GEOSYNTHESIS: TESTING A SAFETY CASE METHODOLOGY AT GENERIC JAPANESE URLS

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Abstract

Site characterisation is a very complex, multidisciplinary process that may extend over many years and involve development of an optimised programme that balances the diverse – and often contradictory – requirements of the many specialists involved in this work. To make things even more difficult, the end users who use this input to steer repository implementation programmes – the designers of waste disposal concepts and the assessors of their safety – require processed data that may involve many steps of synthesis and integration before it is in a form that is applicable for their purposes. For the additional requirements of repository licensing, the entire process termed geosynthesis in the paper should be transparent and fully documented. Indeed, in a perfect world, the methodology should be user-friendly and capable of providing feedback to set priorities in the field programme and provide guidance in the (likely) event of surprises occurring. As a step towards this goal, JAEA is developing a geosynthesis methodology and testing its application with real data. The paper describes the geosynthesis methodology and its applicability to site selection in Japan, which involve provisional safety case development to support key decisions. Using the JAEA database for the two URLs at Mizunami and Horonobe, the maturity of the existing technology will be illustrated and key challenges for future development discussed.

Introduction

On the basis of technical achievements summarised in the "H12" suite of technical reports [1-5], by JNC (now JAEA), the Japanese geological disposal programme for vitrified high-level radioactive waste (HLW) moved in 2000 from a pure R&D stage towards implementation. At this time, the law regulating implementation ("Specified Radioactive Waste Final Disposal Act") was passed following deliberations at the national diet and the implementing entity, the Nuclear Waste Management Organization of Japan (NUMO), was established.

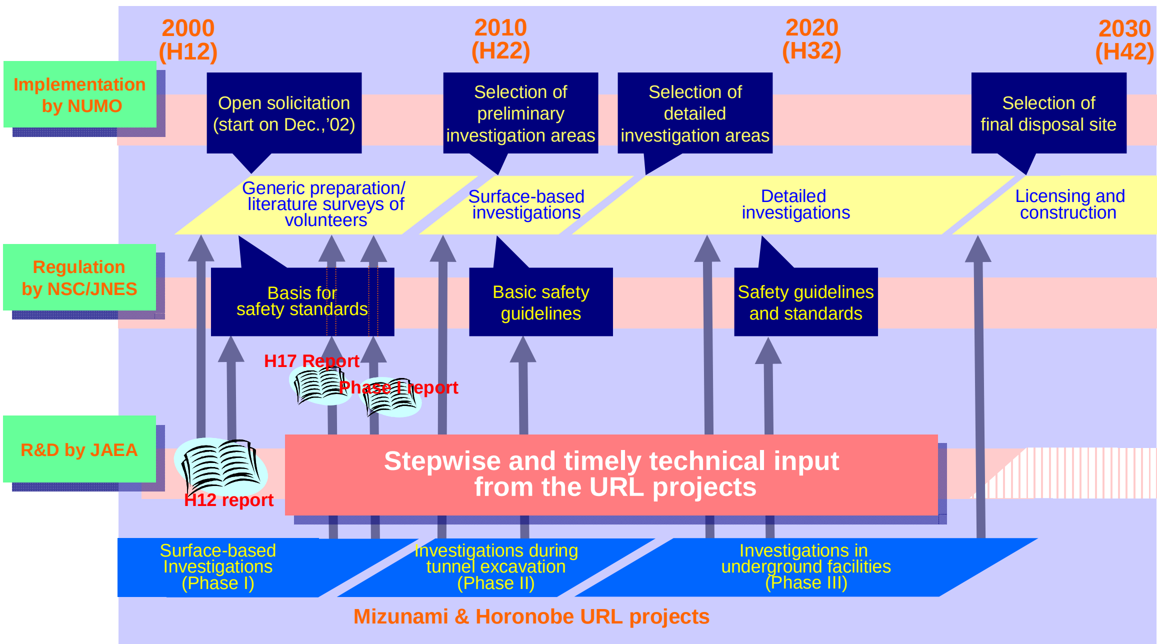
According to the open solicitation process [6] initiated by NUMO in 2002, site selection of a HLW repository in Japan will proceed in a stepwise manner; initial literature surveys will lead to selection of areas for preliminary investigations, based on investigations from the surface. One or two sites are then selected for detailed investigations from underground characterisation facilities that eventually leads to choice of a site for repository implementation. The decisions at the end of each stage are highly sensitive, involving large commitments of resources.

The Specified Waste Act also states that regulations on the safety of final disposal shall be established separately. The discussions required to define such regulations have already been underway for some time, mainly involving the Nuclear Safety Commission of Japan (NSC) and the Japan Nuclear Energy Safety Organization (JNES). The NSC, taking the achievements from the H12 project into consideration, published the first report on the basis for safety standards of HLW disposal [7] in November 2000. The report specifies safety fundamentals, general guidelines for site selection, basic considerations for safety assessment and procedures for management of the disposal site. NSC also published the "Requirements on the Geological Environment in the Selection of Preliminary Investigation Areas for High-Level Radioactive Waste Disposal" in the year 2002 [8]. The requirements have been reflected in NUMO siting factors, to be used for the selection of areas for preliminary investigation.

In accordance with "Framework for Nuclear Energy Policy" [9] specified by the Atomic Energy Commission of Japan (AEC) in 2005, JAEA has responsibility in the implementation phase for R&D to enhance disposal technology, safety assessment methodology together with associated databases and to develop a knowledge management system for the Japanese HLW disposal programme. Therefore, JAEA R&D contributes to both the implementation of deep geological disposal and the formulation of associated safety regulations.

A particular feature of JAEA activities in this phase is advanced R&D in two purpose-built generic URLs (Underground Research Laboratories): one at Mizunami in crystalline rock and the other at Horonobe in sedimentary rock. These URLs are generic research facilities and thus distinct from the site-specific underground facilities to be constructed by NUMO at the detailed investigation stage. However, the output from investigations carried out in the URLs is timely contributed to the stepwise implementation and regulation processes as shown in Figure 1.

Figure 1. **Japanese HLW disposal programme and supporting R&D activities in URL projects** (after [10])



A key issue – and the focus of this paper – is the integration of information from different disciplines in the surface-based investigations at the Mizunami and Horonobe URLs as a "geosynthesis". Indeed, the geosynthesis methodology is being developed further in the underground facilities at these sites. Thus the applicability of geosynthesis process can be tested with the datasets from these two generic URLs, serving as "dry runs" of the investigations of a real site in order to demonstrate site characterisation methodologies for specific geological environments.

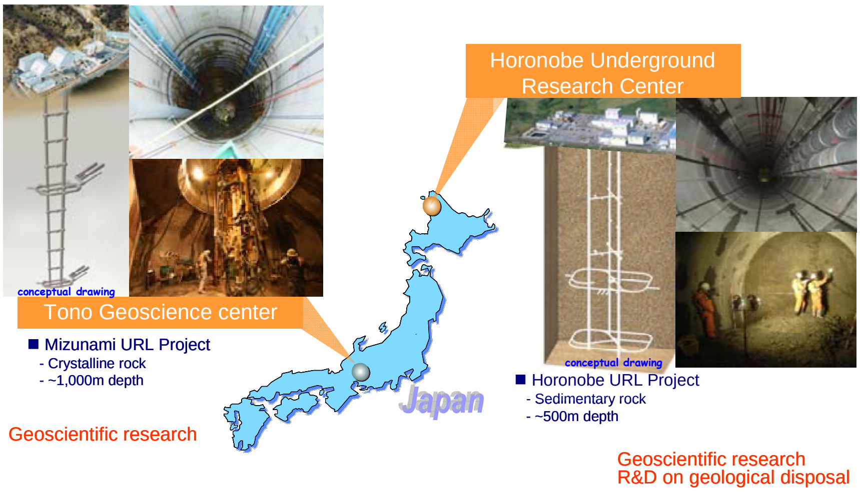
Overview of URL projects at Mizunamimi and Horonobe

The AEC proposals for a "Long-Term Program for Development and Utilization of Nuclear Energy", published in 1994 and 2000, recommend that two or more URLs should be constructed, based on considerations of the ranges in characteristics and distributions of the geology of Japan [11-12]. On this basis, JAEA has initiated the Mizunami URL Project for investigating crystalline rock and the Horonobe URL Project for investigating sedimentary rock. Locations and conceptual layouts for the Mizunami and Horonobe URLs are shown in Figure 2.

The establishment of JAEA by merging Japan Nuclear Cycle Development Institute (JNC) and Japan Atomic Energy Research Institute (JAERI) in October 2005 included formulation of a 5-year "mid-term" policy plan [13]. This reinforced the fundamental commitment to R&D in the fields of geoscientific research and geological disposal technologies based at the URLs.

The URLs have the primary goals of applying and demonstrating the geoscientific investigation methods, the disposal technology and the safety assessment methodology developed in the generic H12 project, in order to confirm their applicability to specific geological environments. Furthermore, the technology and methodology should be optimised through the actual application and the evaluation of the applicability for deep geological disposal on the basis of stepwise R&D activities carried out in the URLs or other JAEA facilities. Both URL projects consist of three investigation phases that extend over a period of around 20 years in accordance with the Japanese HLW disposal programme as shown in Figure 1: surface-based investigations (Phase I), investigations during tunnel excavation (Phase II) and investigations in the underground facilities (Phase III).

Figure 2. **Locations and conceptual layouts of generic Japanese URLs** (after [10])



Conceptual layouts may be optimised on the basis of experience from site characterisation and future plan.

Mizunami URL Project

Surface-based investigations in the Mizunami URL Project, located in Mizunami City, Gifu Prefecture, have been carried out since 1996 with a focus only on geoscientific research in the area covering the URL construction site that was owned by JAEA. However, the URL construction site has been forced to move to other location owned by Mizunami City for social reasons in 2002. The URL construction site features Cretaceous granitic basement rocks (Toki granite), overlain by Miocene (Mizunami Group) and Miocene to Pliocene (Seto Group) sedimentary rocks. The major E-W striking Tsukiyoshi Fault crosscuts the Toki granite and the Mizunami Group. Deep groundwater is generally low salinity, of meteoric origin. These characteristics are not so different from the previous construction site. Thus, the characterisation concentrates on a "site scale" area (2 km × 2 km) that includes the URL construction site.

In the URL construction site, surface-based investigations (Phase I) began in March, 2002 and shaft excavation (Phase II) started in July, 2003. According to the current design, the URL will consist of two 1 000 m deep shafts for ventilation and main access. At the end of March 2008, the excavation progressed to a depth of 230 m for the main shaft and 200 m for the ventilation shaft and the excavation of a horizontal tunnel connecting the shafts at a depth of 200 m level was competed.

Horonobe URL Project

Horonobe URL is located in the Hokushin-area of Horonobe Town, Hokkaido Prefecture. The investigations area in Horonobe Town was selected in a stepwise manner taking account of factors such as social conditions, the geological environment, geographical constraints, safety and technological feasibility. Investigations concentrate on the URL area (3 km × 3 km) covering the URL site (19 ha). Here Neogene to Quaternary sedimentary sequences (in ascending order: the Soya coal-bearing Formation, Onishibetsu Formation, Masuporo Formation, Wakkanai Formation, Koetoi Formation, Yuchi Formation, and Sarabetsu Formation) are underlain by igneous and Paleogene to Cretaceous sedimentary basement. There are some major faults in the area of interest, in particular the Omagari Fault and the Horonobe Fault. The Wakkanai and Koetoi Formations, which are Neogene argillaceous sedimentary formations, have been selected as the hosts for the URL, and saline groundwater is found in the host geological formations.

In the Horonobe URL Project, surface-based investigations (Phase I) started in March, 2001 and were completed in 2005. According to the current design, the URL will consist of three 500 m deep shafts, one for ventilation and two (east and west) for access. Investigations during tunnel excavation (Phase II) started in 2005 in the ventilation and east access shafts. At the end of March 2008, excavation had progressed to depths of 161 m for the ventilation shaft and 110 m for the east access shaft. Additionally, the excavation of the -140 m level horizontal tunnel was underway.

Unlike the Mizunami URL Project, R&D activities on disposal technologies and safety assessment methodologies related to HLW geological disposal have run in parallel with geoscientific research in the Horonobe URL Project since the initiation of the project. Such studies will use research galleries for *in situ* testing and technology development, which will be initiated in Phase II and will be fully implemented in Phase III.

The role of the generic URLs

As described by Umeki *et al.* [10], the generic Japanese URLs also provide a wide range of possibilities for underground research by universities and other research institutes, as well as serving as a tool for enhancing public understanding of R&D activities related to geological disposal. The outputs from the URLs are widely published and expected to make a timely contribution to the Japanese disposal programme and the establishment of safety regulations (Figure 1) as follows:

- Techniques have been developed for characterising the deep geological environment based on investigations from the surface (Phase I). This takes into account data requirements for the design of underground facilities and infrastructure, along with associated safety assessment.
- Data obtained from investigations during the excavation phase (Phase II) serve to verify the results from the surface-based investigations and, additionally, characterise the perturbations caused by the excavation process. Such perturbations, e.g. changes in groundwater flow and rock mechanical properties, are monitored and compared to prior model predictions.

- Detailed investigations in the underground facility (Phase III) will contribute to improving investigation techniques for the deep geological environment. Data will also be compiled to specifically test models and their associated databases.
- Making the URLs available for visits by all interested stakeholders, including local communities, national academics, professional expert groups, and the general public, can promote understanding and acceptance of geological disposal projects. A key factor here is the considerable visceral impact of directly experiencing the conditions in the deep geological environment and seeing the scale of investigation activities and the demonstration of disposal technology.
- Apart from technical and scientific aspects, the URLs could be used as an effective tool for establishing dialogue between the general public and staff working on geological disposal projects, to enhance understanding and build confidence in the credibility of the organisations involved.

Relevant processes and properties of geological environment

The geological environment in which a repository is constructed is expected to physically isolate the waste for very long time periods, provide a suitable environment for installing the engineered barriers and ensuring their long-term performance and function as a natural barrier to constrain radionuclide migration. A suitable geological environment is expected to have the following properties and functions:

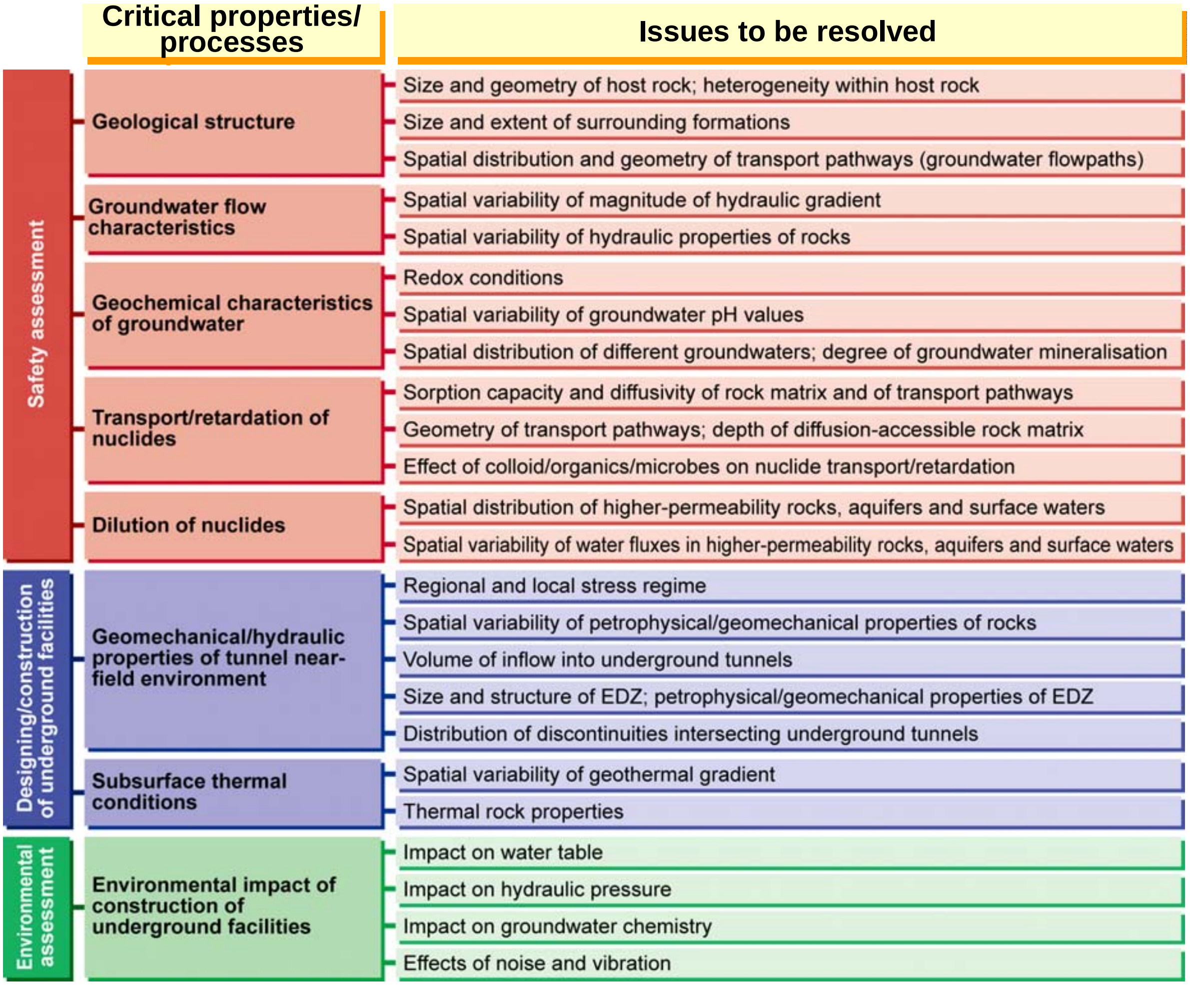
- Demonstrated existence over an appropriate depth range and sufficient spatial extent.
- Relatively homogeneous stress conditions and low temperatures, to ensure operational safety and ease design, construction and maintenance of the engineered barriers, and other underground facilities.
- Low groundwater flux through the repository horizon, ideally with neutral to slightly alkaline chemistry and reducing conditions, which would serve to restrict erosion of the buffer material, corrosion of overpack, dissolution of the waste glass matrix, and radionuclide migration.
- Slow groundwater movements and long flow paths between the repository and the accessible environment to reduce the rate of radionuclide migration.
- High dilution and dispersion during transport to the biosphere, resulting in reduction of radionuclide concentrations.

To focus the surface-based investigations in the URL projects at Mizunami and Horonobe, relevant properties and processes of the geological environment in relation to repository design, safety assessment and environmental assessments were identified (Figure 3). Based on these, the synthesis of information from the progress from raw field data obtained in the investigations to the key properties and processes required by safety assessment, design engineer and environmental assessment users was determined in a systematic manner. This is termed the "geosynthesis methodology", which is based on an approach originally developed and applied by NAGRA in Switzerland [15]. The key properties/processes should be reviewed and updated as understanding of the site improves.

Geosynthesis methodology

The geosynthesis methodology aims to improve the site characterisation methodologies and the transparency of the production of the information needed by end users. The two key components of this methodology are a synthesis data flow diagram and an iterative approach for its development, which aim to be sufficiently rigorous to serve as a contribution to the safety case for assuring safety both during construction and operation of a repository and also post closure.

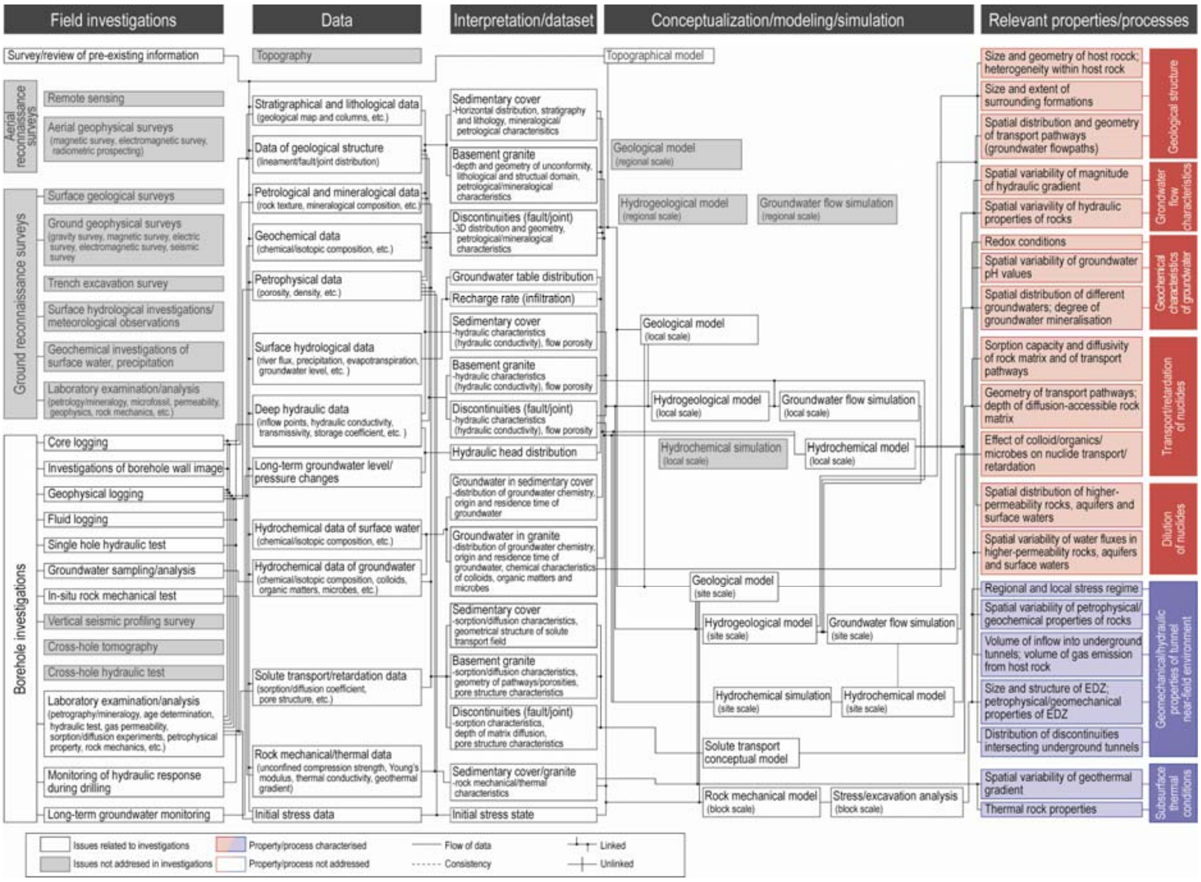
Figure 3. **Relevant properties/processes of the geological environment relating to repository design, safety assessment and environmental assessment** (after [14])



Synthesis data flow diagram

To establish a systematic geosynthesis framework, the concept of a data flow diagram was introduced. Figure 4 shows an example of the synthesis data flow diagram for surface-based investigations (Phase I) in the Mizunami URL Project, showing how raw data obtained from investigations are integrated, interpreted and synthesised. This diagram provides basic roadmap for guiding investigations in a systematic manner and yields clarification of properties and processes that are relevant to repository design and safety assessment, along with an assessment of the uncertainties that are inevitable in such a synthesis process. Importantly, the impact of limitations in knowledge and uncertainties in data can be assessed by the end users to provide feedback to guide focusing or prioritisation of subsequent investigations. Such feedback may not only be obtained for the entire geosynthesis at major project milestones (e.g. moving between Phases I, II and III in the URL projects), but also may also be important for sub-systems on shorter timescales (steps within an individual phase). The synthesis data flow diagram is not static, but evolves to reflect the technical knowledge and system understanding accumulated during stepwise progress of the investigations. Thus, improved understanding the relevant properties and processes for geological disposal is complemented by an optimised, site-specific flow diagram that illustrates the supporting knowledge base.

Figure 4. **An example of synthesis data flow diagram for surface-based investigations** for site scale in Mizunami (Step 3) (after [16])



Iterative approach

Based on worldwide experience, it is clear that investigations from the surface have relatively larger constraints to characterise the deep geological environment and the applicability of different tools is dependent on the site-specific setting. It is essential, therefore, that a site characterisation programme has sufficient flexibility to respond to the gradually improving understanding of the local geology and, in particular, the surprises that inevitably occur. There is a fundamental dichotomy, however, between the desire for advanced planning – to simplify logistics and optimise use of limited resources – and this need for flexibility. The solution identified is to have a structured strategy, outlined within the synthesis data flow diagram. The particular advantage here is that the refocusing incorporates feedback from the end users – which is very different from traditional approaches which depend very much on the practical experience of field geologists and hence tend to concentrate only on ensuring that initially defined raw/conditioned data are obtained. Important components of the geodatabase for end users, which are particularly sensitive to site uncertainties (e.g. hydraulic properties) may be iterated very regularly – whenever new data are obtained or when new observations deviate from expectations – whereas less sensitive/better defined components (e.g. rock thermal properties) may be considered directly only in the entire geosyntheses associated with major project milestones.

Development of a provisional safety case at the URLS

Demonstration of safety is a key requirement for social acceptance of geological disposal of HLW. In the past, quantitative performance assessment has been the basis for evaluating the safety of specific HLW repository systems. However, this has been recognised to be insufficient to meet the requirements of all stakeholders. Therefore, the concept of a safety case, which recognises that the demonstration of safety needs a wider base of supporting argumentation, has been introduced recently.

Definition of safety case

The IAEA safety standards [17] contain the following definition of a safety case;

"The safety case substantiates the safety, and contributes to confidence in the safety of the geological disposal facility. The safety case is an essential input to all the important decisions concerning the facility. It includes the output of safety assessment, together with additional information, including supporting evidence and reasoning on the robustness and reliability of the facility, its design, the design logic, and the quality of safety assessments and underlying assumptions. The safety case may also include more general arguments relating to the need for the disposal of radioactive waste, and information to put the results of the safety assessments into perspective."

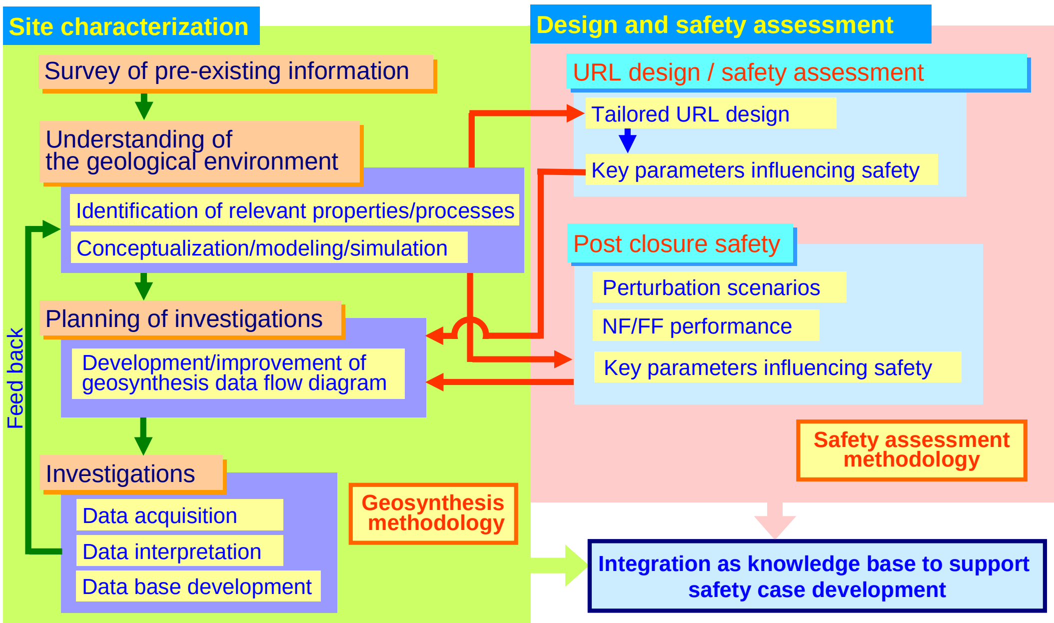
In the process of developing a safety case, the link among site characterisation, repository design, and safety assessment would be clearly defined.

Framework for developing and testing a safety case at URLs

The JAEA research at Mizunami and Horonobe is distinct from preliminary and detailed site investigations to be carried out by NUMO. However, the concept of phased site investigations adopted for the URLs is similar to that for implementing actual repository projects. Developing a provisional safety case based on information obtained from the URL projects is helpful to emphasize the similarities involved and optimise technical knowledge transfer to the implementing and regulatory organisations.

Throughout the site characterisation according to the geosynthesis methodology and subsequent design/safety assessment for the underground facilities, a provisional safety case utilising the URLs was developed and tested. The consistent framework for developing and testing the safety case developed through the surface-based investigations carried out in the URL projects is illustrated in Figure 5. As shown in Figure 5, safety case can be composed of work areas in both site characterisation and design/safety assessment. In the site characterisation, identification of relevant properties and processes of the geological environment based on the previous investigation results, planning for the investigations along the developed and improved synthesis data flow diagram, and carrying out the investigations according to the plan are iterated in a stepwise manner for optimising the investigations. In the design/safety assessment, safety during URL construction/operation and post closure safety are evaluated based on information obtained from the stepwise investigations. As for safety during URL construction, URL facilities are designed based on analysis/evaluation of tunnel stability using data from surface-based investigations (Phase I) in the URL site, and then observational construction of the underground facilities is carried out in parallel with evaluation of rock properties of surrounding rock investigated during the stepwise shafts/drifts excavation (Phase II). Even during investigations in the URL facilities (Phase III), the tunnel stability is continuously monitored. Accordingly, the design of the URL facilities would be changed for the safety by taking the evaluation of measurement data obtained during both the construction and the operation into consideration where necessary. As for post closure safety, solute transport model is developed for the safety assessment based on relevant properties/processes of the geological environment. Parameters for sensitivity/uncertainty analysis in the safety assessment are collected and the analysis is carried out. Then, the safety for the geological environment as natural barrier system by also taking account of the long-term evolutions as described in Niizato *et al.* [20] and the URL facilities containing engineered barrier system would be evaluated. Therefore, safety case is composed of systematically refined information for assuring the safety accumulated in the site characterisation based on the geosynthesis methodology, the design/safety assessment based on the safety assessment methodology and the linkages among them, in accordance with the framework shown in Figure 5. Finally, information used for developing and testing the provisional safety case at the URLs would be integrated as knowledge base to support safety case development for the actual geological disposal system. Furthermore, the methodology for developing the safety case and various components to be contained in the safety case could be transferred to the implementing and the regulatory organisations.

Figure 5. **A framework for safety case development and testing at URLs**



Major components of the framework for the safety case

According to the framework for the safety case as shown in Figure 5, investigations of geological environment and design/safety assessment at the URLs were carried out. The actual process for developing the provisional safety case at the URLs can be outlined by following major components 1 through 3 of the framework.

1. Planning of investigations.
2. Investigations/understanding of the geological environment.
3. Post closure safety.

The outline of the planning of investigations including development and improvement of synthesis data flow diagram has already been described above. Thus, the components 2 and 3 are discussed below.

Investigations/understanding of geological environment

In each step in the surface-based investigations at the URLs, models for the geological environment are iteratively improved by applying the geosynthesis methodology described above. The justification for this, in terms of both implementers and regulators, is also summarised by Umeki *et al.* [10] and briefly outlined below. The details of output from the surface-based investigations at the Mizunami and Horonobe URLs are summarised in JAEA technical reports [14,16,18].

Surface-based investigations in the Mizunami URL Project

In the surface-based investigations in the site scale area in Mizunami URL Project, a series of various investigations, such as compilation of pre-existing information, geological mapping, reflection seismic surveys, existing borehole investigations, shallow borehole investigations, deep borehole investigations, and cross-hole tomography/cross-hole hydraulic tests were conducted within 5 steps of investigations as shown in Figure 6. The geosynthesis methodology was applied to each step of investigations. Updated models of the geological environment were developed based on information obtained from each step of investigations, which allowed key issues for clarification during the next investigation step to be identified.

Figure 6. **Conceptual illustration of stepwise investigations for site scale in Phase I of Mizunami URL Phase I** (after [16])

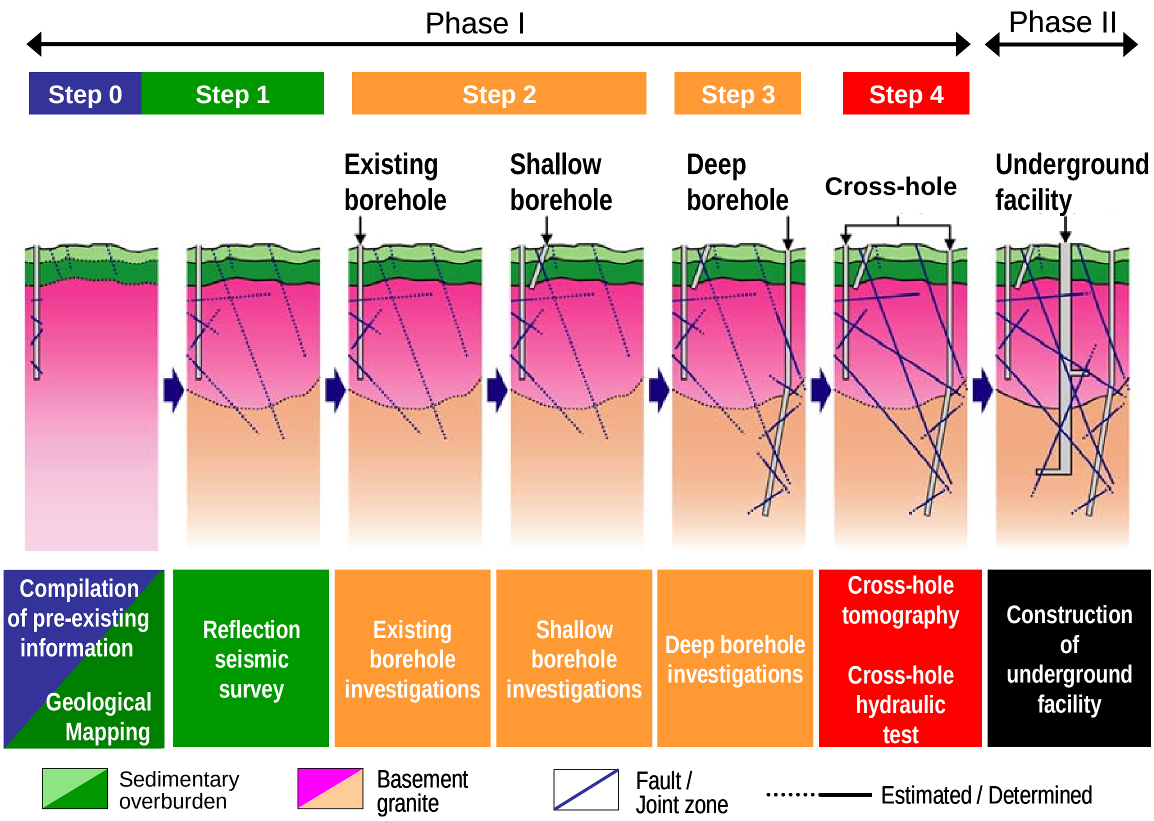
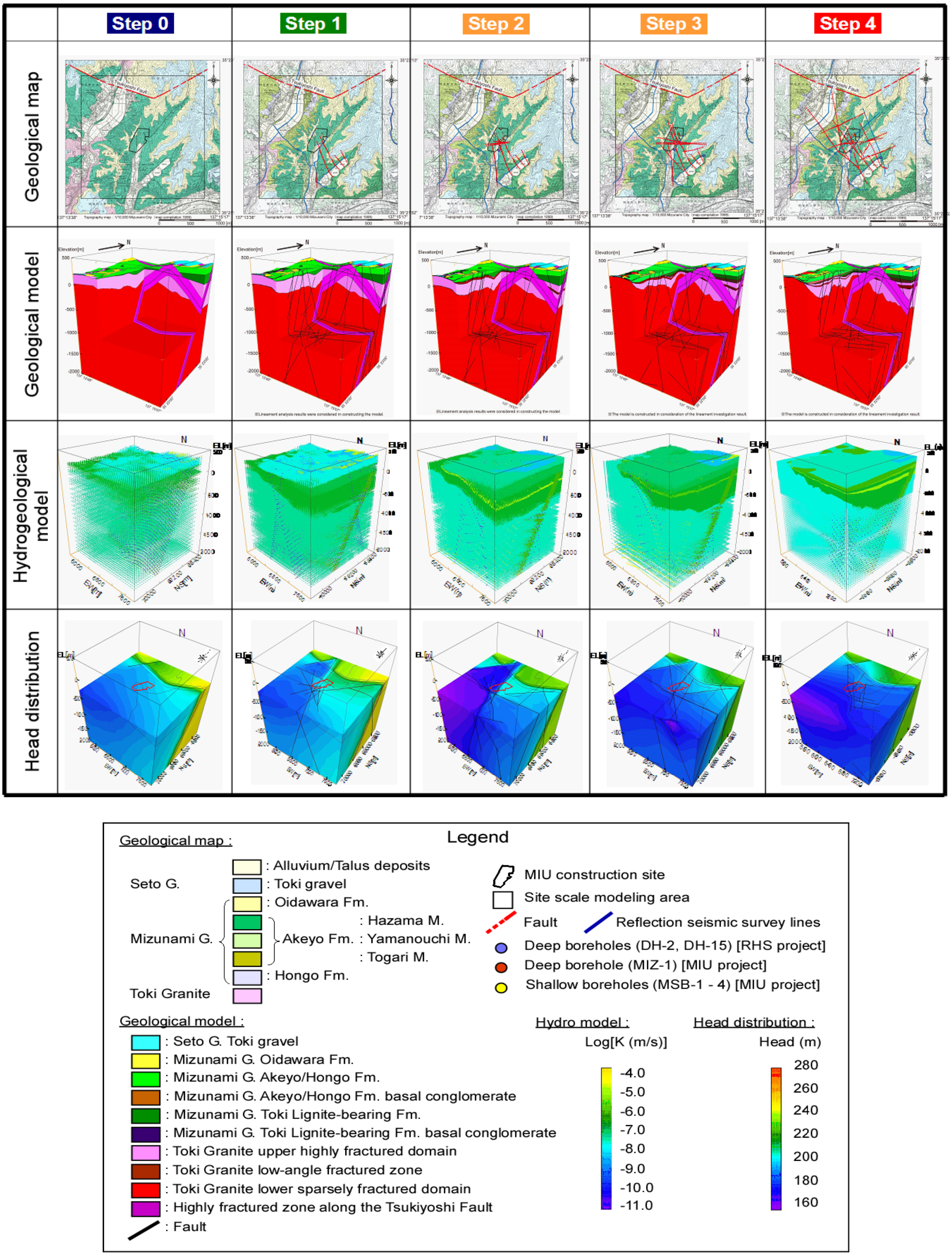


Figure 7 shows the evolution of the geological model, the hydrogeological model, and the results of groundwater flow simulations (represented as head distributions) from Step 0 to Step 4. A large amount of raw data is integrated to produce these representations. Especially at earlier stages, however, there are also considerable associated uncertainties, which are represented by a large number of alternative simulations which are not shown. As later investigations target such uncertainties, the number of variants that need to be considered tends to decrease and the ability of the models to simulate reality – as assessed by comparison of simulated and measured data at relevant points in boreholes – generally improves. As indicated in Figure 4, hydrogeological models can also be tested by assessment of isotope hydrology and patterns of distribution of groundwater chemistry; however, during Phase I, the database is insufficient for more than qualitative evaluation of general compatibility. Details of the hydrogeological modelling in site scale in the surface-based investigations at Mizunami are described in Saegusa *et al.* [19].

Figure 7. **Model evolution with stepwise investigations for site scale in Phase I of Mizunami URL Project** (after [16])



Surface-based investigations in the Horonobe URL Project

The application cases of the geosynthesis methodology to the surface-based investigations in the Horonobe URL Project, which are divided into two stages: "investigations covering the whole Horonobe Town area" and "investigations in/around the URL area," are described in this section. In the investigations covering the whole Horonobe Town area (approximately 40km × 20km) carried out in 2000-2001, the first two years of Phase I, a URL area (3km × 3km) and a URL site (19ha) were selected in a stepwise manner taking account of factors such as social conditions, the geological environment, geographical constraints, safety and technological feasibility. Along with the progress of the selection process, the investigations have been carried out by using pre-existing data collected from open literatures, the aerial geophysical surveys, surface investigations, and deep borehole investigations. The URL area, which is the main focus for investigations and modelling carried out after the URL site selection, was selected in the Horonobe Town area through a couple of steps. After selection, surface-based investigations were intensively carried out in and around the URL area over the period 2002-2005. Three steps of surface-based investigations, which were investigations using pre-existing information, non-invasive surface investigations and borehole investigations, were carried out. The pre-existing information included open literature and regional data from aerial geophysical surveys, ground geophysical/geological surveys, and places for deep borehole investigations, which were carried out in the investigations covering the whole Horonobe Town area; this yielded a first general overview of the expected site geology. Surface investigations included geological mapping, gas analyses in shallow boreholes, and reflection seismic and magnetotelluric surveys covering the URL area, particularly focused on characterising large scale structures such as the Omagari Fault and the geometry of the main geological formations. Deep borehole investigations then aimed to improve understanding of key characteristics of the geological environment, specifically for the Wakkanai and Koetoi Formations, to determine the 3-D geometry and characteristics of the Omagari Fault and to quantify in more detail the characteristics of the geological environment required for designing and constructing the URL. The investigations for understanding the long-term evolution of the geological environment in the Horonobe Town area are summarised by Niizato *et al.* [20].

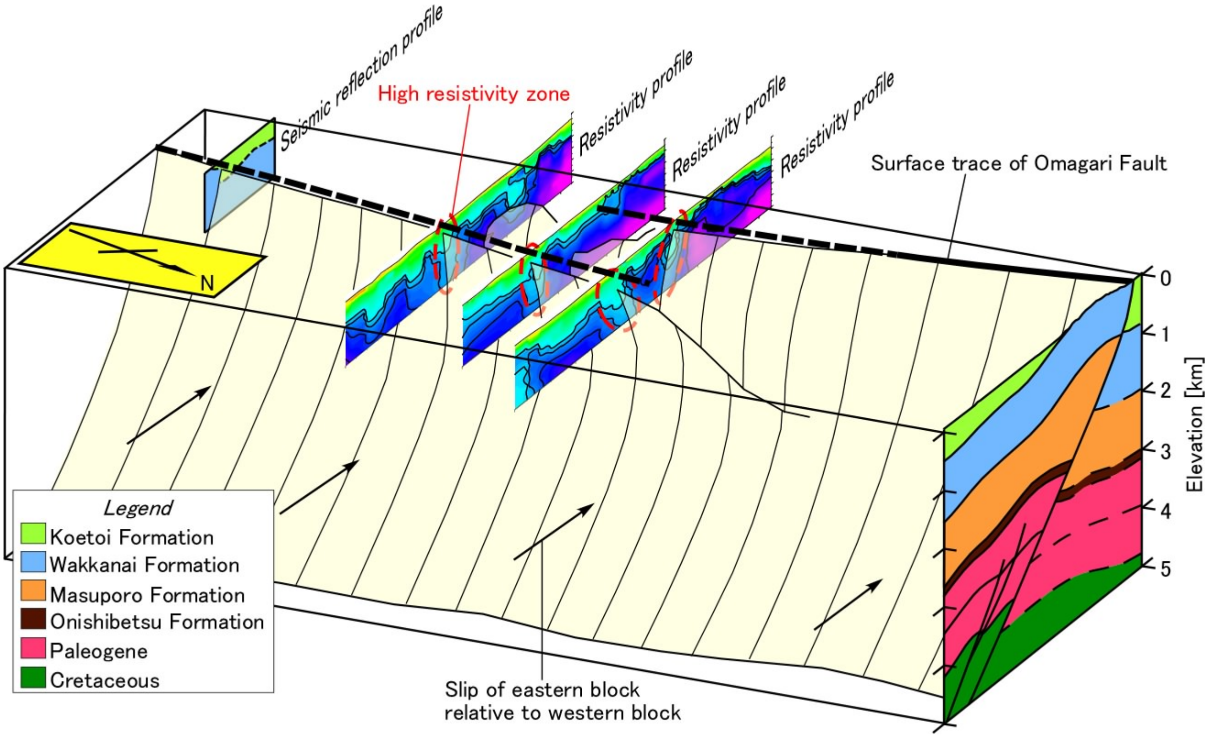
In the surface-based investigations, a focus on relevant geological structure for groundwater flow and solute transport led to the Omagri Fault being identified as a major water-conducting feature (WCF) and other smaller scale faults as potentially significant WCFs.

Major WCF

Although reflection seismic surveys covering the URL area were carried out in 2002, the profiles were not clear enough to accurately establish the 3-D geometry of the Omagari Fault. However, interpretation of the AMT (audio-frequency magnetotelluric) surveys conducted later in the same area allowed this key feature to be localised. The 3-D illustration of the Omagari Fault was improved by integrating information from outcrop surveys, reflection seismic surveys and borehole investigations including observation of drilled core, image analysis of borehole wall, resistivity logging, and chemical analysis of groundwater, as presented in Figure 8. Further important considerations in developing a model of the Omagari Fault included:

- Integrating all investigation results, the main high resistivity feature is interpreted as a zone where meteoric fresh water infiltrates preferentially along the Omagari Fault. Based on the continuity of this high resistivity zone, the 3-D geometry of the Omagari Fault was illustrated as shown in Figure 8.
- Based on observations of outcrops, as shown in Figure 9, the Omagari Fault may form a feature approximately 120 m wide, which consists primarily of a damaged zone. Such a structure would be expected to act as a permeable zone.

Figure 8. **Definition of 3-D structure of the Omagari Fault based on data from surface geophysical surveys** (from [14])



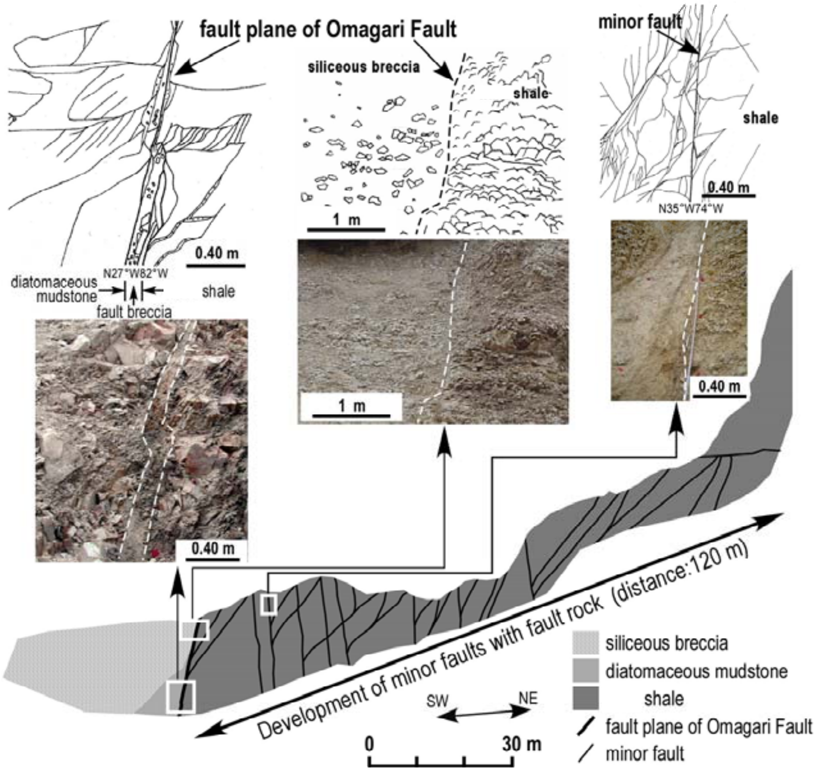
- The estimated location of the Omagari Fault on the basis of reflection seismic surveys and additional borehole investigations roughly corresponded to the location of a high resistivity zone obtained from AMT electromagnetic survey.
- Although the location of the Omagari Fault can be derived from interpretation of geophysical methods, information from deep boreholes is essential to confirm the interpretation and to check the calibration used to estimate the depths of specific features.
- The inverse relationship between the resistivity of formations and the concentration of chloride in formation water indicates that high resistivity zones could be areas where meteoric water is infiltrating to depth.

OtherWCFs

Deep borehole investigations included examinations to clarify the distribution and orientation of faults, and the presence of striations and slickensides on the surface in these. On this basis, most of the features observed in the borehole investigations were confirmed to be shear faults. These faults can be classified into minor faults at a high angle to the bedding plane and those roughly parallel to the bedding plane (Figure 10). Minor faults at a high angle to the bedding plane are considered to play an important role as WCFs based on data from hydraulic tests and fluid logging conducted in the deep boreholes. Further characteristics of the minor faults are summarised as follows:

- The formation age of the minor faults at a high angle to the bedding planes was estimated to be more recent than regional folding and much younger than the Omagari Fault; these were thus the youngest of the faults observed in these formations.

Figure 9. **Sketches at an outcrop of the Omagari Fault** (from [14])



- The minor faults at a high angle to the bedding plane were possibly formed by residual compressive stresses that had accumulated since the fold was formed, and were thus assumed to be distributed widely along the fold structure. The minor faults roughly parallel to the bedding plane were considered to be formed by bedding slips associated with flexural-slip folding and thus expected to be distributed widely in the limb area of the fold structures.
- Minor faults at a high angle to the bedding plane tend to be gathered together densely and connected with each other en echelon, forming a minor fault zone with a length of 10-100 m, as shown in Figure 10.
- Based on the observed development of an oxidised zone along faults near the surface, the expected generation processes of the faults and relationship between fault orientations and the stress field, the minor faults at a high angle to the bedding plane, especially when grouped to produce minor fault zones, are likely to be important pathways for flow and transport, while the minor faults roughly parallel to the bedding plane are not.

Conceptualisation/modelling/simulation

Based on the information above, a conceptual model of the geological structure in/around the URL area was developed as shown in Figure 11. Geological formations explicitly considered are the Wakkanai Formation consisting of siliceous mudstones (or siliceous shale), the Koetoi Formation consisting of diatomaceous mudstones and the Yuchi Formation consisting of poorly consolidated sandstones. Discrete geological features considered in the conceptual model are the Omagari Fault (including the associated damaged zone) as a major WCF and minor faults at a high angle to the bedding plane as WCFs. In addition, the minor faults parallel to the bedding plane, which was considered not to be connected each other and not to be water conducting, are also shown in the conceptual modelling. For groundwater flow modelling covering the characteristics of the geological formations, the Omagari Fault as a major WCF is explicitly considered in the modelling. All other WCFs are integrated into equivalent porous media (EPM) for this model; although this is clearly a great simplification, it was considered appropriate given the limited database for the minor faults. It should be noted, however, that if the sub-vertical fault zones created by the minor faults commonly extend to repository-relevant depths (in the order of 500 m), as indicated in Figure 10, then a consistent modelling strategy including all such features may be needed to realistically represent site hydrogeology.

Figure 10. **Characterisation of WCFs in a deep borehole (HDB-6)** (after [21])

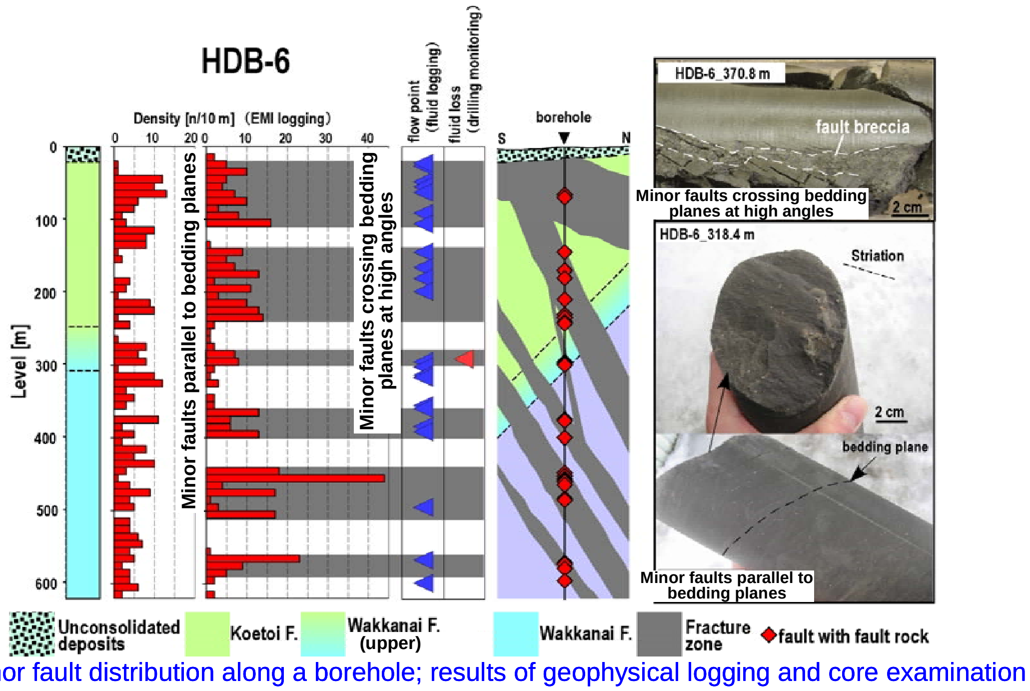
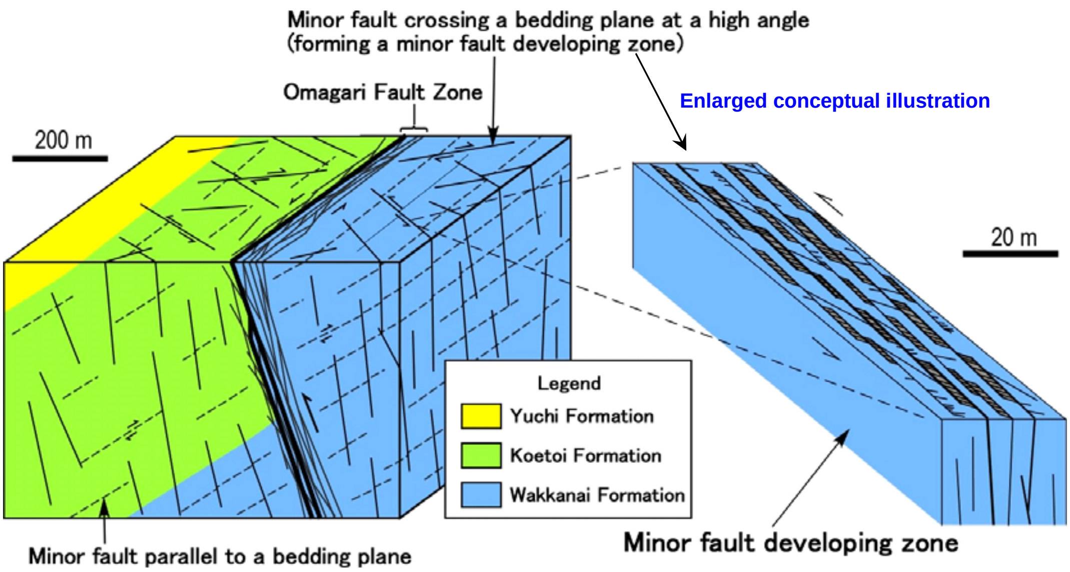


Figure 11. **Conceptual model of geological structures and WCFs In/around the URL area of Horonobe** (from [17])



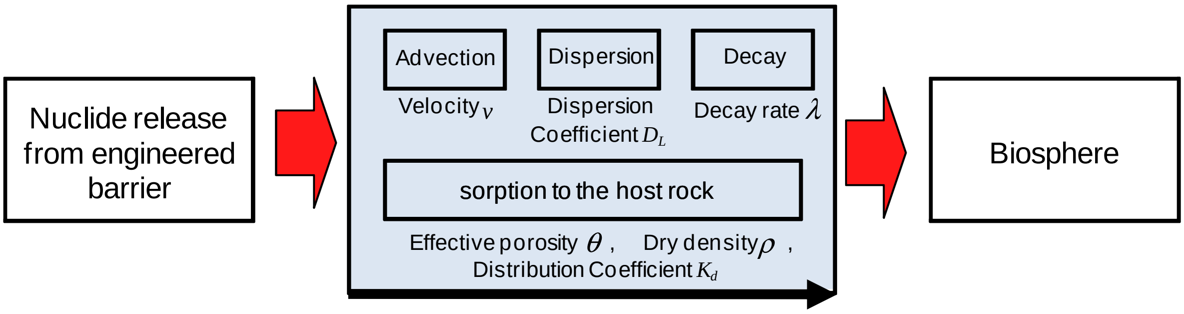
Post-closure safety

The post closure safety assessment was carried out on the basis of information from investigations covering the whole Horonobe Town area using pre-existing data at the initiation of the project. Although solute transport modelling is one component of a safety case (which may even be of limited importance at early stages of site characterisation), in order to ensure the relevance of groundwater flow model covering the whole Horonobe Town area, porous media model was used as the basis for a solute transport in the post closure safety assessment. This model was then used to evaluate the significance of output and its sensitivity to hydrogeological model uncertainties.

Solute transport modelling

The Wakkanai and Koetoi Formations were selected as target formations (analogues of repository host formations) for solute transport modelling and subsequent sensitivity/uncertainty analysis. As a starting point for model development, flow paths were simulated by a particle tracking method based on the hydrogeological model developed in the stage of investigations covering the whole Horonobe Town area using pre-existing data. Solute transport along the flow paths was simulated with a 1-D porous media model. Although this represents the level of analysis carried out in H12, it is recognised that, especially for solute transport, representation of a fracture-flow system by an equivalent porous medium is not only formally incorrect, it may also lead to results that are highly non-conservative. Nevertheless, as long as emphasis is on trends and not absolute values of migration rates, such a simple model may allow the sensitivity of radionuclide transport models to hydrogeological uncertainties to be examined. The 1-D equivalent porous media transport model along these flow paths includes relevant processes such as advection, dispersion considering diffusion and mechanical dispersion, radioactive decay, and radionuclide retardation as sorption to the host rock, as shown Figure 12.

Figure 12. **1-D solute transport model based on the investigations covering the whole Horonobe Town area in Phase I of the Horonobe URL Project** (after [18])



Conceptual solute transport model for porous sedimentary rock (1-D porous media model)

Uncertainty/sensitivity analysis

The solute transport analysis focuses on identifying sensitivity to uncertainties in the hydrogeological parameters used. Radionuclide considered in the solute transport analysis is Cs-135, which was identified as one of relevant radionuclides in the H12 safety assessment [4] and gives highest doses in many release scenarios. Parameters required for the radionuclide transport analysis include:

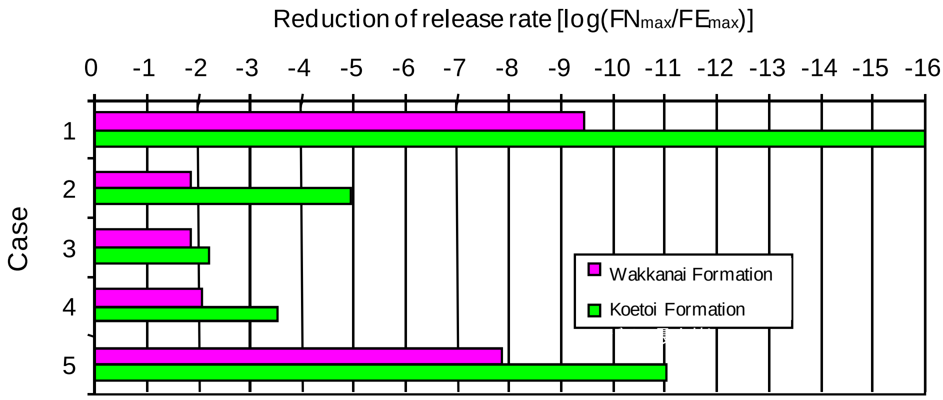
- Hydrogeological data – average velocity and flow path length.
- Source term and transport parameters in the near field, including overpack failure time, glass leach rate, effective diffusion coefficient, and distribution coefficient of solute buffer material to derive a flux from the EDZ.

- Properties of the natural barrier influencing solute transport such as porosity, density, effective diffusion coefficient, dispersion length, and distribution coefficient of the radionuclide.

Average velocity and flow path length (and an estimate of the flow rate in EDZ) were calculated based on the results of the groundwater flow simulations conducted in stage of investigations covering the whole Horonobe Town area. Effective diffusion coefficient and distribution coefficient in buffer material for the radionuclides considered were taken from H12 [4]. Porosity, effective diffusion coefficients, and distribution coefficients in the natural barrier were measured on relevant rock cores from deep boreholes in the URL area. In the solute transport analysis, five cases were analysed to examine sensitivity of hydraulic parameters:

- Case-1: base case, best estimate parameters.
- Case-2: ten times higher Darcy velocity in the Wakkanai/Koetoi Formations compared to the base case.
- Case-3: shorter transport path length in the Koetoi Formation compared to Case-2.
- Case-4: ten times lower effective porosity in the Wakkanai/Koetoi Formations compared to Case-3.
- Case-5: higher radionuclide distribution coefficients in the Wakakanai and Koetoi Formation compared to Case-4.

Figure 13. **Results of solute transport analysis for Cs-135** (after [18])



FN_{max}: Maximum release rate from natural barrier.
FE_{max}: Maximum release rate from engineered barrier.

The results of uncertainty/sensitivity analysis for Cs-135 are shown in Figure 13, presented as reduction of maximum release rates between EBS and natural barriers in the Wakkanai and Koetoi Formations. As it can be seen, the reduction of the release rate varies considerably among the cases – showing the sensitivity of transport to the input data. In general, reduction of release rate in the Koetoi Formation is larger due to the low hydraulic conductivity regardless of existence of fractures than that in the Wakkanai Formation in which WCFs with hydraulic conductivities in a wide range distribute. However, great care must be taken with interpreting such results, given the conceptual limitations of the hydrogeological model and the potential non-conservatism of the EPM model.

Conclusions and future work

JAEA R&D on geological disposal utilise two generic URLs at Muzinami and Horonobe for confirming the applicability of the technical basis provided by H12 project to specific sites and for further developing site characterisation techniques and the engineering technologies for constructing and operating underground disposal facilities. The experience and knowledge obtained in these URL projects will contribute to the site characterisation and subsequent safety assessment at potential repository sites by NUMO and the formulation of guidelines by regulatory organisations. In the investigations carried out in the URL projects, a geosynthesis methodology that involves iterative development of a systematic data flow diagram has been applied and tested for applicability to representative geological environment in Japan. In developing the geosysthesis data flow diagram, link between site characterisation and the relevant geological properties/processes required by end users are explicitly taken into consideration.

So far, the geosysthesis methodology appears to be a practical tool for planning, implementing, and analysing the output from site investigations at the Japanese URLs. Step-wise investigations using the geosynthesis methodology have proven to be effective for enhancing understanding of the geological environment and providing feedback from the design engineers and performance assessors who require data supported by such understanding. Surface-based investigations at the URL sites have also provided input that can be used to develop provisional safety cases, which should be transparent due to the framework provided by the geosynthesis methodology. This framework can be extended to development of models to support safety assessment and assessing their sensitivity to uncertainties in site chartacteristics – as illustrated for the specific case of solute transport at the Horonobe Town area. In the future, this work will continue as the site databases are expanded from construction of the URLs and subsequent underground testing – providing further opportunities to improve the geosynthesis methodology and develop the experience that will be needed by NUMO and regulators when the Japanese HLW programme eventually moves towards detailed site investigation and then licensing of a first repository.

Acknowledgements

We thank Dr. Ian McKinley of McKinley Consulting in Switzerland for his careful reviews and helpful comments on this paper. And, we also thank Mr. Takehiro Yamaguchi of JAEA Horonobe for his efforts to prepare clear figures used in this paper.

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