

Safety assessment of high-level nuclear waste disposal in Japan from the standpoint of geology

— Methodology of long-term forecast using geological history —

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Concerning the geological disposal system of high-level nuclear waste, the term subject to safety assessment of the system after closure is considered to exceed several hundred thousand years. We are faced with the major issues of how to guarantee such long-term safety and on what kind of criteria the system should be regulated. Because the Japanese islands lie in the mobile belt where earthquakes and volcanic activities often occur, a variety of geological issues required for the safety assessment have to be taken into consideration. In this paper, issues are extracted from a series of facts or scenario where incidents occur one after another provoked by one incident, and one such example is given of analysis results of the eruption history of volcanic activities. A methodology for long-term forecast addressing the causes of geological phenomena is also presented.

Keywords : High-level nuclear waste, geological disposal, seismicity, volcanism, long-term forecasting

1 Introduction

Geology is a science that studies the series of changes in the earth that occurred in the past, as described in the *Principles of Geology* by Charles Lyell, written in the early half of the 19th century. The greatest contribution of geology to humankind is the discovery of deep time, and 4.6 billion years of earth history have been unraveled from the records left in the rocks and strata. The stronghold of geology is the understanding of how a region was formed, by looking at the natural phenomenon in a time frame of several thousand to several million years. Geology was traditionally deployed in the exploration of natural resources such as oil and metals, and has recently been applied to mitigate the geological disasters such as earthquakes and volcanic eruptions.

Recently, a new issue that must be handled geologically arose due to the changes in social demand. This is the issue of geological disposal where the radioactive waste from nuclear power generation is buried underground, far away from the environment in which people live. To ensure safety of this disposal, the underground geological environment must be stable over a long term of several hundred thousand years. It is impossible to guarantee the safety over such time scale by covering the waste with an artificial structure using engineering methods. Safe disposal is possible when the underground geological environment itself functions adequately as the natural barrier against nuclear waste. Only geological knowledge can provide solutions to the issue of long-term stability assessment required for geological disposal, and geological disposal will not be realized

without the safety regulation and assessment utilizing this knowledge to the maximum. Figure 1 shows the outline of the relationship of the investigation and assessment items for geological disposal site investigation and the security after closure of the site. This paper describes the extraction of the geological investigation and assessment items required for the safety assessment of geological disposal, and the methodology for long-term forecast based on the model building for the investigated geological phenomena.

2 What is geological disposal?

According to the Japanese law, various radioactive wastes must be disposed in either the category 1 or the category 2 waste disposal facility, depending on the radioactivity level. Category 1 is the so-called geological disposal, and it is a disposal method taken when the wastes must be isolated from the biosphere for a long time, and therefore is buried underground at 300 m or deeper. The wastes that must be disposed in this manner include the high-level radioactive (HLR) waste and certain low level radioactive (LLR) waste (such as the long half-life, low-heat-generating radioactive wastes). The HLR waste is the vitrified HLR waste liquid generated in the processing of the spent fuel. It is characterized as a nuclear waste with a long “lifespan” because it contains radionuclides with a long half-life. This is the reason for selecting the geological disposal method that does not require human management. The time required for the radioactivity of the HLR waste to drop to the level of original uranium ore (high concentration of 1 % grade ore) is about a hundred thousand years after power generation^[1]. The category 2 waste

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disposal is a method that assumes human intervention for management, and the LLR waste other than the one mentioned above is buried in relatively shallow ground.

While the forms of radioactive waste disposal differ by the waste type, all must maintain the radiation exposure of the general public at certain value or less, and must keep it as low as reasonably achievable^[2]. Considering this point as basic security, the final disposal site must be constructed from several layers of barriers consisting of the artificial barrier that includes the waste material itself and the natural barrier or the surrounding geological structures^[3]. The artificial barrier plays the role of containing the radionuclides as long as possible and mitigating the release into the natural barrier. The natural barrier is expected not only to isolate the radionuclides from the biosphere, but also to provide a stable external environment to maintain the constant environment for the artificial barrier over a long period. These barriers are expected to function complementarily. The waste material itself and the multiple barriers around it are generally called the disposal system. In the case of the geological disposal, the time period that must be considered for the safety assessment of the closed disposal system must be over several hundred thousand years. The major issues are how to ensure such long-term security and what kind of standard should be set.

The geological disposal business of HLR waste in Japan is based on the “Specified Radioactive Waste Final Disposal Act” established in June 2000. This law states that the site selection is done in three stages as shown below.

(1) Selection of the preliminary investigation area (PIA): A survey of literature and other source materials (literature

search) is done to select the PIA from the area that is reviewed by literature search.

(2) Selection of detailed investigation area (DIA): Land surface investigations including outcrop survey, boring, trench excavation, or physical exploration are conducted at the PIA, and the DIA is selected among the PIA candidates.

(3) Selection of the final disposal facility construction site: In addition to the detailed survey on the land, the actual facility is constructed underground, the physical and chemical properties of the strata are conducted, and the construction site for the final disposal facility is selected among the DIA candidates.

The Nuclear Waste Management Organization of Japan (NUMO) was established in October 2000 to conduct the disposal work based on the Specified Radioactive Waste Final Disposal Act. This organization has been soliciting disposal site candidates to the cities, towns, and villages throughout Japan since December 2002, but no local government has applied as of October 2011.

3 Extraction of the geological issues for the geological disposal in Japan based on FEP (feature, event, and process)

One of the major interests in the geological disposal in Japan is the point, “Is it possible to conduct sufficiently safe geological disposal in Japan where earthquakes strike frequently?” For the security of geological disposal, of course, it is necessary that the geological environment of

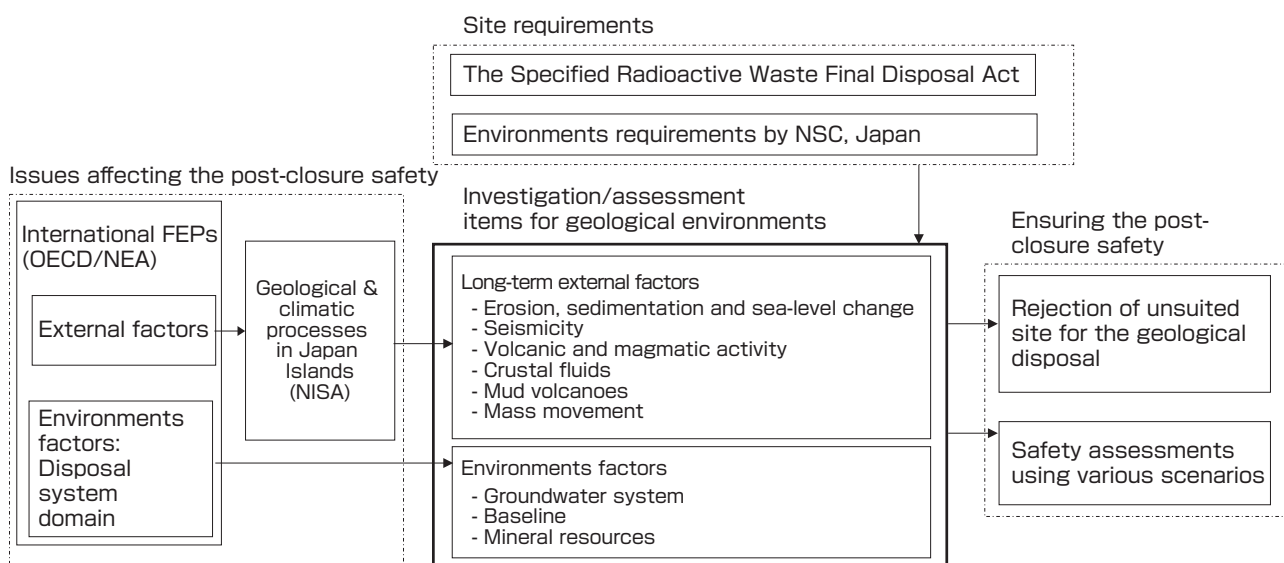


Fig. 1 Relationship between the issues affecting the site-selection survey and the post-closure safety on the geological disposal of high-level radioactive waste

the area where the disposal facility will be built is stable for a long period. The Specified Radioactive Waste Final Disposal Act requires the disposal site candidates that “there is no record of significant changes in the strata by natural phenomena such as earthquake, volcanic eruption, uplift, erosion, and others” and that “it is expected that significant change in the strata is not likely to occur due to such natural phenomena in the future”. In geological disposal, it is important that the HLR waste is isolated in a stable geological environment where the effects of natural phenomena such as earthquakes will not extend. To do so, it is required to conduct a comprehensive and quantitative assessment on what kind of external impact there will be on the geological disposal system, through the long-term changes in the geological environment over a hundred thousand years. At the Research Core for Deep Geological Environments (formerly Research Center for Deep Geological Environments), AIST organized the knowledge necessary to investigate the safety regulations pertaining to the geological disposal, at the Waste Safety Subcommittee that was set under the Nuclear and Industrial Safety Subcommittee, Advisory Committee on Energy and Natural Resources, which is an advisory panel for the Minister of Economy, Trade and Industry.

Figure 2 shows the correlation diagram that identifies the phenomena that may affect the geological disposal system

as external disturbances in Japan, based on the international FEP list for geological disposal created by the Nuclear Energy Agency, Organisation for Economic Co-operation and Development (OECD/NEA)^[4]. The FEP is categorized into those with the geology-related FEPs that arise from the internal energy of earth “F1.2.01 Tectonic movement and orogeny”, and the climate-related FEPs caused by the solar incident energy “F1.3.01 Climate change, global”. In Fig. 2, these are arranged on the left and right, and the disposal system domain is shown in the lowest part. The whole process is seen as a series of phenomena (scenario) where one event undergoes a process to cause the next event (as shown by the arrows), and this in turn causes the next process and event. The FEPs in parenthesis that are not joined by the cause-effect arrows are eliminated from the investigation since their effects can be ignored in Japan.

The Research Center for Deep Geological Environments investigated the geological and climatic phenomena that may affect the aforementioned disposal system, and in 2007 publicized the “Technical Report on the Features for Preliminary Field Investigations of HLW Geological Disposals” (<http://www.gsj.jp/GDB/openfile/files/no0459/0459index.html>)^[5]. This indicates the assessment items and investigation methods necessary for the security of the closed disposal site, in the investigations (various

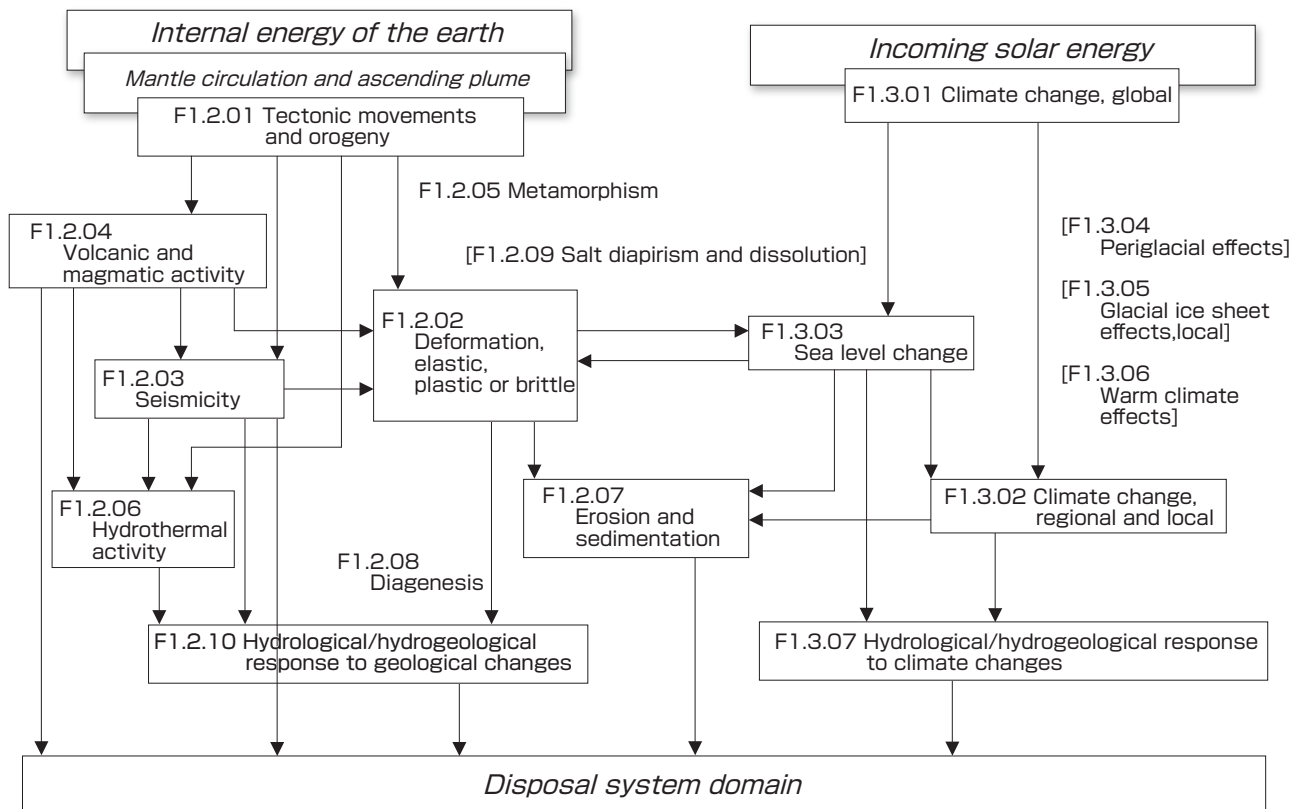


Fig. 2 Geological and climatic processes in Japan Islands using international FEPs database of OECD/NEA
 Arrows indicate the effecting direction. FEPs in [] means ignorable ones in Japan Islands. After Yamamoto and Kodama^[4]

investigations from the land surface in the PIA selection phase) as designated by the Specified Radioactive Waste Final Disposal Act. The following items are extracted:

(1) Erosion, deposition, and sea level change

- It is necessary to avoid areas where the estimated erosion may become greater than the depth of burial, because the disposed material may become exposed to the surface.
- It is necessary to consider the effects of relative sea level change in the areas where the flow or quality of underground water may change and may affect the containment function of the radioactive materials in the future, due to the changes in relative sea level by uplift, subsidence, or glacial sea level change.
- It is necessary to consider the future stability of the tectonics that may affect the uplift and subsidence.

(2) Seismicity

- It is necessary to avoid the range to which the effect of the faulting may extend in areas that are found to have faults that were active in the Quaternary period, because the disposed material may be directly damaged due to the rupture along the fault.
- It is necessary to consider the range to which the effect of the rupture may extend if there is a large fault on the surface or underground, even if there was no activity in the Quaternary period, because there may be possibilities of reactivation and induced dislocation of the fault.
- It is necessary to consider the effect of the seismicity in areas where the seismicity may cause changes in the flow or quality of the groundwater that may affect the containment of the radioactive materials.
- It is necessary to consider the future stability for the tectonics that may affect the seismicity.

(3) Volcanic and magmatic activities

- It is necessary to avoid the areas that were found to have Quaternary volcanoes, because there are possibilities that the disposed materials may become directly damaged or pushed up to the surface by eruptions.
- It is necessary to avoid the areas where new volcanoes may emerge even if there are no Quaternary volcanoes, because there are possibilities that the disposed materials may become directly damaged or pushed up to the surface by eruptions.
- It is necessary to consider the effect of volcanic and magmatic activities in the areas around the Quaternary volcanoes or in the range with possibilities of large-scale eruptions, where there may be changes in the ground temperature or in the flow or water of the underground water that may affect the containment function of the radioactive substances in the future.
- It is necessary to consider the future stability of the tectonics that may affect the volcanic and magmatic activities.

(4) Crustal fluid

- It is necessary to consider the effect of the crustal fluid activities in the areas where there may be changes in the flow or quality of the underground water that may affect the containment function of the radioactive substances in the future, due to the activities of the crustal fluid.
- It is necessary to consider the future stability of the tectonics that may affect the crustal fluid activities.

(5) Mud volcano

- It is necessary to avoid the areas where there are mud volcanoes that were active in the Quaternary period, because there are possibilities that the disposed materials may become directly damaged or be pushed up to the surface by eruptions. (Mud volcano: phenomenon where the mud with abnormally high pressure gushes out to the surface with groundwater, gas, or sometimes oil.)

(6) Mass movement

- It is necessary to avoid the areas in which the effect of creep and ruptures may extend and where the signs of large-scale mass movement become apparent in the investigation, because the disposed materials may become directly damaged by the creep and fault ruptures due to slope movement. (Mass movement: general term for the movement of materials on the ground surface, and it includes landslides and debris flow.)

4 Methodology for long-term forecast

4.1 Basic thinking

As mentioned earlier, in the safety assessment of geological disposal, it is necessary to make forecasts of the geological and climatic phenomena for several hundred thousand years into the future. For example, the assessment of seismicity is divided into short-term (immediately before~about one year) and long term (about 1~100 years) according to the time scale in question, and following this categorization, the time span for the forecast for geological disposal must be called super long-term. The methodology for seismicity assessment differs by the assessment period. The main methods for short-term assessment are geophysical, geodetic, geochemical, and hydrological observations. On the other hand, the main method for long-term assessment is the statistical inference from past history. In Japan, the long-term assessment of earthquakes was done actively since the South Hyogo Prefecture Earthquake (Great Hanshin Earthquake) in 1995, and the earthquakes at the plate boundary and along the major active faults can be assessed by the recurrent rate (Headquarters for Earthquake Research Promotion, http://www.jishin.go.jp/main/p_hyoka02.htm). However, as the 2011 Earthquake off the Pacific Coast of Tohoku (M9.0) was an “unexpected phenomenon”, it cannot be said that this long-term assessment functioned sufficiently in preventing the disaster. Moreover, if the current long-term forecast is extrapolated to super long-term, the uncertainty of whether the initial

conditions and reoccurrence intervals that are the basis of the long-term assessment is constant over super long-term is unknown, and we currently cannot conduct reliable assessment. Therefore, to handle the super long-term time span of a hundred thousand to million years, various geological surveys are necessary in addition to statistical inferences.

In the forecast of geological and climatic phenomena for geological disposal, the foundation will be to clarify the trends of the geological changes for the phenomena that occurred in the assessment area, and to extrapolate this into the future. If the extrapolation is done for a hundred thousand to a million years into the future, it is necessary to track back the same number of years or more into the past. If the activity history of the phenomena with sufficient quantity and quality in terms of statistical inferences can be obtained, it may become possible to conduct probabilistic assessment, as in the long-term assessment of earthquakes. However, not all histories of activities are stored geologically, and there is overwhelmingly greater number of cases where sufficient history cannot be obtained. Therefore, forecast must be done from limited data, and it is necessary to consider the fact that quantitative handling cannot necessarily be done. For example, with the plate boundary earthquakes, the activity history depends on the historical records and tsunami deposits, and there is a limit in understanding the geological marks from surface survey over a long period. Also, for major earthquakes along the active fault, the activity history of only within about 10 thousand years can be obtained depending on the relationship of the fault and the cover stratum, and many cases are expected where the amount of information will

be insufficient for the assessment period. In the case where the erosion history is studied by tectonic geomorphology, the geomorphic surface index with sufficient sequence appropriate for the assessment period may not necessarily be found in the assessed area or the surrounding area. For hydrogeological phenomena, only the current value that is the sum of all past changes can be observed, and in most cases it is difficult to separate the individual history of changes.

In the case where it is difficult to extrapolate the super long-term history of change by statistical inferences, a different explanation is necessary to guarantee the stability of the geological environment of the assessed area over super long-term. For example, it is necessary to present a qualitative forecast by establishing the model of the structural development history of the assessed area, where the seismicity and uplift that accelerate erosions can be described. In hydrogeological change, qualitative forecasting will be possible only by establishing the mechanism for water quality formation that includes the chronology axis. Which kind of forecasting model is specifically necessary differs by the geological property of the area, and it is necessary to consider the forecasting theory according to the individual areas.

4.2 Example of analysis of long-term geological history for Japanese volcanic activities

To develop the analysis and assessment methods for the long-term geological history of the Japanese volcanic activities, as a typical cross-section model of the island arc, we conducted the research of the spatiotemporal distribution of the volcanic activities in the area from the Pacific Ocean side of southern

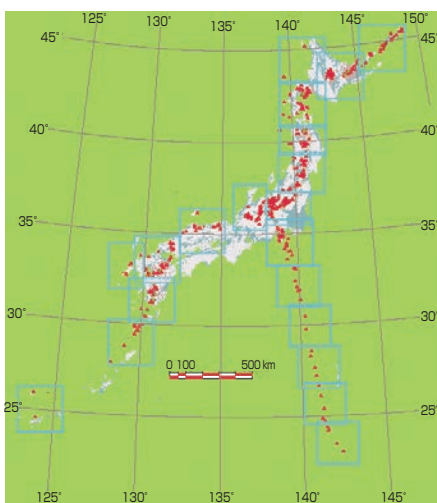


Fig. 3 Index map in “Quaternary Volcanoes in Japan, RIO-DB, AIST”
Red triangles are Quaternary volcanoes.

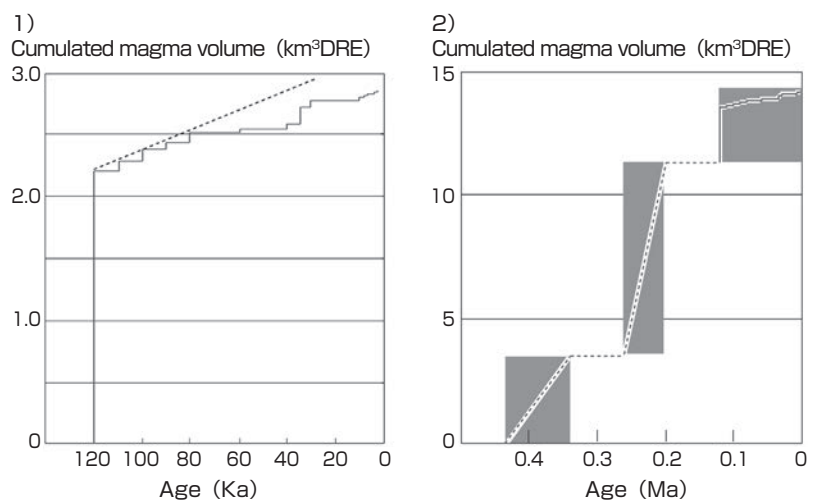


Fig. 4 Cumulated erupted magma volumes of Adataro volcano
1) and 2) diagrams are different in time scale. After Yamamoto and Sakaguchi^[7]

Northeast Japan to the Japan Sea side from 2004. The example of the analysis is described below.

In Japan, there are about 100 active volcanoes (those that erupted within the last 10 thousand years or volcanoes with vigorous fumarolic activity), and over 200 volcanoes that erupted in the Quaternary period (from 1.7 million years ago to present according to the old definition) (Fig. 3). However, the volcanoes are not distributed evenly throughout the Japan Islands, and their presences are determined by the plate arrangements. This means that the Quaternary volcanoes of the Japan Islands are most densely distributed on the volcanic front located 200~300 km away from the subduction boundary of the plates toward the plates on the landside, and there is no volcano between the volcanic front and the subduction boundary (fore-arc side). Also there is a significant tendency where the volcano distribution becomes sparse in the area distant from the back-arc side or area opposite the volcanic front. In soliciting the disposal site candidates, NUMO sets the condition “the area within the circle of 15 km radius with the center at a Quaternary volcano shall not be included” for the purpose of avoiding the effect of the volcanic activity^[6]. However, in thinking about the volcanic activity several hundred thousand to million years into the future, is it possible to avoid the effect with this exclusion condition only? Next, we shall consider the specific analysis of the spatiotemporal distribution of the volcanic activities.

When analyzing the eruption history of the volcanic activities, the so-called step diagram of eruptive volume is created, in which the horizontal axis represents time and the vertical axis is the cumulative eruptive magma volume.

Figure 4 is an example created for the eruptive magma material of Adataro volcano, a representative active volcano in southern Northeast Japan^[7]. Each magmatic eruption event is a geological instant shown as the vertical line, and during the non-eruptive state, it is shown as the horizontal line because there is no magmatic eruption. Figure 4.1 is a step diagram of the eruptive volume that goes back 120 thousand years, and as indicated by the average eruption rate shown by a dashed line, it can be seen from the step diagram that the eruptions occurred repeatedly at a certain frequency. However, when the history is extended to the time scale surpassing 120 thousand years for this volcano, as seen in Fig. 4.2, there is a major dormancy period 120 thousand to 200 thousand years ago, and the average eruption rate up to 120 thousand years ago cannot be extended into the past. There were separate magmatic activity periods 200~260 thousand year ago and 320~430 thousand years ago, but the individual average eruption rate differs by the activity period, and it is clear that the activity of Adataro volcano up to 120 thousand years ago, assuming a consistent rate, cannot be extrapolated to the past. In other words, it indicates that there is a lifespan on the magma supply that supports the individual activity periods, and for the forecast surpassing 100 thousand years, the assessment of the reactivation of the dormant volcanoes will become important rather than the currently active volcanoes.

Figure 5 shows the spatiotemporal distribution change of the volcanoes in the southern Northeast Japan including Adataro volcano, from about 1.8 million years ago or the beginning of Early Pleistocene to present^[8]. The important point in the distribution pattern of the volcanoes in this period is that there is almost no change at the volcanic front while there

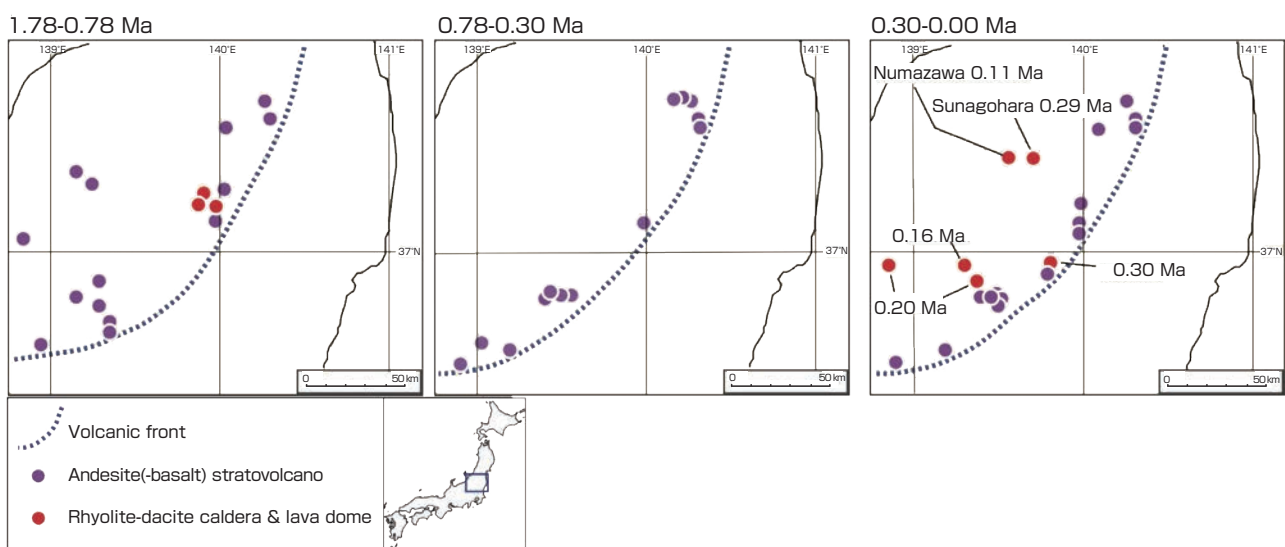


Fig. 5 Temporal change of the distribution of Quaternary volcanoes in the southern part of NE Japan arc
After Yamamoto^[8]

are always volcanoes along the front. On the other hand, the distribution of the volcanoes in the back-arc region differs greatly by intervals, and the volcano that was active in the back-arc region during the Early Pleistocene became dormant in the first half of the Middle Pleistocene. 0.3 million years ago and after or the latter half of Middle Pleistocene, the new back-arc volcanic activities (Numazawa volcano, Sunagohara caldera) began, and it should be noted that they are located in the areas of volcanic activity gap. This means that if the time is set back 0.3 million years, Numazawa volcano and Sunagohara caldera appeared outside the “range within the circle of 15 km radius with the center being an existing Quaternary volcano”, and the volcanic activities cannot be eliminated based on location under this condition. To understand the spatiotemporal change of the volcanoes in southern Northeast Japan shown in Fig. 5, it is necessary to extend the time scale further and to look at the tendency of the magmatic eruption rate for the entire area. Figure 6 is the result, and the time scale of the horizontal axis is in the unit of million years, and the vertical axis is the sum total of the magmatic eruptive volume from all volcanoes in the Aizu region, from the Nasu volcano group along the volcanic front to the Numazawa volcano on the back-arc side^[9]. It is clear from the ladder diagram of eruptive volume of the entire region in Fig. 6, that the long-term magmatic eruption rate shown in a dashed line for this area is dominated by the mega-eruptions where the single eruptive volume surpasses

100 km³ and which occur at 1~2 million year intervals. The eruption site is covered with overlapping large collapse structures (caldera, shown in pink in the diagram) with diameters of over 10 km in the range of 60 km × 50 km, and the activities can be traced back to 10 million years ago^[10]. The appearance of Numazawa volcano and Sunagohara caldera occurred in this volcanic activity region, and they cannot be fully positioned only by the investigation of the activity history limited to Quaternary volcanoes. The existence of the hierarchical structure of the phenomena, as presented here, shows the difficulty of forecast by simple extrapolation of the history of change. To reduce the uncertainty of the forecast for several 100 thousand to a million years into the future, it is necessary to understand the structural development history of the subject region, by tracing way beyond the assessment period, and effort must be made to minimize any “unexpected phenomenon”.

4.3 Limit of probabilistic assessment: need for a forecast that steps into the geological understanding of the phenomena

In the United States, Yucca Mountain in Nevada was determined as the HLR waste disposal site in 2002, and the safety assessment for the approval of construction was started from September 2008. However, President Obama decided to terminate the Yucca Mountain project, and the appeal to withdraw the application for approval was submitted in

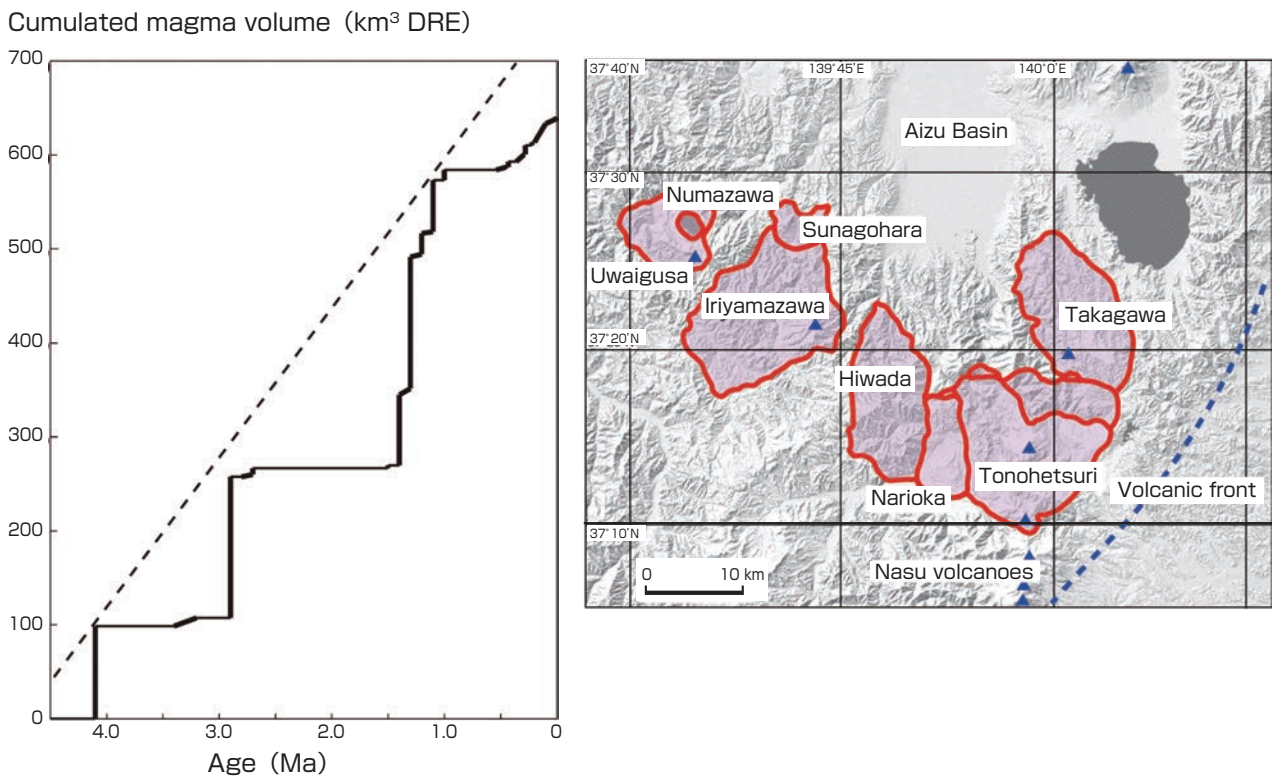


Fig. 6 Cumulative erupted magma volumes from the Aizu regions in the southern part of NE Japan arc
The average eruption rate (dotted line) is controlled by huge eruptions from caldera volcanoes (red solid lines). After Yamamoto^{[9][10]}

March 2010. The geological disposal is essentially on hold. Aside from this course of event, reconsideration must be done for the geological disposal in Japan, as there was a major geological problem in the safety assessment for Yucca Mountain. The Yucca Mountain site was located within the basalt magma monogenetic volcano group that was active in the Quaternary period, and various assessments had to be done for the volcanic activities for the site. The US Department of Energy (DOE) that conducted the project assessed the probability of eruption at the site by calculating the average re-eruption interval from the eruption history of the past monogenetic volcanoes, assuming that a mega-eruption that may form a caldera will not occur^[11]. However, the eruptive activities of monogenetic volcano groups are distributed unevenly in both time and space, and do not occur uniformly. Considering the peak of the activity and distribution state, it was inevitable that the probability shown by DOE would be considered an underestimate^[12]. There is an arbitrary aspect in which the values may differ according to how the scales of time and space are set in calculating the probability, and it must be said that probabilistic forecast without scientific basis for explaining the uneven distribution of the activity frequency lacks reliability. There are some researches that apply the probabilistic assessment of the volcanic activity to Northeast Japan^[13], but these are extrapolations of the distribution of the Quaternary volcanoes directly as a function of probability, and do not consider the changes in spatiotemporal distribution or magmatic eruptive volume as shown in Fig. 4 and 5 of this paper.

In evaluating the volcanic activities, it is necessary to understand the conditions of magma generation in the deep underground that is the source of volcanic activities, in accordance to the spatiotemporal changes of the activity region. Although it will not be explained in detail in this paper, the rise in partial fusibility was observed through the changes in the chemical composition of the eruptive materials in Numazawa volcano that newly appeared in the aforementioned Northeast Japan back-arc region, and it is thought that the magma was generated by the reheating of the crust^[8]. In the major caldera eruption in the Aizu region in southern Northeast Japan, it was shown that the large-scale melting of the lower crust and the rearrangement in the up-down direction of the crust occurred when a large amount of magma was formed, from the geochemical property of the eruptive material. This corresponds well with the underground temperature structure shown seismologically^[9]. In the forecast of the volcanic activities, the assessment that steps into the geological, geophysical, and geochemical basis as well as the magma genesis will be demanded. The probabilistic assessment that simply matches the numbers without theoretical backing not only will be questioned, but may also lead to unnecessary confusion as in the Yucca Mountain project.

5 Summary

As there is a great amount of radioactive wastes already in Japan as the product of nuclear power generation, and they continue to increase, we face a situation where the wastes must be quickly and effectively disposed. Particularly, in geological disposal, the social consensus for this project is mandatory, aside from the issue of long-term safety assessment of the geological disposal environment. While the business executor is responsible to be accountable for safety, the regulating authorities must have the ability to decide whether the application of the disposal business company is appropriate, and to disclose the information to society to obtain consensus. The Research Core for Deep Geological Environments, AIST handles the supportive research for government regulations, and its purpose is to utilize the research results and to provide technological support in the safety regulations. Particularly, the presentation of the safety thinking at a time scale that surpasses the ordinary daily perception, as in the forecast of several hundred thousand years into the future, is an issue that must be solved by the Research Core for Deep Geological Environments. The geological phenomenon may have extremely major effect on society if it happens, even if it is a rare natural phenomenon (event that occurs at extremely low frequency), and we must learn from the experience of the 2011 Earthquake off the Pacific Coast of Tohoku. This paper described the methodology of forecast and the geological issues in geological disposal. Particularly, in the assessment of the natural phenomena that may affect the disposal system, the reconstruction of the geological structure development history as the just history at the candidate site is important, and it is necessary to conduct the assessment at a time scale with sufficient likelihood to eliminate any “unexpected events”. Recently, the Nuclear Safety Commission of Japan stated that the earthquake and volcanic activities should be assessed as rare natural phenomena in the safety regulation for subsurface disposal, which is a form of category 2 waste disposal facility^[14]. However, according to the current thinking of the Nuclear Safety Commission, there is arbitrariness in the way in which rare natural phenomenon is determined, and the ways of excluding the arbitrary event settings such as maintaining the low assessed dosage among the various natural phenomena have not been clarified. Moreover, in the geological disposal, which is a non-managed category 1 waste disposal facility, it is assumed that the problematic natural phenomena are eliminated in selecting the site as stated in the Specified Radioactive Waste Final Disposal Act. There is a great disparity in the fact that the earthquake and volcanic activities that were supposedly eliminated are assessed for safety as rare natural phenomena. I shall repeat that in the safety assessment of geological disposal, the basis must be the accurate geological understanding of the candidate site, and the original purpose is the maximum reduction of uncertainty through such understanding.

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Discussions with Reviewers

1 General comment

Comment (Shigeko Togashi, Evaluation Department, AIST)

In terms of synthesiology, this paper can be viewed from the perspective of the methodology for impact assessment of the natural phenomena on human activities with very long time scale.

The fact that the geological phenomena, even if it is a rare natural phenomenon, can have extremely large impact on society if it should happen, had been shown by the 2011 Earthquake off the Pacific Coast of Tohoku, and is an important issue that must be dealt with by society.

In this paper, taking the example of the geological issues required in the safety assessment of geological disposal of the HLR waste, the method of extracting the issues based on the series of events (scenario) or the process where one event will induce the next event one after the other, the limitation of the probabilistic method for the geological phenomenon investigated, and the necessity of long-term forecast based on the model of geological phenomenon genesis are described.

I think it provides an extremely important viewpoint in terms of synthesiology. In the process of review, improvements were made to clarify the characteristics as a generalized methodology.

2 Significance of the research

Comment (Akira Ono, AIST)

I think this is an excellent research that presents the methodology for assessment by integrating and synthesizing geological elemental technologies pertaining to the disposal of radioactive wastes produced by nuclear power generation.

As it became apparent from the accident at the Fukushima Daiichi Nuclear Power Plant, not only decisions by regulating authorities but wishes of people and local governments are very important in selecting the locations for nuclear power plants and waste disposal sites. I think such decisions must be made based on scientific evidences. In that sense, results of scientific researches should be shared widely by people and not only by regulating authorities. I hope this paper is read and referenced widely across the disciplines.

3 Overall processes leading to the decision of waste disposal site and the positioning of the research

Comment (Akira Ono)

I think it is easier for the readers to understand if you show the overall processes leading to the decision and where this research is positioned within the processes, because there are many people involved as disposal sites for radioactive waste are determined.

Answer (Takahiro Yamamoto)

In accordance to your comment, I added the relationship between this research and the security after closure of the geological disposal repository in Fig. 1. The ways of conducting the geological disposal business or the procedure for selecting the final disposal site are set by the Specified Radioactive Waste Final Disposal Act, and the selection of the disposal site itself is conducted by NUMO, the executive body, but the content of the safety regulation has not been established. The final goal of this research is to establish the index for selecting and deciding the investigation and assessment items for the disposal site selection investigation. For example, as described in this paper, places that may be affected by volcanic activities or places in which new volcanic activities may occur are not appropriate as disposal sites. The theme of this research is the methodology for how to establish the assessment method to determine such matters.

4 Responsibility of the current generation to the future generation

Question (Akira Ono)

In this paper it is stated that it is necessary to assess the safety of the radioactive waste disposal at a time range of several hundred thousand to a million years, and that is because this time span is required for the radiation level of the HLR waste material to decrease to a level of naturally existing radioactive substances. After this time range has elapsed, the current humanity will be in the next evolutionary stage, and it is imagined that the current civilizations, cultures, and ethnic groups will be totally gone. I think this paper is based on the thinking that the current humankind should be responsible for the earth environment and biosphere of such a distant future. What does the author think about the adequacy of this thinking?

Answer (Takahiro Yamamoto)

I think the generation that received the benefit of nuclear

power should be responsible for the disposal of the waste. Since the accident at the Fukushima Daiichi Nuclear Power Plant, the public opinion is to move away from nuclear dependency, but the disposal of the existing radioactive wastes that had been produced cannot be avoided in decommissioning the plants. “No nuclear” cannot be achieved only by stopping the power generation, and our generation must be responsible for the final disposal of the nuclear waste whether we continue or discontinue nuclear power.

As for the human activities in the future, Japan is engaging in the safety assessment after closure of the geological disposal sites with this point in mind, just as in other countries. For example, it says “mineral resource” in “Investigation/assessment items for geological environment” in Fig. 1. This is because the presence of underground resource that may be mined is set as an exclusion condition, to avoid the disposed materials to come in contact with the human activities in the future.

5 Scenario for the assessment of risk occurrence in the future

Question (Akira Ono)

The risk of disposed radioactive waste to humans at a time in the future may be the product of the radiation of radioactive substances at that time and the possibility that the radioactive substances may affect humans.

The radiation level of radioactive substances can be estimated to decrease logarithmically from the nuclear physics data. On the other hand the possibility that the radioactive substances from the waste substances may affect humans is a geological issue. What scenario of geology is envisaged for the risk assessment?

Answer (Takahiro Yamamoto)

The natural barrier in geological disposal not only attempts isolation by distance. The waste materials including the artificial barrier buried deep underground will eventually lose the containment function due to corrosion. After that, the radioactive substances are expected to undergo reduction in radioactivity in the process of travelling through the natural barrier by underground water, and through delay by absorption by minerals and dilution by underground water, before it arrives to the ecological environment on the surface. The safety assessment after closure is based on such underground water transfer scenario.