1:50,000 quadrangle geological mapping project in Japan

—Overall and individual scenarios of mapping project—

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[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

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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

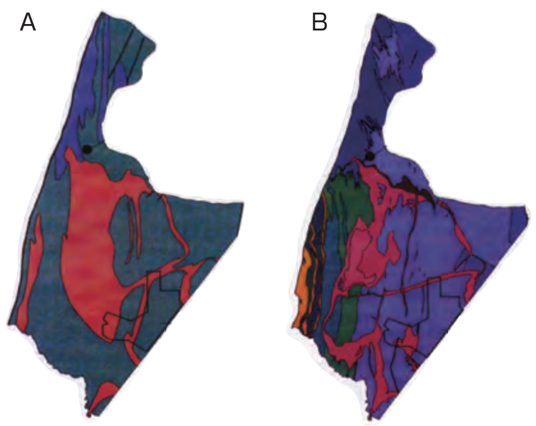

Fig. 1 Geological map of eastern Loudoun County, VirginiaH
A. Part of the geological map of Virginia, 1963 (Mineral Resources Department, Virginia). Green = sedimentary rock (sandstone and shale are not differentiated). Pink = igneous rock (diabase and gabbro are not differentiated). Blue = conglomerate (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.

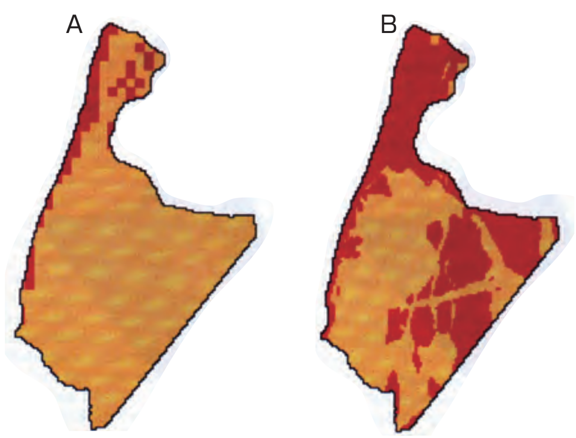

Fig. 2 A is the geological map of Virginia in 1963, and B is the distribution of cells that are not suitable as locations for waste disposal sites based on the USGS geological map of Loudoun County, Virginia, 1992.
Yellow = location is not restricted. Red = location is restricted (Fig. 4, Introduction, 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

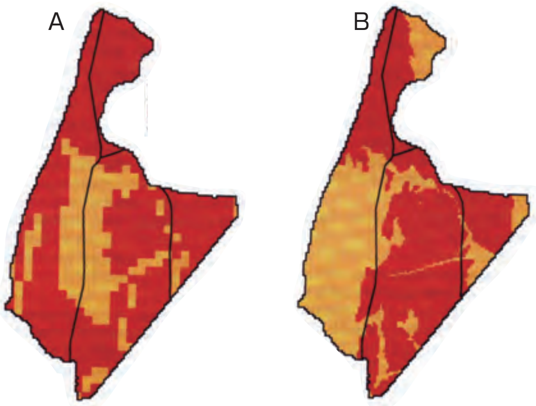

Fig. 3 Distribution of cells that require measures to prevent landslides that may be caused by construction of arterial road

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

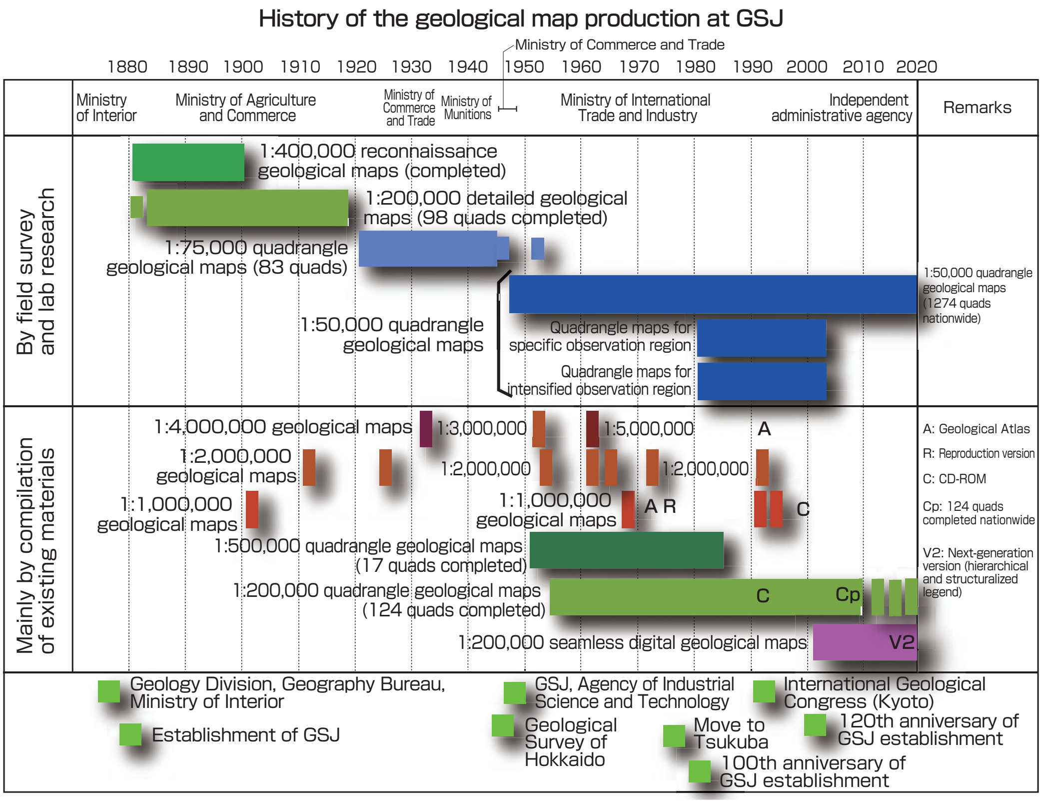

Fig. 4 History of geological maps at Geological Survey of Japan (GSJ)

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.

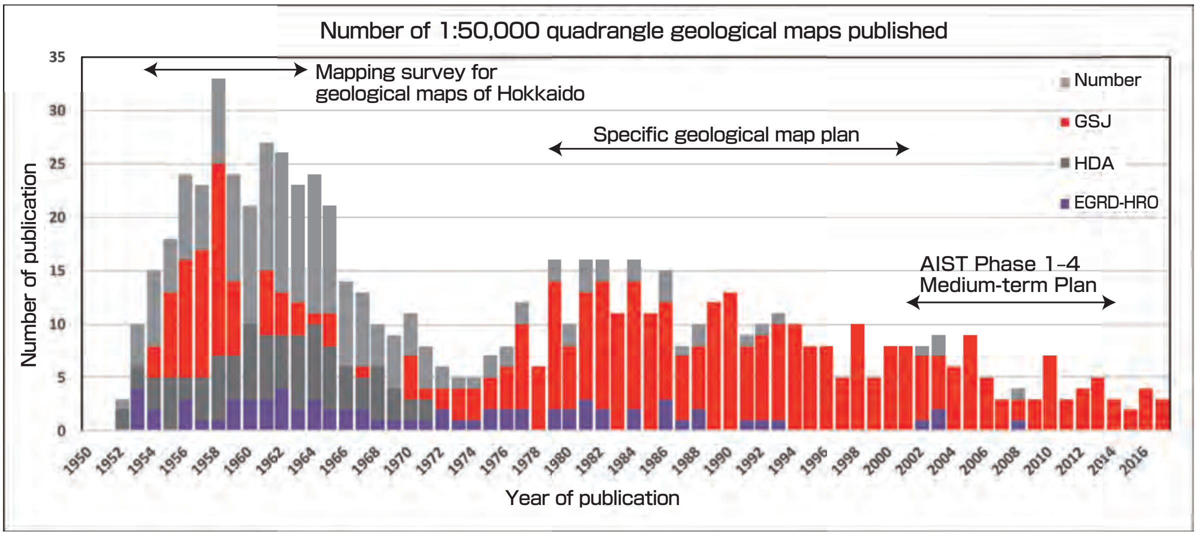

Fig. 5 Transition of publication of 1:5,000,000 quadrangle geological maps
GSJ: Geological Survey of Japan. HDA: Hokkaido Development Agency. EGRD-HRO: Environmental and Geological Research Department, Hokkaido Research Organization (former Geological Survey of Hokkaido).

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).

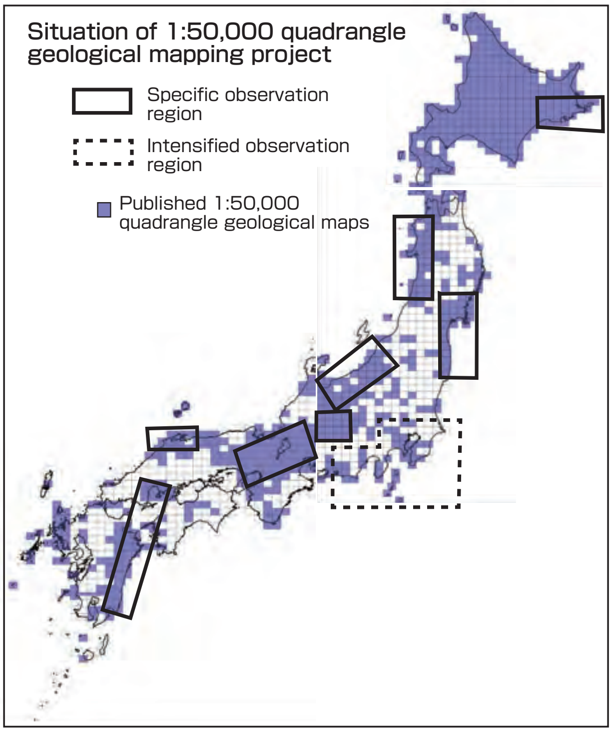

Fig. 6 Situation of 1:50,000 quadrangle geological maps (as of 2013)

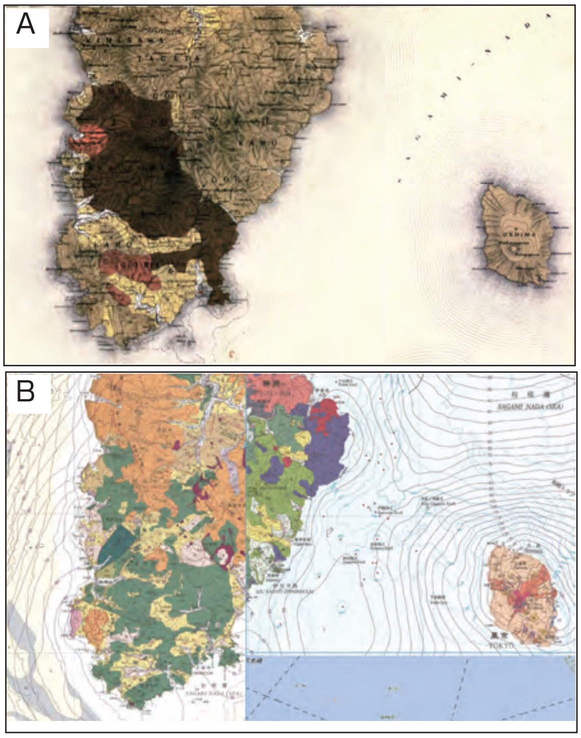

Fig. 7 Comparison of 1:200,000 detailed geological map and 1:200,000 quadrangle geological map

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

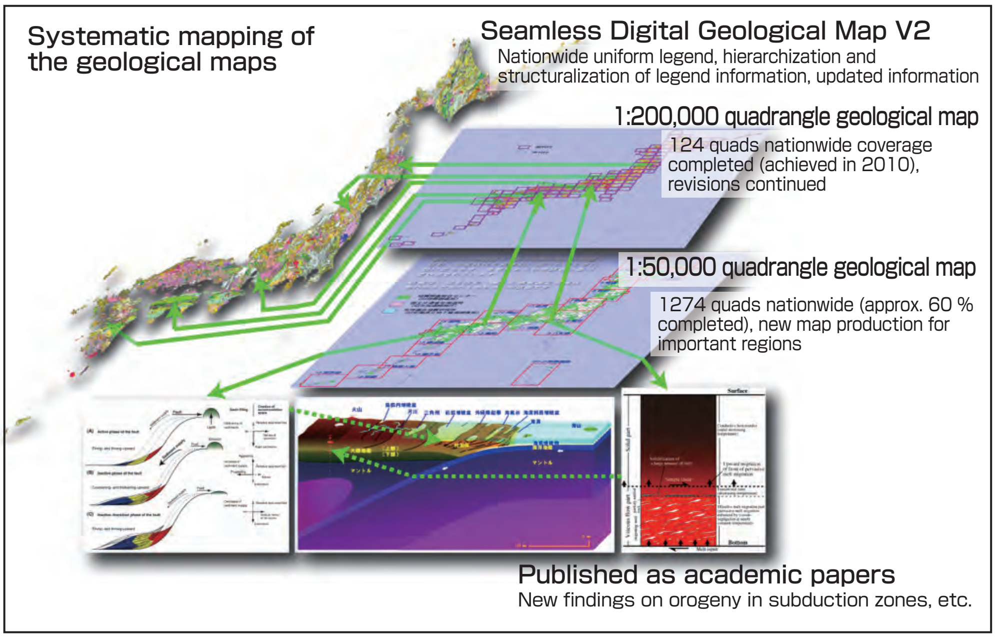

Fig. 8 Systematic mapping project for quadrangle geological maps at GSJ-AIST

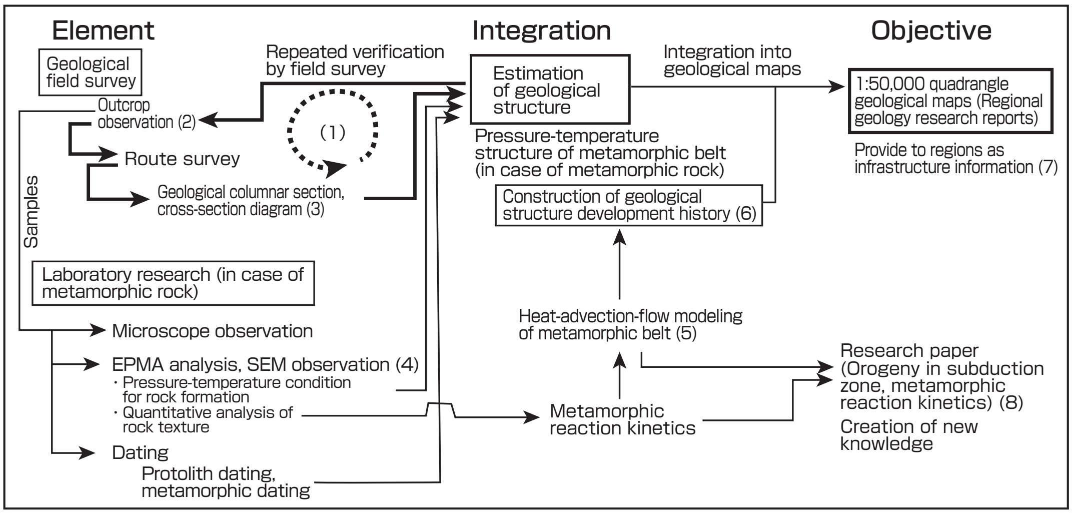

Fig. 9 Elements and scenario of 1:50,000 quadrangle geological map production

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

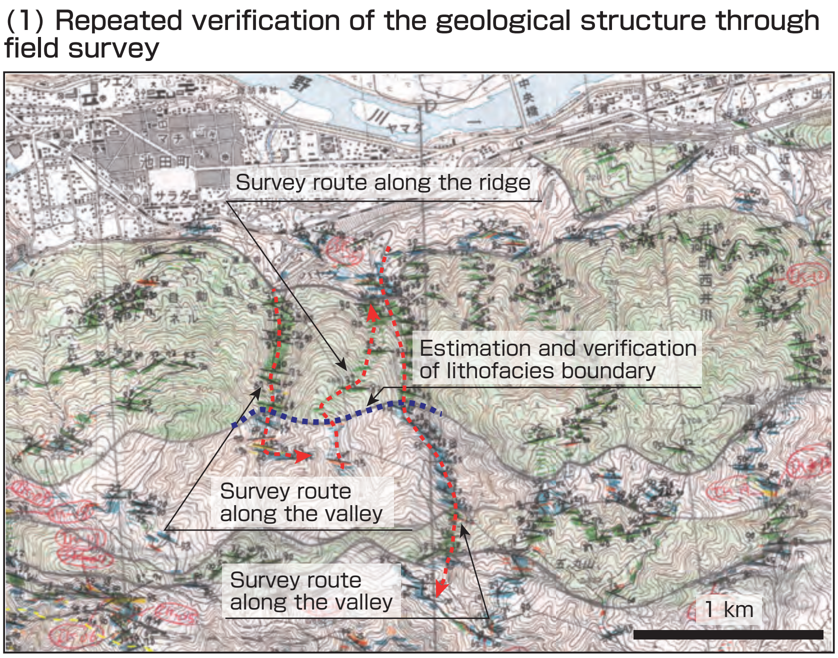

Fig. 10 Repeated verification of geological structure through field survey
Number in the title corresponds to the number in Fig. 9. The figure shows part of a route map of a certain region in a 1:50,000 quadrangle geological map that is currently being produced. In the route map, different types of observed 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.

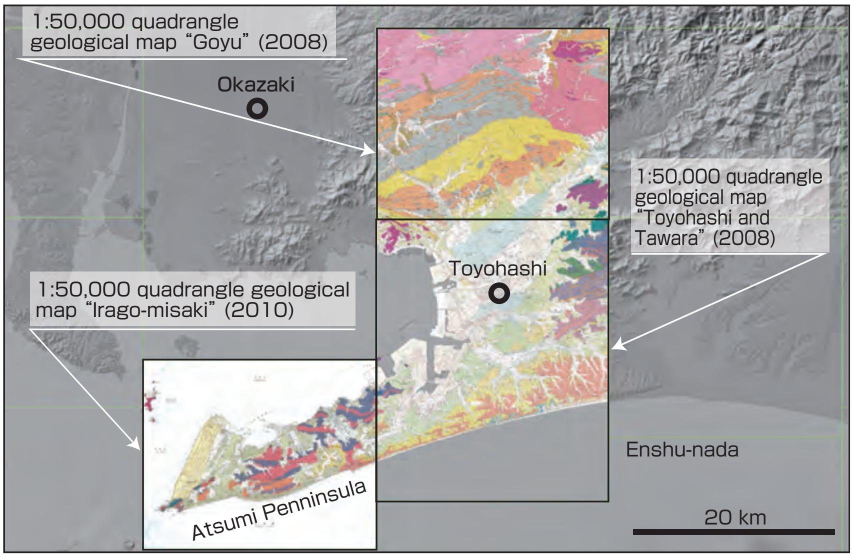

Fig. 11 1:50,000 quadrangle geological map of Toyohashi region[7][11][12]

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

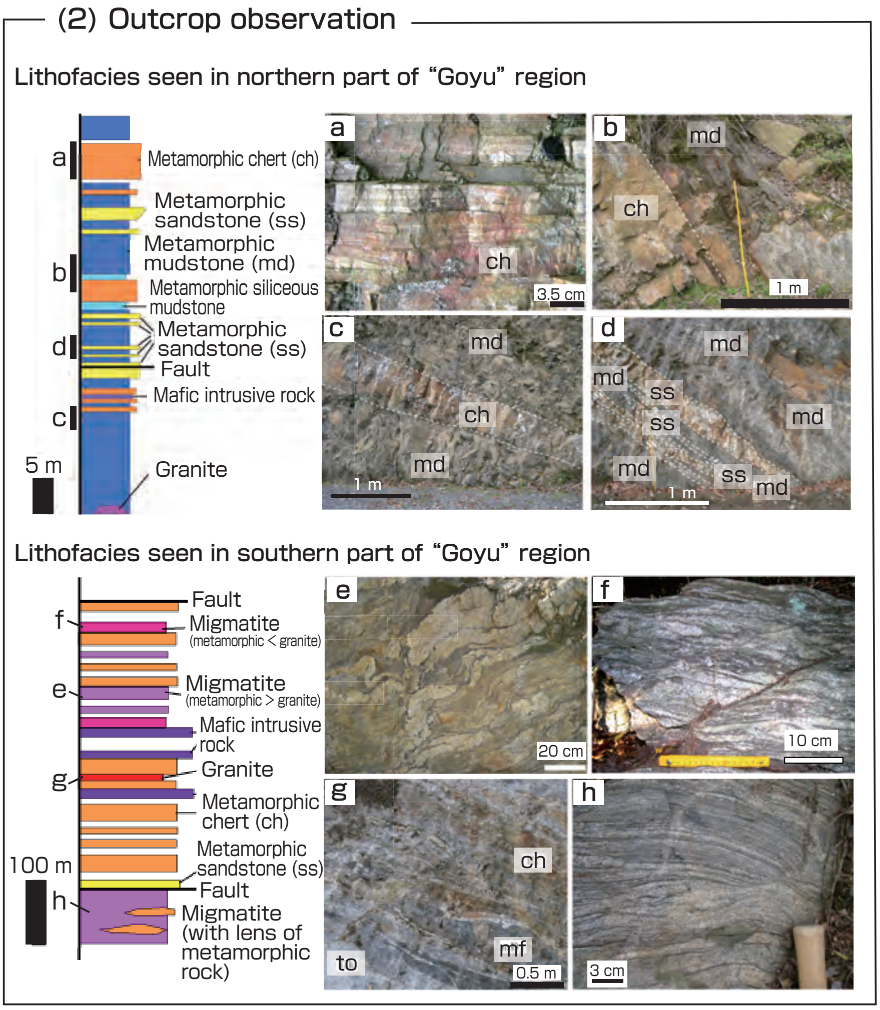

Fig. 12 Example of outcrop observation in field survey (quadrangle geological map "Goyu")[7]
Number in the title corresponds to the number in Fig. 9.
a-d Lithofacies seen in the biotite zone in the northern part of "Goyu" region. a outcrop of metamorphic chert (ch); b metamorphic siliceous shale sandwiched 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

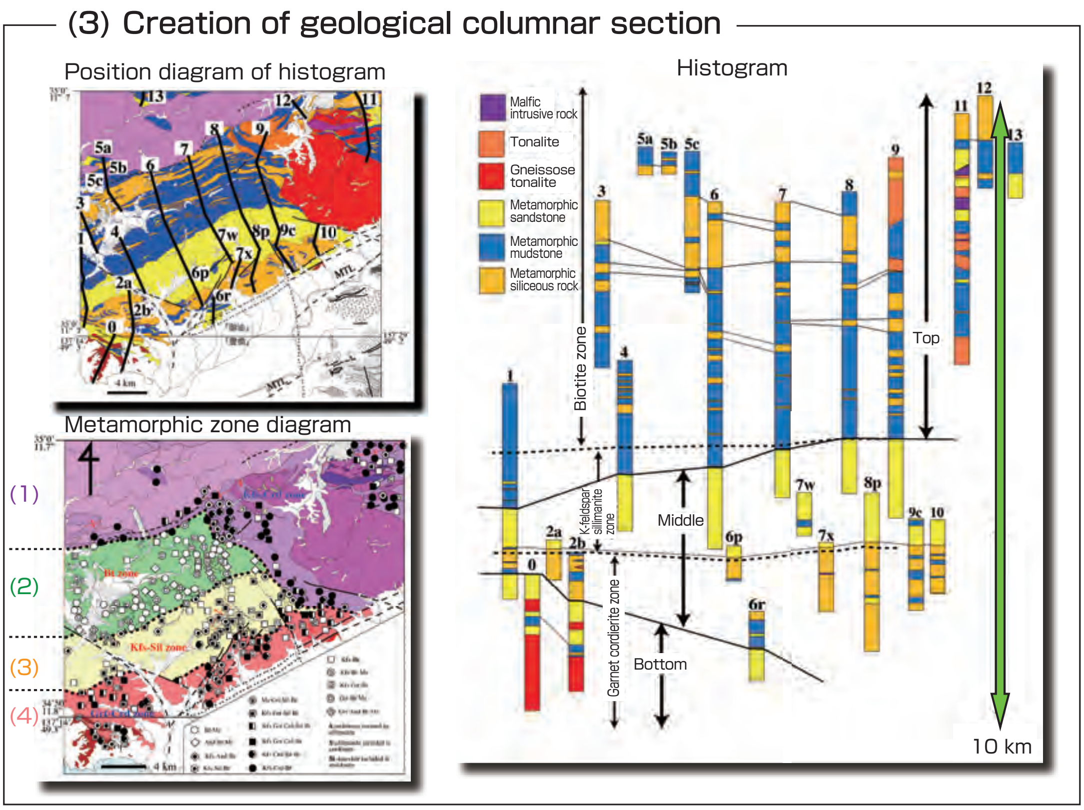

Fig. 13 Example of geological columnar section created in field survey (quadrangle geological map “Goyu”)[7]

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

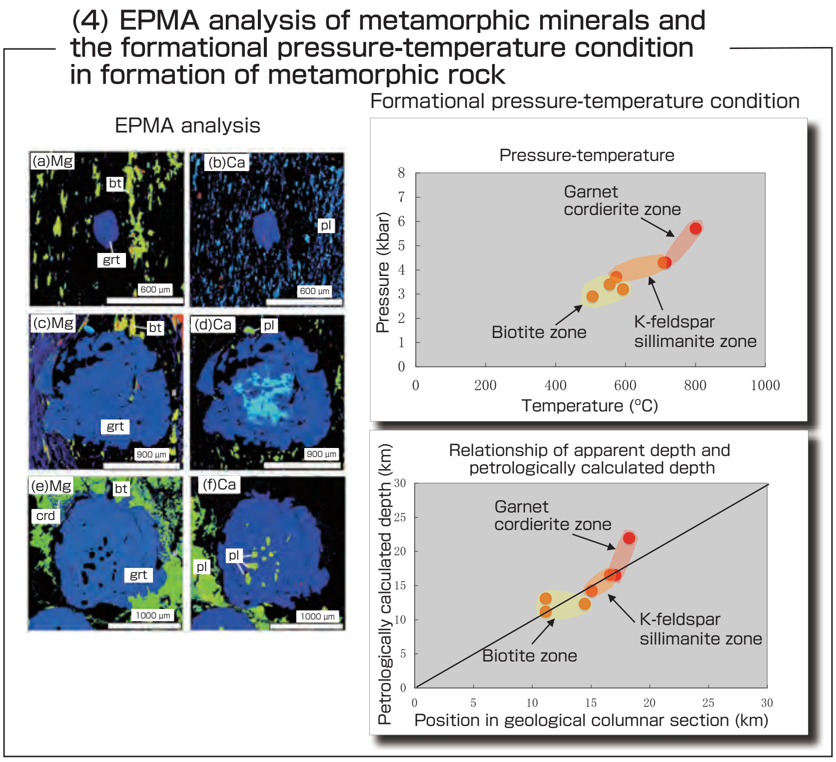

Fig. 14 Examples of EPMA analysis of metamorphic minerals and estimation of pressure-temperature condition in forming metamorphic rock in laboratory research (quadrangle geological map "Goyu")
Number in the title corresponds to the number in Fig. 9. The (a) and (b) on the left side show X-ray intensity 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.

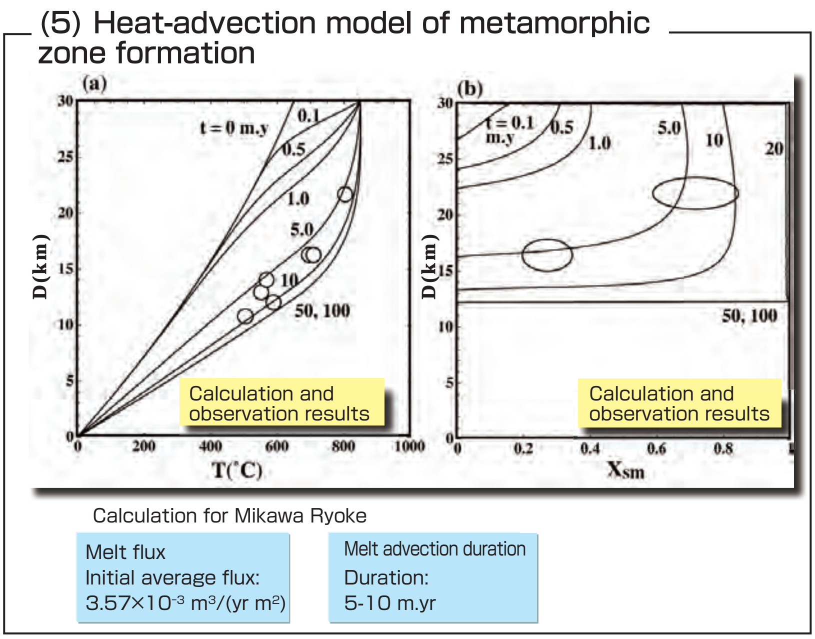

Fig. 15 Example of heat-advection model for formation of metamorphic zone (Ryoke metamorphic rock, Mikawa plateau) in laboratory research[8]
Number in the title corresponds to the number in Fig. 9. Refer to Reference [8] for details.

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

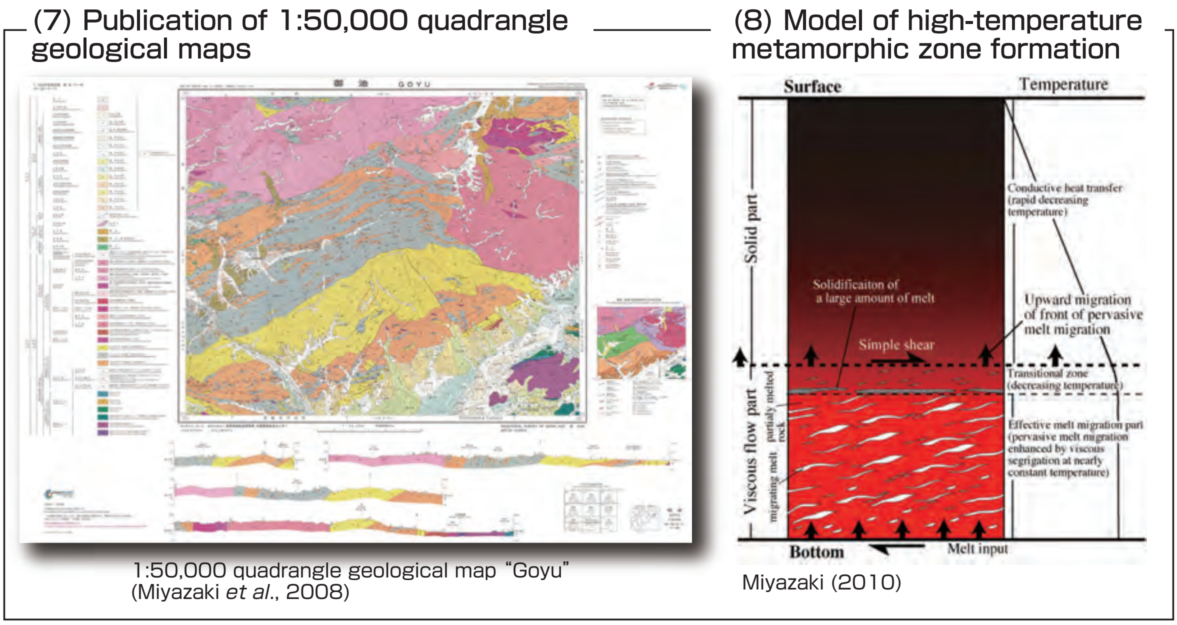

Fig. 16 Example of result of integration of field survey and laboratory research
Left: 1:50,000 quadrangle geological map “Goyu.”[7] Right: Model of high-temperature metamorphic zone formation.[8]

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.

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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.