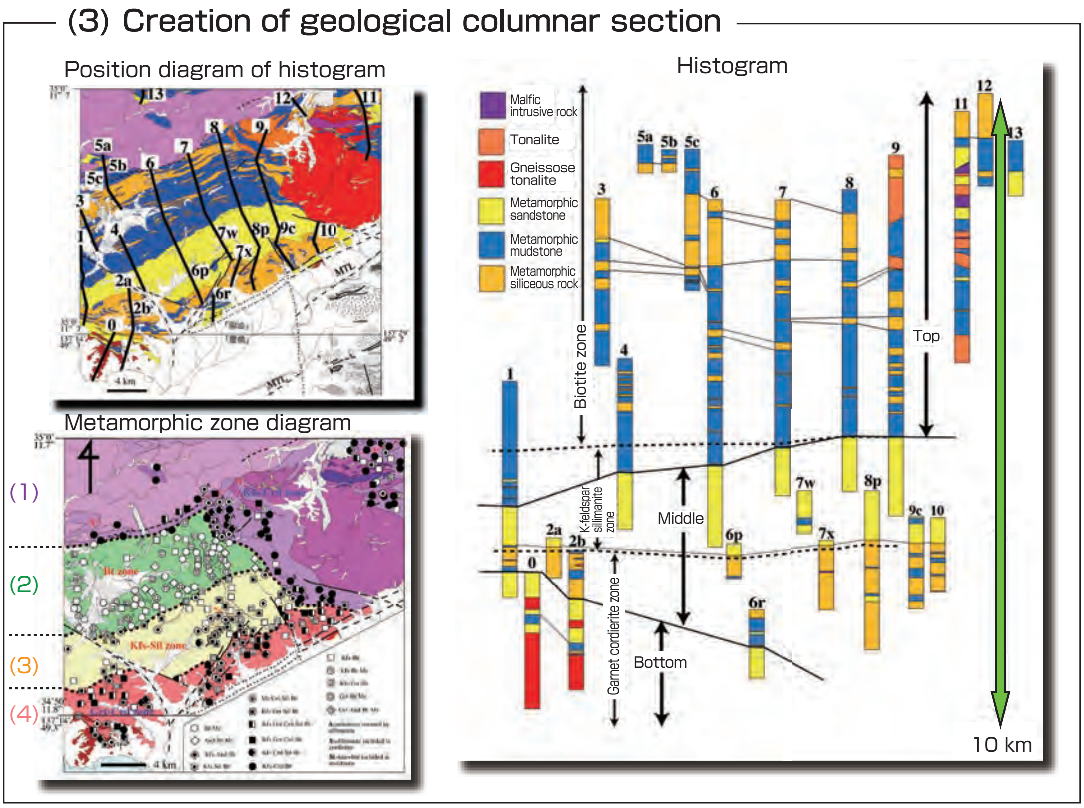


Fig. 13 Example of geological columnar section created in field survey (quadrangle geological map “Goyu”)[7]

Number in the title corresponds to the number in Fig. 9. Left-top is the position diagram of the histogram. The numbers correspond to the numbers in the histogram on the right. Left-bottom is the result of metamorphic zoning done by mineral assemblage of metamorphic mudstone. A symbol is assigned to each mineral assemblage. Refer to References [7] and [8] for details. On left-bottom of the figure: (1) Kfs-Crd zone is potassium (K) feldspar cordierite zone, (2) Bt zone is biotite zone, (3) Kfs-Sil zone is potassium (K) feldspar sillimanite zone, and (4) Grt-Crd zone is garnet cordierite zone. The pressure-temperature conditions in metamorphosis increases from biotite, K-feldspar sillimanite, and then to garnet cordierite zones. K-feldspar cordierite zone is the range of contact metamorphosis that developed around granite that intruded afterward into the metamorphic zone. The result of metamorphic zoning is shown in the histogram on the right.

the distance that was in a vertical direction in schist of a geological columnar section created from field surveys roughly matched. That is, the result obtained showed that the direction perpendicular to schistosity roughly represented the gravitation direction at the time the metamorphic rock was formed. In the "Goyu" map, the crustal cross-section at depth of 20 km to 10 km of the Cretaceous period is exposed. At the same time, it was found that the crust at the time was of considerable high temperature such as 500 °C at depth of 10 km and 800 °C at depth of 20 km. We predicted such high-temperature crust was beneath the volcanic arc, and the formation of such high-temperature crust by latent heat transported by melts was demonstrated by a heat-advection model (Fig. 9(5) and Fig. 15). Such a heat-advection model could explain the production of migmatite that was distributed widely in the apparent bottom in this region, and we succeeded in comprehensively constructing the tectonic history of the geological structure of Ryoke metamorphic rock (Fig. 9(6)). By integrating field surveys and lab research, the geological map and tectonic history were constructed, and this was finally published as the 1:50,000 quadrangle geological map "Goyu"[7] (Fig. 9(7) and Fig. 16). The new

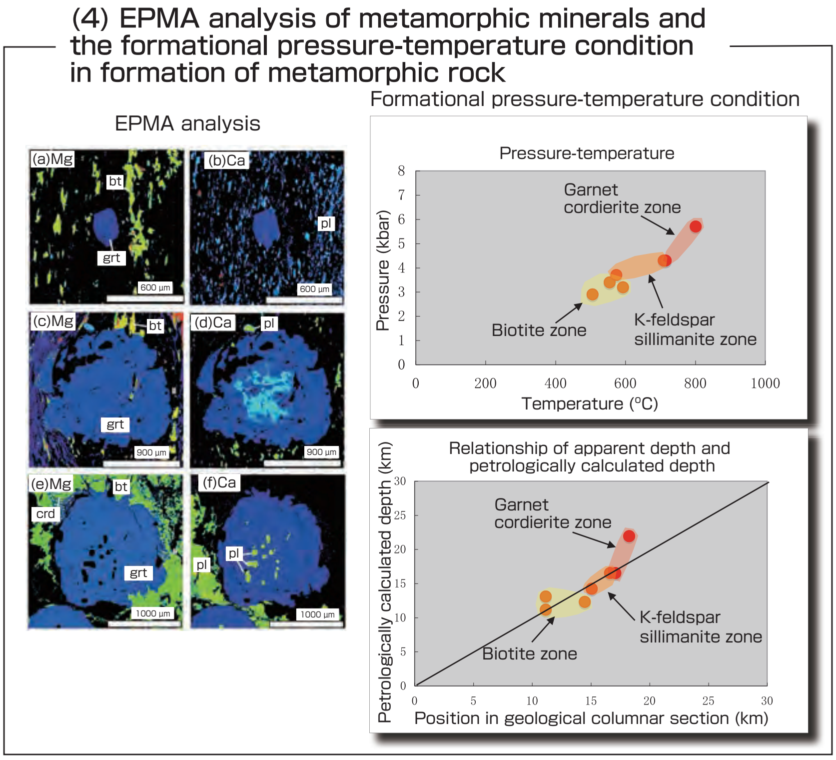


Fig. 14 Examples of EPMA analysis of metamorphic minerals and estimation of pressure-temperature condition in forming metamorphic rock in laboratory research (quadrangle geological map "Goyu")
Number in the title corresponds to the number in Fig. 9. The (a) and (b) on the left side show X-ray intensity maps by EPMA for Mg and Ca in garnet (grt), biotite (bt), and plagioclase (pl) of the biotite zone. (c) and (d) are X-ray intensity maps by EPMA for Mg and Ca in garnet (grt), biotite (bt), and plagioclase (pl) of the K-feldspar sillimanite zone. (e) and (f) are X-ray intensity maps by EPMA for Mg and Ca in garnet (grt), biotite (bt), and plagioclase (pl) of the garnet cordierite zone.

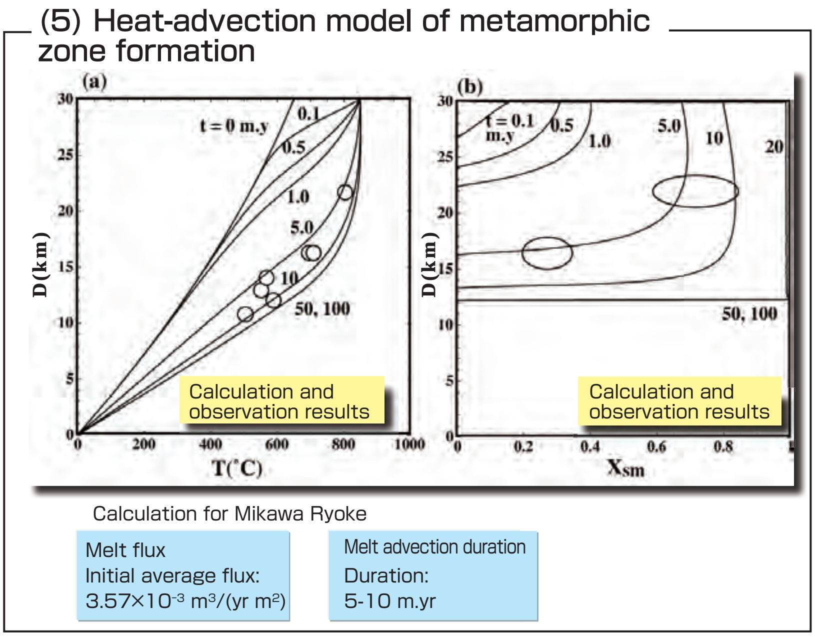


Fig. 15 Example of heat-advection model for formation of metamorphic zone (Ryoke metamorphic rock, Mikawa plateau) in laboratory research[8]
Number in the title corresponds to the number in Fig. 9. Refer to Reference [8] for details.

academic findings were published as research papers[8] (Fig. 9(8) and Fig. 16). This is an example of a scenario for the production of a 1:50,000 quadrangle geological map.

5 Future of 1:50,000 quadrangle geological mapping project

We looked back at the history of geological mapping projects at GSJ, and saw the transition of the general scenario. From Meiji to prewar periods, the objective was national coverage of geological maps by original geological surveys. Complete coverage by 1:200,000 detailed geological maps was achieved, whereas the project for 1:75,000 quadrangle geological maps was interrupted by WWII and then switched to the 1:50,000 quadrangle geological maps, and complete coverage was not achieved. After the WWII, geological map production based on original survey was carried over to 1:50,000 quadrangle geological maps due to the demand for precision and user's convenience. For the 1:50,000 quadrangle geological maps, there are 1,274 blocks to cover entire Japan, and it became realistically impossible to complete them in less than 100 years. Looking back at the history of the 1:50,000 quadrangle geological mapping project that has continued since the 1950s, concentrated efforts have been made in the region to Hokkaido. Since the 1980s or the period of specific geological maps, concentrated work limited to certain regions were conducted. What should be noted is that by clarifying the social mission of the concentrated production of geological maps by limiting to certain regions, the coverage of geological maps advanced. Since the establishment of AIST, the central role of the mapping project has been played by the nationwide coverage of the 1:200,000 quadrangle geological maps, the 1:200,000 Seamless Digital Geological Maps that consider user convenience, as well as the production of the next-generation version. These are obtaining a certain degree of success. That is, the users of the digital maps have increased significantly. In the next-generation 1:200,000 Seamless Digital Geological Map,[9] hierarchization and structuralization of the legends are conducted, enabling response to open data geological maps in the future. However, the number of quads published for the 1:50,000 quadrangle geological maps for which we conduct original surveys remain low in recent years (Fig. 5). Since the framework for a systematic geological mapping project is now in place, we are at a stage where a general scenario for the 1:50,000 quadrangle geological mapping project should be restructured. That is, considering that the mapping projects were planned and executed as long-term projects such as complete coverage of 1:200,000 detailed geological maps was planned for 12 years (actually 40 years were required), the complete coverage of 1:75,000 quadrangle geological maps was for 40 years (actually incomplete), and the specific geological maps was for 20 years, a general scenario must be set looking at a long-term of about 20 years. Moreover, to ensure the quality of the geological maps, individual scenarios for producing the 1:50,000 quadrangle geological maps are important. The individual scenarios depend heavily on the target regions. It may be difficult to harmonize all individual scenarios of the target regions and the general scenario. However, the geological mapping project is essential infrastructure information for the sustainable development of society in the future, and demand for complete national coverage of the 1:50,000 quadrangle geological maps is strong.[10] Although complete coverage is

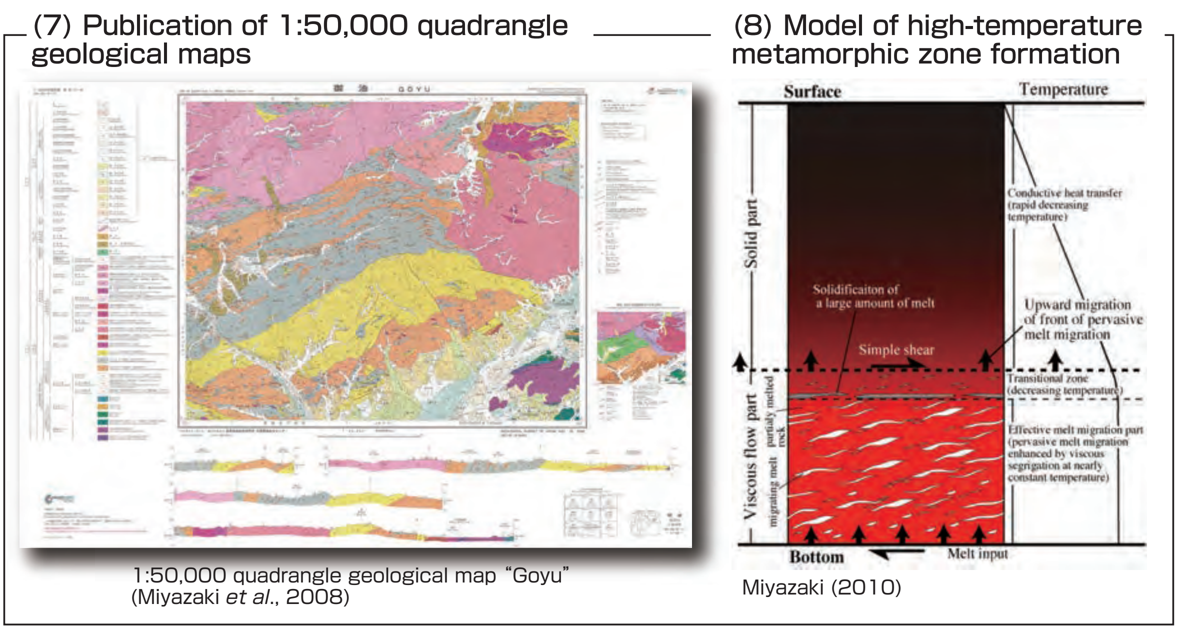


Fig. 16 Example of result of integration of field survey and laboratory research
Left: 1:50,000 quadrangle geological map "Goyu."[7] Right: Model of high-temperature metamorphic zone formation.[8]

not possible, we have perhaps entered the stage in which the general scenario for 1:50,000 quadrangle geological maps shall involve limiting the regions and giving them priority.

Terminologies

Term 1. Quadrangle geological map: Rectangular map sectioned by longitude and latitude in the north, south, east, and west directions. GSJ-AIST publishes the 1:50,000 and 1:200,000 quadrangle geological maps.

References

[1] Measurement Standards and Intellectual Infrastructure Division, Industrial Science and Technology Policy and Environment Bureau, METI: Chiteki kiban no katsuyo jireishu (Collection of Case Studies for Utilization of Intellectual Infrastructure), (2012) (in Japanese).

[2] M. Ogasawara and K. Ohi (eds.): Chishitsuzu no shakaiteki kachi—Beikoku chishitsu chosajo circular 111 (Nihongo hon'yaku ban) oyobi beikoku ni okeru chishitsuzu no keizaigakuteki hyoka no doko [Social value of geological maps—USGS Circular 111 (Japanese translation edition) and economic evaluation of geological maps in USA], *GSJ Interim Report*, 37, 66 (2006) (in Japanese).

[3] *Chishitsu Chosajo Hyakunen Shi* Editorial Board (ed.): *Chishitsu Chosajo Hyakunen Shi* (100 Year History of the Geological Survey of Japan), Geological Survey of Japan (1982) (in Japanese).

[4] M. Kawai: Chishitsu zufuku jigyo no rekishi to genjo (History and current situation of geological map project), *Chishitsu News*, 220, 2–37 (1972) (in Japanese).

[5] H. Kato: Sengo (Showa 30 nendai zenki) chishitsu chosajo shi hoi [Supplement of history of GSJ in post-war period (late 1950s)], *GSJ Chishitsu News*, 6, 12, 390–395 (2017) (in Japanese).

[6] N. Yamada, K. Miyazaki, C. Kurimoto and H. Kato: Completing the 1:200,000 Quadrangle Geological Map for Japan, *Journal of Geography*, 121 (3), N29–N41 (2012) (in Japanese).

[7] K. Miyazaki, Y. Nishioka, R. Nakajima and M. Ozaki: Goyu chiiki no chishitsu (Geology of Goyu region), *Chiiki Chishitsu Kenkyu Hokoku (5 Man Bun No 1 Chishitsu Zufuku)* [Regional Geological Research Report (1:50,000 Quadrangle Geological Map)], GSJ-AIST, 97 (2008) (in Japanese).

[8] K. Miyazaki: Development of migmatites and the role of viscous segregation in high-T metamorphic complexes: Example from the Ryoke Metamorphic Complex, Mikawa Plateau, Central Japan, *Lithos*, 116, 287–299 (2010).

[9] Seamless Digital Geological Map of Japan Editorial Board: Seamless Digital Geological Map of Japan (1:200,000) Version 2, https://gbank.gsj.jp/seamless/v2.html, accessed 2018-01-25 (in Japanese).

[10] GSJ: Chishitsu jiban joho ni kansuru chosa—Chishitsu chosa kigyo anketo kekka Heisei 26 nendo (Survey on the geological infrastructure information—Results of questionnaire survey to geological survey companies, FY 2014), GSJ-AIST (2015) (in Japanese).

[11] R. Nakajima, N. Hori, K. Miyazaki and Y. Nishioka: Toyohashi oyobi Tawara chiiki no chishitsu (Geology of Toyohashi and Tahara regions), *Chiiki Chishitsu Kenkyu Hokoku (5 Man Bun No 1 Chishitsu Zufuku)* [Regional Geological Research Report (1:50,000 Quadrangle Geological Map)], GSJ-AIST, 113 (2008) (in Japanese).

[12] R. Nakajima, N. Hori, K. Miyazaki and Y. Nishioka: Irago-misaki chiiki no chishitsu (Geology of Irago-misaki region), *Chiiki Chishitsu Kenkyu Hokoku (5 Man Bun No 1 Chishitsu Zufuku)* [Regional Geological Research Report (1:50,000 Quadrangle Geological Map)], GSJ-AIST, 69 (2010) (in Japanese).

Author

Kazuhiro MIYAZAKI

Completed the master's course at the Department of Geology, Graduate School of Sciences, Kyushu University in 1987. Joined the Geological Survey of Japan, Agency for Industrial Science and Technology, Ministry of International Trade and Industry in 1987. Participated in the production of geological maps for metamorphic rock regions, with research topics of progression of metamorphism and formation of metamorphic belt in the subduction zone and deep volcanic arc. Doctor of Science, Kyushu University in 1994. Research group leader since 2005. Project leader for the production of 1:50,000 and 1:200,000 quadrangle geological maps, and leader of the terrestrial geological mapping project for Seamless Digital Geological Map, for five years since 2007. Deputy Director, Institute of Geology and Geoinformation, AIST in 2007. Council Member, Commission for the Management and Application of Geoscience Information, International Union of Geological Sciences (IUGS-CGI) from 2012. Specialty is petrology.

Discussions with Reviewers

1 Overall

Comment (Masahiko Makino, AIST)

It is significant that you discuss the scenario for the geological mapping project by reviewing the 135-year history since the establishment of the Geological Survey of Japan. This paper describes the process by which GSJ was established to produce geological maps necessary for economic development as basic information of our country, presents the scenario on which the geological maps were produced with increasing scale, from 1:200,000, 1:75,000, and 1:50,000, according to the demand of society at the time, and also explains how such maps were used in society. The high quality and high precision geological maps have provided major benefits to society as the basis of infrastructure construction, location planning, resource development, and disaster mitigation.

In field surveys, a hypothesis is set up about the geological structure of a certain area, it is verified and corrected through field surveys, and the precision of the geological map is increased by repeating this work. New academic findings obtained through geological map production are published as research papers. For example, in the 1:50,000 quadrangle geological map "Goyu," it was found that the crust during the Cretaceous period was of considerable high temperature of 500 ºC at 10 km depth and 800 ºC at 20 km depth, and it was clarified that such high-temperature crust may be formed by latent heat transported by melts under the volcanic arc through research of the heat-advection model.

These findings were published as research papers. The geological map and the tectonic history are constructed by integrating field surveys and lab research.

Such geological mapping projects are important as basic information of our country, and I think it is appropriate for publication in *Synthesiology*.

Comment (Toshihiro Matsui, Institute of Information Security)

The paper overviews the history of the development of geological maps in Japan, and describes the method of precise map development using examples of certain regions. I am impressed with the author's continuous efforts in the geological mapping project. As a paper for *Synthesiology*, I am interested in how such geological maps have contributed to the safety of Japan and innovations in Japanese industry. While innovation is often discussed as creation of new ideas, I feel that the continuous accumulation of knowledge by the author and others served as the background of "changes."

2 Objective of quadrangle geological mapping project

Comment (Masahiko Makino)

You describe AIST's medium-term plan in the general scenario, but you do not mention the Intellectual Infrastructure Project of the government that is the basis of the AIST plan. You also do not mention that the scale of the Seamless Digital Geological Map is 1:200,000, and this may cause it to be confused with the 1:50,000 maps.

If you provide images of the geological maps of different periods, I think people will better understand the historical transition and development of the contents.

Answer (Kazuhiro Miyazaki)

I added a text about the geological mapping project after reorganization to AIST and the government's Intellectual Infrastructure Project. I also added explanation about the scale of the Seamless Digital Geological Map. I also explained that there was a social demand for complete national coverage of the geological maps, and that the objective had been complete national coverage up to the 1:75,000 quadrangle geological mapping project. Although there is social demand for complete national coverage by 1:50,000 quadrangle geological maps that is the main subject of this paper, realistically this is difficult. In the 1:50,000 quadrangle geological mapping project that started after WWII, concentrated effort was made on specific regions such as Hokkaido and specified observation regions for earthquakes. As you commented, I added the comparison of the 1:200,000 detailed geological maps and the current 1:200,000 quadrangle geological maps. The former is the geological maps published in 1884, and the latter those published in the 2010s. I think this shows the development of the contents during the period in between.

Comment (Toshihiro Matsui)

This is a very interesting paper to overview the history of geological map development in Japan. However, the history is stated too simply, and there is lack of *Synthesiological* expression about why the geological maps were made and what kinds of innovation they generated. You simply mention resource development and land safety, but the value of maps is not quite understood by your simply mentioning that the importance was proposed in a document at that time. Currently, the topological maps are generating great innovative values in the applications of the Internet, car navigation, and smart phones. Do geological maps have the power to bring about such innovation? This is also a question about what the goal of the scenario of the geological mapping project is that you mention in the subtitle. The goal does not have to be specific innovation. I mean, intellectual infrastructure is not something that has a narrow purpose. Please explain how the geological maps will provide rich "infrastructure" for industry and society.

Answer (Kazuhiro Miyazaki)

I added a text about specific case studies of how the geological maps are used. Although difficult, I think innovation using the geological maps is possible. Related to it, I added "2 Role of the geological maps in society." I stated that producing and using high quality and high precision geological maps are beneficial for the whole society. Like this example, I think it is possible to generate innovation that brings benefit to society by producing high quality and high precision geological maps.

3 Explanation of geological maps

Comment (Toshihiro Matsui)

You explain two types of geological maps: one based on the geological field survey and laboratory research, and the other made by compiling existing materials. Is the geological map produced by original survey the former? This part is unclear. If this difference is important, please show the actual example of two types of maps and explain their differences.

Answer (Kazuhiro Miyazaki)

The 1:50,000 quadrangle geological map shows the geology in the range of east-west 24 km x south-north 19 km, and it includes the geological cross-section diagram to about 500 m underground. It is published along with a research report that is 70 to 100 pages long. The research report describes the detailed information about the strata and rocks. As explained in this paper, for one quad or sheet of 1:50,000 quadrangle geological maps and its report, about 250 days of field survey is done, and about three to five years of research is necessary including the laboratory experiments. The 1:200,000 quadrangle geological map covers the area equivalent to 16 sheets of 1:50,000 quadrangle geological maps, and it is suitable for knowing the overall regional geology.

Question & Comment (Toshihiro Matsui)

What kind of survey, observation, and estimation are done, and which takes up most of the cost in the production of geological maps? At the same time, from both the aspects of use and production of geological maps, please explain the meaning of scale, particularly the meaning of "1:50,000" that is in the title. How do you evaluate precision? I think you should also compare the production method for global topological maps that can be made by satellite photos, against the three-dimensional geological maps for which you conduct boring. Also, I think maybe you should address the changes in the map of Japan from the Meiji to the Showa periods. (Is the geological map with larger scale more detailed or rougher? Please make this point clear so people will not make mistakes.) You write about the method of producing geological maps in Subchapter 4.2. What kind of industrial and social value can be created from the findings obtained there?

Answer (Kazuhiro Miyazaki)

In the production of 1:50,000 quadrangle geological maps, field survey consumes the most time. The meaning of scale was described in "2 Role of geological maps in society." Locational precision and accuracy of geological strata and rock category increase as the production date of the map is more recent and with larger scale. The social benefit using more accurate maps will also increase. The choice of scale is a matter of cost and time required for production, but the industry demands for the 1:50,000 quadrangle geological maps. Faults and lithofacies boundaries are displayed accurately on the geological maps according to JIS. The 3D geological map is important in understanding the geology of the plane area where strata are deposited almost horizontally. Currently, there is a project in progress that involves the production of geological maps for the metropolitan area. Large scale means more detail, while small scale means roughness. As it can be seen in Fig. 4, the geological map progresses from small to large scale with time.

Question (Toshihiro Matsui)

Why is the mapping of "uniform" geological maps that cover the whole country set as an important strategy? What kind of value will arise by completely covering the country? In the initial objectives for geological maps, there seem to be regions that are important and regions that are not. In "3.4 1:50,000 quadrangle geological map after reorganization to AIST," it is written that the plan to produce geological maps of specific regions was terminated after reorganization to AIST, but before that, were there objectives other than for coal resource exploration in Hokkaido?

Answer (Kazuhiro Miyazaki)

I added a new chapter "2 Role of geological maps in society," and stated that high quality and high precision geological maps will be beneficial to society. If you look at the historical transition in Fig. 4, you can see the progressive achievement of high quality and high precision, starting with the completion of 1:200,000 detailed geological maps, 1:75,000 quadrangle geological maps, and the current 1:50,000 quadrangle geological maps. There was a scenario for concentrated effort to produce maps for the Hokkaido region during the postwar recovery period, and the maps for specific earthquake observation areas in eight regions throughout Japan after 1979 up to the reorganization to AIST.

Traditional craftwork that can be washed with a dishwasher, "nanocomposite *tamamushi-nuri*"

—Expansion from exhibits to daily necessities—

Takeo EBINA[1*], Midori SAURA[2] and Yasukatsu MATSUKAWA[2]

[Translation from *Synthesiology*, Vol.11, No.2, p.69–80 (2018)]

We developed highly durable lacquerware by applying a protective layer in which resin and clay were mixed on the surface of the lacquerware. The components of the protective layer were selected from the viewpoints of dispersibility in a solvent, transparency of the layer, and hardness of the layer. It was confirmed that even after repeated washing with a dishwasher, the color, gloss, and surface flatness of the protective layer resisted deterioration. We optimized the paste viscosity, spray blowing pressure, and number of coatings to establish a method of giving a protective layer to products. In addition, we examined designs and productivity, considered user ratings, and created a product that exhibited the above-mentioned superior characteristics.

Keywords **:** Lacquerware, *tamamushi-nuri*, clay, nanocomposite, hard coat

1 Introduction

1.1 Goal of research

The goal of the research is to develop lacquerware with excellent abrasion resistance, UV resistance, and dishwasher resistance and its manufacture method, by adding a protective layer containing clay on top of the *tamamushi-nuri* coat, to improve the durability of *tamamushi-nuri*, a traditional craft. Moreover, the coating method is investigated and a product with the aforementioned excellent characteristics is created.

1.2 Research goal and relationship to society

The *urushi* lacquerware manufacturing technology represents the high level of Japanese manufacturing since ancient times, and is highly evaluated overseas. In general, it involves woodwork and coating with plant-derived resin that requires no heating, and it is also recognized as manufacturing technology with a low environmental load. Lacquerware includes bowls, tableware, and artistic objects, but it is not expected to be used in dishwashers that require durability at a wide temperature range. Lacquerware does not have abrasion resistance, UV resistance, or durability. Therefore, attempts were made to increase the durability by coating and other methods.[1] In this research, the characteristics are enhanced by adding a transparent protective layer containing clay, thereby adding value to the craft.

The *tamamushi-nuri* (jewel beetle coating) is a traditional craft designated by the Miyagi Prefecture.[2] This research aims to develop next-generation lacquerware by matching the traditional *tamamushi-nuri* and clay film, an innovation of AIST. While passing down the Japanese traditional craftwork technology, it also attempts to create innovation through companies that were affected by the earthquake and tsunami of 2011. Also, this research achieves high functionality of a traditional craft, in the field of chemical manufacturing, as high functional materials and parts, and attempts are made to apply the innovative technology to fields and products that were conventionally considered impossible.

2 Scenario for development of high-durability lacquerware

The *tamamushi-nuri* consists of undercoat, midcoat, semitransparent layer containing silver powder, and then a semitransparent topcoat containing dyes (Fig. 1).[3] For undercoat, midcoat, and topcoat, *urushi* (natural resin collected from Japanese lacquer trees), cashew, or urethane coats are used according to the product usage. When incident light passes through the topcoat that contains a dye, light is scattered by silver powder and then passes through the topcoat again, and depending on the type of dye, a characteristic deep appearance is exhibited according to the reflected light with red, green, blue, or black colors. However, lacquerware has low surface hardness, and it is about F in the pencil hardness test[1] (a general hardcoat layer is 3H or higher).

On the other hand, AIST possesses material technologies for mixing organic and inorganic materials such as clay at nanolevel.[4]-[6] In this research, this technology is applied to the surface protective layer, to create traditional craft products with excellent durability. The composition of the proposed new *tamamushi-nuri* is shown in Fig. 1.

1. Research Institute for Chemical Process Technology, AIST 4-2-1 Nigatake, Miyagino-ku, Sendai 983-8551, Japan ∗ E-mail: takeo-ebina@aist.go.jp, 2. Tohoku Kogei Co., Ltd. 3-3-44 Kamisugi, Aoba-ku, Sendai 980-0011, Japan

Original manuscript received March 5, 2018, Revisions received April 27, 2018, Accepted May 1, 2018

To incorporate the desired function, the following composition can be considered as the fine structure (Fig. 2). With clay being evenly distributed as fine particles in a film, it is possible to make a highly transparent coating film.[7] As for nanocomposite hardcoat agents, it has been reported that abrasion resistance increases when the particle size is 1 μm or less.[8] Also, there is a stabilizing effect for unstable molecules adsorbed on clay crystals.[9] Therefore, we expected that high UV resistance could be achieved by increasing the stability of UV absorbers by adding UV absorbers to the clay.

Tohoku Kogei Co., Ltd. has conventionally used brush-coating on lacquerware, but around 1955, it started using spray-coating for the first time on traditional lacquerware. Currently, it uses spray-coating on products with various shapes such as glass, vase, plate, and others. Expert skill is required to apply even coating to the entire surface of products with complex shapes, and the coating technology based on long experience accumulated by Tohoku Kogei was utilized in this development. This development was achieved after the material composition was ultimately determined for the balance between beauty and coating condition of *tamamushi-nuri*, and after repeated lab investigations at AIST and sample coating at Tohoku Kogei.

3 Development of high-durability lacquerware

3.1 Design of protective layer

As the protective layer of *tamamushi-nuri*, three types were considered including the organic, inorganic, and organic-inorganic composites, and initial evaluations were conducted by selecting candidate materials from each category. When candidates for the organic material including acrylic resin and others were used, we were unable to realize surface hardness of 3H that was our goal, although the paste had excellent long-term stability. Next, silica coating, an inorganic material, was considered, and surface hardness 3H was obtained with room temperature processing only. However, the disadvantage was poor stability of the paste. Therefore, we decided to achieve a protective layer using organic-inorganic composite materials that have the stability of organic materials and high surface hardness of inorganic materials. For organic-inorganic composite materials, high-temperature treatment is normally conducted to increase water resistance. However, some base materials for *tamamushi-nuri* do not have heat resistance, and *tamamushi-nuri* itself is not heat resistant, and therefore the heating process cannot be used. Therefore, we used UV curing resin in which hardness could be attained without heating, and the aim was to obtain high hardness with room temperature processing only by adding clay. The characteristic diagram for the development of high-durability lacquerware is shown in Fig. 3. There was a case in which UV curing resin was used in a polymer clay composite material, but the transparency was reduced when the amount of clay added

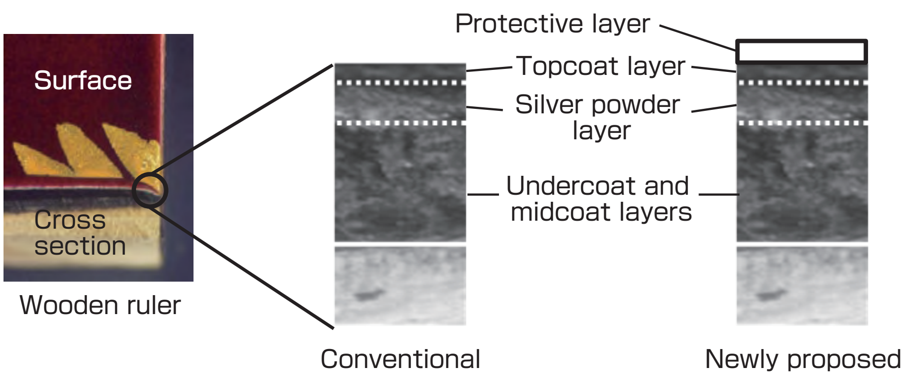


Fig. 1 Structure of conventional *tamamushi-nuri* and structure of newly proposed *tamamushi-nuri*

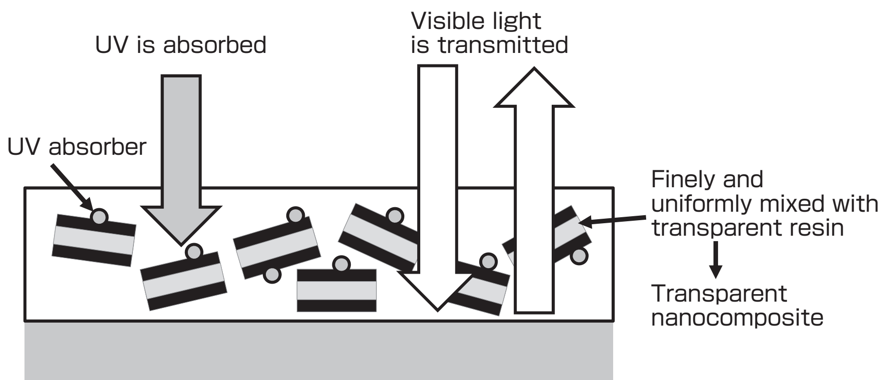


Fig. 2 Expected internal structure of protective film and its optical property

Table 1. Organoclay and organification agents used

Clay (product name)	Organification agent	
	Component name	Carbon number
SPN	Polyoxypropylene methyldiethyl ammonium chloride	75
STN	Methyltrioctyl ammonium	8
SAN	Dimethyldistearyl ammonium	18
SAN316	Dimethyldistearyl ammonium	18

Table 2. Average values of the particle size of organoclay in organic solvent and haze value of glass coat samples

Clay	Average value [nm]	Standard deviation [nm]	Haze value [%]
Glass plate	−	−	0.41
SPN	8.8×10^2	9.2×10^2	21.3
STN	1.1×10^3	6.4×10^2	68.6
SAN	1.9×10^4	2.9×10^4	42.3
SAN316	1.9×10^4	3.4×10^4	23.4

(Particle size is from histogram analysis; thickness of glass plate is 1 mm.)

increased to 5 wt%.[10] It was found that high transparency could not be obtained unless the solvent, clay, and resin were carefully selected and an optimal combination was found. To form a coating that adhered firmly to the *tamamushi-nuri* surface without peeling off, a solvent, clay, and resin were selected, the mixture ratio was optimized, and the mixing method was investigated.

3.2 Selection of the nanocomposite protective layer ingredient

For even distribution of clay in resin, organification is conducted in which sodium ions between the clay layers are replaced by organic cations.[11] Since dispersibility in resin changes according to the type of organic cations used, the selection of organic cations is important. Here, we investigated four types of organoclay using different organic cations (Table 1). First, four types of organoclay were dispersed in toluene, an organic solvent that was initially considered, and the dispersibility was evaluated. The solid to liquid ratio of the toluene dispersion was 0.1 wt%. The particle size distribution was measured using a fiber-optical dynamic light scattering spectrophotometer (FDLS-2000; Ohtsuka Electronics Co., Ltd.). The result is shown in Table 2. In the histogram analysis, the average values of SPN and STN were small, while those of SAN and SAN316 were large.

Next, about 0.3 g of toluene dispersion of four types of synthetic clay (5 wt%) was placed on a glass plate with thickness of about 1 mm, the dispersion was spread out to about 3 × 3 cm in size, and this was dried at room temperature. The haze values of the dried glass plates were measured using a haze meter (NDH5000; Nippon Denshoku

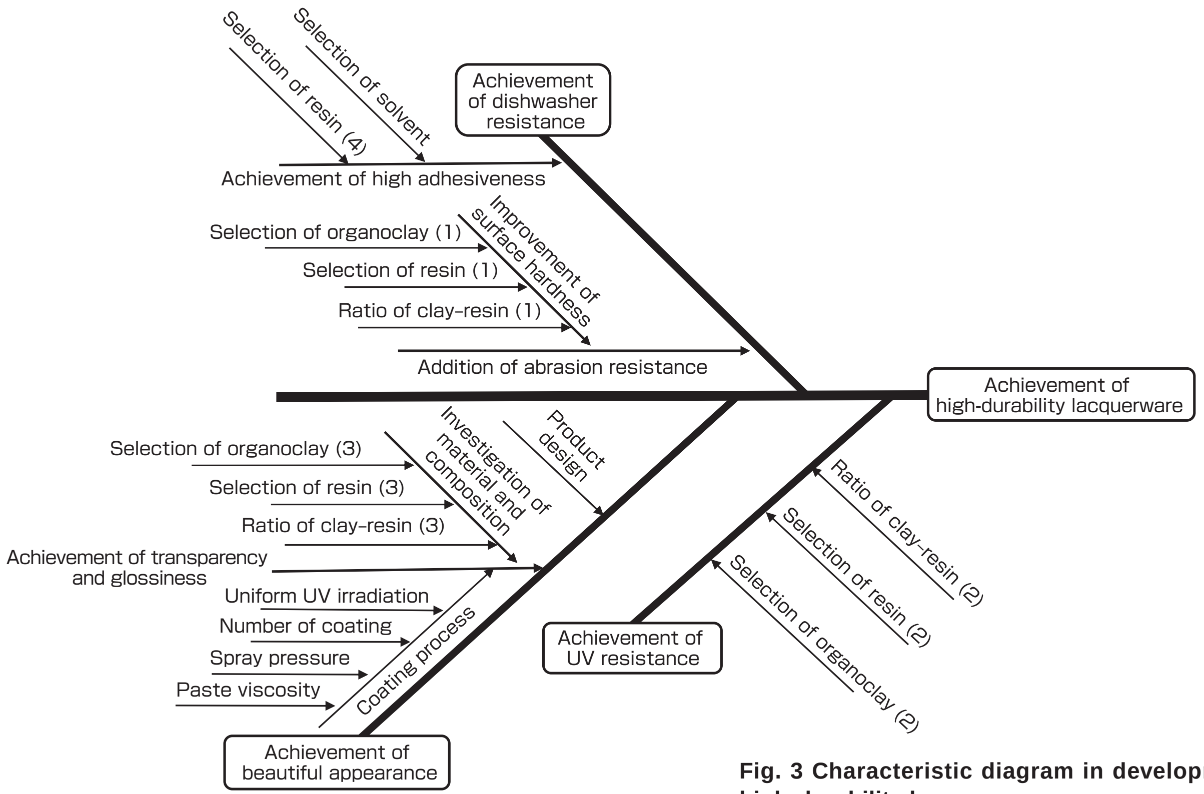


Fig. 3 Characteristic diagram in development of high-durability lacquerware

Industries Co., Ltd.). The haze values were small in the order of SPN, SAN316, SAN, and STN. A small haze value indicates that the light does not scatter and the appearance is clear, and this is desirable.

From the above result, it was found that SPN that had the most carbon number among the organification agents dispersed most finely in the dispersing liquid and haze was low for the glass coated film. Therefore, we decided to use SPN as the clay.

For UV curing resin, we selected three candidates, UV-7605B, UV-7640B, and UV-1700B (all of The Nippon Synthetic Chemical Industry Co., Ltd.) that have catalog value pencil hardness of 3H or more that was the goal value of this research. These are urethane acrylate resin, and the molecular weight/number of oligomer functional group for UV-7605B, UV-7640B, and UV-1700B are 1100/6, 1500/6-7, and 2000/10, respectively. The method for adding the protective layer using these types of resin is shown in Fig. 4. This involved mixing UV curing resin, toluene, clay, and a photopolymerization initiator at a certain ratio into a paste, applying an even paste to a glass slide or to *tamamushi-nuri* using a bar coater, and allowing polymerization to take place in the UV curing device.

For the solvent, toluene was used since it was suitable for the selected SPN. Here, the weight ratio of resin and toluene was unified to 30:70. Since clay thickened the paste, coating was not possible if there was excessive clay, as that increased viscosity. Therefore, we studied the relationship between the amount of clay that could be added to the paste and the viscosity of liquid. Specifically, the paste viscosity was studied by changing the amount of organoclay added to UV-7605B, and the procedures were as follows. First, 30 g of resin was dispersed in 70 g of toluene. Then, a weighed amount of SPN was put into a screw cap bottle, and the bottle was shaken until the clay was dispersed. When the paste was made using the above method, we could make the mixture only up to 25 g of added SPN, and the liquid became immobile when the amount of SPN reached 30 g (Fig. 5). Since UV-7605B had the lowest molecular weight among the three types of resin, it was thought to have low viscosity. Therefore, it was found that the percentage of additive organoclay that could be shaken was up to 25 g for 30 g of resin and 70 g of toluene. Here, from the perspective of ease of handling, the paste was made with 21 g of SPN added.

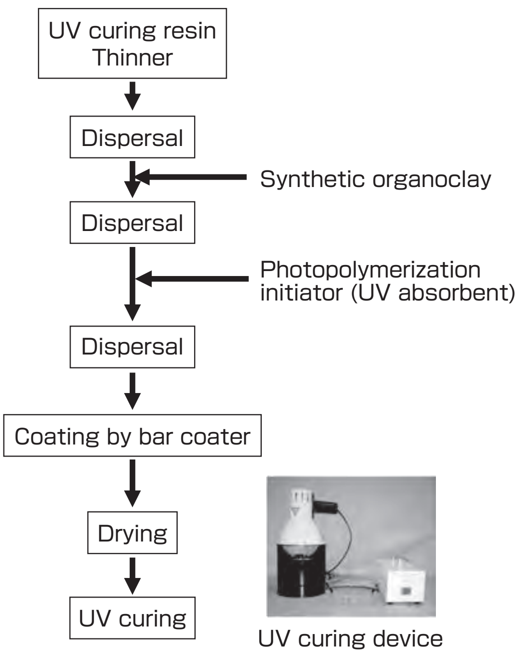


Fig. 4 Preparation procedure of protective layer

The UV visible absorption spectra of the protective layers on the glass slides are shown in Fig. 6. It was found that the protective layers had no absorption in the visible light range. Also, it was confirmed that when resin and clay coexisted, the absorption peak of the UV absorber shifted remarkably to the long wavelength side. This is a phenomenon that is observed when the concentration of the UV absorber is high, and it indicates that the UV absorber was concentrated and attached onto the clay surface. Also, as the absorption shifted to the long wavelength side, the UV blocking effect of the protective layer increased, and increased UV resistance of the lacquerware was expected.

In the hardening experiment of the protective layer on a glass slide, it was confirmed that UV curing occurred even when the solvent was toluene or a thinner (mixture of toluene, xylene, and others) used at Tohoku Kogei (dried thickness of about 10 μm). At Tohoku Kogei, an *urushi* bath[12] is used for drying, and it was checked whether drying was possible without heat. An *urushi* bath is a wooden shelf with no particular temperature control. *Urushi* lackerwares gradually dry and harden as they are placed in the *urushi* bath. According to the experiment at AIST, the drying process that normally took 3 min at 60 ºC could be replaced by 1 hour at

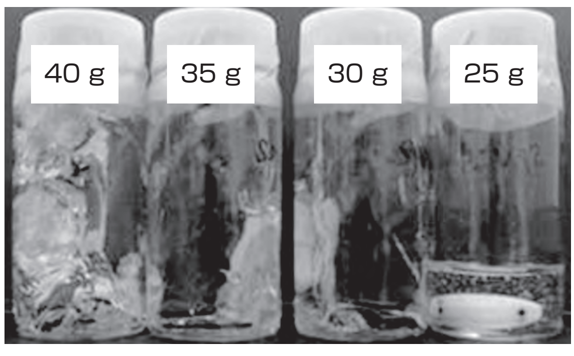


Fig. 5 Amount of organoclay added and the condition of liquid

The numbers in the figure show the amount of SPN added to 30 g. of resin. *From Abstracts of 58th Annual Meeting of the Clay Science Society of Japan,* A6 (2014).

room temperature. Through this finding, it became possible to conduct drying by placing the products in an *urushi* bath within a clean environment, without taking them to a drying oven outside the clean environment where spray-coating was done, and dust adherence could be avoided.

3.3 Evaluation method and results

3.3.1 Evaluation of transparency

With the configuration of 30 g of resin, 70 g of toluene, 0 to 40 g of SPN, and 6 g of initiator, the protective layer was applied to a glass slide with a bar coater, and the transparency was evaluated. Cissing occurred in the coats that did not contain SPN, and samples could not be made. The total light transmittance and haze of the film applied to the glass were measured (Figs. 7 and 8). In Fig. 7, it is shown that the total light transmittance of the film surpassed 90 %, which was our target value, regardless of the amount of added clay, and the transparency was sufficient. In Fig. 8, it is shown that haze was 0.6 or higher and 1.8 or lower, and the lowest value was obtained when the amount of clay added was between 20 to 30 g.[13] From this result, it was shown that sufficiently high total light transmittance could be obtained when the amount of clay added was in the range of 5 to 40g.

3.3.2 Evaluation of surface hardness

The protective layer made from the samples of aforementioned paste applied to glass with a bar coater was evaluated for abrasion resistance using the pencil hardness test (JIS K5600). As a result, UV1700B failed to reach 3H that was our target. On the other hand, it was found that UV7640B and UV7605B achieved hardness of 3H or higher.[13] It is thought that resin gains higher hardness with more oligomer functional groups, but in the clay-resin mixture, it is thought that there is an optimal molecular weight as well as amount of oligomer

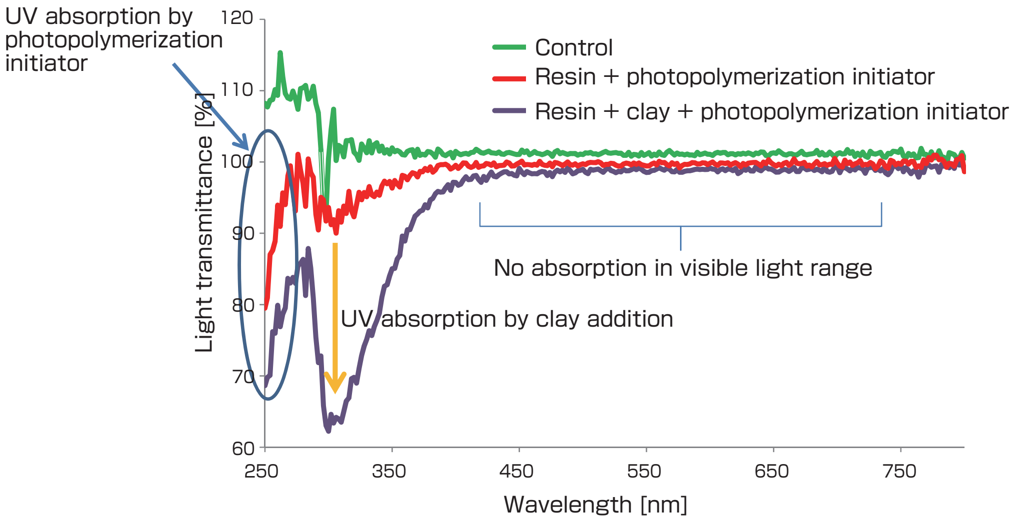


Fig. 6 UV-visible absorption spectra of protective film

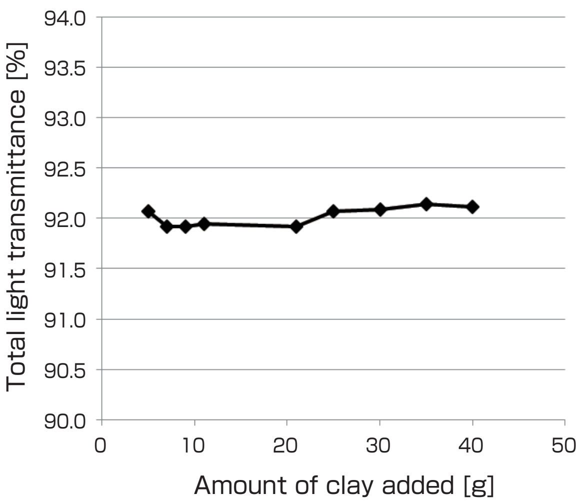


Fig. 7 Relationship between amount of clay added and total light transmittance

From *Abstracts of 58th Annual Meeting of the Clay Science Society of Japan*, A6 (2014).

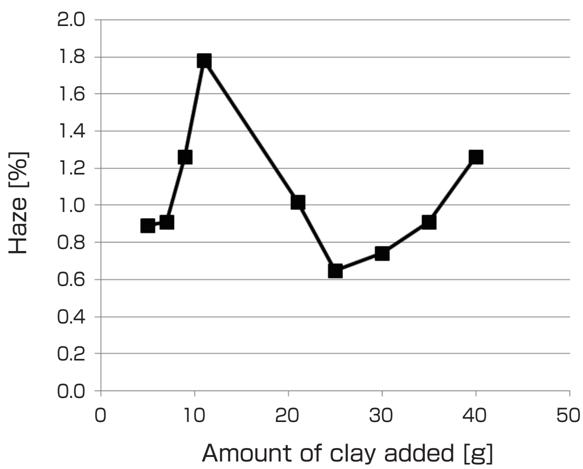


Fig. 8 Relationship between amount of clay added and haze

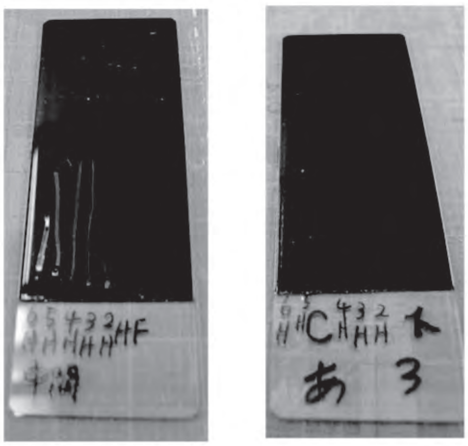
From *Abstracts of 58th Annual Meeting of the Clay Science Society of Japan*, A6 (2014).

function groups. The amount of the initiator was set at 6 g that allowed sufficient hardness. For resin, since the viscosity of UV7640B was much higher than that of UV7605B, and there was the problem that UV7640B had to be diluted with more solvent during spray coating, we decided to use UV7605B.

While no problem was encountered during film forming with a bar coater, we were unable to obtain sufficient gloss when a solvent was added for the purpose of decreasing viscosity during spray-coating. This occurred as unevenness formed on the surface due to low leveling of paste with high clay content. It was possible to decrease the viscosity by reducing the amount of clay added, and the amount of 7 g, 3 g, and 1.5 g of added clay were investigated, and it was confirmed that the leveling property improved with those compared to 21 g.

The organoclay was selected from the haze value and dispersibility. The relationship between viscosity and amount of added organoclay was checked, and the visible light absorption property, transparency, spray-coatability, and leveling property were evaluated. In the subsequent film forming evaluation, we used the evaluation with 3 g of added clay (for 30 g of resin).

In the case in which 3 g of SPN was added to 30 g of resin, the result of evaluation using pencil hardness as surface hardness is shown in Fig. 9. The samples are all black *tamamushi* layers (urethane resin) on glass slides spray-coated with the protective layer. Pencil hardness was from 4H to 5H, and sufficient surface hardness of 3H or higher that was our target value was obtained (Fig. 9 right). On the other hand, the black *tamamushi* surface with no protective layer had pencil hardness F (Fig. 9 left). As shown above, sufficient improvement in abrasion resistance was seen by applying the protective layer. Coats of *tamamushi-nuri* use cashew or urethane in most cases. Since urethane was already evaluated for the black color, we conducted tests for the samples in which cashew resin (red color) was coated on the glass slide. The pencil hardness of cashew resin was determined to be HB, and it was somewhat softer compared to pencil hardness F of urethane (Fig. 9 left). When a protective layer equivalent to Fig. 9 was applied to cashew resin, it was confirmed that the surface hardness improved to 3H. It was found that the protective layer increased the hardness of both the urethane and cashew surfaces.



No protective layer; F　With protective layer; 4H

Fig. 9 Result of pencil hardness test

3.3.3 Evaluation of dishwasher resistance

There was no standard method for evaluating dishwater resistance. Therefore, washing using a dishwasher was repeated a set number of times, evaluation test was done before and after, and the goal was to find the least change. The evaluated items were color, gloss, and surface flatness.

First, a dishwasher (NP-TR6; Panasonic Corporation) was set in the AIST lab. Washing was done in a standard course, including sterilizing mist, washing, and rinsing processes. To reduce time, drying was not done. The washing temperature was set to about 70 ºC. The washing time per cycle was about 30 min. The detergent used was Charmy Crysta Clear Gel (Lion Corporation). A sample was made by applying black *tamamushi* and others on a glass, and then spray-coating a protective layer consisting of 30 g of resin, 70 g of toluene, 3 g of SPN, and 6 g of initiator (there were three *tamamushi-nuri* thicknesses: thin, medium, and thick). These were placed in the dishwasher 20, 60, and 100 times, the samples were taken out, and changes in color compared to the start were measured using a color difference meter (Fig. 10). A smaller figure for color difference ΔE*ab showed that the before-after color difference was small. When there was no protective layer, the color difference after 100 wash cycles was on average 0.97, and with a protective layer, it was 0.76. The figure 0.97 is categorized as AA level tolerance[14] or the "level in which some color difference can be seen in side-by-side color comparison." On the other hand, 0.76 is AAA level tolerance or the "limit at which strict color tolerance can be set from the viewpoint of reproducibility of visual determination." After 100 wash cycles, there was no case

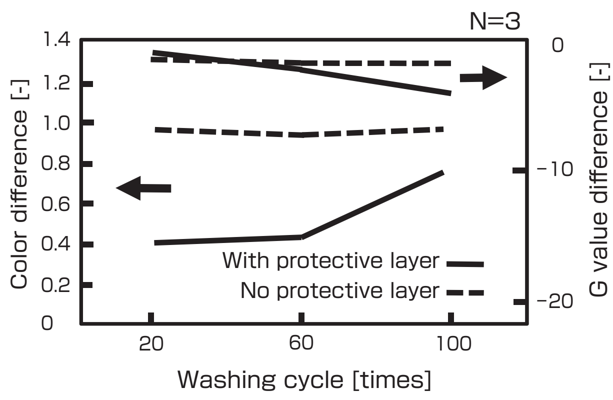


Fig. 10 Color difference and G value difference before and after dishwasher test

where the color difference was 1.6 or higher, that is, a level tolerance or the “level in which one can hardly detect any difference in color comparison from a distance.” From this result, it was found that the protective layer did not undergo discoloration even with repeated washing with a dishwasher.

“G value” that is the measurement of “gloss” was evaluated as part of the evaluation of appearance. G value is calculated by subtracting the value of specular component exclude (SCE), that does not include specular reflection light, from the value of specular component include (SCI) that includes specular reflection light.[15] Larger value indicates higher gloss. The G value was measured with a spectrophotometer (CM-2600d; Konica Minolta Japan, Inc.). The angle of incidence was 8 degrees. The measurement values of samples with a protective layer added to black *tamamushi* were between 98 and 99. When the G value is around 100, it is equivalent to glossy plastic, and it was found that the surface was shiny. The changes in G value were measured before and after the dishwasher test. All samples showed a trend of slight reduction in G values after dishwashing. In the case without the protective layer, the difference was 2, and in the case with the protective layer, the difference was 4 (Fig. 10). Although the value was slightly larger when there was a protective layer, the change was almost unnoticeable in terms of appearance.

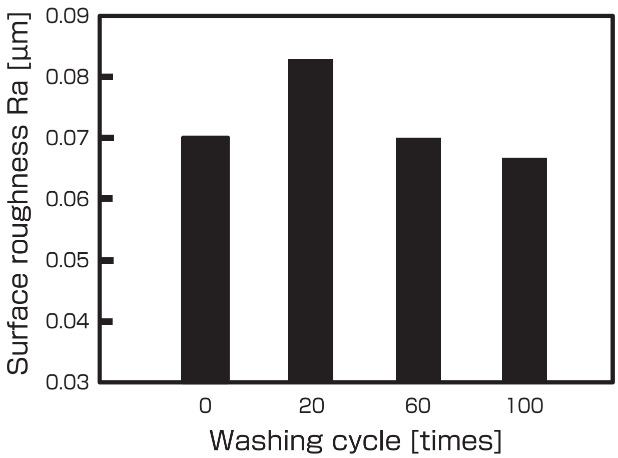


Fig. 11 Relationship between washing cycle and surface roughness

Next, the surface roughness Ra value was measured using a laser microscope (Keyence Violet Laser Color 3D Profile Microscope VK-9500; Keyence Corporation). Figure 11 shows the relationship between the number of wash cycles and surface roughness. The surface roughness ΔRa of the coating layer before washing was between 0.07 and 0.08 μm, and it was between 0.09 and 0.06 μm after washing. The increase in surface roughness by washing was not confirmed. As seen above, by the addition of the protective layer, it was confirmed that there was almost no deterioration of color, gloss, or surface evenness.

3.3.4 Evaluation of UV resistance

For UV irradiation, Handy Cure Lab (HLR100T-2; Sen Lights Co., Ltd.) was used (intensity 12,000 μW/cm^2, wavelength 365 nm). Setting the distance from the light source to the sample at about 10 cm, irradiation was done for 1 to 5 hours, and the color change in the sample was evaluated using a color difference meter. From the illumination measured using an illuminometer under this condition and the annual average value of irradiation in Tsukuba,[16] it was calculated that one hour irradiation was comparable to the irradiation dose for 2.6 years in a room.

Samples consisted of three types of *tamamushi-nuri* postcards: no protective layer; protective layer with SPN; and protective layer without SPN. These were irradiated with the UV light at the same time, left overnight, and the color change was measured. The color change increased in the order of no protective layer > protective layer without SPN > protective layer with SPN, and the effect of clay addition was confirmed (Fig. 12). The color change was large in the order of blue > green > red.

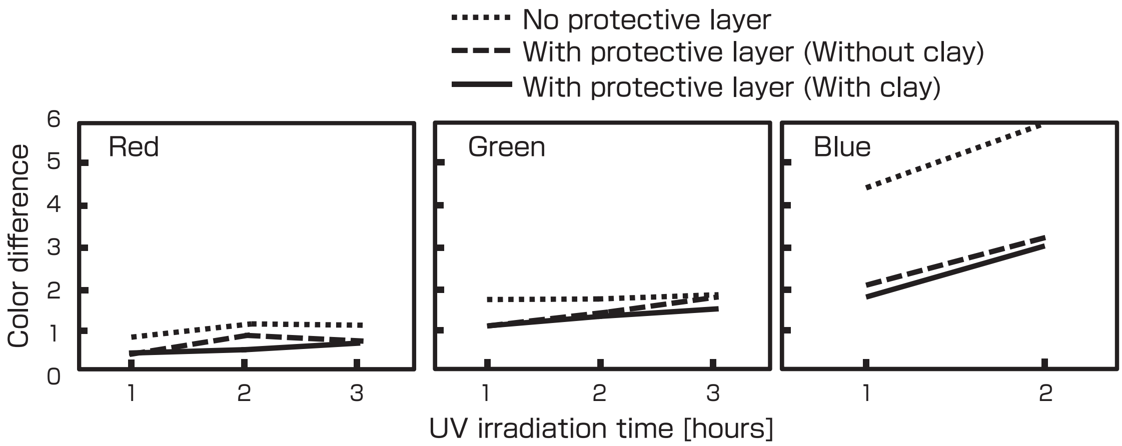


Fig. 12 Relationship between UV irradiation time on postcard samples and color difference

For blue, in addition to the postcards, evaluation for glass substrates was conducted. Samples consisted of three types: no protective layer; protective layer without SPN; and protective layer with SPN. These were irradiated with the UV light at the same time, and the color change was measured. As a result, the ΔE*ab of no protective layer, protective layer without SPN, and protective layer with SPN after 1 hour irradiation were 3.6, 0.7, and 0.5, respectively. The color change of the sample with protective layer that includes SPN was the smallest, and the effect of clay addition was confirmed.

3.3.5 Evaluation of adhesiveness

A tape peel test (JIS K5600) was conducted for the protective layer applied using a bar coater and spray, with the composition of 30 g of resin, 70 g of toluene, 3 or 0 g of SPN, and 6 g of initiator. No peeling of the protective layer was observed. Also, a cross-cut tape test (JIS K5600) was conducted for the same sample. No peeling was observed, and all 25 test areas that were set as goals were categorized as Category 0 where there was no peeling, and sufficient adhesiveness was confirmed. Furthermore, concerning samples of wood molded plate and aluminum surface to which the same protective layer was applied, the results were Category 0, and sufficient adhesiveness was confirmed.

3.4 Establishment of coating method

The above investigations were evaluations of planar samples. However, actual products are 3D, and it was necessary to add the protective layer to 3D surfaces. Therefore, coating was conducted with a spray rather than a bar coater. Due to the viscosity property of the paste liquid, it was important whether it was possible to add a protective layer of even and sufficient thickness. Therefore, the developed paste was spray-coated at the Tohoku Kogei studio to seek optimal conditions that allowed transparent, even, and highly artistic coating on the lacquerware surface. Specifically, optimization was done for paste viscosity through solvent addition, spraying pressure, and number of coats, to investigate the coating method to obtain a high-quality coating layer.

3.4.1 Spraying condition with high evenness

In *tamamushi-nuri*, there is optimal paste viscosity according to the shape of the product to be coated. Specifically, between products with numerous sides and those with numerous flat surfaces, the viscosity is lower for the latter, and even for the same flat surfaces, the larger the surface the viscosity is reduced. In the newly developed paste, a urethane thinner (Strone Thinner; Cashew Co., Ltd.) was used as an additional solvent, and it was confirmed that the viscosity could be adjusted by changing the amount. Optimal paste viscosity was confirmed for application to ten types of products, including regular products [bookmarker, tumbler, rocks glass, and wine cup (two types)] and prototypes (*sake* cup, lipped bowl, small plate, square bowl, and plate). From the above findings, appropriate amount of solvent to be added was obtained per product shape.

In the *tamamushi-nuri* that uses spray-coating, the spraying speed is adjusted by air pressure. In the usual *tamamushi-nuri* coating, the optimal pressure is around 0.2 to 0.4 MPa. However, when the newly developed paste was sprayed at this pressure, an "orange peel" surface or unevenness appeared, and the glossiness that characterized the *tamamushi-nuri* disappeared. As a result of study, it was found that the optimal pressure for this paste was 0.15 MPa.

3.4.2 Number of coats

In this research, high transparency was mandatory for the protective layer since it was added as the finishing coat of *tamamushi-nuri*. It was confirmed that transparency of the protective layer was obtained, and the brightness and glossiness were not lost through the additional number of coats. Specifically, the content of SPN was adjusted finely, and we found the combination that did not alter the appearance compared to products without the protective layer (i.e. a regular *tamamushi-nuri* product). The process of UV irradiation after coating with the protective layer was done with the utmost care to avoid adhesion of dust. For UV irradiation, a special box was created so that sufficient intensity of UV can be irradiated from the sides as well as the top. This box was set in the room where topcoat spraying was done, and a series of processes of UV drying could be completed in that room. The original device was made by using a light-reflecting aluminum plate with a rotary table.

3.4.3 Reproducibility by difference in shapes

As mentioned above, the viscosity of the coating paste is controlled according to the shapes of the *tamamushi-nuri* products. In one of the prototypes that was manufactured this time, we were able to obtain almost the same appearance as Tohoku Kogei's regular *tamamushi-nuri* products and parts. Also, we were able to reproduce the *tamamushi-nuri* appearance equivalent to the regular products from materials that were already used such as wood, resin (acrylic, ABS), and glass, as well as ceramics that is expected to be used in the future.

3.5 Establishment of product specification

3.5.1 Manufacture of prototypes, evaluation test, and surveys at exhibitions

G value measurement and a monitor evaluation questionnaire were conducted for *sake* cups that were spray-coated with four types of paste, in which the amount of clay added was changed from 1.5 to 7.0 g for 30 g of resin.

A total of five types of *sake* cups, consisting of a regular *tamamushi-nuri sake* cup (no protective layer) and four types of *sake* cups which were spray-coated at the studio with varying ratio of clay in UV curing resin, were shown at exhibitions, and questionnaires were given to the visitors (Fig. 13). They were asked to select the cup that was closest in appearance to the one without the protective layer. The questionnaire was given to 91 people. The *sake* cup that was considered the most similar was the one with 1.5 g, the least amount of clay added, and it was over 60 percent of the total response. As seen in Fig. 14, as a result of evaluation using the glass plate samples, there is a tendency that the G value increased as the amount of clay loaded decreased (Fig. 14). The result of the questionnaire matched the relationship of the amount of clay loaded and G value as shown in Fig. 14.

3.5.2 Monitor survey at restaurants

In the next step, in addition to the *sake* cup, prototypes were manufactured using the developed paste for six product types including lipped cup, tumbler, rocks glass, ceramic plate, and ceramic small bowl. Some of the products were evaluated at restaurants A, B, and C. At a kaiseki restaurant A, a product was used as a cup for local Japanese *sake* and explanation was provided about the product. We received comments that it was good, and it could be used as PR for tourists and other people who wish to enjoy the local cuisine. Restaurant B was a French restaurant where there was a sommelier with knowledge of French cuisine and wine, and the sommelier was actually the owner of the restaurant. Wine cups were used, and although there was no problem about durability, it was indicated that the color of wine could not be seen through the cup, and we reconsidered the shape of the glass so that the wine color would show. Restaurant C was an Italian restaurant, and plates and wine cups were used (Fig. 15). The plates with and without protective layer were used, and after washing in the dishwater, it was confirmed that there were less scratches on plates with the protective layer.

The user evaluation was positive, and we received comments that the overall design and usability were good, and people said they wished to purchase them when the products became commercially available.

3.5.3 Product realization

When creating a product, it is necessary to sell a certain number of products, and though we initially considered various products, we decided to select final candidates. When we asked the restaurants that actually used the products as well as people of various fields, we were told that wine cups could be used as souvenirs overseas and could be used for a

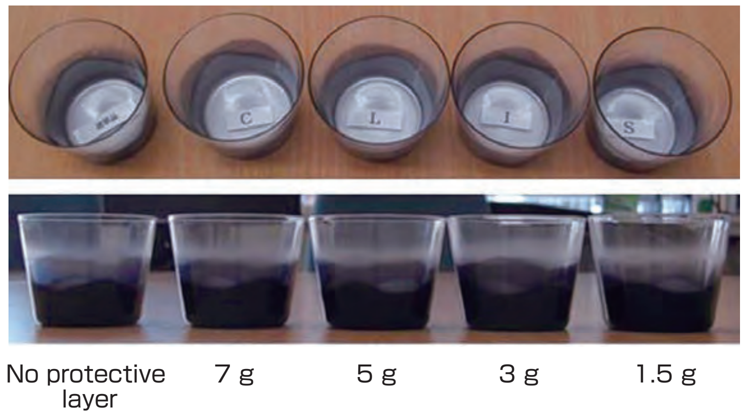


Fig. 13 Appearance of sake cup sample used in user evaluation
Numbers indicate the amount of clay added to 30 g of resin.

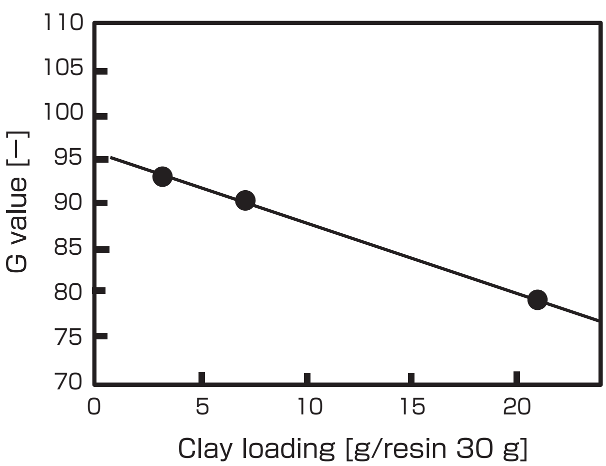


Fig. 14 Relationship between clay loading and G value

Fig. 15 User evaluation at a restaurant

wide range of beverages. Therefore, we commercialized the wine cups in two colors in April 2015 (Fig. 16). The wine cups were used as souvenirs at the G7 Finance Ministers and Central Bank Governors Meeting held in Sendai on May 2016.

After achieving product realization, the product received the Minister of Economy, Trade and Industry Award of the 6th Monodukuri Japan Award. It was also listed in the Monodukuri White Paper and selected as Miyagi Sugure MONO (Excellent Products of Miyagi). Support was obtained from the City of Sendai, Miyagi Prefecture, METI, Reconstruction Agency, and others. An NHK TV documentary "Ippin" that featured this product was received with such enthusiasm that it was re-aired four times, and the product became known throughout Japan. In NHK World's "Science View," it was aired internationally. There was also coverage by various newspapers and magazines, and the product continues to be taken up in product reviews. As of February 2018, for the wine cups, there is a waiting period of three months from order to delivery.

4 Summary and future prospect

For the protective layer, we achieved the goal for appearance, abrasion resistance, UV resistance, and others. The process of applying this to a product was established and the product was commercialized. In the future, we hope to enhance the durability of *tamamushi-nuri* itself. Also, since the newly developed protective layer can be applied to a wide range of plastic products with soft surfaces, it can be expanded to use other than lacquerware.

Appendix: Collaboration and cooperation of traditional craft and advanced technology

The efforts for the development of high-durability lacquerware was started when a worker saw an exhibit in the "Exhibition Room for Craft Prototypes"[2] that was established in the first floor of Building C at AIST Tohoku, from 2004 to 2011, under the supervision of Akiko Shoji, Honorary Professor, Tohoku Institute of Technology. The National Institute of Industrial Art (NIIA), which was the predecessor of AIST Tohoku, was established for the purpose of promoting the industries of Tohoku, and prototypes of the craft of the Tohoku Branch of the Industrial Art Institute and NIIA were stored and exhibited there. Since AIST Tohoku was set in the area where there were many natural smectite mines, it succeeded in the industrialization of synthetic smectite in cooperation with smectite companies.[17] The clay material used in this research is the organified product of synthetic smectite. Moreover, clay film is a material that takes advantage of the characteristic that "high film formability" of synthetic smectite. Since both *tamamushi-nuri* and clay film are coating materials, the idea of merging the technology developed at AIST Tohoku with lacquerware led to this collaboration.

Fig. 16 Commercialized a pair of wine cups
About 6 cm in diameter, about 15 cm in height.

While in general, collaboration of materials development and craft is difficult, the respective fields worked closely together for collaboration and cooperation. Feedback was applied to results of investigation, improvements were made, and we believe the collaboration of industry-academia-government was conducted effectively. We think this is largely due to Tohoku Kogei's stance of incorporating new things while carrying on the tradition.

Through the collaboration with companies that supply the clay material, we were able to create the flow of product supply from paste to lacquerware production, and we believe it is an excellent example of integrated development.[18]

The development of high-durability lacquerware was conducted within the Revitalization Promotion Program of the Japan Science and Technology Agency after the Great East Japan Earthquake. With the support toward commercialization by a JST coordinator, it was evaluated highly as an industry-academia-government collaboration product along with AIST Tohoku and members of Tohoku Kogei.

In December 2017, Tohoku Kogei was selected as the "Company that Leads the Region to the Future" by METI, and by government-civilian collaboration, the brand was established for high-durability lacquerware and nanocomposites. In the future, we hope this will lead to participation by different industries and products to generate new values. With the history of Sendai from which modern craft was started and the technique of *tamamushi-nuri* that was born from industry-academia-government collaboration, we shall continue this collaboration to pass on this technique to the future.

Acknowledgement

Parts of this research were conducted under the Japan Science and Technology Agency (JST) Revitalization

Program A-STEP Seeds Actualization Type "Development of high-durability lacquerware with added protective layer containing clay"; the JST A-STEP High Risk Challenge Type (Revitalization Promotion) "Development of High-Durability Surface Treatment Technology by Inorganic-Organic Nanocomposites and Its Application to *Tamamushi-nuri*, a Traditional Craft of Miyagi"; and the Grant for Product Development by Small to Medium-sized Manufacturing Companies of Sendai "Application of High-Durability Surface Treatment Technology by Inorganic-Organic Nanocomposites to *Tamamushi-nuri*, a Traditional Craft Designated by Miyagi Prefecture." We would like to thank the following people who were involved in this development: Professor Akiko Shoji (Tohoku Institute of Technology); Mr. Jun'ichi Isoe (JST); Mr. Noriyuki Kuwanaga, Mr. Yukiteru Sato, and Mr. Mitsuhiro Endo (Bureau of Industry, Sendai City); Mr. Tatsuji Hajimesawa (K.K. Sendai Yamarai); Mr. Yasuhiro Saura and Mr. Shinsuke Kimura (Tohoku Kogei Co., Ltd.); Mr. Shin'ichi Iwata and Ms. Rie Tanaka (AIST at the time): Ms. Asami Suzuki, Ms. Emiko Tomon, Dr. Hiroshi Nanjo, Dr. Ryo Ishii, Dr. Hiromichi Hayashi, Dr. Takafumi Aizawa, Dr. Yoshito Wakui, Dr. Takashi Nakamura, and Mr. Masayuki Abe (AIST); and many others.

References

[1] N. Kajii, T. Egashira and Y. Fujishima: Study of improvement of weather resistance by coating technology for *urushi* films, *Report of the Industrial Research Institute of Ishikawa FY 2013*, 25–28 (2013) (in Japanese).

[2] A. Shoji: Sendai Miyagi design shi (History of design in Sendai, Miyagi Pref.), *Nihon Chiiki Design-shi II* (A History of Regional Design in Japan 2) [Special Committee for History of Regional Design, Design Research Association (ed.)], Bigaku Shuppan, Tokyo, 235 (2016) (in Japanese).

[3] M. Saura: Nanocomposite coating ni yoru kotaikyusei shikki: Tsukaeru kogei no jitsugen (High-durability lacquerware by nanocomposite coating: Realization of craftwork for daily use), *Japan Plastics*, 68 (2), 58–61 (2017) (in Japanese).

[4] T. Ebina: Junan na jiritsu tainetsusei film Claist (Claist, a flexible, self-standing heat resistant film), *FC Report*, 23 (3), 109–112 (2005) (in Japanese).

[5] T. Ebina: Shinki tainetsu film "Claist" no kaihatsu (Development of new heat-resistant film "Claist"), *Expected Materials for the Future*, 6 (5), 22–25 (2006) (in Japanese).

[6] T. Ebina: Development of clay-based films, *Chem. Rec.*, 18 (7–8), 1020–1032 (2018).

[7] Y. Imai, A. Terahara, Y. Hakuta, K. Matsui, H. Hayashi and N. Ueno: Synthesis and characterization of high refractive index nanoparticle/poly(arylene ether ketone) nanocomposites, *Polymer Journal*, 42, 179–184 (2010).

[8] N. Shinohara: Nanocomposite hardcoat zai no kaihatsu (Development of nanocomposite hardcoat material), *Yuki Muki Nano Fukugo Zairyo No Shin Kyokumen* (New Phase in Organic-Inorganic Nanocomposite Materials), NTS, Tokyo, 122–130 (2004) (in Japanese).

[9] K. Kawasaki, K. Sakakibara, F. Mizukami and T. Ebina: Development and evaluation of novel radical-trapping sheets composed mainly of clay, *Clay Science*, 13, 217–224 (2008).

[10] E. Pavlacky, N. Ravindran and D. C. Webster: Novel *in situ* synthesis in the preparation of ultraviolet-curable nanocomposite barrier coatings, *J. Appl. Polym. Sci.*, 125 (5), 3836–3848 (2012).

[11] M. Alexandre and P. Dubois: Polymer-layered silicate nanocomposites: preparation, properties and uses of a new class of materials, *Mat. Sci. Eng. R.*, 28 (1–2), 1–63 (2000).

[12] *Toso Gijutsu Binran* Editorial Board; *Toso Gijutsu Binran* (Handbook of Coating Technology), Nikkan Kogyo Shimbun, Tokyo, 191 (1956) (in Japanese).

[13] T. Ebina, E. Tomon, T. Hayashi, J. Ishii, Y. Wakui, T. Nakamura, Y. Matsukawa and M. Saura: Yukika nendo/polymer composite coating no dentoteki shikki hogoso toshite no kento (Investigation of organoclay/polymer composite coating as protective layer for traditional lacquerware), *Abstracts of 58th Annual Meeting of the Clay Science Society of Japan*, 40–41 (2014) (in Japanese).

[14] Nippon Denshoku Industries Co., Ltd.: Iro no kyoyosa no jirei (Case of color tolerance), http://www.nippondenshoku.co.jp/web/japanese/colorstory/08_allowance_by_color.htm, accessed 2018-03-05 (in Japanese).

[15] H. Hasunuma: Kotaku to sono sokutei (Luster and its measurement), *Journal of the Metal Finishing Society*, 8 (5), 155–160 (1957) (in Japanese).

[16] Japan Meteorological Agency: Nichisekisan UV-V ryo no tsuki heikinchi no suchi data hyo (Numerical data table for monthly average values of daily total UV-B amount), http://www.data.jma.go.jp/gmd/env/uvhp/uvb_monthave_tsu.html, accessed 2018-03-05 (in Japanese).

[17] K. Torii: Kinosei nendo sozai no kogyo oyoshi (History of industrial application of functional clay materials), *Kinosei Nendo Sozai No Saishin Doko* (Latest Trend in Functional Clay Materials) [M. Ogawa (ed.)], CMC Publishing, Tokyo, 151–189 (2010) (in Japanese).

[18] T. Ebina: Development of clay-based film: A *Full Research* scenario from a viewpoint of encounter, *Synthesiology*, 1 (4), 267–275 (2008) (in Japanese) [*Synthesiology English* edition, 1 (4), 242–250, (2008)].

Authors

Takeo EBINA

Completed the doctor's course at the Graduate School of Engineering, Tohoku University in 1993. Joined the Government Industrial Research Institute, Tohoku, Agency of Industrial Science and Technology, Ministry of International Trade and Industry. Visited the University of California at Santa Barbara twice to study functional materials including clay. Currently, Prime Senior Researcher, Research Institute for Chemical Process Technology, AIST. Started the development of film materials with clay as main component in 2004. Conducted wide-ranging research from synthesis of clay materials to mass production of application products. Use of clay-based films include transparent film using synthetic clay and electronic device that employs the film. In this paper, was in charge of the materials development for protective layer and its evaluation.

Midori SAURA

Graduated from the Faculty of Law, Tohoku Gakuin

University in 1991. Joined a bank, and then joined Tohoku Kogei Co., Ltd. in 1996. Currently, Managing Director, Tohoku Kogei. In charge of sales and product planning. In this paper, was in charge of relaying information about coating properties, user evaluation, and product realization.

Yasukatsu MATSUKAWA
Graduated from Tohoku High School in 1981, and joined Tohoku Kogei Co., Ltd. in 1981. Currently, Plant Manager, Tohoku Kogei. In charge of production and control of the products. In this paper, established spray-coating method and method to add protective layer to products.

Discussions with Reviewers

1 Overall

Comment (Shigeki Naito and Akira Kageyama; AIST)

This paper describes the technologies for *tamamushi-nuri*, which is lacquerware with distinctive appearance and ways of producing it invented by the National Institute of Industrial Art, Ministry of Commerce and Industry (current METI) that was established in 1928 to vitalize the industry after the Great Depression. It also describes the new technology that was developed through collaboration of Tohoku Kogei that nurtured the *tamamushi-nuri* into a craft that characterizes Sendai, and AIST Tohoku that succeeded in the commercialization of synthetic smectite and was seeking usage of this product. It explains the course of technological development and the results obtained to significantly improve abrasion resistance that was a disadvantage of lacquerware, while maintaining the excellent appearance of *tamamushi-nuri*.

It is a valuable case study when it was thought difficult to generate new values for society through collaboration of traditional craft and advanced science and technology, by overcoming the weaknesses and barriers of the conventional products. As this may provide guidance to other fields, I think this paper is appropriate for publication in *Synthesiology*.

2 Overall picture of the elemental technologies

Question (Akira Kageyama)

In this technology, I think the overall optimization technology is important for the following issues: (1) indices to provide the product performance (transparency, surface hardness, abrasion resistance, UV resistance, dishwasher resistance, adhesiveness, etc.); (2) parameters when designing protective layer materials (organoclay, UV curing resin, solvent, composition of clay ingredient, dispersed particle size, etc.); and (3) issues in setting coating conditions (suitable viscosity, paste dilution technique according to the shape of object to be coated, avoidance of orange peel, hardening at room temperature, etc.). However, I think it is difficult for the reader to understand since there is no diagram that shows the overall picture. Can you show the overall picture by using a characteristic diagram, for example, a fishbone diagram or a table?

Answer (Takeo Ebina)

As you pointed out, there are many indices that represent product performance. Also, since the indices are correlated, I decided to show the cause-and-effect relationship using a fishbone diagram. I added Fig. 3.

Comment (Akira Kageyama)

Since you added Fig. 3, now the overall picture of the elemental technologies can be understood easily. I think the major characteristic of this technological development is to maintain the "beautiful appearance," and it is necessary to investigate from both the material composition side as well as the coating process side. Therefore, if you create a characteristic diagram showing the two sides, I think people would better understand the contribution of Tohoku Kogei.

Answer (Takeo Ebina)

Thank you for your comment. By remaking the diagram as you pointed out, the contribution of Tohoku Kogei became clearer. I also added the "achievement of transparency and gloss" within the frame of "beautiful appearance," and it is shown that the two major categories, investigation of materials and composition and investigation of coating process, were needed to solve this issue, and the various listed factors are shown in the next layer.

3 Reinforcement of data that show the result of R&D

Comment (Shigeki Naito)

In the abrasion resistance evaluation, you mention that the UV curing resin was selected according to pencil hardness, and that UV7605B was selected considering viscosity. I think you should show the outline of the chemical structure of UV curing resin and the scientific reasoning behind it.

Answer (Takeo Ebina)

I think your comment is valid. Therefore, I added the scientific explanation, not only the phenomenal description. Specifically, I added the description that the UV curing resin investigated is a urethane acrylate resin, and the molecular weight/oligomer functional group number for UV-7605B, UV-7640B, and UV-1700B are 1100/6, 1500/6-7, and 2000/10, respectively, to show the chemical properties of the resin. Since UV-7605B has the smallest molecular weight among the three types of resin, it has low viscosity, and it is thought that the hardness increases as the number of oligomer functional group increases. However, in the clay-resin composite, it is thought that there is an optimal molecular weight and an optimal number of oligomer functional groups.

Comment (Akira Kageyama)

I think you should add a bit more data as figures or tables, about optimization of materials technology, in addition to the text, to clarify the basis of your decisions. Also, you evaluate SPN, STN, SAN, and SAN316, I think these were treated by quaternary ammonium salts with different chemical structures, as the organification agents for the organoclay. Can you show the outline of their chemical structures?

Answer (Takeo Ebina)

As you pointed out, I added Figs. 5, 7, 8, and 14 to show that the decisions were made based on the data. The four types of organoclay were treated by different quaternary ammonium salts, and I added Table 1 showing the organification agents and their carbon number.

4 Division of role between AIST and Tohoku Kogei

Comment (Akira Kageyama)

I believe there were elements that could not have been achieved without the participation by Tohoku Kogei. Can you highlight those elements more? One is the realm of art of *tamamushi-nuri* (lacquerware) including a sense of beauty such as coloring, depth of color, gloss and others. Second is the realm of craftsmanship. Both are difficult to quantify, but weren't there decisions made about the materials composition to strike a balance between the coating condition and the total beauty of *tamamushi-*

nuri? If there were such situations, I think you should give some cases to show the close collaboration between the organizations that have different strengths.

Answer (Midori Saura and Takeo Ebina)

As you pointed out, this development was only possible through AIST’s strength in material development and Tohoku Kogei’s design and craftsmanship. There wasn’t enough focus on this point. Therefore, the following text was added to “2 Scenario of development of high-durability lacquerware.”

“Tohoku Kogei Co., Ltd. has conventionally used brush-coating on lacquerware, but around 1955, it started using spray-coating for the first time on traditional lacquerware. Currently, it uses spray-coating on products with various shapes such as glass, vase, plate, and others. Expert skill is required to apply even coating to the entire surface of products with complex shapes, and the coating technology based on long experience accumulated by Tohoku Kogei was utilized in this development. This development was achieved after the material composition was ultimately determined for the balance between beauty and coating conditions of *tamamushi-nuri*, and after repeated lab investigations at AIST and sample coating at Tohoku Kogei.”

5 Chapter for collaboration and cooperation of traditional craft and advanced technology

Comment (Shigeki Naito)

I think it is a good attempt to present the uniqueness of this paper by introducing this perspective, but I feel it is somewhat out-of-place within the paper. Therefore, how about placing this part outside the text, and putting it in an appropriate place as “Appendix”? Also, please revise it so the text can be more easily understood.

Answer (Takeo Ebina)

As you advised, I detached this part from the main text of the paper, and I made an Appendix of this content in front of Acknowledgements and References. Also, expressions that might be difficult to understand were revised.

Additive manufacturing of ceramic components

—Towards innovation of ceramic industry—

Tatsuki OHJI

[Translation from *Synthesiology*, Vol.11, No.2, p.81–93 (2018)]

Aiming for innovative ceramic manufacturing technologies which enable creative and novel products, a national R&D project “High-Value Added Ceramic Products Manufacturing Technologies (HCMT)” has been initiated since 2014 as part of the Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Innovative design/manufacturing technologies” program in Japan. The project deals with two key technologies: additive manufacturing (AM) for realizing complex-shaped ceramic products and reducing their lead-times, and hybrid coating on 3D bodies for enhancing their functionality and durability. Following an overview of this project and a brief description on the general status of AM technologies, this article focuses on the R&D strategies and the latest achievements on AM of ceramics in this project. Among a variety of AM approaches, we employ two AM technologies for making ceramic green bodies; powder layer manufacturing (powder bed fusion or indirect selective laser sintering) and slurry layer manufacturing (vat photo-polymerization or stereolithography), because of their dimensional accuracy, shape-flexibility, density-adjustability, etc. The former is a dry forming process, and is suitable for large/porous components, while the latter is a wet one, being good for small/dense parts. In addition, intensive research efforts are being devoted to ceramic laser sintering (direct selective laser sintering) which enables concurrent forming and sintering (saving post-sintering-process). This paper describes several 3D prototype models produced for various application targets using the developed AM technologies, which are never attainable with conventional methods. The current issues and future perspective for AM of ceramics will be addressed and discussed as well.

Keywords : Additive manufacturing, ceramics, components, powder, slurry, powder bed fusion, stereolithography, laser sintering, ceramic industry

1 Introduction

Because of their unique and excellent material properties, ceramics are often used as key parts in many advanced products and systems in a variety of fields including manufacturing, energy, environments, IT, electronics, optics, bio-technologies, and transportation. It is also noteworthy that Japanese ceramic industries have maintained the world’s highest-level manufacturing technologies, which have brought about almost a half of the global market share of ceramic-related products, thanks to their incessant efforts for technological innovation.

Ceramic manufacturing process has been composed of several miscellaneous steps including powder preparation, mold making, granulation, forming, dewaxing, sintering, machining, finishing, *etc*. (Fig. 1, top). In addition, some of the steps such as granulation, dewaxing and sintering require a great deal of thermal energy, indicating higher ratios of labor and energy expenditures to the total production cost in comparison with those of other materials. As a result, production from countries of lower labor and energy costs has been gradually increasing in recent years, along with their progress of manufacturing technologies. To maintain and consolidate the technological superiority and international competitiveness of Japan’s ceramic industry, it is now crucially required to develop innovative manufacturing technologies which enable us to produce creative and novel products of high value. For this purpose, a national R&D project “High-Value Added Ceramic Products Manufacturing Technologies (HCMT)” has been initiated since 2014 in the CSTI, SIP, “Innovative design/manufacturing technologies” program of the government of Japan.[1]-[3] The HCMT project intends to integrate the above-stated miscellaneous steps of manufacturing process into the two key technologies, “additive manufacturing (AM)” and “hybrid coating (HC)” (Fig. 1, middle), which bring about many advantages in terms of production process as well as product performance. AM realizes complex-shaping of ceramic products and reduces their lead-times as will be described later, while HC provides better surface modification of products and enhances their functionality and durability,[4] strengthening the international competitiveness of Japan’s ceramic industry. This article will first briefly outline the HCMT project and describe the general status of the current AM technologies; then it will focus on the R&D strategies and the latest achievements on AM of ceramics in this project.

2 Overview of HCMT project

The HCMT project deals with R&D on “product manufacturing (PM)” as well as AM and HC. Figure 2 shows the R&D items in each of AM, HC, and PM. In AM, powder-layer manufacturing (PLM) and slurry-layer manufacturing (SLM) technologies are being developed for actualizing mold-free production of green (or formed) bodies of complex-shaped components, in addition

Fellow, AIST 2266-98 Anagahora, Shimo-Shidami, Moriyama-ku, Nagoya 463-8560, Japan E-mail: t-ohji@aist.go.jp

Original manuscript received July 20, 2017, Revisions received January 30, 2018, Accepted February 3, 2018

to ceramic laser sintering (CLS) which realizes concurrent forming and sintering. HC focuses on hybrid aerosol deposition (HAD) and fine-particle thermal spraying (FTS) for highly adhesive coating onto 3D shaped substrates (including polymer and metal), enhancing functions and durability of products. Based on these two developed platforms, we try to establish manufacturing technologies for a variety of target products of high value in PM. Examples are semiconductor production parts, plasma-resistant parts and ceramic cores of gas-turbine blades in the industrial field; water-purifying filters and portable toilets in areas related to everyday life; bone prostheses and ceramic heads for hip joints in the medical field (Fig. 1, bottom).

Figure 2 also shows the participating organizations of the HCMT project.[1] The core R&D sites are placed at the National Institute of Advanced Industrial Science and Technology (AIST) and Osaka University for intensive R&D using common research facilities and equipment. TOTO Ltd., NGK Insulators, Ltd., NGK Spark Plug Co., Ltd. and Noritake Co., Limited dispatch their researchers to core R&D sites for developing platform technologies in collaboration as well as product manufacturing for their own targets. These four companies are known as the “Morimura” Group which has established the foundation of modern ceramic industries of Japan since the beginning of the 20th century. In addition, Japan Fine Ceramics Center (JFCC), Kyushu University and Tohoku University are in charge of R&D on CLS.

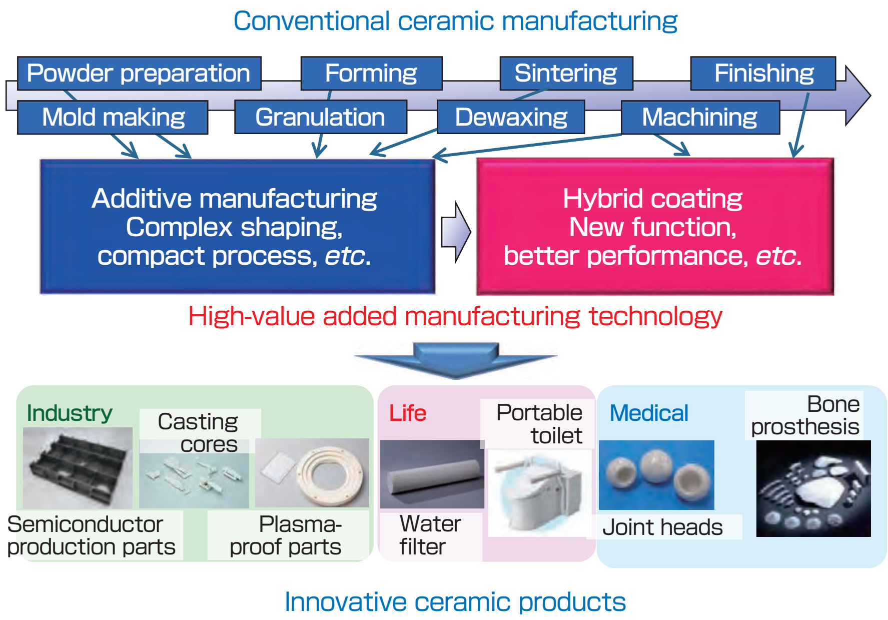


Fig. 1 Conventional ceramic manufacturing process and high-value added manufacturing technology to be developed

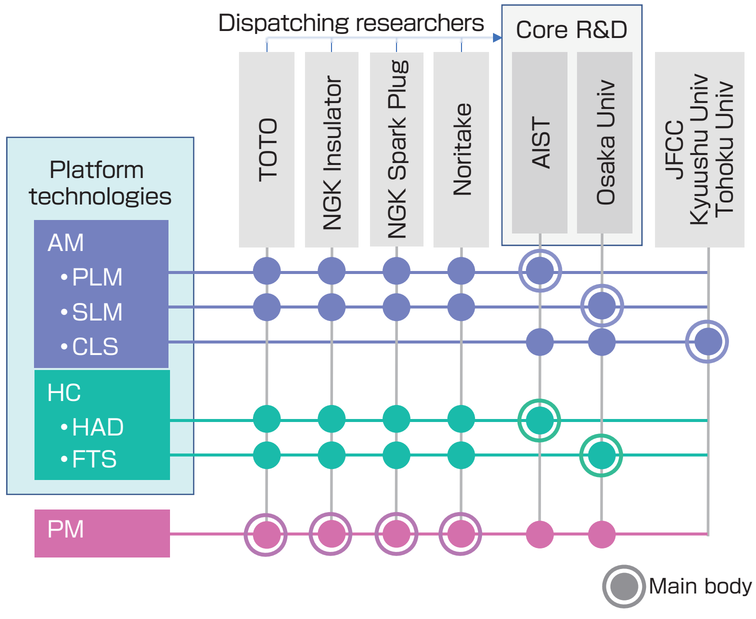
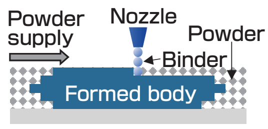
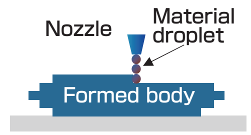
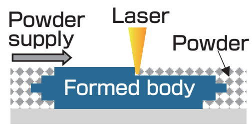
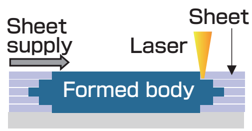
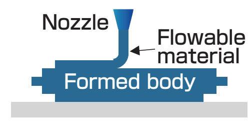
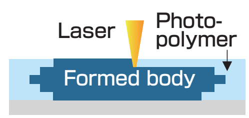
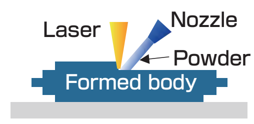


Fig. 2 R&D items and participating organizations of HCMT project

AM: Additive Manufacturing, PLM: Powder-Layer Manufacturing, SLM: Slurry-Layer Manufacturing, CLS: Ceramic Laser Sintering, HC: Hybrid Coating, HAD: Hybrid Aerosol Deposition, FTS: Fine-particle Thermal Spraying, PM: Product Manufacturing

Table 1. Classification of additive manufacturing technologies, according to ASTM F2792-12a

Method	Outline	
Binder jetting (Aka, 3D printing)	Liquid binder through a nozzle is selectively deposited to join powder materials.	
Material jetting	Droplets of build material through a nozzle are selectively deposited.	
Powder bed fusion (Selective laser sintering, PLM)	Heat, typically of laser, selectively fuses area of a powder bed.	
Sheet lamination (Laminated object manufacturing)	Sheets of material are bonded and selectively cut by laser.	
Material extrusion (Fused deposition modeling)	Flowable material is selectively dispensed through a nozzle or orifice.	
Vat photo-polymerization (Stereolithography, SLM)	Liquid photopolymer in a vat is selectively cured by light, typically of laser.	
Directed energy deposition	Focused heat, typically of laser, selectively fuses materials as being deposited.	

3 R&D strategies for AM of ceramics

AM (additive manufacturing), also known as 3D printing, is a process by which a three-dimensional body is built through point, line or planar deposition of material typically using a print head, a nozzle, or another appropriate equipment. Objects are produced by not subtracting but adding material, based on computer-aided design (CAD) files or 3D model data, without using machining tools or forming dies and molds. The advantages include the following: (1) Realizing complex-shaped or integral-structured bodies which are never attainable by conventional molding approaches (this enables us to make totally new design of products enhancing their performance and durability), (2) Saving production time and cost due to a moldless process (this is particularly true for large variety-small amount production such as for new product prototypes and artificial bones and teeth), and (3) Saving raw materials since only a necessary amount is consumed while substantial amount of machining loss is generated in subtractive manufacturing, (4) Actualizing unique material structures including compositionally or functionally gradient layer textures. There are a variety of AM methods, which are classified into seven categories according to ASTM F2792-12a, “Standard Terminology for Additive Manufacturing Technologies.” Table 1 shows this classification with illustrations.

AM has been well developed in the field of polymers and already has been widely used for fabricating 3D products of this sort of material to such an extent that household 3D printers for resin have been commercially available for some time.[5] Some key metal parts have also been successfully produced by AM;[6]-[8] for example, GE Aviation has introduced the additive-manufactured metal fuel nozzles in combustion systems of aircraft engines that could not be made conventionally.[8] The benefits include “25 % lighter weight than its predecessor part,” “the number of parts of the nozzle reduced from 18 to 1,” and “5 times higher durability due to more intricate cooling pathways and support ligaments.”

Regarding AM of ceramics however, though some complex-shaped 3D bodies have been prepared with relatively high precision using vat photo-polymerization (stereolithography), *etc*.,[9]-[18] their product size has been generally limited, typically to a few centimeters or less, and the status is far from manufacturing technologies to be used in industries. Hence, comprehensive R&D efforts on manufacturing processes including powder preparation, lamination, and post-process suitable for ceramics are crucially required to grow AM of ceramics to the level of industrial application, and this has triggered the HCMT project.[1]-[3]

When applying AM methods, which have been used in the fields of polymers and metal, to ceramics, because of the difficulty in directly obtaining sintered bodies due to their intrinsic nature such as high refractoriness and less-sinterability, it is general to produce green or formed bodies instead, which are to be sintered in a conventional furnace afterwards. For example, in powder bed fusion, laser heat melts polymer binder which is mixed with ceramic powder to form green bodies. The HCMT project employs PLM and SLM for forming green bodies as stated above; the former is categorized into powder bed fusion (also called “indirect selective laser sintering”) of the ASTM F2792-12a classification (Table 1), and the latter into vat photo-polymerization thereof. This is because these two approaches are known to be superior to the others in terms of homogeneous microstructure, good properties of the produced materials, wide shape flexibility, and high dimensional accuracy of the obtained products. In addition, material density (or porosity) can be adjusted over a wide range by combining these two approaches. Typical forming procedure of PLM is shown in Fig. 3. It consists of the following: (1) Mixing ceramic powder and polymer binder and putting them in the supply part, (2) Supplying the mixed powder to the forming stage and smoothing them using a squeegee (Fig. 3) or a roller to make a thin layer (typically ~0.1 mm), (3) Melting the binder of the desired part by scanning laser heat and bonding the ceramic powder, (4) Lowering the forming part by the formed layer thickness, (5) Repeating the above process of (2) to (4) for a 3D green body of a desired shape, and (6) Dewaxing and post sintering the obtained green body in a conventional furnace. PLM is a dry forming process itself and does not need a drying process of a wet body which often leads to undesired distortion and deformation of a green body. This, therefore, is advantageous particularly in making large-scaled products. On the other hand, the lack of fluidity of powder results in low density of green and sintered bodies, indicating that PLM is suitable for producing porous bodies. For example, a previous study on similar AM approaches for alumina showed that the green and sintered densities are around 30 % and 40 %, respectively.[19] It has been reported that the sintered density was substantially improved to 80 % or more when additional treatments of warm isostatic press and slurry infiltration on the green bodies were done; however, it is essentially important to increase the densities without such treatments in view of industrial application. For this purpose, in the HCMT project, we adjust and optimize the whole process from powder preparation (binder selection, powder mixture, powder fluidity evaluation, *etc*.) and lamination (powder supply, laser irradiation, *etc*.) to post-process (dewaxing, sintering, *etc*.), resulting in the sintered density of 84 %, without the additional treatments, in a simple-shaped alumina plate (50 x 50 x 5 mm) for specific mixed powder and experiment conditions.[20]

Figure 4 shows SLM’s procedure, which includes the

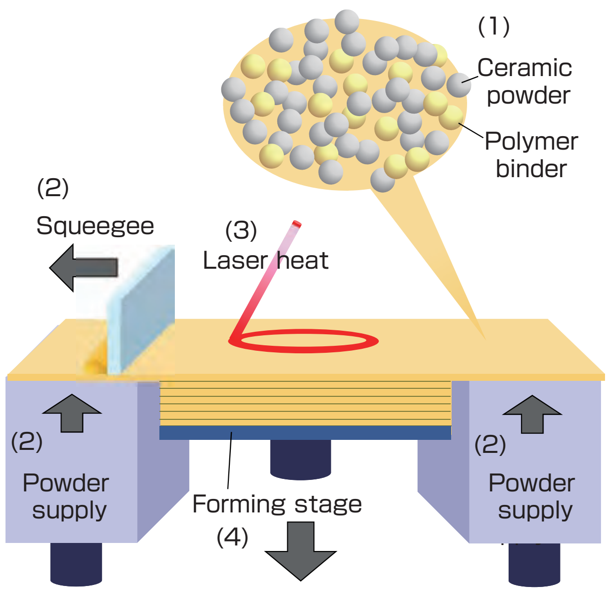


Fig. 3 Typical forming procedure of powder-layer manufacturing (PLM). The number in parenthesis corresponds to that of the description in the text.

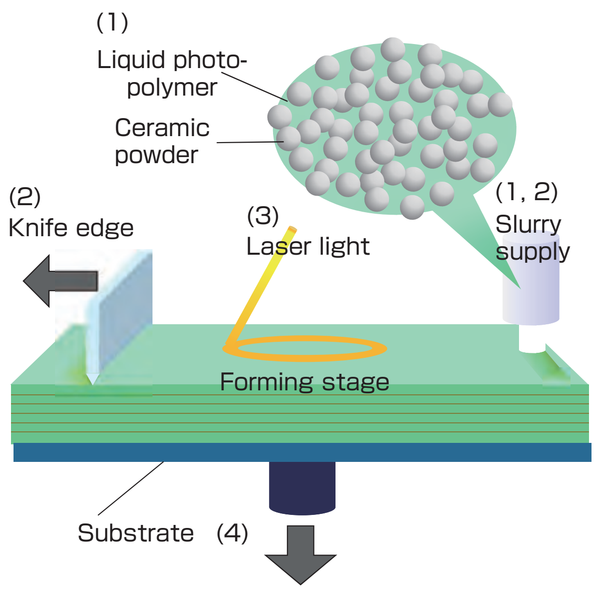


Fig. 4 Typical forming procedure of slurry-layer manufacturing (SLM). The number in parenthesis corresponds to that of the description in the text.

following: (1) Mixing fine ceramic powder and liquid photopolymer and putting them into the slurry supply, (2) Supplying the mixed slurry from the slurry supply on the substrate and smoothing them using a knife edge for forming a thin layer (typically several 10 μm), (3) Curing the photopolymer by laser light for the desired part, (4) Lowering the substrate by the formed layer thickness, followed by the same remaining processes as PLM (5, 6). SLM is a wet approach and therefore has characteristics totally opposite to PLM; due to the high fluidity, it is advantageous for producing dense parts of complex-shapes with high precision. It has been reported that careful selection of raw powder in SLM of alumina resulted in a high sintered density of 99 % with a bending strength of ~800 MPa.[14] On the other hand, undesired deformations and distortions often are generated during the drying process, which leads to unsuitability for making large-sized products. Therefore, the HCMT project is aimed at avoiding such deformations and distortions by optimizing the processing conditions and modifying the forming apparatus. It is also critically important to disperse the fine ceramic particles densely into the slurry, for example by using ceramic powder having bi-modal size distribution, with sufficient degassing for reducing sintering-shrinkage as well as obtaining dense bodies.

As stated above, it is extremely difficult to obtain sintered bodies by directly laser-sintering ceramic powder in AM. For example, Qian, *et al*.[21] investigated direct-laser-sintering of alumina, and revealed three detrimental phenomena in the sintered body including glassy parts due to overheating/rapid cooling, unsintered parts due to heat lack, and cracks due to thermal stress. If it is realized successfully, however, it will bring enormous benefits of savings in the post sintering process which needs substantial cost and time. The HCMT project, therefore, also deals with direct laser sintering of oxide and non-oxide ceramics (CLS); the approach includes full-packing ceramic powder in a layer, optimizing laser irradiation conditions for critical temperature control, *etc*.

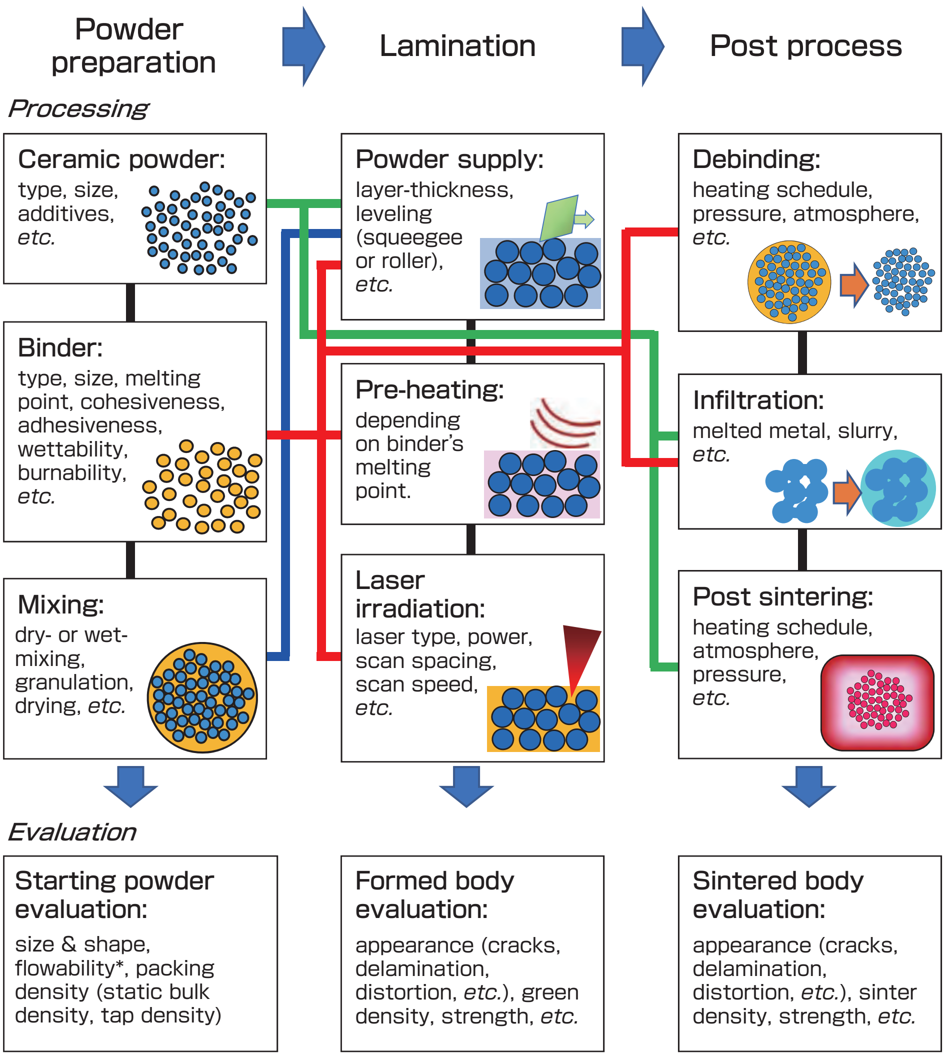
4 Platform technologies in PLM

For optimizing AM procedures of ceramics, there are a number of technical items that should be carefully examined and properly selected. This chapter discusses what sorts of technical items there are, how they are connected and correlated to each other and what should be considered and selected in each of the technical items in order to obtain sound products through an AM approach, taking an example of PLM.[22] The total procedure of PLM can be roughly divided into three processes, including powder preparation, lamination (or PLM itself), and post process. Figure 5 shows technical processing items as well as evaluation items in each of these three processes.

In the powder preparation, ceramic powder is mixed with polymer binder to be melted by laser heat as described above by some appropriate method. The mixed powder used in PLM should have sufficient flowability, which is generally obtainable with a spherical shape and size of ~50 μm. Therefore, when the powder size is below 10 μm which is typical for so called fine ceramics, granulation process including spray-drying is frequently used to produce spherical granules of such a size. The mixed powder is evaluated in terms of flowability including angle of repose, compression ratio, Hausner ratio as well as their size and shape, *etc.* Angle of repose is the angle measured in degrees between the horizontal plane and the steepest slope at which loose powder remains in place without sliding. Compression and Hausner ratios are given by $(D_t\text{-}D_b)/D_t$ and D_t/D_b, respectively, where D_t is the tap density and D_b is the static bulk density. When the flowability increases, these three indices all decrease. Suitability of powder to lamination of PLM is also examined in a simple preliminary powder test, where a lump of powder placed in the forming stage is leveled by using a squeegee. If the powder is flowable enough and not so cohesive, the surface becomes smooth without dimples and cracks, which appear with powder cohesive and less flowable, as shown in Fig. 6 (a) and (b), respectively. The powder flowability is also important for making a sufficiently filled powder layer. Because the layer is formed only by smoothing the powder by a squeegee, *etc.* without pressure, the powder density of the layer is almost equivalent to the static bulk density of the powder. It should be noted that since the mixed powder contains polymer binder as well, the density of ceramic powder itself is further lowered. It is, therefore, essentially required to have a well filled powder layer to get high densities of the resulting green and sintered bodies, which also leads to reduction of undesired deformation/distortion. It has been known that proper combination of coarse and fine powders leads to closer packing; however, powder flowability is generally degraded when containing fine powder.

In the lamination, the first step is formation of the powder layer, whose thickness is to be determined from the mixed powder size; it is preferably 1.5 to 5 times larger than the powder's maximum size. The thicker the layer is, the higher the production rate; however, it results in larger steps of side surfaces. The thickness also should be determined so that laser-heat is sufficiently transferred to the bottom of the layer. Insufficient heat transfer causes a large temperature distribution thickness-wise, frequently resulting in warping and inter-layer delamination of a green body. Next, pre-heating mixed-powder is made before lamination, depending on the binder's melting point. For example, when employing wax-based binder whose melting point is 80–120 °C, temperature difference is usually small thickness-wise and successful lamination is easily attainable without pre-heating. On the other hand, for nylon-based binder with melting point of 150–200 °C, higher laser power or slower laser scan is usually required to melt it, which leads to a large temperature difference thickness-wise and frequent appearance of warping as described above. An example of warping which was observed in a green body with nylon-based binder is shown in Fig. 7 (a). Pre-heating the mixed powder closely to the melting point is effective for avoiding such warping. Laser irradiation conditions including laser type, power, scan spacing, and scan speed should be carefully chosen depending on the types of the polymer binder and ceramic powder, *etc*. An issue often occurring during the lamination is sliding of a green body embedded in powder and formation of a gap, as shown in Fig. 7 (b). This sliding is made when the body is trailed by powder being re-coated on it and is more likely to occur typically in the following cases: (1) the binder is still heated and adhesive, (2) the squeegee moves too fast, or (3) the mixed powder is too flowable. Thus, it can be resolved by cooling the binder sufficiently, lowering the squeegee movement speed, or lowering the powder flowability. Figure 7 (c) shows an example of successful formation of a green bogy without the above issues (embedded in powder).

In the post process, first the binder is removed from the obtained green body by burning it out. The heating schedule, pressure, atmosphere, *etc.* for this process should be carefully selected so that undesired deformation and distortion would be minimized while the binder is melted and burnt out. Infiltration is often employed for densification. A typical example is siliconized silicon carbides (SiSiC), where melted Si is infiltrated through porous SiC-C green bodies produced by PLM, followed by reaction between Si and C for formation of secondary SiC and densification.[23] Free carbon produced during burning the polymer binder can be used for this reaction. Slurry infiltration into green bodies also can increase green and sinter densities as already stated.[19] In post-sintering, selection of conditions including heating schedule, pressure,



*Flowability: angle of repose, compression ratio, Hausnerratio, preliminary powder test for lamination, *etc.*

Fig. 5 Technical processing items and evaluation items in starting powder preparation, lamination, and post-process

atmosphere, *etc*. is crucial for obtaining sound sintered bodies, and knowledge and experiences so far on sintering of conventional green bodies are of great use for it. The green and sintered bodies are evaluated in terms of appearance (cracks, delamination, distortion, *etc*.), green/sinter densities, strength, and others.

As seen so far, many of the technical processing items are closely connected and correlated to each other; such close relations are expressed by solid lines in Fig. 5. It can be said that particularly powder preparation substantially affects many of the subsequent processes of lamination and post process. For example, the properties of the binder are critically important for the powder supply, pre-heating and laser irradiation of the lamination (melting point, cohesiveness, adhesiveness, wettability, *etc*.), while they are also crucial to the debinding and infiltration (where burnt binder is often used for reaction with infiltrated ones) of the post process (melting point, burnability, *etc*.). Thus, powder preparation is the most essential process in PLM, similarly to the cases of conventional ceramic processing. Sound products can be obtained only after all the technical items are properly selected and performed. It should be noted that the approach for examining and integrating the technical items into optimal AM technology described in this chapter is employed similarly in SLM and CLS.

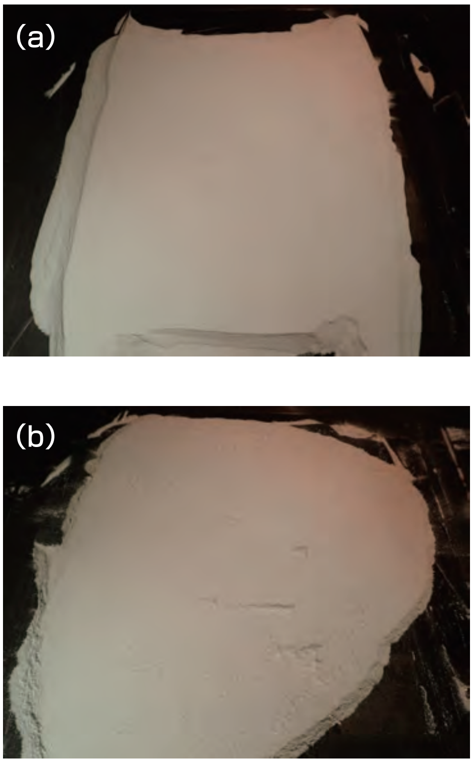


Fig. 6 Preliminary powder test for lamination, (a) Smooth surface with flowable powder, (b) Dimples and cracks with less flowable powder

5 Prototype models produced by AM

Taking advantage of the developed AM technologies, the HCMT project has manufactured several types of unique prototypes aimed at various target applications, some of which are described in this chapter. The first are stage models produced by PLM, which are anticipated as basic structures for ceramic exposure stages used in future semiconductor industries; some examples are shown in Fig. 8, in comparison with a conventional structure.[1][24]-[26] A light and stiff exposure stage of large scale and complex shape is critically needed for next generation IC chip production where more accurate positioning and higher throughput will be strongly required. While the conventional rib structure produced by molding consists of simple walls (a), AM can make that having windows in the walls (b), and furthermore truss structures of light weight/high stiffness (c-e), which were not obtainable until now. The models of (b-e) are siliconized silicon carbides (SiSiC) which are obtained by Si infiltration into SiC-C green bodies followed by reaction-sintering, as described above. Their feature is high specific stiffness (Young’s modulus/bulk density) and very little sintering-shrinkage, both of which are advantageous for application to large-sized exposure stage products. In order to fully recognize AM as industrial manufacturing technologies, it is crucially important for products produced by AM to have

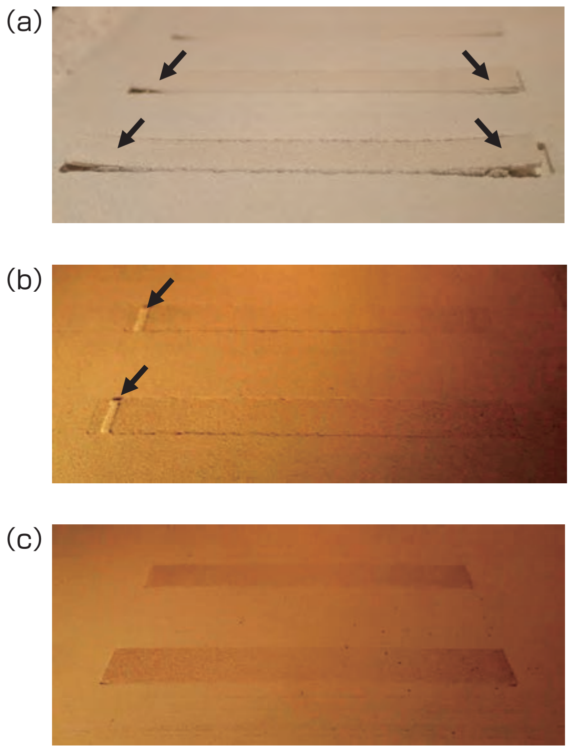


Fig. 7 (a) Warping observed in a green body with nylon-based binder, (b) Sliding of a green body and formation of a gap, (c) Successful formation of a green body embedded in powder. The body is rectangular-shaped with 7 mm width and 50 mm length.

Table 2. Bulk density, Young's modulus, specific stiffness (Young's modulus/bulk density) and flexural strength of PLM-produced SiSiC and conventional one (molding approach).

	PLM	Conventional
Bulk density	3.0	3.0
Young's modulus (GPa)	340	340
Specific stiffness	113	113
Flexural strength (MPa)	290	320

properties equivalent to those of conventional ones. Table 2 compares bulk density, Young's modulus, specific stiffness, and flexural strength of PLM-produced SiSiC with those of the conventionally manufactured high-rigidity SiSiC.[26] It should be noted that specific stiffness, which is the most important property for stage application, equals to that of the conventional ones. R&D should proceed for improving flexural strength to 320 MPa or higher.

One of the advantages of AM is its capability of producing complex-shaped parts directly from computer aided design files or data. Using computer simulation based on structural topology optimization techniques, it is now possible to optimize rib structures of stage models. Figure 9 shows an optimal rib structure obtained thereby in comparison with a conventional one, and a SiSiC exposure stage model (green body) produced by PLM based on that structure.[22] The weight is reduced to half or less while maintaining the same vertical stiffness (the simulation neglects horizontal stiffness). The thinnest part of the model is approximately 3 mm in thickness.

Because of their chemical resistance, durability, and other properties, ceramic filters currently are used for various applications, one of which is in a water-purification device. The water paths of the filters are unidirectional straight channels, simply because they are produced by extrusion molding. Employing the AM techniques, however, enables us to make the channels more complicated, such as, for example, spiral channels as shown in Fig. 10 (a).[1][26] It will bring several potential benefits including increase of contact area between water flow and the channel, local control of water flow (flow velocity, laminar flow vs. turbulence, *etc.*) and others, which may lead to improving the performance and miniaturizing the device. Figure 10 (b) shows an alumina filter model produced by PLM, containing spiral channels of 3 mm diameter, which can be identified from the traces of the cut model.[1][22] Similar filter models have been also manufactured by SLM, and the joining technologies for making a long-sized filter base are also under development.[26]

Besides the above-stated ones, the HCMT project has manufactured several other types of prototype models, including artificial alumina knee joints whose internal surface has salient parts, which were difficult to make conventionally, to improve fixation into bones,[1][27] bone prosthesis with uniform pore size and no closed pores which leads to sufficient infiltration of bone cells and dense bones,[1][27] and ceramic cores for cooling systems of gas-turbine blades with remarkably shortened production time and wide flexibility of the structure design.[1][28]

Notable progresses have been made in direct laser sintering of ceramics as well.[1][29][30] A thin formed layer of alumina with high green density of 83 % has been successfully obtained by dewaxing and drying slurry layer containing

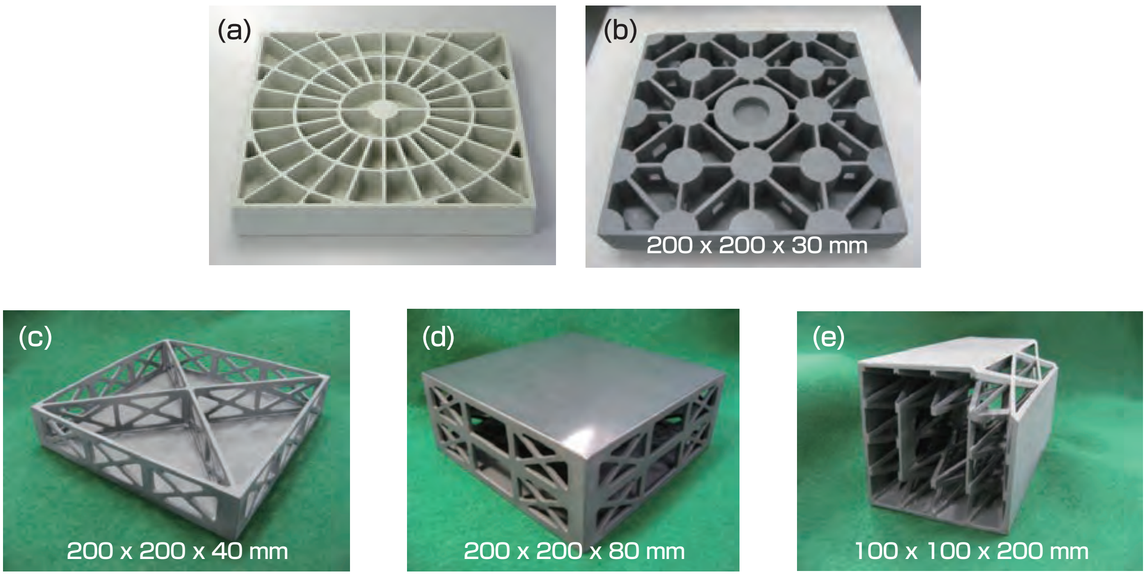


Fig. 8 SiSiC exposure stage models for IC chip production
(a) Conventional rib structure produced by molding approach, (b) PLM-produced rib structure having windows in the walls, and (c), (d) & (e) PLM-Produced truss structure of light weight/high stiffness

optimal mixture of different sorts of alumina powder. Laser-irradiating this highly-packed green alumina layer has led to full densification without such glassy parts, unsintered ones, and cracks as reported previously.[21] The laser absorption coefficient was adjusted by using a proper amount of material having a different coefficient from alumina.

6 Summary and future perspectives

This article describes the R&D strategies and the current achievements on AM of ceramics in the HCMT project, which has been initiated since 2014. The two AM technologies, PLM and SLM, which are advantageous in terms of dimensional accuracy, shape-flexibility, density-controllability, *etc*., are being developed for producing ceramic green bodies. A variety of 3D prototype models for varied target products have been manufactured so far by using the developed AM technologies. Furthermore, intensive research efforts are being devoted to ceramic laser sintering. In order to ensure the developed technologies, 7 and 26 patents have been applied for on PLM and on the HCMT project as a whole, respectively, as of March, 2018.

While AM of ceramics has numerous advantages as already stated, there are also several issues which should be taken into consideration when using it for industrial applications: (1) Profitable almost only for large variety-small amount products, (2) Facilities sometimes can be very expensive, requiring substantial initial costs, (3) Difficult to apply to ceramics, for which melting and solidification are not available in principle, (4) Currently usable only for producing green bodies, which are to be post-sintered in a conventional furnace, (5) Whether AM products give us the same properties as those of conventional ones is not certain, (6) Some restrictions apply to powder used, *e.g.*, the grains should be free flowing, requiring a preferably spherical shape and size of ~50 μm when supplying them to the forming stage in some methods including binder jetting and powder bed fusion. In order to overcome these issues and establish AM as manufacturing technologies in ceramic industry, further R&D efforts are critically required in the future.

Acknowledgements

This work was conducted as part of the “High-Value Added Ceramic Products Manufacturing Technologies” project supported by CSTI, SIP, “Innovative design/manufacturing technologies (managed by NEDO).”

The author, who serves as a leader of the AM group of this project, is most grateful to the participants for their courtesy of allowing him to describe their achievements in this article.

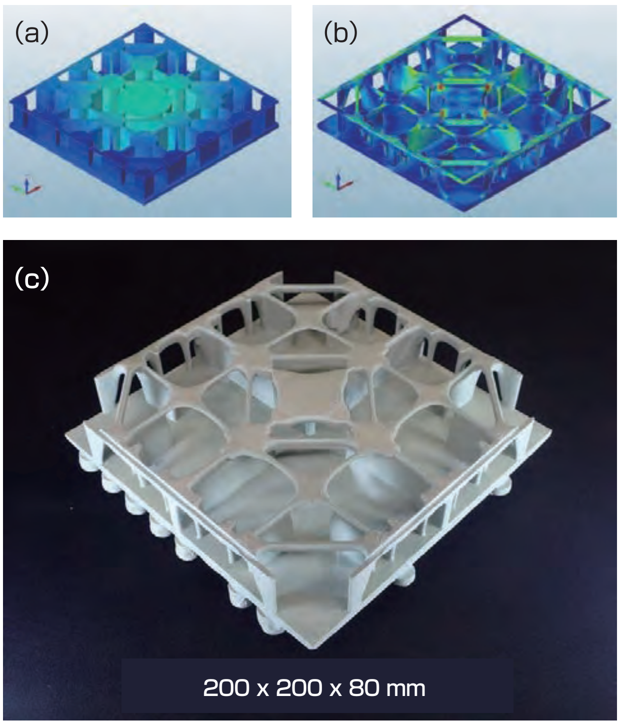


Fig. 9 (a) Conventional rib structure, (b) Optimal rib structure obtained by computer simulation based on structural topology analysis, and (c) an SiSiC exposure stage model (green body) produced by PLM based on the structure (b)

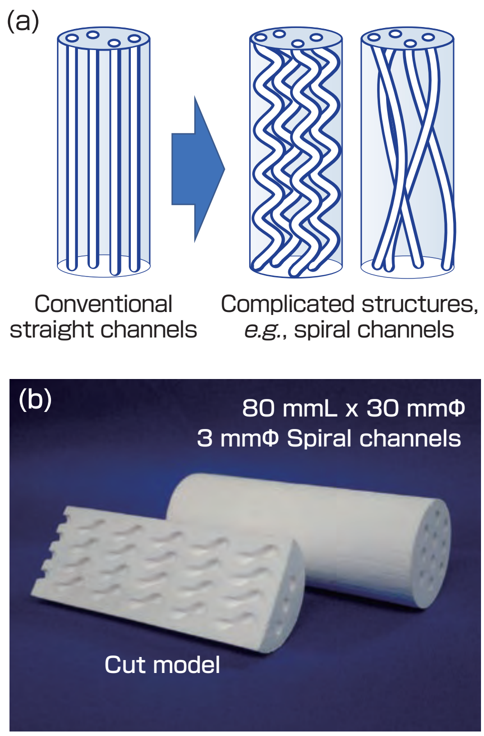


Fig. 10 (a) Conventional water-purification ceramic filter has unidirectional straight channels, while the AM techniques enable more complicated channels, *e.g.*, spiral ones. (b) an alumina filter model produced by PLM, containing spiral channels of 3 mm diameter whose traces are observed in the cut model

References

[1] High-Value Added Ceramic Products Manufacturing Technologies, http://www.hcmt.website, accessed 2017-07-20.

[2] K. Nonomura: Future of ceramics exploited by 3D printer, *Nikkei Monodukuri*, 742, 75–82 (2016) (in Japanese).

[3] T. Ohji: Additive manufacturing of ceramics, *Bull. Ceram. Soc. Japan*, 52 (10), 683–686 (2017) (in Japanese).

[4] J. Akedo and K. Shinoda: Overview: Hybrid coating technologies, *Bull. Ceram. Soc. Japan*, 52 (10), 687–691 (2017) (in Japanese).

[5] S. Singh, S. Ramakrishna and R. Singh: Material issues in additive manufacturing: A review, *J. Manu. Proc.*, 25, 185–200 (2017).

[6] D. Herzog, V. Seyda, E. Wycisk and C. Emmelmann: Additive manufacturing of metals, *Acta Mater.*, 117, 371–392 (2016).

[7] B. Jodoin, M. Brochu, J. Y. Hascoet and T. Palmer (eds.): Special focus on metal additive manufacturing, *J. Therm. Spray Tech.*, 26 (4), 581, 587–626 (2017).

[8] GE Global Research: 3D Printing Creates New Parts for Aircraft Engines, http://www.geglobalresearch.com/innovation/3d-printing-creates-new-parts-aircraft-engines, accessed 2017-07-20.

[9] N. Travitzky, A. Bonet, B. Dermeik, T. Fey, I. Filbert-Demut, L. Schlier, T. Schlordt and P. Greil: Additive manufacturing of ceramic-based materials, *Adv. Eng. Mater.*, 16 (6), 729–754 (2014).

[10] A. Zocca, P. Colombo, C. M. Gomes and J. Gunster: Additive manufacturing of ceramics: issues, potentialities, and opportunities, *J. Am. Ceram. Soc.*, 98 (7), 1983–2001 (2015).

[11] K. Monri and S. Maruo: Three-dimensional ceramic molding based on microstereolithography for the production of piezoelectric energy harvesters, *Sensors and Actuators A*, 200, 31–36 (2013).

[12] S. Kirihara: Stereolithography of ceramic components: fabrication of photonic crystals with diamond structures for terahertz wave modulation, *J. Ceram. Soc. Japan*, 123, 816–822 (2015).

[13] S. Kirihara: Free form fabrication of ceramics components by three-dimensional stereolithography, T. Ohji and M. Singh (eds.): *Engineered Ceramics: Current Status and Future Prospects*, 330–351, Wiley, Hoboken, NJ, USA (2016).

[14] S. Kirihara: Stereolithographic additive manufacturing of ceramic components with functionally modulated geometries, presented at 40th Int. Conf. Adv. Ceram. Compo., Jan. 24–29, 2016, Daytona Beach, FL, USA.

[15] M. Schwentenwein and J. Homa: Additive manufacturing of dense alumina ceramics, *Int. J. Appl. Ceram. Technol.*, 12 (1), 1–7 (2015).

[16] T. Chartier, C. Dupas, M. Lasgorceix, J. Brie, E. Champion, N. Delhote and C. Chaput: Additive manufacturing to produce complex 3d ceramic parts, *J. Ceram. Sci. Tech.*, 6 (2), 95–104 (2015).

[17] G. V. Franks, C. Tallon, A. R. Studart, M. L. Sesso and S. Leo: Colloidal processing: enabling complex shaped ceramics with unique multiscale structures, *J. Am. Ceram. Soc.*, 100 (2), 458–490 (2017).

[18] M. Ahlhelm, E. Schwarzer, U. Scheithauer, T. Moritz and A. Michaelis: Novel ceramic composites for personalized 3D structures, *J. Ceram. Sci. Tech.*, 8 (1), 91–99 (2017).

[19] K. Shahzad, J. Deckers, J.-P. Kruth, and J. Vleugels: Additive manufacturing of alumina parts by indirect selective laser sintering and post processing, *J. Mater. Proc. Tech.*, 213 (9), 1484–1494 (2013).

[20] M. Hotta, A. Shimamura, N. Kondo and T. Ohji: Powder preparation for indirect selective laser sintering of alumina-binder composite powder, presented at 40th Int. Conf. Adv. Ceram. Compo., Jan. 24–29, 2016, Daytona Beach, FL, USA.

[21] B. Qian, L. Taimisto, A. Lehti, H. Piili, O. Nyrhilä, A. Salminen and Z. Shen: Monitoring of temperature profiles and surface morphologies during laser sintering of alumina ceramics, *J. Asian Ceram. Soc.*, 2 (2), 123–131 (2014).

[22] N. Kondo, M. Hotta, A. Shimamura and T. Ohji: Development of powder layer manufacturing technology for ceramics, *Bull. Ceram. Soc. Japan*, 52 (10), 700–702 (2017) (in Japanese).

[23] M. Ahlhelm, H.-J. Richter and K. Haderk: Selective laser sintering as an additive manufacturing method for manufacturing ceramic components, *J. Ceram. Sci. Tech.*, 4 (1), 33–40 (2013).

[24] M. Ando: Development of the ceramic parts by "3D-printing," Ceramic Expo, April 25–27, 2017, Cleveland, OH, USA.

[25] M. Ando, T. Ide and T. Tokizono: Development of ceramic parts for semiconductor manufacturing equipment using powder layer manufacturing, *Bull. Ceram. Soc. Japan*, 52 (10), 716–718 (2017) (in Japanese).

[26] Y. Sato and Y. Fuji: Development of ceramic filters using slurry layer manufacturing and hybrid coating, *Bull. Ceram. Soc. Japan*, 52 (10), 710–712 (2017) (in Japanese).

[27] M. Sato and J. Otsuka: Development of custom-made artificial bone using slurry layer manufacturing, *Bull. Ceram. Soc. Japan*, 52 (10), 713–715 (2017) (in Japanese).

[28] A. Kawahara: Manufacture technology development of the ceramic core by the 3D printer, *Bull. Ceram. Soc. Japan*, 52 (10), 707–709 (2017) (in Japanese).

[29] T. Kimura and S. Suehiro: Development of laser sintering process of oxide ceramics, *Proc. 29th Fall Meeting Ceram. Soc. Japan*, 3T05 (2016).

[30] T. Kimura, H. Miura and T. Goto: Development of ceramic direct manufacturing technologies using laser, *Bull. Ceram. Soc. Japan*, 52 (10), 692–695 (2017) (in Japanese).

Author

Tatsuki OHJI

Joined AIST in 1983, and currently is Fellow thereof since 2017. BS and MS in mechanical engineering from Nagoya Institute of Technology and Ph. D. in inorganic materials engineering from Tokyo Institute of Technology. Has authored more than 350 peer-reviewed papers and 20 book chapters, and has edited more than 40 books and conference volumes. Research interests include mechanical/physical properties, microstructural control, and novel processing of ceramics and related materials. Fellow of American Association for the Advancement of Science (AAAS), American Ceramic Society and ASM International, and Academician of World Academy of Ceramics. Currently serves as Governor of Acta Materialia Inc., Vice President of the Ceramic Society of Japan, and Editor in Chief of *Ceramic International and Journal of the American Ceramic Society.*

Discussions with Reviewers

1 Overall

Comment (Toshimi Shimizu, AIST)

This “report” describes research centered on additive manufacturing (AM), of which the author serves as the leader, of the R&D project on high-value added ceramic products manufacturing technologies (HCMT) of the Cross-ministerial Strategic Innovation Promotion Program (SIP). It is a focused presentation of the technological platform of powder-layer manufacturing (PLM), an AM technology for making ceramic products that have uneven thickness or complex shapes that are difficult to process, and of prototypes made from the technology. It is a very effective presentation in understanding the processes that form PLM and the interconnection of the related technological elements. As a report that presents an example of development of technology that has practical value that is expected to lead to innovation, it is suitable for *Synthesiology*.

Comment (Akira Kageyama, AIST)

Of ceramic technology and industry in which Japan has excelled, this report summarizes the process by which the HCMT project was started as a national strategical project, and how it succeeded, against the decline of Japan’s world market share along with the improvement of technological level of developing countries. It presents the selection of elemental technologies and integration of each technology, focusing on AM as technology that forms ceramic products of complex shapes that were difficult to make with the conventional technology. It is also worth reading as a report on management of R&D in which collaboration and role assignment was necessary among the participating universities, AIST, and companies. Of the necessary technologies covering a wide range, PLM is selected, and it describes in detail, within the allowed range of disclosure, each of the elemental technologies such as the optimization of raw material powder, which is bound by confidentiality. R&D discussion is presented in an easy to understand manner, and it is well worth being printed in this journal.

2 Content, structure, research scenario (draft report)

Comment (Toshimi Shimizu)

The first draft that was submitted as a research paper and the second draft that was submitted as a report did not satisfy the qualities that are required of *Synthesiology*. For a writing to be accepted, it needs to cover seven topics: 1. research objective, 2. research target and relationship to society, 3. scenario, 4. selection of elements, 5. relationship among elements and their integration, 6. evaluation of results and future perspectives, 7. originality. The first and second draft did not cover these. Specifically, 1) for 3. scenario, the scenario of hypothesis was not rationally described; 2) for 5. relationship among elements and their integration, the relationship among elements and integration were not rationally described using scientific words; 3) for 7. originality, much information that was already publicly known was presented and it lacked originality. Therefore, its content as it was unfortunately did not apply to a research paper or a report of Synthesiology, which need to focus on the research scenario and specific research processes. The draft covered the whole R&D of AM, and lacked depth in its description of the scenario and hypothesis, and the relationship and integration among elements.

The reviewer suggests focusing on PLM technology actively being promoted at AIST as a revision of the content of the report. How about using a diagram which would help the reader to understand and describing in detail each elemental technology related to PLM, how they are corelated, and the process by which they are integrated and optimized?

Answer (Tatsuki Ohji)

According to your advice, I revised the text, and in Chapter 4 “Platform technologies in PLM,” I have categorized and described in detail each elemental technology of the three processes of powder preparation, lamination, and post process, have presented the relation to other elemental technologies using a diagram (Fig. 5). Especially with strongly related elemental technologies, they were emphasized in the diagram, and the process by which they were integrated and optimized was described. Evaluation items for each process are also considered. Furthermore, in Chapter 5 “Prototype models produced by AM,” the subject was narrowed down to a ceramic stage model and a ceramic filter model attained by PLM, and other prototype models were simply described along with references.

Comment (Akira Kageyama)

The first draft was submitted as a research paper, and after a review, additions were made, and the manuscript was resubmitted as a report. In the second draft, the significance of the technologies and their positions are easier to understand as more detailed descriptions were added of the R&D that was bound by confidentiality. However, as a report, it needs to strongly state how technology is introduced to society and how it is to be useful, but this point is not expressed clearly. I suggest a revision on this line. If you rearrange and reorganize the structure, the way of expression, and figures and tables, the point of the report will become clear. For example, a report according to the editorial policy needs to present 1) the aim, 2) the process of development (the course to the goal), and 3) the outcome. Keeping this in mind, the report can be arranged to include 1) the global state of ceramic industry and the situation that Japan faces (situation analysis), 2) the issues that need to be solved in order to overcome the situation, and why the issues were chosen (problem analysis), 3) what was decided technically and in management in order to clear or solve the issues (decision analysis), and 4) the results of R&D and management executed in this project with the above-mentioned 1) to 3) in mind (output and/or outcome). The manuscript already includes these aspects, so why not revise the whole structure and try to make it simpler and clearer?

The manuscript is also rather long. In the second draft, as, taking PLM as an example, the relationship and integration of elemental technologies are described, couldn’t the section concerning other R&D related to AM be reduced or deleted by stating that “similar integration of elemental technologies is attempted as PLM”? It is also useful to use references. I also suggest narrowing down examples presented in the Chapter 5 “Prototype models produced by AM.”

Answer (Tatsuki Ohji)

As you pointed out, I have revised the manuscript as follows: The global state of ceramic industry and the situation of Japan, and the significance of the HCMT project in order to break through the situation was described in Chapter 1 “Introduction”; R&D under this project and the managerial system was written in Chapter 2 “Overview of HCMT project”; the technical strategy of AM was summarized in Chapter 3 “R&D strategies for AM of ceramics” and Chapter 4 “Platform technologies in PLM”; and the outcomes up to now were presented in Chapter 5 “Prototype models produced by AM.”

As I have responded to the previous comment, I have focused on the prototype model of PLM in Chapter 5 “Prototype models produced by AM,” and have greatly reduced the descriptions of technologies other than PLM in Chapter 3 “R&D strategies for AM of ceramics,” and have added a sentence that you suggested to the end of Chapter 4 “Platform technologies in PLM.”

3 Technical terms and drawings (figures)

Comment (Toshimi Shimizu)

The readers of *Synthesiology* are not specialists of ceramic technology, but general engineers, researchers, and readers. For the engineers not related to the ceramic field, it would be difficult to understand the various and numerous technical terms that are used throughout this report. Since the report is written assuming that the technical terms are understood, understanding of the content by the general reader would not be deepened with such difficulty. Lack of unity of terms can also be seen.

The shortest course to explain technical terms is to use drawings. Extreme examples are the processes of shaping the raw material, sintering, and the post process, which are nothing special for engineers of the field, need to be explained from the basics by using drawings to the general reader and engineers from other fields. Regarding classification of AM, and technological explanation of PLM and slurry layer manufacturing (SLM), how about organizing technologies with overviews and characteristics by using drawings?

Answer (Tatsuki Ohji)

As you pointed out, I have used drawings in Table 1 “Classification of AM,” and diagrams (Figs. 3, 4) of PLM and SLM of the revised (final) draft. In the diagrams on PLM and SLM, I have used numbers that correspond to explanations in the text. In the related diagram of elemental technologies (Fig. 5), I have also used simple illustrations. Concerning technical terms, they have been unified to the most general terms that are used in the materials field.

4 Intellectual properties (draft)

Comment (Akira Kageyama)

I imagine that there are many intellectual properties generated through this project. Couldn’t you write about this in the last chapter, Chapter 6” Summary and future perspectives”? For example, it can be a phrase like “so and so number of patents on PLM, and so and so number of patents on the HCMT project as a whole have been filed.” Intellectual property is one of the important outcomes of R&D, and is a yardstick to measure international competitiveness of technology.

Answer (Tatsuki Ohji)

As you indicated, I have added the following sentence to Chapter 6 “Summary and future perspectives”: “In order to ensure the developed technologies, 7 and 26 patents have been applied for on PLM and on the HCMT project as a whole, respectively, as of March, 2018.”

Earth science in safety regulations of radioactive waste disposal

—Translation of scientific research to site selection criteria—

Kazumasa Ito

[Translation from *Synthesiology*, Vol.11, No.2, p.94–105 (2018)]

AIST has been supporting scientific aspects of the Nuclear Regulatory Authority (NRA), mainly in regard to the regulation of site selection for radioactive waste disposal. NRA is constructing regulation criteria and examination guides for the disposal of intermediate level radioactive waste (ILW) at intermediate depth prior to the geological disposal of high-level radioactive wastes (HLW). This paper introduces some examples of utilizing AIST's R&D results for regulation of ILW disposal. This paper also presents examples of future tasks by analyzing the differences between the ILW and HLW disposal, and the differences between ILW regulation and criteria in the "Nationwide Map of Scientific Features for Geological Disposal" to categorize areas based on favorability for HLW disposal.

Keywords **:** Radioactive waste disposal, safety regulation, site selection, permission standards, geological event

1 Introduction

Regarding the safety regulation of deep underground disposal of high-level radioactive waste (hereinafter, will be called "geological disposal"), AIST started research to support safety regulation at the Research Center for Deep Geological Environments, since the establishment of AIST in 2001, by gathering scientific findings and by transferring such findings to regulatory agencies. The safety regulation of geological disposal was the responsibility of the Nuclear and Industrial Safety Agency that was also established in 2001. Although there were some changes in the organization of regulatory agencies, the support for research of radioactive waste disposal is being continued by the Research Institute of Earthquake and Volcano Geology, AIST. On the other hand, parts of the R&D for geological disposal project led by the Agency for Natural Resources and Energy are conducted by the Research Institute for Geo-Resources and Environment (GREEN), AIST.

The disposal of radioactive waste is supervised by the Nuclear Regulatory Authority (NRA) that was established in 2012. NRA works on the safety regulation for disposal of reactor components that were contaminated by long half-life radionuclides produced at nuclear power plants scheduled for decommissioning (hereinafter, these will be called intermediate-depth disposal to distinguish from geological disposal). Currently, the regulatory standards and examination guides are being organized by NRA.

The intermediate-depth disposal is similar to geological disposal in the point that it involves burial disposal of radioactive waste underground. Therefore, it was expected that the research results for volcanoes and faults that AIST had been engaging in could be used for geological disposal site location search, but in fact, fault activity results were never directly utilized.

The Designated Radioactive Waste Final Disposal Act (Final Disposal Law) and its enforcing body Nuclear Waste Management Organization of Japan (NUMO) were established in 2000. The cities, towns, and villages throughout Japan were called upon to participate in the literature survey that is the first stage of location search, and while this started in 2002, no actual literature survey has been initiated. Therefore, the government changed the basic policy for final disposal of designated radioactive waste, and decided to select the locations based on scientifically based evidence and to ask the local governments for cooperation to the survey (Cabinet decision May 22, 2015). The requirements and criteria for geological disposal were presented from the perspective of geological suitability, the features that should be considered when conducting geological disposal were extracted based on the existing geological data obtained throughout Japan, and the Nationwide Map of Scientific Features for Geological Disposal was published on July 28, 2017 to provide a general picture of the distribution throughout Japan of such possible locations.

In the future, the Geological Survey of Japan, AIST, conducting safety regulation support research must transfer the research results that can be used for regulatory standards and the review guides for geological disposal to NRA and the secretary

Geological Survey of Japan Research Institute of Earthquake and Volcano Geology, AIST Tsukuba Central 7, 1-1-1 Higashi, Tsukuba 305-8567, Japan E-mail: kazumasa-ito@aist.go.jp

Original manuscript received September 4, 2017, Revisions received May 6, 2018, Accepted May 7, 2018

of NRA that are the regulatory agencies. Therefore, in this paper, in addition to the summary of research results for intermediate-depth disposal, the Nationwide Map of Scientific Features (Scientific Feature Map) is referenced. By considering the common and different points of safety regulation for intermediate-depth and geological disposal, we shall propose how the research results can be transferred smoothly to the regulatory agencies so the research results can be reflected in the safety regulation for geological disposal in the future.

2 Categorization of radioactive waste disposals and involvement of regulation

2.1 Categorization of radioactive waste and disposal methods

The disposal of waste generated by nuclear power plants and fuel processing plants is categorized into Category I (high level) and Category II (medium to low level) radioactive waste disposal, according to the “standard set by law that categorize the radioactive materials according to the radioactivity concentration of the radioactive substance set by law, that may have major effect on human health,” under the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (Nuclear Reactor Regulation Law).

High-level radioactive waste (HLW) consists of spent nuclear fuels that undergo reprocessing in which radionuclides remaining after separation from uranium and plutonium are solidified into glass (vitrified waste). Medium-low level or intermediate level radioactive waste (ILW) includes materials with relatively high radioactivity concentration such as core internals and fuel cladding tubes of nuclear power plants, radioactive metal such as control rod and concrete structures, or radioactive waste that is generated at reprocessing plants and MOX fuel processing plants. Low level wastes include those with low radioactivity concentration such as ventilated air from buildings, washing waste liquid, used paper towels, and used work clothes and gloves.

The disposal methods of radioactive waste are categorized into the following: shallow disposal where waste is stored in trenches or pits dug near the ground surface; intermediate-depth disposal where tunnels are dug at depth of about 100 m that is deeper than the depth at which underground is utilized such as for traffic tunnels; and geological disposal where the waste is disposed in deep underground at depth of 300 m or more. Here, the waste disposed by geological disposal is HLW, as well as ILW or those that contain trans-uranium elements with very long half-life that are generated by MOX fuel processing plants. Intermediate-depth disposal may include ILW with relatively high radioactivity concentration such as core internals from nuclear power plants. The disposal methods are applied according to the half-life and concentration of radioactive materials. Figure 1 shows the schematic diagram of the disposal depth for each type of radioactive waste.[1]

2.2 Involvement of regulation in waste disposal projects

The radioactive waste disposal project is composed of the following phases: siting and design of disposal sites, safety assessment to evaluate future dose levels, construction of underground facilities, transport and burial of waste, closure of facilities, maintenance, and decommission of the project. Figure 2 shows the outline of the regulation at each project stage of the intermediate-depth disposal that is being

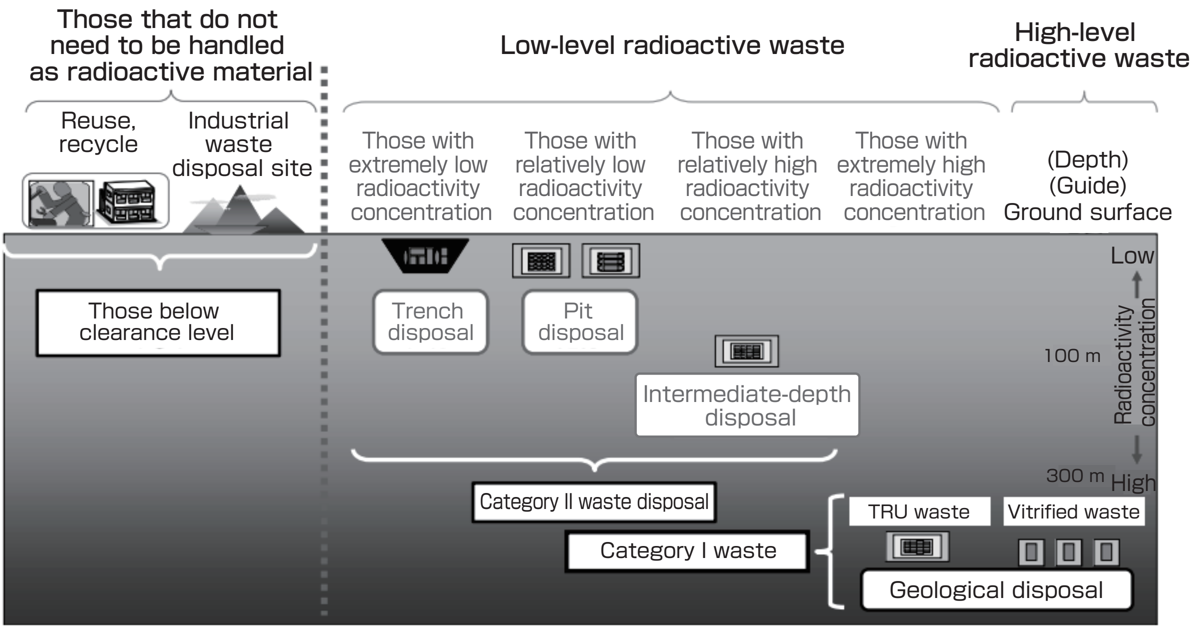


Fig. 1 Categories of radioactive waste and concept for their disposal
Category I and Category II are categorized according to radiation level.[1]

considered by the Nuclear Regulatory Agency.[2] In this system, the period during which the regulation is directly involved starts from the examination of the permit for basic plans submitted by the implementor, and ends at the final confirmation of decommission of the project. In the case of the intermediate-depth disposal, this period is expected to be about 300 to 400 years, and the implementor is expected to dissolve when the decommission procedure is completed and the regulation period ends.

The time course of radioactivity concentration of HLW in geological disposal and that of reactor materials that are objects for intermediate-depth disposal are shown in Fig. 3.[1] Both will decrease to 1/1000 of the initial radioactivity concentration in a few hundred years that is also the completion of the regulatory period. However, the time required for the initial radioactivity concentration to decrease to 1/1,000,000 is about ten million years for HLW and about a hundred thousand years for intermediate-depth disposal waste such as core internals. Therefore, the regulatory criteria of intermediate-depth and geological disposal must have regulations to guarantee there will be no radioactive damage (exposure) even after the completion of the regulatory period. Such regulations must be secured by the selection of the disposal site to avoid leakage of radionuclides due to the effects of volcanic or fault activities, by engineered barriers composed of buffer materials and disposal containers to contain radionuclides and to delay migration of radionuclides, and by site design including natural barriers such as surrounding bedrock.

Regarding intermediate-depth disposal, NRA and the secretary of NRA are preparing regulatory standards that indicate what the implementors must follow for each item, explanation of regulations that show examples that satisfy technological requirements, and an examination guide that provides specific case studies of survey and assessment methods to check compatibility to technological requirements, in order to check the adequacy of the survey and assessment results obtained by the companies. For

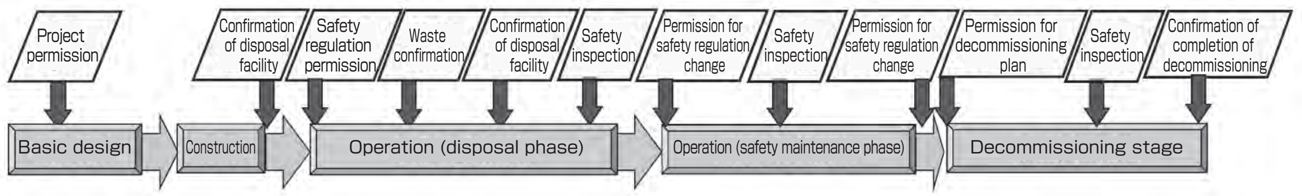


Fig. 2 Examples of procedures that must be taken in regulations of radioactive waste disposal project
Period to termination is assumed to be 300 to 400 years.[2]

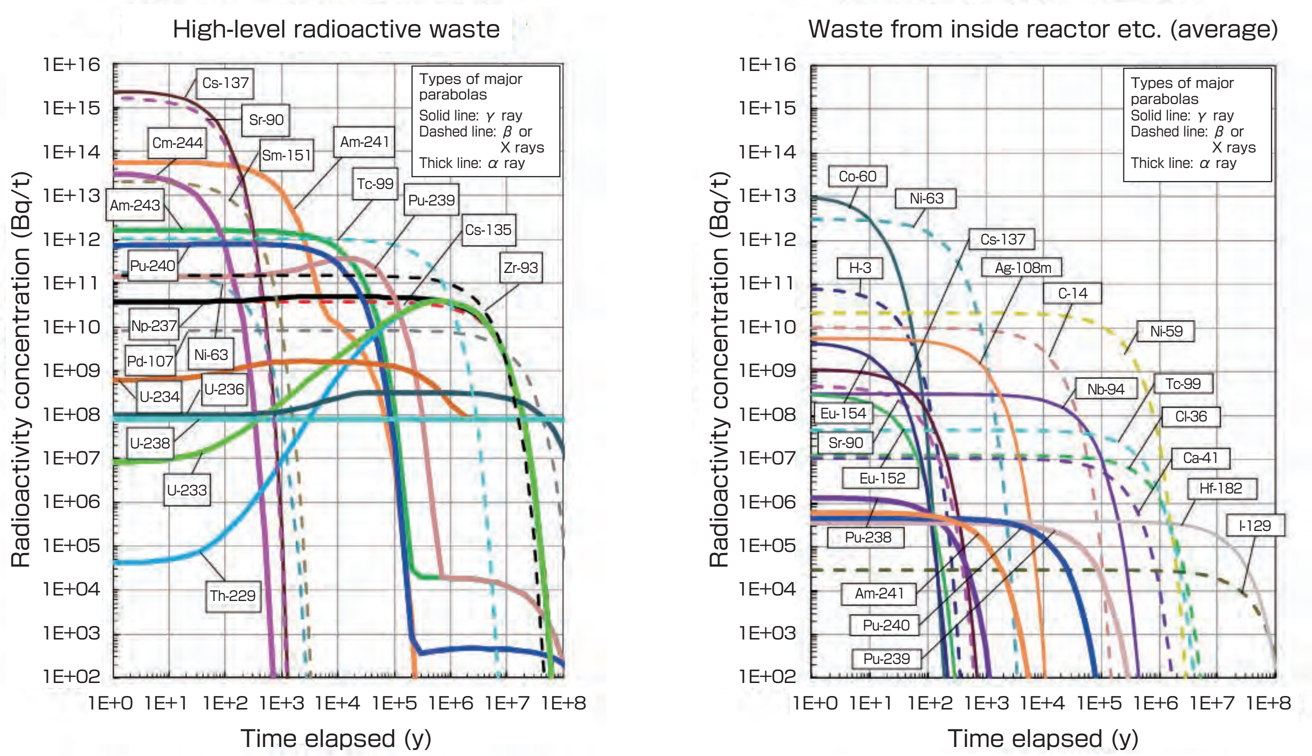


Fig. 3 Relationship between time and radioactivity concentration of radioactive waste, created by Nuclear Regulatory Agency (from [1])

example, in the proposed regulatory standard outline, volcanic activity, fault activity, achievement of depth, natural resources, and other events that must be considered are listed as categorical requirements for disposal site location. Taking one example for volcanic activity, it is stated as follows: "The waste disposal facilities must be set in an area where there will be no significant change in geology due to volcanic activities in the future." According to the explanation, "future" means at least a hundred thousand years, and "there will be no significant change in geology" means that it is determined that no records of volcanic vents or dikes are found in the activity history in the Quaternary Period. It is also stated that the implementor must prove that there will be no expected volcanic activity in the future for at least a hundred thousand years.[3]

In the examination guide, survey and assessment methods are shown as cases of survey to negate the possibility of future volcanic activity based on scientific evidence, in addition to the literature survey, geomorphological survey, and geological survey through databases for areas in the range of 15 km from the disposal facilities.[4]

3 Existing research results and safety regulation for intermediate-depth disposal

3.1 Setting of period during which safety must be maintained after termination of regulatory period

As mentioned in the previous chapter, the concentration of radioactive materials in waste to be buried in intermediate-depth disposal does not decline for a long time. Yet on the other hand, the period in which the regulatory agency can directly be involved through periodical reviews, etc. is about 300 to 400 years or the period to the termination of the disposal project. In Japan, since there is high possibility that the waste materials may come into contact with groundwater over a long period, radionuclides that dissolve may reach the biosphere through groundwater flow over a long period, and this may expose residents to radiation in various ways such as through wells or agricultural products. The regulatory criteria require that the residents' dose level must be at a certain level or lower even after a long period, but as a precondition, the location selected must not be subject to damage from direct hit by fault or volcano activities on the waste disposal site, or must not be subject to geological events in which waste materials are rapidly thrust up to the surface due to ground erosion. The period of at last a hundred thousand years is designated as the time during which such geological event will not occur, in the proposed regulatory standard outline.

In setting this time period, it is important that the predictability is assured for the changes in the radioactive properties of waste materials that will be disposed, the occurrence of volcano and fault activities in the future, and the tendency of uplift and erosion. For the radioactive properties of waste, many of the radionuclides decline to a sufficient level in about a hundred thousand years as shown in Fig. 3. On the other hand, prediction of geological events is difficult. In assessing erosion that directly affects and may change burial depth, in cases in which a hundred or more meter rise of sea level that can be observed in the past sea level change, geomorphic change occurs by lateral erosion and deposition in the horizontal direction in the coastal area, and therefore, it is difficult to predict how the erosion by sea level rise may spread during the next sea level cycle.[5] However, since behavior during the fall of the sea level is relatively predictable, the period of a hundred thousand years was set as the time until the next expected sea level rise would start.

3.2 Outline of regulatory requirements for each geological change events

3.2.1 Regulatory requirements for volcanic activities

For volcanic activities, it is required to check that there is no volcano that was active in the Quaternary Period (about 2.58 million years ago) within a 15 km range of the disposal site, to ensure that no deformation or damage of the waste disposal facilities will occur by the intrusion or ejection of magma in the next hundred thousand years.[3]

AIST analyzed the space-time distribution of past volcanic activities to present features of the fore-arc and back-arc volcanic activities, for example, in the Tohoku region.[5] For the Japanese islands, the "Database of quaternary volcanic and intrusive rock bodies in Japan" that combines survey data and existing data has been published.[6] In the examination guide for intermediate-depth disposal, it is clearly written that a survey utilizing these data must be conducted in the literature survey stage of location search.

3.2.2 Regulatory requirements for fault activities

For the examination guide of nuclear reactors for power generation, the definition of faults that may become active in the future is "those of which activities cannot be denied after the Late Pleistocene (120–130 thousand years ago to present)."[7] On the other hand, for intermediate-depth disposal, as mentioned in Subchapter 3.1, unlike the nuclear reactors for power generation which is expected to be in operation for 40 years in principle, it is necessary to maintain safety for a hundred thousand years into the future.

Looking at the examples of earthquakes in the past, there are cases like the 2003 Northern Miyagi Earthquake that occurred due to a fault which had no clear record of activity in the Quaternary Period,[8] and it was decided that there was too much uncertainty in terms of future prediction to consider the possibility of future activities from the latest activity history only. Therefore, in the examination guide for intermediate-depth disposal, unlike the nuclear reactors for power generation, the fault whose presence is determined in literature or on-site survey should be considered possibly becoming active in the future regardless of its activity history. It is required that the area where the waste material is buried within the disposal tunnel (waste disposal facilities) should be placed outside the fault and peripheral areas that may be affected. However, the lower limit of fault length that must be considered is set at 5 km or more, assuming that safety can be maintained by engineered barriers even if a slip occurs in one activity.

In a case in which a waste disposal facility is placed outside the area of influence of a fault of 5 km or more, i.e. it is compatible with the above-mentioned criteria, it is stated that “in a case where there is a fault near the waste disposal facility, the possibility of extension of the fault must be assessed, considering the form, scale, and activeness of the fault, and its effect on the waste disposal facility.” However, a specific assessment method is not clearly stated in the current proposed examination guide outline.

AIST has engaged in regulation support research mainly for the assessment of reactivation possibility of low-activity faults, including developing methods of assessment using mineral and chemical properties of fault gouge (fracture zone composed of fault clay and fractured rock) in the granite region,[9] and developing methods to assess motion possibilities of faults using mechanical indices (slip tendency[Term 1]), that involves stress that act on 3D fault surfaces.[10] AIST applied this assessment method using mechanical indices to different tectonic blocks in Tohoku, Chubu, Kinki, and other areas.[11] As a result, as shown in Fig. 4, it was shown that the faults, for which the activity history had been confirmed in the Quaternary Period in the Tohoku region, could be extracted significantly by slip tendency in many cases. However, in the Chubu and Kinki regions, the slip tendency was distributed widely in varying scales for faults for which no activity history was recognized in the Quaternary Period. The reasons include the effects of pore water pressure in the fault surface and friction coefficients of faults, or the fact that assessment cannot be done accurately by geomorphological or geological methods, since the activity interval is long despite the presence of activity history during the Quaternary Period. With this in mind, it is concluded that some faults for which activity history is not recognized may become active in the future due to the current crustal stress state. Such analysis is only possible with the results of crustal stress that act on a certain area through observation of micro-earthquakes, in addition to the survey of 3D morphology, etc. of faults, and such research results are representative accomplishments of the Geological Survey of Japan which is capable of gathering and integrating such data.

However, in the examination guide, concerning faults that should be avoided in setting waste disposal facilities, the AIST results were not directly reflected since fault length was employed as the requirement rather than the activity history as mentioned above. This is because there exists conservative judgment about fault activity as mentioned above, there are not sufficient case studies of applying mechanical indices to assessments, and also because there remains uncertainty in setting the stress field and data parameters that are the limiting conditions.

3.2.3 Uplift and erosion

In the underground disposal of radioactive waste as in intermediate-depth and geological disposal, the reduction of burial depth may cause exposure by human intrusion such as boring for wells or underground space use such as for traffic tunnels, although it may not lead to waste material being exposed to the ground surface. Therefore, in the proposed regulatory standard outline for intermediate-depth disposal, the requirements pertaining to future erosion are set in the criteria for location of waste disposal facilities from the perspective of preventing human intrusion.

In the proposed regulatory standard outline, the requirement for depth is 70 meters for a waste disposal facilities for at

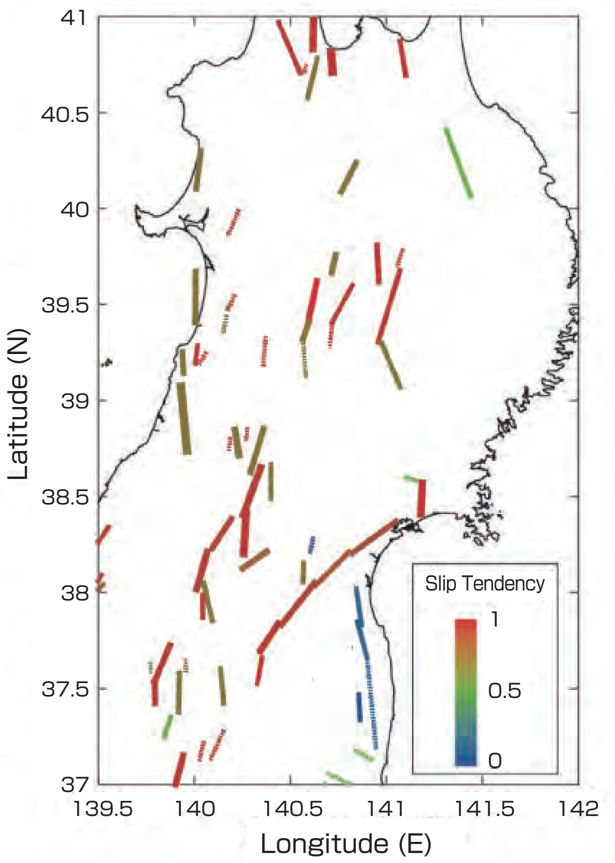


Fig. 4 Results of activity assessment by mechanical index for active faults in Tohoku region. Regional stress field was calculated from the earthquake data before the 2011 off the Pacific Coast of Tohoku Earthquake (East Japan Earthquake) ([10] was partially revised).

least a hundred thousand years into the future, based on experience of underground space use such as for traffic tunnels. Therefore, it is necessary to indicate the standard survey and assessment methods of erosion or uplift level in the past several hundred thousand years by extrapolating from the past, to determine the erosion or uplift quantity that may cause erosion in the next hundred thousand years. In the examination guide, chronology of the marine/river terrace that occurred by past erosion, or geochemical survey conducted as necessary are indicated as survey and assessment methods.

For the dating method that can be applied to the chronology of the index geomorphic surfaces such as marine terraces, AIST is working on the dating of sedimentation of shallow sea deposits by an optically stimulated luminescence method using potassium feldspar,[12] and the increased precision of uplift rate assessment of the past several hundred thousand years based on the determination of the sea level index by detailed analysis of the sedimentary facies.[5] On the other hand, for the method for directly assessing the rate of regional erosion in a several hundred thousand year time scale, we have conducted research on assessment using depth distribution of cosmogenic nuclides that were formed by the exposure of rocks near the ground surface to cosmic rays.[13]

For the former, in the chronology of index geomorphic surfaces, the general method is to detect wide-spread tephra[Term 2] for which dates are known from the terrace composition, and to indirectly estimate the stage of sea level change when the geomorphic surface was formed. However, there was a problem that in many cases, there was no tephra that might serve as the dating index in the old geomorphic surface that has undergone several cycles of sea level change. The research conducted by AIST allows assessment of the formation age of the geomorphic surface by directly assessing the sedimentation age of sediments, to enable application to such surfaces. The general luminescence method using quartz particles has a measurement limit of about a hundred thousand years,[5] and it was not possible to conduct sufficient assessment of the uplift and erosion for at least a hundred thousand years into the future. However, it became possible to expand the applicable limit to several hundred thousand years ago using the luminescence method by looking at the potassium feldspar particles. To precisely conduct prediction of future hundred thousand years by extrapolation from the past, it is necessary to precisely assess the uplift rate and the chronology of the geomorphic surface to at least several hundred thousand years in the past. This will increase the accuracy of the prediction for future hundred thousand years, and we have been able to provide results that may serve as scientific evidence for determining the adequacy of the method for selecting the actual disposal site location, in areas where the chronology by tephra is particularly difficult.

For the latter, measurement of cosmogenic nuclides is an assessment method independent from the sea level change. In the proposed examination guide outline, an example of a survey and assessment method that should be applied to check the adequacy of application filed by the implementors is shown, as a method that can directly assess the erosion rate and that is applicable even in cases where a clear index geomorphic surface cannot be observed. However, for the application to radioactive waste disposal, there are many issues that must be solved such as the investigation of space scale to which individual erosion assessment can be applied. Also, it is necessary to accumulate knowledge for the prediction of erosion in the horizontal direction in the next hundred thousand years by lateral erosion and river erosion in the coastal area accompanying sea level change, as these are difficult to assess with the current erosion assessment method.

3.2.4 Other geological events, etc.

In the proposed examination guide outline, large-scale mass movements[Term 3] and mud volcanoes[Term 4] are listed as events that may cause a site to be excluded as a disposal site location, other than the aforementioned geological events. Also, although not included in the exclusion conditions, the events for which impact assessment will be done considering the location condition include hydrothermal activities, crustal fluid flow, climate change, and sea level change, and individual safety assessment include THMC or the thermal, hydrological, mechanical, and chemical properties.

For such individual factors, AIST published a large-scale mass movement database[14] and a mud volcano database,[15] and is engaging in organizing the knowledge that may be used for the examination. For hydrothermal activities and crustal fluid flow, a database is made for the upwelling area of slab-derived aqueous fluids in the Japanese islands, and the origin and chemical properties of crustal fluids in the Japanese islands are categorized.[16] In the future, not only detecting the presence of crustal fluid upwelling but also developing an assessment method for the possibility of future upwelling of crustal fluids and the chemical properties when this occurs is necessary. Also, it is necessary to consider the accelerated dissolution of radionuclides into groundwater, or the possibility of the decreased function of engineered barriers such as bentonite to isolate or delay the dissolution of radionuclides, due to the relatively shallow disposal depth and the surrounding groundwater becoming an oxidizing environment.

On the other hand, technological summary and development of a method using drilling surveys and geophysical exploration of the so-called baseline survey before artificial disturbances occur due to construction of underground disposal facility have been done for the THMC properties.[5] Particularly, for hydrological properties, detailed investigation has been done for the assessment method of influence on abnormal pore water pressure, groundwater flow, and solute transport.[17] In the baseline assessment of such underground environment and long-term change prediction, research is being done on hydraulic and geochemical properties that may be a problem in safety assessment, and on the assessment method for predicting their long-term change. It is necessary to then organize the results so they will be reflected in the examination guide for survey and monitoring for which organization and revisions will be done in the future.

4 Ways of reflecting results to regulation of geological disposal

4.1 Common and different points in safety regulation compared to intermediate-depth disposal

The way of thinking about the regulation for geological disposal is characterized by the fact that the concentration of long-term half-life radionuclides in HLW is several digits higher compared to intermediate-depth disposal. Since the specific required depth and assessment period in geological disposal is considered different from those of intermediate-depth disposal, further technological investigation is necessary. However, as basic measures for protecting the living environment and the general public over a long period, the way of thinking about requesting measures to implementors concerning isolation and containment design is the same as the ones for intermediate-depth disposal.[1] Here, the differences in specific technological issues will be clarified between geological and intermediate-depth disposal, as we analyze the technological requirements of safety regulations for geological disposal and the issues in reflecting our research results in the regulations.

The “Nationwide Map of Scientific Features for Geological Disposal (Scientific Feature Map)”[18] published by the Agency for Natural Resources and Energy is a map to provide a general, bird’s-eye view on what scientific features must be considered when selecting sites for geological disposal, and how such possible sites are distributed throughout Japan. The requirements and criteria for undesirable ranges are shown, for example, for each topic such as volcanic, magmatic, and fault activities.[18] The Scientific Feature Map shows the overall geological feature distribution from existing data obtained at a national scale, as a preceding argument to the official selection of sites by the disposal companies. On the other hand, the regulatory criteria are criteria by which an implementor is examined after it conducts geological surveys for site selection and determines a disposal facility location, and the objectives of the two are greatly different. Therefore, simply arguing the differences for individual requirements by directly comparing the two criteria is not meaningful. However, comparing the requirements that must be considered when conducting geological disposal and the geological conditions for safety regulations of intermediate-depth disposal may be useful as reference when extracting the technological issues necessary to investigate the regulatory criteria for geological disposal in the future.

The requirements and criteria of the Scientific Feature Map and the regulatory criteria for intermediate-depth disposal are compared in Table 1. This will serve as the basis of discussion pertaining to the research issues that will be necessary in setting the regulatory criteria for geological disposal that will be organized in the future. As mentioned earlier, the two have different types of waste, and the Scientific Feature Map is presented from the standpoint of site selection that is determined from the available nationwide data at this point, while the regulatory criteria are used to determine the compatibility of the disposal site selected after the surveys are completed. It is necessary to notice the difference in the viewpoints as well as the stages in which the requirements and criteria are used.

For the time scale to be considered, in the report that summarizes the discussion for the Scientific Feature Map,[19] it is written, “The geological environment of disposal site scale must have features of a suitable locational environment where functions of engineered barriers can be maintained for a certain period, and natural barriers can prevent dissolving and transferring of radioactive materials. Moreover, such characteristics must remain within a tolerable range as they may change in a long time scale of several tens of thousands of years.” It is stated that no major change should occur in the delay characteristic of bedrock that will be the natural barrier for at least several tens of thousands of years. In the Scientific Feature Map, there is no clear result of the discussion on time scale because its objective is to provide an overview of scientific features to be considered and their distribution. However, a hundred thousand years is set as a time scale since the uplift volume of 300 m for a hundred thousand years is used as a criterion in uplift and erosion. On the other hand, for intermediate-depth disposal, as described in Subchapter 3.1, a hundred thousand years is considered from the perspective of predictability of depth reduction due mainly to erosion and the reduction of radioactivity concentration. Considering the characteristics of waste in geological and intermediate-depth disposal, for geological disposal, the time scale should be equivalent to or longer than that of intermediate-depth disposal.

Looking at the individual natural events in Table 1, for volcanic and magmatic activities and mineral resources, almost the same criteria are set for the two. On the other hand, in fault activity, the Scientific Feature Map assumes that “a fault that has repeatedly been active, has high possibility of being active in the future, that has large deformation must be avoided,[18]” and sets active faults and fracture zone widths (1/100 of length of fault on both sides) as undesirable areas that will be affected. However,

Table1. Comparison of requirements and criteria for individual geological events in the Nationwide Map of Scientific Features for Geological Disposal and the regulatory standards of intermediate-depth disposal

Precondition and assessment item	Conditions of undesirable range in the Nationwide Map of Scientific Features (categorization of features from the perspective of geological disposal)	Regulatory standard and examination guide for intermediate-depth disposal (NRA)
Objective and stage of use	Interactive activity to deepen understanding of general public in preliminary stage of official site location setting by the company	Safety examination for permit application by implementors
Base data	Literature data to fulfill the following conditions 1) Quality is established (perspective of trust) 2) Inter-regional data are objectively comparable through systematic organization at national scale (perspective of fairness among regions) 3) Generally available at this point (perspective of transparency and verifiability)	Survey and literature data after the implementor engages in actual location survey
Time scale of safety requirement	Delaying characteristic of natural barrier can be maintained for period of several 10,000 years; 100,000 years for uplift and erosion	At least 100,000 years
Volcanic and magmatic activities	· 15 km from center of Quaternary volcano · Range of caldera where the Quaternary volcanic activity range is over 15 km	· Region with record of Quaternary volcanic vents and dikes · Region where volcanic activity may occur in the next 100,000 years based on time-space distribution of Quaternary volcanic activities
Fault activity	· Range with leeway of 1/100 of seismogenic fault length or active segment length	· Range subject to the effect of fault length of 5 km projected onto ground surface, or its mechanical effect (distance from subject fault is maximum 1/100 of the length of fault)
Uplift and erosion	· Region with more than 300 m erosion volume by uplift and sea level decrease in the next 100,000 years (perspective of rising of site to ground surface)	· Maintain depth of 70 m during the next 100,000 years · Consider lateral erosion by sea level change (perspective of depth at which underground is used for traffic tunnels etc.)
Geothermal activity	· Geothermal gradient where the buffer material temperature cannot be kept below 100 °C at disposal depth	· Region in which geothermal resources that can be used for electric power generation are present · Although heat characteristics are not exclusion conditions, effect must be assessed while considering the condition of location
Volcanic hydrothermal activity, deep groundwater flow	· For groundwater characteristic ranges, pH less than 4.8 or carbonate concentration 0.5 mol/L or higher	· Not an exclusion condition, but effect must be assessed while considering the condition of location
Nonconsolidated sediments	· Range to which strata after Middle Pleistocene are distributed at depth 300 m or deeper	· Not an exclusion condition, but effect must be assessed while considering the condition of location
Pyroclastic flow etc.	· Range at which Holocene pyroclastic flow sediment, volcanic rock, volcanic debris are distributed	· Range of distribution of Holocene pyroclastic sediments etc. for surface facilities · Although not exclusive, item is important in assessing the performance of disposal system in actual geological survey
Mineral resources etc.	· Range at which mineral resources with large reserves, as designated by the Mining Laws, that can be technically mined are present in the literature data that was organized at a national scale	· Set in area where significant natural resources are not found · Natural resources are resources that are currently used in society, or those that may be potentially used in the future

in intermediate-depth disposal, faults with length of 5 km or more and mechanically affected areas (1/100 of length of maximum fault surface on one side) are set as conditions to be avoided. In the difference in fault to be targeted, the criteria of Scientific Feature Map is based on the active fault database obtained on a nationwide scale at this point, while the criteria for intermediate-depth disposal is based on the way of thinking that a fault, which has a certain length or more, has the possibility of becoming active in the next hundred thousand years, after the 3D structure of a fault including its surrounding area has been revealed through an actual survey. For the range of effect of fault activity, the Scientific Feature Map assumes the width of the fracture zone from the fault length of the database and uses this as the criteria of undesirable factors for geological disposal, while the intermediate-depth disposal assumes the surrounding damage area as well as the fracture zone by survey, and employs this way of thinking that the maximum width of assumption is 1/100 of the length of the fault on one side.

For uplift and erosion, the values for standard erosion are different according to the depth of disposal. The Scientific Feature Map sets the criteria of an undesirable range area as having high possibility that erosion by lowered sea level and uplifting will surpass 300 m in the next hundred thousand years, while the intermediate-depth disposal sets as requirement to maintain the depth deeper than general underground use in the next hundred thousand years, as mentioned in Section 3.2.3. They are in common in the point that they require that the disposal facilities and waste materials do not rise close to the ground surface in the future.

In other items, for geothermal activity, hydrothermal activity, crustal fluid flow, unconsolidated sediments, and pyroclastic flow, specific criteria are shown in the Scientific Feature Map, while for the intermediate-depth disposal, there are no exclusion conditions, and these items are set as individual site features that must undergo safety assessment. However, particularly for hydrothermal activity and crustal fluid flow, problems remain in the assessment method of future activities and current water quality in the disposal depth, and in the setting method of geochemical properties for conducting safety assessment.

4.2 Requirements that must be considered for safety regulation of geological disposal

After the regulatory criteria and guide for intermediate-depth disposal are organized at the regulatory agencies, there is the possibility that the regulatory criteria on geological disposal will also be organized due to the social trend and demand as shown in Chapter 1. Since the geological events that must be considered for both intermediate-depth and geological disposal are similar, even in the case where the regulatory criteria of geological disposal are organized based on the standard of the intermediate-depth disposal, it is necessary to take notice of the following items.

4.2.1 Time scale to be considered

HLW requires a long period for the radioactivity concentration to decrease compared to waste materials of intermediate-depth disposal, and it is thought that the time scale to be considered for regulatory criteria should be equivalent or much longer than that of the intermediate-depth disposal. As an example, the Swiss Nuclear Regulatory Safety Inspectorate (Eidgenössisches Nuklearsicherheitsinspektorat = ENSI) states in the “Specific design principles for deep geological repositories and requirements for the safety case (ENSI-G03)” that the safety standards should be satisfied for at least one million years. In the Japanese islands, since there are regional characteristics in the predictability of geoscientific events pertaining to locational criteria, it may be necessary to clarify the predictable period for each event at a certain probability, and to present a methodology to assess safety in the future when uncertainty increases. When investigating the geological events at one million year scale, it is necessary to expand the range of investigation to the continuity and future changes of plate movements that are the basic driving force of geological phenomena for the entire Japanese Archipelago. An example of the existing research result by AIST for this issue is the research result of plate movement around the Japanese islands, changes of crustal movement, and future prediction.[20] Here, by reproducing the crustal and plate movements of the past 25 million years, the predictability of future plate movement is assessed, and it is shown that there is no active evidence that shows the possibility of crustal change due to plate movements for the next hundreds of thousands of years, and therefore, it is shown that at least in the next hundred thousand years, the current framework is likely to be maintained. The plate movement and the accompanying crustal movement are basic factors of natural events that must be considered in the regulatory criteria, and therefore, it is necessary to show the range of long-term uncertainly and the period of predictability for natural events that may affect the disposal site, under preconditions of future predictions.

4.2.2 Effect of depth difference

While the assumed disposal depth of intermediate-depth disposal is about 100 m, the geological disposal is assumed at a “stratum 300 m or more underground set by the ordinance” in the Final Disposal Act. While groundwater flow at depth of 100 m are circulation of water originating from meteoric water in many cases, when the depth increases, abnormal pore water pressure occurs in the sedimentary rock region, as mentioned in Section 3.2.4, and in many cases, it is not simple circulation of meteoric water. Depending on the cause of the abnormal pore water pressure, there may be cases where a conventional numerical analysis model cannot be applied to the groundwater flow and migration of radionuclides. It is necessary to assess the cause of abnormal pore water pressure when it is observed, and the knowledge must be gathered concerning the effects on groundwater flow and mass transfer, and these must be reflected in the examination guide.

In a case where there is no significant effect of heat and chemical fields on groundwater flow even with increased depth, the hydraulic gradient is relatively small compared to the ground surface, the hydraulic conductivity tends to be small, and the flow rate of groundwater tends to be slow.[19] In the intermediate-depth disposal, for the investigation of groundwater flow analysis results and the setting of the route of radionuclide transfer, it is required in the examination guide to provide explanation using the information for hydraulic head, water chemistry, and groundwater age, etc. as well as their analytical investigation. For geological disposal, longer time is required compared to the case of intermediate-depth disposal for the groundwater recharged from the ground surface to reach the required depth. Moreover, the groundwater at disposal depth may be a mixture of meteoric water, and water derived from multiple origins such as seawater and crustal fluids, and it is urgently necessary to conduct groundwater age assessment using multiple isotopes, and to build a method to organically integrate the results of numerical analysis and groundwater age assessment, as a result of change in underground environment through uplift, erosion, and sea level change.

5 Transferring to safety regulation frameworks

To have the research results of research institutions reflected in the regulatory standards and guides is primarily what the regulatory agencies do. On the other hand, the preparation of regulatory standards and examination guides for disposal site selection requires the knowledge of wide-ranging fields including geology, geomorphology, seismology, volcanology, quaternary studies, hydrogeology, geochemistry, and others. The regulatory agencies must collect the latest research results in those fields, organize them, and create the regulatory standards and examination guides. Therefore, the Geological Survey of Japan, the leading research institution for geosciences in Japan, must provide scientific support by delivering the results in response to the demands of regulatory agencies, and this is effective in raising the expertise of the regulatory agencies in the future. Here, topics on the regulation of geological disposal that must be organized in the future and must be addressed by a research institution, and ways of transferring scientific findings will be discussed and summarized.

The regulatory standards and examination guides, taking the example of intermediate-depth disposal, are composed of items to be examined and assessed (geological events and environments that are subjects of examination and safety assessment), examination criteria (period for assessment and exclusion standard for each event), and survey and assessment methods that must be conducted to verify compatibility. Here, the author extracts the investigation items to be added to the regulatory standards and examination guides for intermediate-depth disposal.

For examination and assessment items, as mentioned in Chapter 4, it is necessary to extract the detailed topics unique to geological disposal considering the difference between geological and intermediate-depth disposals, and present the assessment method for the geological events that must be considered in the regulatory criteria of intermediate-depth disposal. One example is the hydrothermal activity and crustal fluids that are shown in the Nationwide Map of Scientific Features. Although the final determination of whether to make an item an exclusion condition of disposal facility location will be done by the regulatory institutions, AIST must continue investigation on whether it is possible to set specific criteria for a long period surpassing a hundred thousand years into the future, or whether it is possible to do specific surveys and assessment during the site selection survey stage.

For the examination criteria, when regulatory agencies set the assessment period, first, it is important to understand the period that can be assessed for a geological event occurrence, as shown in Section 4.2.1. Next, as a discussion of possibility of occurrence during the assessable period for each event, the assessment will be done for future events through the assessment of time-space distribution of past activities. The research results of AIST include, for example, the database for volcanic activities as shown in Section 3.2.1, or cases in which time-space distribution of events that occurred in the past can be assessed. However, when conducting long-term prediction, it is necessary not only to simply extrapolate the events that occurred in the past into the future, but also to make assessments by understanding the mechanism by which the events occur and the history of structure development in the region.[21] Therefore, AIST must present a long-term prediction method for each natural event basing it on future predictions of crustal movements at a Japanese island scale, as shown in Section 4.2.1. The regulatory agencies will then show the period during which assessments should be made and the minimum criteria for exclusion (for example, depth that should be maintained during the assessment period considering the effect of erosion), and the judgment indices etc. during a long period when uncertainty will increase.

For example, the criteria of fault activities in geological disposal differ from volcanic activities[5] etc., for which it is thought there are regions where assessment of the next hundred thousand years is possible from past history, and there is a possibility that only fault length will be considered, as in intermediate-depth disposal, rather than activity history or possibility assessment of activity. In that case, it will be difficult for fault activity assessment by mechanical indices conducted by AIST to be applied directly to establishing the criteria. However, similar to the examination guide for intermediate-depth disposal, when the criteria are set for assessing the impact of fault activity near the waste disposal facilities, it is necessary to assess the activity of peripheral faults, extension, and the possibility of connection of plural faults. Currently, there are few cases in which such research has been done, not only at AIST, but also around the world, and this will be an important topic in supporting regulatory agencies. Therefore, it is necessary to develop the fault activity assessment method by mechanical indices, evaluate the relationship between fault activities and fault extension, investigate stress change that influences fault activities, and publish the results, so the methodologies of assessment and criteria pertaining to the effects of peripheral faults can be reflected in the examination guides etc.

For survey and assessment methods, as in the example shown in Chapter 3, some of the AIST results have been utilized in the examination guide for the current intermediate-depth disposal. A particularly important topic in geological disposal compared to intermediate-depth disposal is the assessment of slow groundwater flow at disposal depth. Particularly, the effect of factors such as uplift and erosion, sea level change, fault activities, etc. on survey results of hydraulic head, water chemistry, and groundwater age in deep underground must be extracted and organized from the results of hydrogeological surveys that AIST has conducted so far. By presenting the points to take notice in the survey and assessment corresponding to individual hydrogeological structures, it is necessary to have them reflected in the examination guide for site selection surveys and future groundwater monitoring.

While the subject is intermediate-depth disposal, after the start of investigation of specific regulatory criteria, transferring of AIST research results to regulatory agencies has been insufficient, even considering the difference in the regulatory criteria proposed for fault activities and the setting of research topics by AIST. The main reason is because the priority of regulation became temporarily unclear for radioactive waste disposal due to the change in the organization of the regulators, information exchange between regulatory agencies and AIST became insufficient, and quick response to organizing regulatory criteria became difficult. For example, for the criteria of intermediate-depth disposal location, the period from serious discussions with external experts to the publication of proposed regulatory standard outline is about three months at regulatory agencies. Since the direction is set in a relatively short period, quick response in a research project that is conducted on a fiscal year basis is difficult. For transferring research results of AIST, we are painfully aware of the need to deliver scientific findings that match the demand of the criteria and guide, as well as proposals of new research topics, through regular communication with regulatory institutions that utilize such research results. Also, through such information exchange, the author believes we can help train regulatory agency personnel who do not specialize in geology.

In the future, as groundwork for discussion with the regulatory agencies, we shall publish technological reference materials that summarize the current latest science and technology including the results of AIST, and provide materials that can be easily used by the regulatory agencies, like the databases that are continuously organized that visualize survey data. Personally, we wish to play the role of remodeling the scientific research results of AIST into knowledge that can be easily used in organizing and examining the regulatory criteria, and would like to propose and set topics that allow flexible response to the policy changes at the regulatory agencies.

Terminologies

Term 1. Slip tendency: Index calculated by the ratio of normal stress and shear stress that act on the fault surface calculated from the stress state, strike and dip of a fault, and pore water pressure acting on the fault plane.[22] In general, it is normalized by the friction coefficient, and is expressed as values 0 to 1. A fault that has large slip tendency is evaluated as likely to become active under the current stress state.

Term 2. Tephra: A general term for volcanic debris deposited on the ground surface after being released from a crater and traveling through air at the time of volcanic eruption. Tephra during a massive eruption may be observed as an independent stratum even in areas that are over several hundred to several thousand kilometers away from the supply source, and such stratum is used in dating as well as to compare ground surfaces.[23]

Term 3. Mass movement: A phenomenon in which rock mass that comprises a slope moves downward by gravity, as seen in landslides and collapse of volcanic edifices. This occurs when the shear force against the rock on the slope surpasses the shear force resistance. Large scale movements are known to have reached moving clod volume of 10 km3, moving distance of 10 km, and depth of sliding surface of 100 m.[5]

Term 4. Mud volcano: Mud volcano is a volcano-like structure that appears on the ground surface, as the underground mud with abnormally high pore fluid pressure pushes the above layers upward in a dome shape, and eventually erupts on the ground along with groundwater (thermal water), flammable gas, or, in some cases, oil. The deposit (convex) or depression (concave) geomorphologies may reach maximum height of several hundred m and diameter of several km.[5]

References

[1] Nuclear Regulation Authority: Dai 27 kai hairo to ni tomonau hoshasei haikibutsu no kisei ni kansuru kento team kaigo sanko shiryo 27-2-2: Ronai to haikibutsu no maisetsu ni kakawaru kisei no kangaekata ni tsuite (kaitei an) [Reference 27-2-2: Approach on the regulation for burial of waste materials from reactors, etc. (Revised), 27th Meeting of the Study Team for Regulation of Radioactive Waste in Decommissioning] (2017), http://www.nsr.go.jp/disclosure/committee/yuushikisya/hairo_kisei/00000028.html, accessed 2017-11-06 (in Japanese).
[2] Nuclear Regulation Authority: Dai 1 kai hairo to ni tomonau hoshasei haikibutsu no kisei ni kansuru kento team kaigo shiryo 1-1: Dai 2 shu haikibutsu maisetu ni kakawaru kisei seido no gaiyo (Reference 1-1: Outline of regulations pertaining to the burial disposal of Category II waste, 1st Meeting of the Study Team for Regulation of Radioactive Waste in Decommissioning) (2015), http://www.nsr.go.jp/disclosure/committee/yuushikisya/hairo_kisei/20150126.html, accessed 2017-08-16 (in Japanese).
[3] Nuclear Regulation Authority: Dai 27 kai genshiryoku kisei iinkai rinji kaigi shiryo 3: Dai 2 shu haikibutsu maisetu ni kakawaru kisei kijun to no kosshi an (Reference 3: Proposed outline of the regulatory criteria etc. pertaining to the

burial disposal of Category II waste, 27th Special Meeting, Nuclear Regulatory Authority) (2017), http://www.nsr.go.jp/disclosure/committee/kisei/00000258.html, accessed 2017-09-22 (in Japanese).

[4] Nuclear Regulation Authority: Dai 27 kai genshiryoku kisei iinkai rinji kaigi shiryo 4: Chushindo shobun ni okeru haikibutsu maisetsuchi no ichi ni kakawaru shinsa guide no kosshi an (Reference 4: Proposed examination guide outline pertaining to the location of waste burial disposal site in intermediate-depth disposal, 27th Special Meeting, Nuclear Regulatory Authority) (2017), http://www.nsr.go.jp/disclosure/committee/kisei/00000258.html, accessed 2017-09-22 (in Japanese).

[5] Research Core for Deep Geological Environments (ed.): Technical report on the review and assessment features: Towards the submission of the preliminary field investigations of HLW geological disposals, *GSJ Open File Report*, 560, Geological Survey of Japan (2011) (in Japanese).

[6] K. Nishiki, J. Itoh and T. Ueno (eds.): Database of Quaternary volcanic and intrusive rock bodies in Japan, *GSJ Interim Report*, 60, Geological Survey of Japan (2012) (in Japanese).

[7] Nuclear Regulation Authority: Shikichi nai oyobi shikichi shuhen no chishitsu chishitsu-kozo chosa ni kakawaru shinsa guide (Examination guide pertaining to the survey of geology and geological structures on site and near site) (2013), https://www.nsr.go.jp/disclosure/committee/kettei/02/kisei_naiki.html, accessed 2017-08-16 (in Japanese).

[8] N. Kato, H. Sato, T. Imaizumi, Y. Ikeda, S. Okada, K. Kagohara, K. Kawanaka and K. Kasahara: Seismic reflection profiling across the source fault of the 2003 Northern Miyagi earthquake (Mj 6.4), NE Japan: Basin inversion of Miocene back-arc rift, *Earth Planets Space*, 56, 1369–1374 (2004).

[9] M. Manaka, K. Fukushi, Y. Miyashita, J. Itoh, Y. Watanabe, K. Kobayashi and A. Kamei: Comparison of fault gouges in the aftershock area and the non aftershock area of the 2000 Tottori-ken Seibu earthquake, *Jour. Geol. Soc. Japan*, 118 (8), 459–475 (2012) (in Japanese).

[10] A. Miyakawa and M. Otsubo: Applicability of slip tendency for understanding long-term fault activity: A case study of active faults in northeastern Japan, *Journal of JSCE*, 3, 105–114 (2015).

[11] A. Miyakawa and M. Otsubo: Evolution of crustal deformation in the northeast-central Japanese island arc: Insights from fault activity, *Island Arc*, 26 (2), e12179 (2017).

[12] K. Ito, T. Tamura, T. Kudo and S. Tsukamoto: Optically stimulated luminescence dating of Late Pleistocene tephric loess intercalated with Towada tephra layers in northeastern Japan, *Quaternary International*, 456, 154–162 (2017).

[13] K. Shiroya: An application of terrestrial cosmogenic nuclides to stability assessment of long-term geological environments, *Chikei*, 35 (2), 187–197 (2014) (in Japanese).

[14] H. Tsukamoto: Database for large-scale mass movements in Japan, *GSJ Open File Report*, 543, Geological Survey of Japan (2011) (in Japanese).

[15] M. Takahashi, T. Kirita, J. Daimaru and K. Kazahaya: A database of mud volcanoes in Japan and adjacent areas, *GSJ Open File Report*, 540, (CD-ROM), Geological Survey of Japan (2011) (in Japanese).

[16] K. Kazahaya, M. Takahashi, T. Kirita, K. Naito and Y. Watanabe: Spatial distribution of upwelling area of slab-derived aqueous fluids in Japan, *GSJ Open File Report*, 616, Geological Survey of Japan (2015) (in Japanese).

[17] M. Takeda, M. Manaka, T. Hiratsuka, S. Miyoshi, T. Tokunaga and K. Ito: Effects of chemical osmosis on groundwater flow in sedimentary formations, *Journal of Geography*, 122 (1), 192–213 (2013) (in Japanese).

[18] Agency for Natural Resources and Energy, METI: Kagakuteki Tokusei Map site (Nationwide Map of Scientific Features site) (2017), http://www.enecho.meti.go.jp/category/electricity_and_gas/nuclear/rw/kagakutekitokuseimap/, accessed 2017-08-16 (in Japanese).

[19] Radioactive Wastes WG, Nuclear Energy Subcommittee, Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy: Chiso shobun ni kansuru chiiki no kagakuteki na tokusei no teiji ni kakawaru yoken kijun no kento kekka (Chiso shobun gijutsu WG torimatome) [Investigation results of requirements and criteria pertaining to the scientific features of geological disposal region (Summary of Geological Disposal Technology WG)] (2017), http://www.meti.go.jp/report/whitepaper/data/20170417001.html, accessed 2017-09-22 (in Japanese).

[20] M. Takahashi: Diastrophism of the Japanese islands based on plate kinematics, Nihon retto no choki chishitsu hendo no yosoku ni muketa torikumi to kongo no kadai: Sujuman nen no kako o kaimeishi shorai o yosokusuru gijutu chiken model (Efforts on the prediction of long-term geological changes of the Japanese islands and future topics: Technology, knowledge, and model to predict the future by clarifying the past several hundred thousand years), 23rd GSJ Symposium, *GSJ Open File Report*, 610, 14–15, Geological Survey of Japan (2015) (in Japanese).

[21] T. Yamamoto: Safety assessment of high-level nuclear waste disposal in Japan from the standpoint of geology: Methodology of long-term forecast using geological history, *Synthesiology*, 4 (4), 200–208 (2011) (in Japanese) [*Synthesiology English edition*, 4 (4), 202–211 (2012)].

[22] A. Morris, D.A. Ferrill and D.B. Henderson: Slip-tendency analysis and fault reactivation, *Geology*, 24 (3), 275–278 (1996).

[23] Association for the Geological Collaboration in Japan: *Earth Science Encyclopedia*, Heibonsha, Tokyo (1996) (in Japanese).

Author

Kazumasa ITO

Completed the master's program at the Department of Resources Engineering, School of Engineering, The University of Tokyo in March 1988. Joined the OYO Corporation. Obtained doctorate (engineering) in 2001. Worked at Lawrence Berkeley National Laboratory, USA in 2001, and then joined Geological Survey of Japan, AIST in October 2005. Currently, Group Leader, Hydrogeology Research Group, Research Institute of Earthquake and Volcano Geology, AIST. Japan Nuclear Energy Safety Organization in 2011, and Chief Technological Research Investigator, Technological Core Group, Secretary of Nuclear Regulatory Agency in 2015–2017. Specializes in hydrogeology. In charge of the survey and assessment of underground hydrogeological environment, as support of regulations for radioactive waste disposal.

Discussions with Reviewers

1 Overall

Comment (Chikao Kurimoto and Yoshio Watanabe, AIST)

This paper describes cases in which AIST's research results were utilized regarding intermediate-depth disposal regulation, and summarizes the challenges in using AIST results for future high-level radioactive waste disposal. The content is organized as an article whose purpose is to provide the trends and analyses for utilization of R&D results in society, and is worthy of publication in *Synthesiology*. It is also significant that there is a comparison with the "Nationwide Map of Scientific Features for Geological Disposal" published by the Agency of Natural Resources and Energy in July 2017.

2 Handling of regulatory criteria

Comment (Yoshio Watanabe)

When outlining the "intermediate-depth disposal" regulation, which precedes the national safety regulations, and comparing it to "geological disposal," it is essential to communicate to the readers that the requirements and criteria in the "Nationwide Map of Scientific Features" published by the Agency of Natural Resources and Energy cannot be handled in the same manner as the ones for "geological disposal" in the discussion of regulation itself. Please try to provide accurate and careful descriptions, as AIST conducts safety research for geological disposal of high level radioactive wastes. Please take care to use easily understandable sentence structures as well as accurate wording, vocabulary, and concept, so the original results described in this article can be conveyed smoothly to the readers.

Answer (Kazumasa Ito)

The two types of disposal compared in this article differ greatly in data volume and quality on which the discussion is based, as well as in objectives and stages of use. To clarify that the comparison cannot be made easily, I added descriptions on the objectives, stages, and comparison of basic data, and also added an explanation that although the two types of disposal cannot be simply compared, they are compared to point out the problems.

3 Research results of AIST

Comment (Chikao Kurimoto)

You describe cases of utilization of AIST's research results in the regulation of intermediate-depth disposal, and briefly summarize the challenges eyeing application to high-level radioactive waste disposal in the future. "3.2.2 Regulatory requirements for active faults" shows a case in which AIST's results were not employed, which is an important precept for future research, and it can be the main point of this article. You state that it is necessary to expand case studies of activity assessment by mechanical indices as well as to establish a rational setting method of parameters, but I think you should emphasize the progress of specific research on this topic, and the contribution and stance (forte) of AIST. I raise similar points for "3.2.3 Uplift and erosion."

Answer (Kazumasa Ito)

For fault activities, I added citations from latest papers on fault reactivation assessment conducted at AIST, and also added that the mechanical index of slip tendency is useful as an assessment method in the first stages of activity assessment of faults that exist near waste burial sites. Also, I added specific research topics that should be pursued so that AIST's method will be recognized as an actual survey and assessment method in the future. For uplift and erosion, I added the progress of research at AIST, as well as topics on erosion in the horizontal direction for which sufficient investigation has not been done, although it is an assessment method required in the current permission standard and examination guide.

4 Transfer of research

Comment (Chikao Kurimoto)

Based on your mentioning the academic level of AIST results and the specific explanation of existing research results in "3.2.2 Regulatory requirements for active faults" and "3.2.3 Uplift and erosion," please emphasize AIST's favorable position and its standpoint, and then discuss the future research policies and measures and plans in making proposals for the examination guide as a national standard.

Answer (Kazumasa Ito)

In Chapter 3, I added AIST's favorable position from the perspective of radioactive waste disposal, pertaining to the current research done by AIST. I also added in Chapter 5, particularly for fault activity, the description of the research policy about transferring results to the examination guide for standard compatibility of intermediate-depth disposal, which is thought to be carried over to the standard for geological disposal.

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 April 1, 2017

1 Types of articles submitted and their explanations

The articles of *Synthesiology* include the following types:
• Research papers, reports, commentaries, roundtable talks, and readers' forums
Of these, the submitted manuscripts of research papers, reports, 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 reviewers will recommend whether the manuscript should be accepted, revised, or declined. 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 Reports
A report describes a development example of technology which has practical value as well as an example of new technology which has been put to practical use. It contains 1) the aim, 2) the process of development (the course to the goal), and 3) the outcomes. The submitted manuscript is checked 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 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 checked 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.

④ 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.

⑤ 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 reports and commentaries 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, reports, and commentaries shall have front covers and the category of the articles (research paper, report, or commentary) 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, 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 with the names of the reviewers disclosed. The edited discussion will be attached to the main body of the paper as part of the article. Regarding the reports and the commentaries, discussion with the Editorial Board members will be opened at the Board's discretion. In this case, the Editorial Board will edit the discussion to about 800 Japanese characters (less than half a page) with the names of the Board members disclosed.
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 web page, Name of website (may be omitted If the name of the website is the same as that of the author(s)), 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 is 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).

Inquiries:

Synthesiology Editorial Board
c/o Public Relations Information Office, Planning Headquarters, National Institute of Advanced Industrial Science and Technology(AIST)
Tel: +81-29-862-6217 Fax: +81-29-862-6212
E-mail: synthesiology-ml@aist.go.jp

Letter from the editor

Synthesiology has entered its eleventh year since its launch. This is a journal in which researchers describe how they want to advance their research based on what kind of scenario so that their research results are shaped into forms that can be used in society. Specifically, this involves recording the R&D process in which a number of elemental technologies are integrated to solve a problem, and what research approach is selected from numerous choices to establish the individual elemental technologies. The journal has three categories of text: paper, report, and commentary. In this issue, there are two papers, one report, and one commentary. Although the technological fields are different, I hope you take the time to compare the different categories.

The paper, "1:50,000 quadrangle geological mapping project in Japan," gives an overview of survey and data organization since the Geological Survey of Japan was established in 1882, to produce geological maps for entire Japan to provide basic land information. It also describes the latest methodology to produce highly precise and reliable geological maps, and states that it is necessary to change the research methods according to the characteristic of the targeted region. The paper, "Traditional craftwork that can be washed with a dishwasher, 'nanocomposite *tamamushi-nuri*'," is a success story that describes the collaboration of different fields and their collaborative innovation. The composition and process conditions were optimized through technological development to apply the latest organic and inorganic nanocomposite materials to traditional lacquerware, for the purpose of achieving scratch resistance and durability without losing the original beauty. The report, "Additive manufacturing of ceramic components," describes an example that may lead to innovation, with plans for mass production, by building additive manufacturing technology that allows the manufacture of ceramics with complex shapes and changing thickness. R&D was conducted by setting up an industry-academia-government collaboration project after thoroughly analyzing the international situation of the ceramic field. The article, "Earth science in safety regulations of radioactive waste disposal," describes case studies and proposes future issues on how earth sciences including geology can contribute to maintaining safety for several hundred thousand years when burying medium to high concentration radioactive waste that is generated by the operation of nuclear power plants. It is an extremely important topic for Japan that has frequent earthquakes and volcanoes.

Recently, many reports show analytical results that Japanese R&D including basic research is losing international competitiveness, and there have been active discussions on how to overcome this situation. According to a proposal, we need researchers engaging in scientific research, producers of science research and science-based industry creation, and innovators who generate economic and social values from science. It is said that scientists and researchers with producer qualities are particularly important. *Synthesiology* requires the creation and verification of a specific scenario to solve a problem and the description of the process for synthesizing and integrating elemental technologies, in order to utilize research results in society. It can be positioned as leading in discussing producer functions mentioned earlier. I hope discussions among the readers of universities, research institutions, and companies will be stimulated and deepen further.

(Akira KAGEYAMA, 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.

c/o Public Relations Information Office, Planning Headquarters, AIST
Tsukuba Central 1, 1-1-1 Umezono, Tsukuba 305-8560, Japan
Tel: +81-29-862-6217 Fax: +81-29-862-6212
E-mail: synthesiology-ml@aist.go.jp
URL: http://www.aist.go.jp/aist_e/research_results/publications/synthesiology_e

Synthesiology - English edition Vol. 11 No. 2, Dec. 2018
Edited by *Synthesiology* Editorial Board
Published by National Institute of Advanced Industrial Science and Technology (AIST)

Synthesiology

Vol.11 No.2 December 2018
-English edition

Highlights of the Papers in *Synthesiology*

Research papers

1:50,000 quadrangle geological mapping project in Japan
—*Overall and individual scenarios of mapping project*—
K. Miyazaki

Traditional craftwork that can be washed with a dishwasher, “nanocomposite *tamamushi-nuri*”
—*Expansion from exhibits to daily necessities*—
T. Ebina, M. Saura and Y. Matsukawa

Report

Additive manufacturing of ceramic components
—*Towards innovation of ceramic industry*—
T. Ohji

Commentary

Earth science in safety regulations of radioactive waste disposal
—*Translation of scientific research to site selection criteria*—
K. Ito

Editorial policy
Instructions for authors
Letter from the editor
Aim of *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-A00005-27 Published by AIST

Synthesiology-English edition ❷ 2018

National Institute of Advanced Industrial Science and Technology (AIST)