SYNTHESISING GEOSCIENTIFIC DATA INTO A SITE MODEL FOR PERFORMANCE ASSESSMENT: A STUDY ON THE LONG-TERM EVOLUTION OF THE GEOLOGICAL ENVIRONMENT IN AND AROUND THE HORONOBE URL, HOKKAIDO, NORTHERN JAPAN

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Abstract

A critical issue for building confidence in the safety case of a HLW geological disposal system is to provide a set of arguments and analyses to demonstrate the stability of the geological environments, taking into account its likely future evolution. In particular for the Japanese disposal programme, arguments on the potential impact of natural events and processes on such long-term stability are essential for assuring repository safety. A prerequisite for establishing such arguments is a transparent and traceable methodology for planning field investigations; this involves linking available investigation techniques on the data to be acquired, interpretation of these data and the synthesis and integration of the results of different studies and analyses. The desired end result is a consistent site model which incorporates long-term evolution of the local geological environment. This study presents an application of a combined method based on "Data Flow Diagrams" and "Process Diagrams" for a sequence of field investigation and analytical activities. It focuses, in particular, on the long-term evolution of groundwater flow properties and the spatial distribution of groundwater salinity in the Horonobe area. This takes account of the impacts of external events and processes, such as uplift, subsidence, denudation, sedimentation, and changes of sea-level and climate. Utilising this approach, the results of field investigations can be integrated to examine evolution of the hydrogeological model as a result of associated changes in boundary conditions, producing output such as hydraulic head distributions and spatial distribution of salinity in groundwater as a function of climatic, topographic, and geological changes from the past to the present. Such a model of the past can be used to support the assessment of changes in the future as required to develop a safety case. This test of the applicability of the methodology has been carried out during the phase of surface-based investigation at Horonobe and will be continued throughout the on-going phase of excavation of the URL facility.

Introduction

A critical issue for building confidence in the safety case of a geological disposal system is to provide a set of arguments and analyses to demonstrate the long-term evolution of the geological environment, taking into account the potential impacts of natural events and processes. In Japan, natural events and processes that could take place over the next several hundred thousand years and could affect a disposal system are identified to include [1]:

- Earthquakes and fault movement.
- Volcanic and hydrothermal activity.
- Uplift, subsidence, sedimentation, and denudation.
- Climatic and sea-level changes.

The first two groups of phenomena could occur suddenly and, potentially, have a major impact on a disposal system in the immediate vicinity; nevertheless, greatest impacts are geographically restricted. Impacts of the latter two groups of phenomena accumulate over long time periods, in the range of over a much larger, regional scale.

For the Japanese disposal programme, selection of a repository site uses a three-stage process as defined in the Specified Radioactive Waste Final Disposal Act of 2000. In the process, the areas to be investigated as potential host areas for a repository (Preliminary Investigation Areas, in short PIAs) will be selected initially based on literature surveys. The Siting Factors for the Selection of PIAs (siting factors) are applied for the selection, in order to identify preferred areas for conducting preliminary investigations and exclude areas that would clearly be unsuitable as repository sites [2,3], e.g. due to the risk of direct damage to the repository caused by natural events and processes.

Based on the above siting process, significant effects of earthquakes, faulting, volcanic and hydrothermal activity should be precluded in the PIAs, but this needs to be confirmed during site characterisation. Nevertheless, a major focus for analysis of the potential impacts of natural events and processes will concentrate on those that cannot be avoided by siting, especially uplift, subsidence, denudation, sedimentation, and climatic and sea-level changes. Arguments to show that these would not degrade the long-term stability of the geological environment are absolutely essential to assure the safety of a geological disposal system.

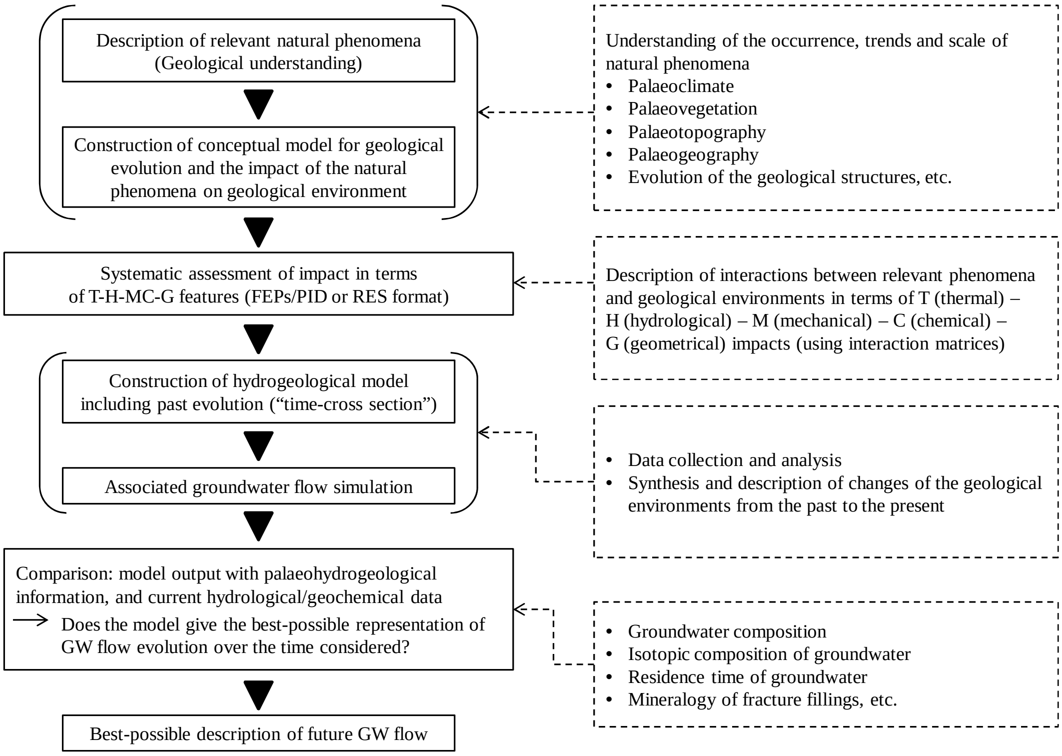
Horonobe Underground Research Laboratory Project (Horonobe URL) is a generic project conducted by the Japan Atomic Energy Agency (JAEA) to enhance confidence in the reliability of key disposal technology by investigations of, and within, the deep geological environment of the sedimentary formations in the Horonobe area, Hokkaido, northern Japan [4,5]. The project proceeds in three overlapping phases, “Phase I: Surface-based investigation”, “Phase II: Construction”, and “Phase III: Operation”, extending over a period of about 20 years [5].

This paper presents results of an application of a combined method based on “Data Flow Diagrams” (a geosynthesis methodology developed in previous site-investigation programmes, for example the Nagra Wellenberg project in Switzerland [6]) and “Process Diagrams” (or Interaction Matrices; developed in the SKB Safety Report 97 [7]). This particularly focuses on the sequence of field investigations and analysis activities for the description of the long-term evolution of the geological environment during Phase I. It concentrates, in particular, on groundwater flow properties and the spatial distribution of salinity in groundwater of the Horonobe area, using input from regional tectonics, palaeogeography, palaeoclimate, historical development of landform and present understanding of groundwater flow properties.

Approach

A geosynthesis approach developed in previous site-investigation programmes [6] is applied for synthesis and integration of the results of different investigations and analysis into a consistent site model, which incorporates long-term evolution of the local geological environment. Generally, the approach can be defined as proceeding in 5 steps, that is 1) field investigations – accumulation of raw data, 2) interpretation of data, 3) development of conceptual models, 4) numerical (and analytical) modelling, and 5) Geodatabase production (or application of output by the end users of site information) [6]. This approach can be utilised to form the framework for a palaeo-hydrogeological study aimed at characterising the long-term evolution of regional groundwater flow [8]. The first step of this study requires information on past hydrogeological conditions. Direct measurement is clearly impossible, thus it is necessary to obtain the information indirectly from a synthesis of material such as paleontological, stratigraphical, tectonic, and isotopic data. The second step is to construct a palaeo-hydrogeological model, based on the data obtained in the first step, which can be used for the third step of palaeogroundwater flow simulation. Such simulation will utilise similar methodology to studies of present groundwater flow. The fourth step of the study involves checking the consistency of the simulation results, using geochemical indicators, such as groundwater chemistry and groundwater residence time.

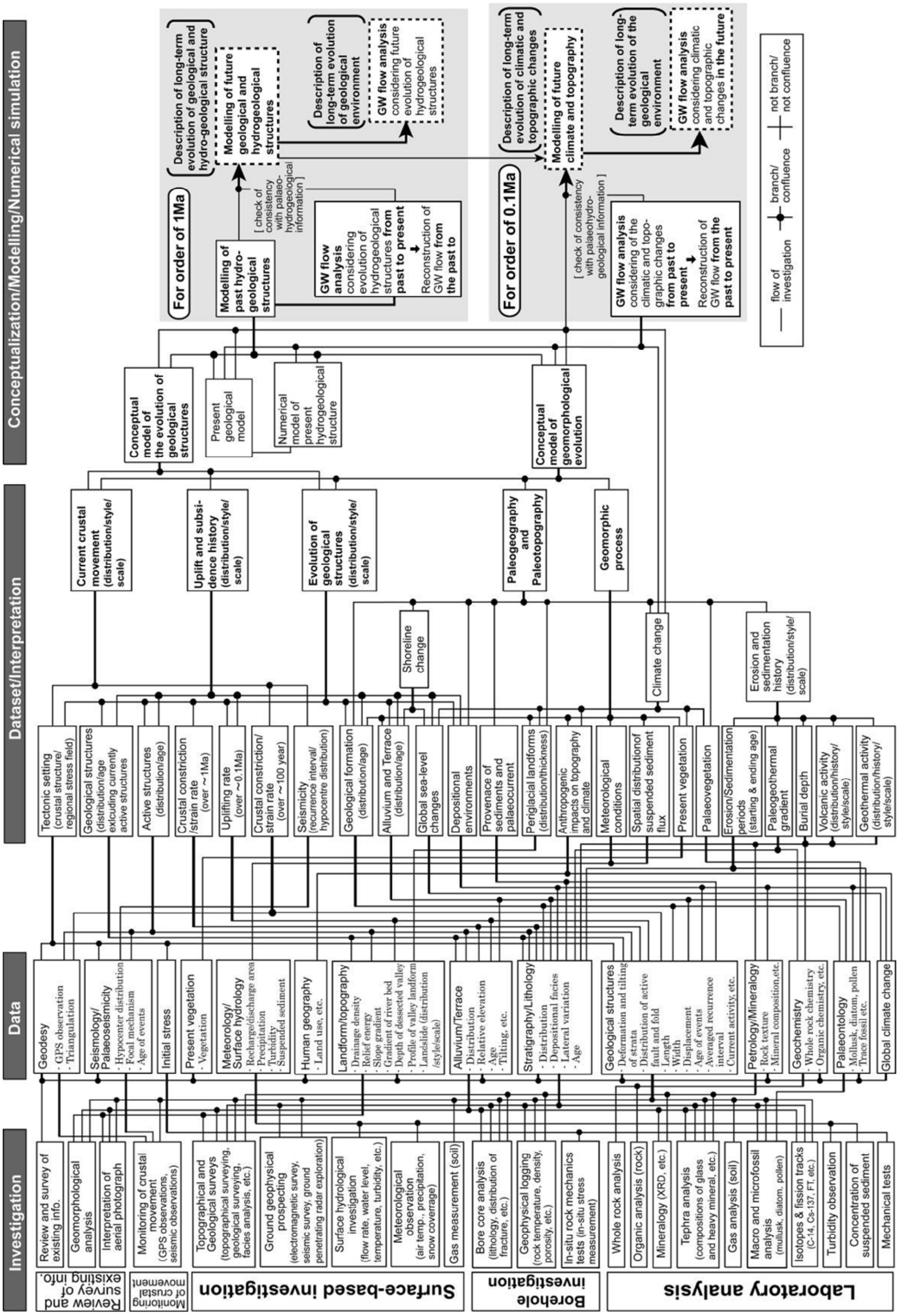
Figure 1. **Basic framework for description of the evolution of groundwater flow properties, taking account of the impacts of natural events and processes**



At first, we developed a basic framework to describe the evolution of the groundwater flow properties in the Horonobe area based on the geosynthesis methodology [6] as applied to a palaeo-hydrogeological study [8] (Figure 1). The detailed sequence of activities was: 1) characterisation of the site geology and identification of relevant natural phenomena based on field investigations, 2) constructing a conceptual model based on the characteristics of the natural phenomena (events and processes) that have occurred in the Horonobe area over geological time (with emphasis on the last 2.5 Ma), 3) systematic assessment of the impacts of these phenomena on the geological environment, 4) constructing geological and hydrogeological models that include temporal evolution, 5) numerical analyses to determine groundwater flow properties and other relevant parameters, 6) checking the consistency of the analytical results by comparing results with groundwater geochemistry data. For example, evolution of a spatial distribution of groundwater salinity can be simulated by mass transport analysis using such groundwater flow results. Utilising the results, we can confirm the consistency of simulated salinity in groundwater with the geochemical data obtained in field investigations. Finally, these understanding, evolution of the geological environments from the past to present, was used to develop descriptions of likely future evolution of groundwater flow properties in this region.

We constructed a "Data Flow Diagram" which connects output from field activities to the final results desired; this allows selection of investigation methods and tools, identification of the type and quality of data to be acquired, determination of the synthesis required for interpretation of the data, and the integration of the results of different investigations and analyses needed to produce a consistent site model which incorporates long-term evolution of the geological environment (Figure 2). The sequence of investigation, analysis, and evaluation processes was iterated and improved understanding of the geological environment incorporated into the data flow diagram [4,9]. This paper shows the results of first step in the iterative approach using this basic framework (Figure 1).

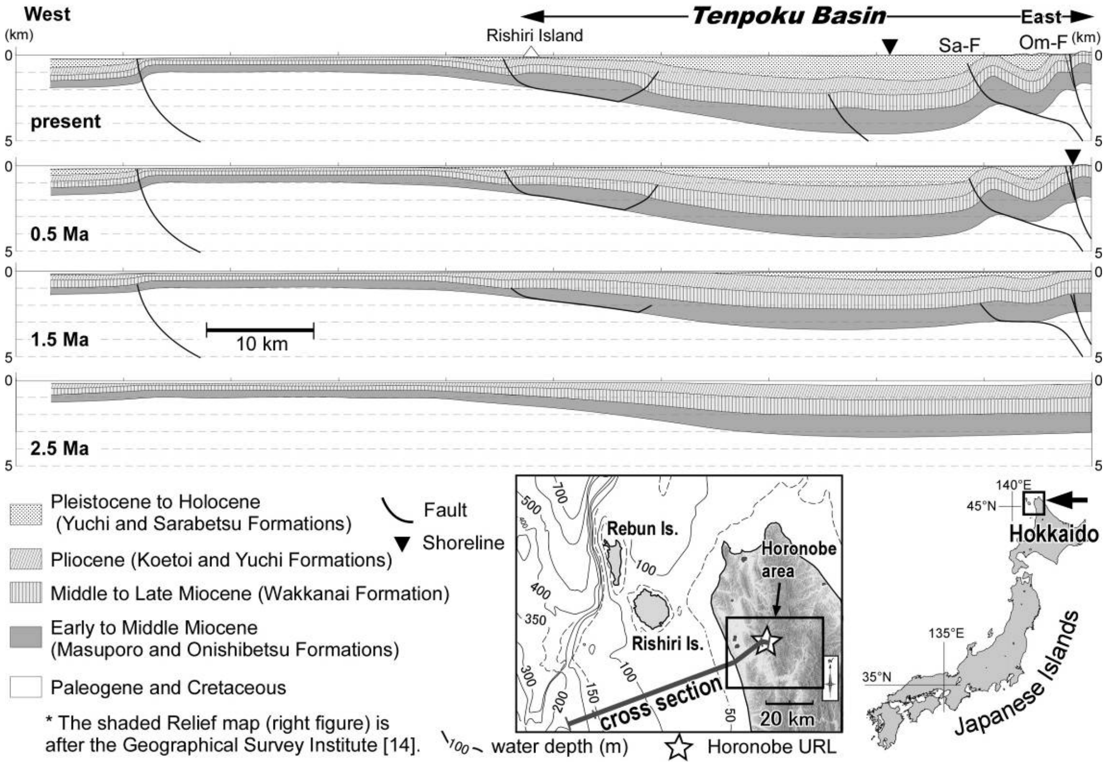
Figure 2. **Data flow diagram for the description of the evolution of the groundwater flow properties in the Horonobe area, Phase I investigations**



Site geology

The Horonobe area is situated in the eastern part of the Tenpoku Basin and its geology is dominated by Neogene to Quarternary sedimentary sequences; that is, Onishibetsu (alternating beds of conglomerate, sandstone and mudstone, intercalated with coal seams), Masuporo (alternating beds of conglomerate, sandstone, and mudstone), Wakkanai (diatomaceous and siliceous shale), Koetoi (diatomaceous and siliceous mudstone), Yuchi (sandstone) and Sarabetsu (alternating beds of conglomerate, sandstone, and mudstone, intercalated with coal seams) Formations, in ascending order. These formations are unconformably overlain by terrace deposits, alluvium and lagoonal deposits (unconsolidated deposits of gravel, sand, and mud). The fold and thrust system within the basin has a north to south trend and a westward vergence. In the land area, the basin has two main faults (fault zones) called the Omagari Fault [5] and the Sarobetsu Fault Zone [10]. In addition, the pre-existing studies indicated that three major fault and fold systems are located in the west of the basin on the basis of the marine seismic and geological surveys [11]. The growth structures of the fold-and-thrust belt of northern Hokkaido, indicated by seismic reflection profiles, suggest that the ongoing EW compressive tectonics (neotectonics) in the western part of the Horonobe area began in the Late Pliocene (Figure 3).

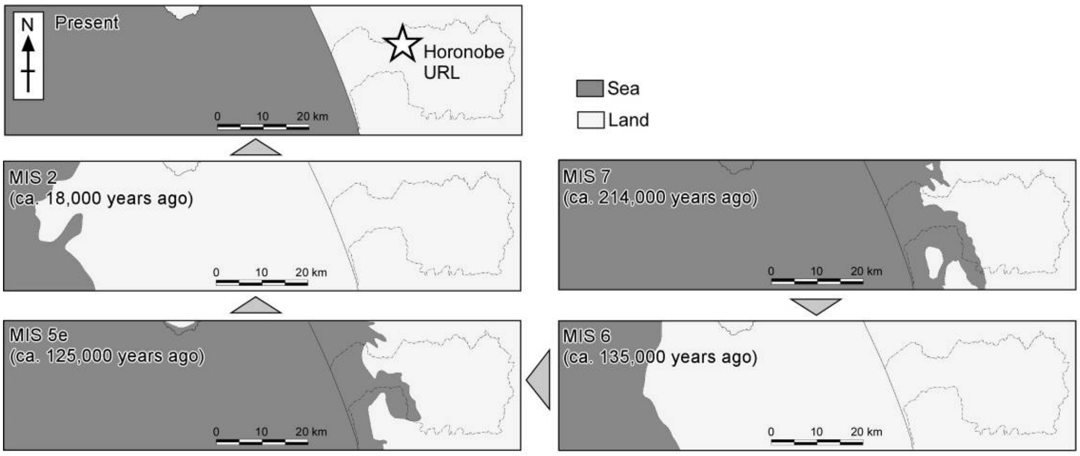
Figure 3. **Geological evolution in the Horonobe area since late pliocene** [13]
Sa-F: Sarobetsu Fault Zone, Om-F: Omagari Fault



Based on the time-stratigraphy and sedimentary analyses, the structural development of the region has resulted in westward migration of the depositional area in the Tenpoku Basin [12]. In addition, the distributions of micro-earthquake hypocenters, active structure locations, and Quaternary sediments indicates that, at present, active tectonics are concentrated in the western part of the Horonobe area.

The Horonobe area has widespread distributions of marine terrace deposits, which are correlated to the marine oxygen isotope stages (MIS) 7 through 5e. Figure 4 shows the palaeogeography in the area, from MIS7 to the present, on the basis of the age and distribution of these deposits, global-scale sea-level changes, and sea-floor topography [13]. The former shorelines of interglacial stages (e.g. MIS5e) have extended ca. 12 km landward from that at present shoreline. In contrast, shorelines of glacial stages (e.g. MIS2) were up to ca. 50 km further seaward. This extensive migration of the shoreline caused by glacial-interglacial cycles is attributed to the gentle slope of sea-floor topography.

Figure 4. **Palaeogeography in and around the Horonobe area from MIS7 to the Present** [13]**. The ages of MIS stage are after Koike and Machida** [17]



Additionally, we can identify key natural phenomena which have potential impacts on groundwater flow properties, including:

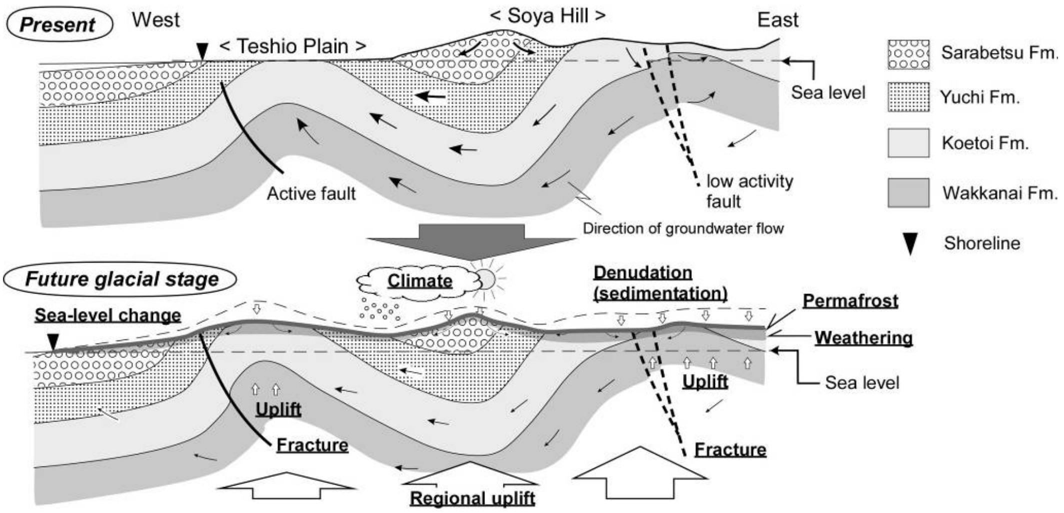
- Distribution of fossil periglacial wedges, suggesting that northern Hokkaido was located at the northern margin of the discontinuous permafrost zone during the maximum cold stage of the Last Glacial Stage (MIS2) [15].
- The relationship between geology and geomorphology (hill morphology, drainage pattern, etc.) suggests that geomorphic processes are different for each geological formation [5].
- Changes in porosity of the sedimentary formations due to consolidation during burial will also change hydraulic conductivity and mass transport properties of formations. This phenomenon will proceed on a time frame of tens of thousands to millions of years.

Three periods of continental ice sheet development are reported in the mountain range of Hokkaido (Hidaka Mountains) at ca. 150, 50-40, and 20-10 ka based on the geomorphological evidence [16]. However, in Horonobe area, there is no geomorphological evidence of any influence of glaciation.

Conceptual model for future evolution of the geological environment

Key natural events and processes which have potential impacts on groundwater flow properties in the Horonobe area are summarised in Figure 5. The figure represents the situation in the present postglacial and a future glacial stage, with some exaggeration, on the basis of the tectonics, palaeogeography, palaeoclimate, development of landform, and present groundwater flow properties. Also, it assumes that future natural events and processes will behave much as they did in the past (the past is the key to the future).

Figure 5. **A conceptual model of natural phenomena with potential impacts on Horonobe area groundwater flow properties** [13]



Present groundwater flow properties (direction and flux) are simplified from the Phase I hydrogeology geosynthesis output [18]. The conceptual sketches of the properties during a future glacial stage are based on an evaluation of the impacts of expected changes as perturbations of the present groundwater flow properties.

The natural phenomena underlined in Figure 5 (lower figure) are those considered important for developing a best-possible description of future groundwater flow properties. For example, the development of the permafrost will prevent infiltration of meteoric water, thus dramatically decreasing groundwater recharge. Figure 5 also illustrates certain interactions between natural phenomena. For example, relative sea-level change is due not only to climate change, but also local uplift – e.g. due to fault movement (see left-hand side on Figure 5). Moreover, a change of the base-level of denudation due to sea-level change causes a change of both sedimentation and denudation areas. Such interactions of natural events and processes must be integrated to determine the net impact on the geological environment.

The interaction matrices of natural events and processes

Identified drivers of geological evolution, including potential impacts of natural events and processes, which are considered relevant in the Horonobe area are summarised in Figures 6a and 6b based on the Phase I investigations, in the form of interaction matrices [7,13]. In the figures, characteristics of groups of natural phenomena are included as diagonal components, while events and processes related to interactions between these phenomena define the off-diagonal components. The upper and lower parts of each box in Figure 6b indicate the general characteristics of the phenomenon group and resultant impacts on the case that would support repository safety, respectively. Using this matrix, key events and processes (and interactions between them) that need to be considered during the next step of numerical modelling can be identified. This reflects the current stage of data integration and conceptual model development [13], which will be updated during subsequent investigations, as additional data and analytical results are obtained.

Figure 6a. **Simplified interaction matrices of natural events and processes in the Horonobe area, partly modified from Niizato *et al.*** [13]**.** See Figure 6b for details of the items enclosed by the bold black line

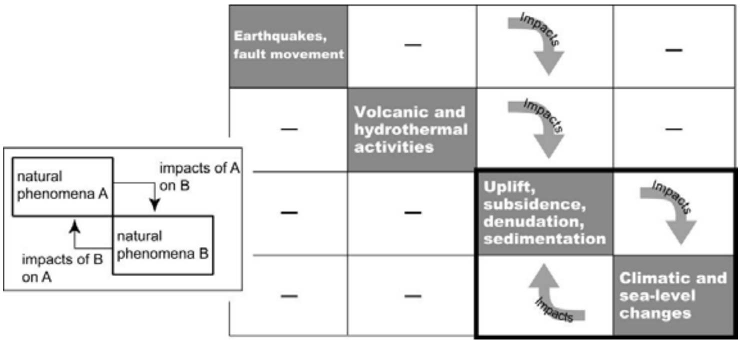
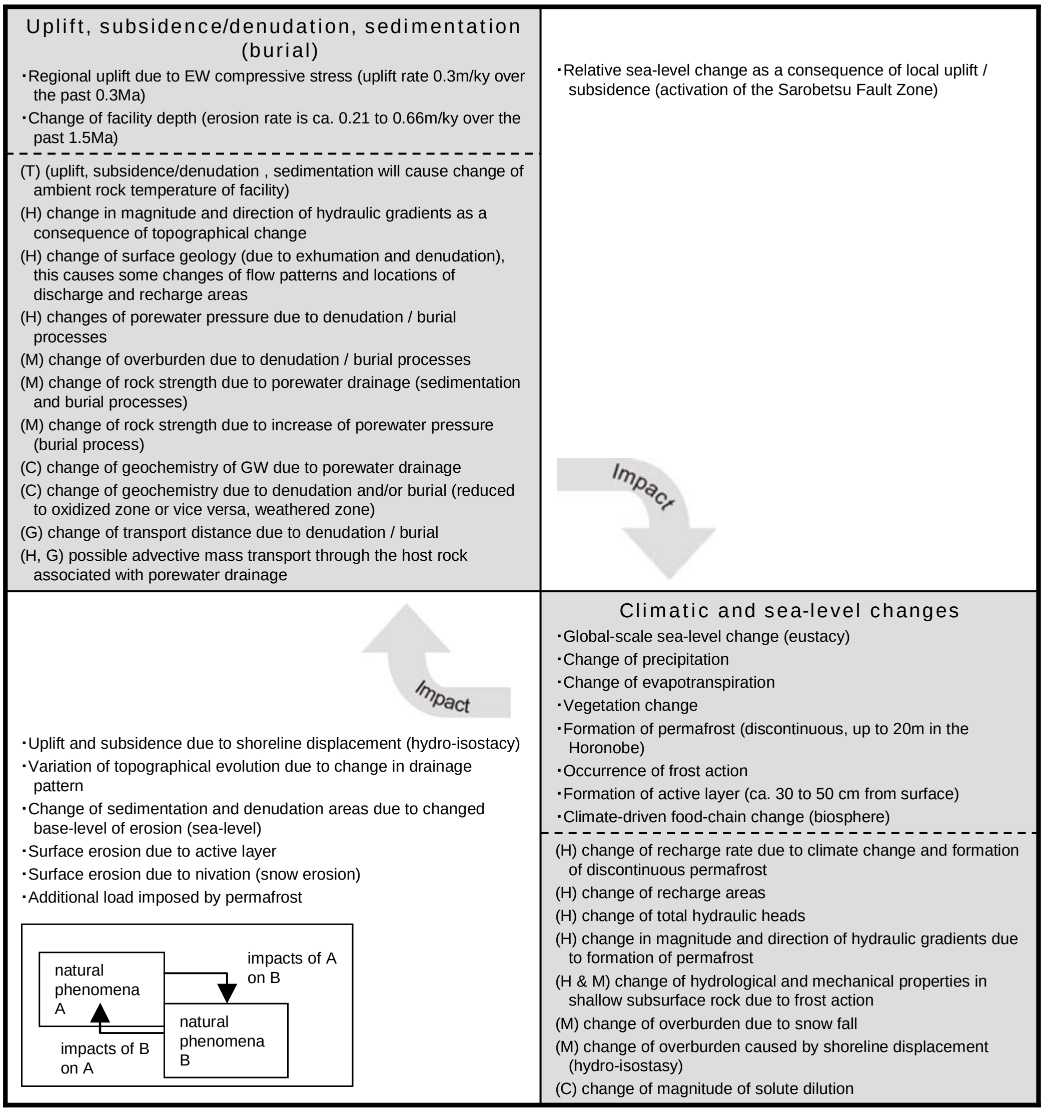


Figure 6b. **Details of natural events and processes, their interactions and potential impacts on future evolution of the geological environment.** This is focused on Uplift/Subsidence, Denudation/Sedimentation, and Climate/Sea-level Changes in the Horonobe Area [13]



Bold face: natural phenomena, Regular face: impacts of natural phenomena ((T) Thermal, (H)Hydrological, (M) Mechanical, (C) Chemical, (G) Geometrical) on geological environments.

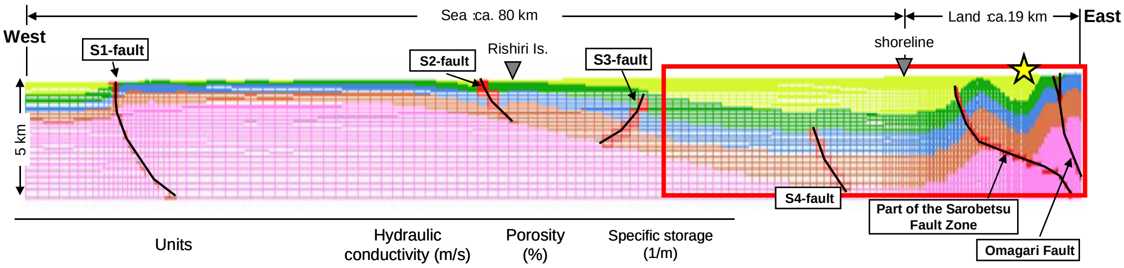
Construction of the hydrogeological model

Hydrogeological model fundamentals

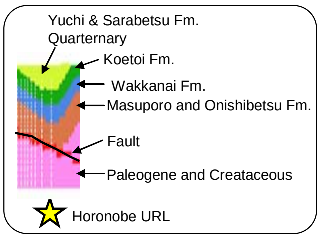
The hydrogeological model, with parameters assigned to each hydrogeological unit, is depicted in Figure 7. Selection of these units and parameterisation is based on the output of hydrogeological synthesis during Phase I of the Horonobe URL Project [5,18]. Evolution of the hydrogeological model from past to present is based on the geological interpretation outlined in Figure 3. In the first step of this iterative approach, it is important to outline the geological and hydrological evolution using a simplified model, which allows understanding of sensitivity of output to the assumed impacts of natural phenomena to be investigated.

Simulations of groundwater flow and spatial distribution of groundwater salinity in a 2-D section (shown in the lower part of Figure 3), assuming the sedimentary formations are porous media, were carried out using a finite element code (Dtrans-3D-EL [19] with several minor modifications). Major fault zones in Figure 7 are assumed to have higher hydraulic conductivity than surrounding sedimentary formations (act as permeable fault zone) in the absence of any direct information (e.g. hydraulic data from borehole). It also assumed that these fault zones are isotropic.

Figure 7. **Hydrogeological model and hydraulic parameters.**
The red box (right hand of the Figure) shows the area covered in Figures 9 and 10



Units	Hydraulic conductivity (m/s)	Porosity (%)	Specific storage (1/m)
Surface deposits (ca. 10 m depth from surface)	1.0E-06	60	1.0E-05
Yuchi & Sarabetsu Fm. and Quaternary	*Depth_Yt* *	60	1.0E-05
Koetoi Formation	*Depth_Kt* *	60	1.0E-05
Wakkanai Formation	*Depth_Wk* *	40	1.0E-05
Masuporo & Onishibetsu Fm.	5.0E-10	30	1.0E-05
Paleogene & Cretaceous	1.0E-11	20	1.0E-05
Faults (Omagari Fault, part of the Sarobetsu Fault Zone, and S1- to S4-faults)	1.0E-07	50	1.0E-05



* *Depth_Yt*, *_Kt*, and *_Wk* are hydraulic conductivities of each formation as a function of depth. K: hydraulic conductivity (m/s), Z: depth (m)

Depth_Yt : $\log_{10}(k) = -0.0034Z - 8.3665$ [upper limit: 1×10^{-8} m/s, lower limit: 1×10^{-11} m/s]

Depth_Kt : $\log_{10}(k) = -0.0039Z - 7.5935$ [upper limit: 1×10^{-7} m/s, lower limit: 1×10^{-11} m/s]

Depth_Wk : $\log_{10}(k) = -0.0061Z - 5.5626$ [upper limit: 1×10^{-6} m/s, lower limit: 1×10^{-11} m/s]

Simulation cases

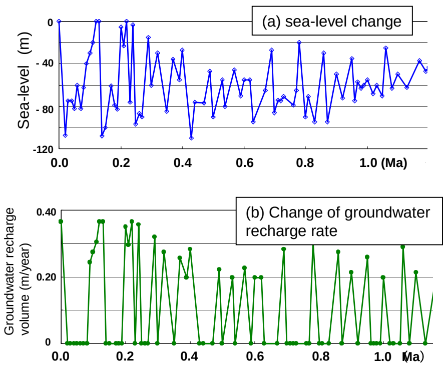
Based on the conceptual model described above, we defined three simulation cases with specific boundary condition (Figure 8). Natural events and processes considered in these simulations are as follows:

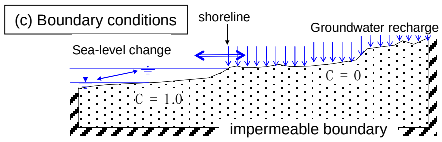
- Climatic and sea-level changes (including of evolution of the groundwater recharge rate caused by the change of precipitation and development of permafrost).
- Evolution of geological structures (uplift, subsidence, denudation, sedimentation, folding, and faulting caused by East-West compressive stress field in the northern Hokkaido).
- Evolution of hydraulic conductivity (due to burial and compaction).

Figure 8. **Simulation cases and boundary conditions.**
Global-scale sea-level change is adapted from Koike and Machida [17]

Variant	Case1	Case2	Case3
Sea-level, groundwater recharge volume	O	O	O
Evolution of geological structures Uplift, subsidence, denudation, sedimentation, folding and faulting - 1.5 Ma to 1.2 Ma: no change - 1.2 Ma to 0.6 Ma: stepwise each 200 ka - 0.6 Ma or later: stepwise each 100 ka	×	O	O
Time-variation of hydraulic conductivity (assumed that hydraulic conductivity at 1.5 Ma is higher than at present)	×	×	O

·The period of simulation is from 1.5 Ma to the present.





There are little data on the evolution of the hydraulic conductivity; hence it is simply assumed that hydraulic conductivity at 1.5 Ma was higher than at present, which reflects burial and associated compaction in the interim. For groundwater flow simulation, the hydraulic conductivities were obtained by linear interpolation between 1.5 Ma and the present. It is also simply assumed that change of groundwater recharge rate is linearly related to sea-level change.

Initial conditions

- Groundwater flow simulation: distribution of hydraulic head was obtained by steady-state analysis for the sea-level and groundwater recharge rate at 1.5 Ma.
- Salt concentration: based on geological and geomorphological evidence (Figures 3 and 4), for the entire simulation area was below the sea at 1.5 Ma and hence salinity throughout was taken to be that of sea water.

Results of the simulations

The results of simulations are summarised in Figure 9, for the distribution of hydraulic head and Figure 10, for the spatial variation of groundwater salinity. In Case 1, considering only temporal variations of sea-level and groundwater recharge rate, we notice little change in these parameters over the last 0.5 Ma. In contrast, Cases 2 and 3 show more marked trends, especially for Case 3 when variation of the hydraulic conductivity of the sediments is considered. These preliminary results indicate that the impact of tectonics, such as uplift and subsidence associated with change of hydraulic conductivity (Case 3), is greater than that of sea-level and climatic changes alone (Case 1).

Figure 9. **Time-variation of the distributions of hydraulic head (total head) from 0.5 Ma to the present**

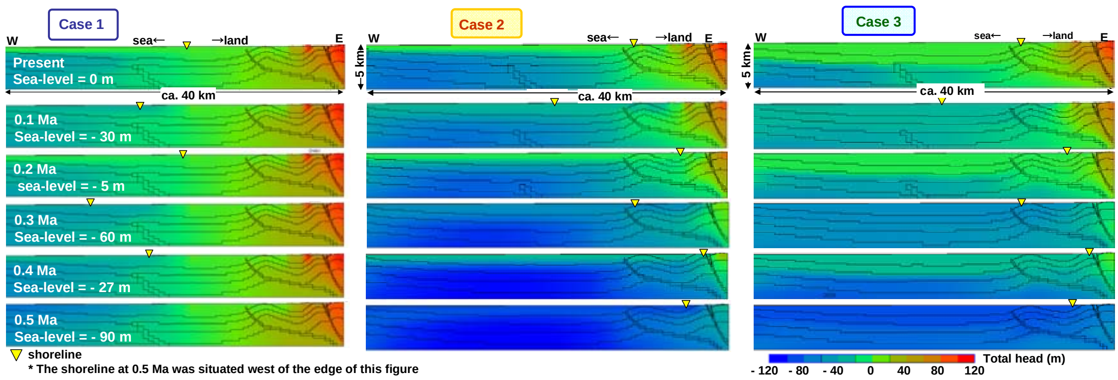
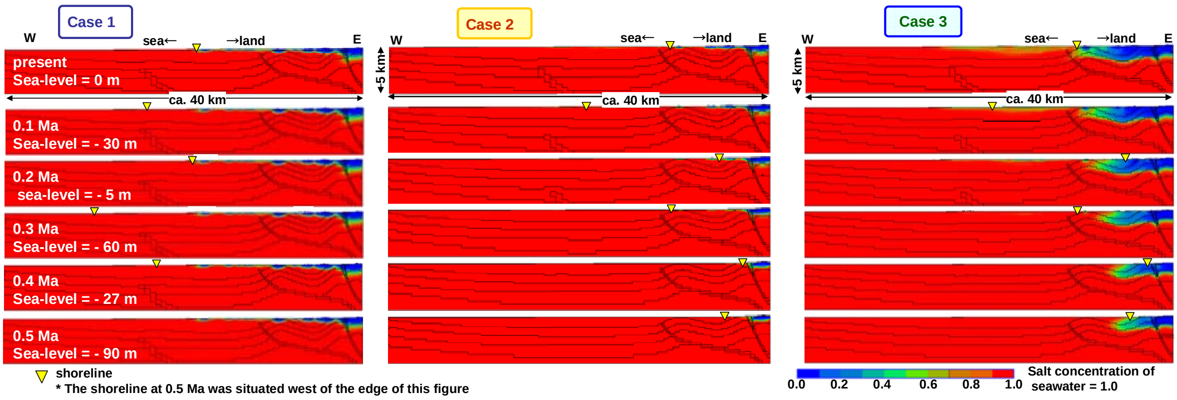


Figure 10. **Time-variation of the spatial distributions of groundwater salinity from 0.5 Ma to the present**



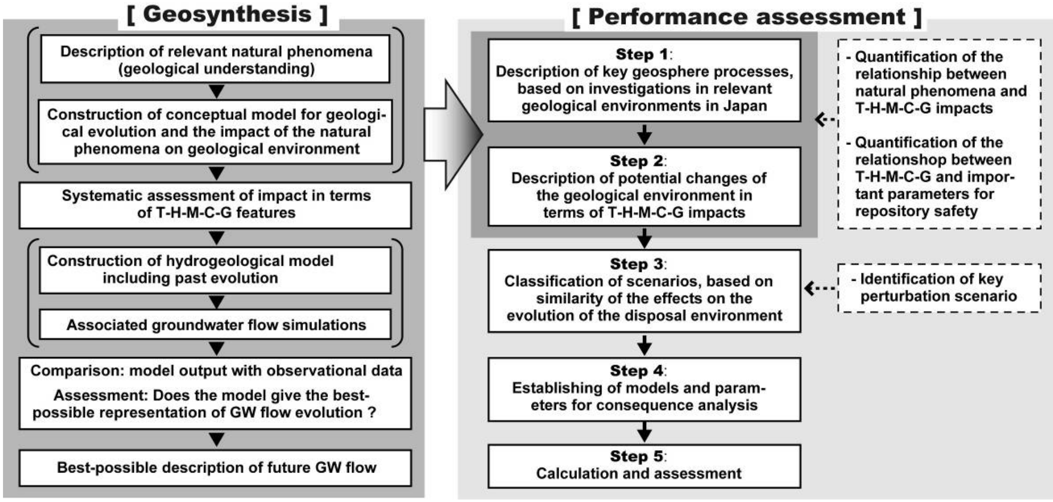
Conclusions and future studies

According to the basic framework (Figure 1), the next step will be consistency checks of the simulation results. Particle-tracking analyses conducted in the Horonobe area, together with the groundwater flow simulations presented above, indicate that groundwater residence times should be in the order of a few million years, except for shallow water (less than about 75 m depth). The residence time of groundwater was estimated directly by measuring radioisotopes (tritium, carbon-14, chlorine-36, helium-3 and helium-4) using water samples pumped from deep boreholes. Based on such radioisotope data, deep groundwater residence time is in the order of a million years [5] and hence there is consistency between simulations and geochemical evidence. Nevertheless, before detailed interpretation of the simulation results and further consistency checks, we must assess the assumptions used to define hydraulic input parameters. Further, the geological evolution model used did not consider lateral displacements despite the compressive tectonic setting. So more analyses, modelling and consistency checks will be needed to draw robust conclusions which would be acceptable to relevant scientific communities.

In this study, we have developed a formal evaluation method for describing evolution of groundwater flow properties and groundwater salinity taking account of impacts of natural events and processes, focused on uplift, subsidence, denudation, sedimentation, and climatic and sea-level changes. To assure the long-term safety of repository, it is essential to develop the method for describing the long-term evolution of the geological disposal system taking consideration of the impacts of evolution of the geological environments caused by natural phenomena on the safety of geological disposal system. Therefore, in the future, it has great significance to combine the framework of this study with a conceptual framework for examination of the safety of a HLW repository [20]. Such a total assessment methodology that includes a well-justified evaluation of future repository evolution will support building confidence in a safety case of a HLW geological disposal system (Figure 11).

It has been said that "… scientists must share their knowledge with society as a whole in the hope that political leaders and citizens of all kinds can work together to make rational decisions about the future of "Spaceship Earth" [21]." The development of the above total assessment methodology will be a key for developing transparent arguments and analysis to assure that the long-term safety of deep geological disposal can be communicated to both scientific communities and the general public. Gaining acceptance of disposal is not only a goal in itself, but is critical for rational selection of the future development of energy resources, which is a critical contribution to the fight against the worldwide catastrophe that could result from global warming.

Figure 11. **Conceptual scheme: total assessment methodology for long-term behaviour of a geological disposal system with consideration of potential impacts of natural phenomena**



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