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DEVELOPMENT OF COMPREHENSIVE TECHNIQUES FOR COASTAL SITE CHRACTERISATION (3) CONCEPTUALISATION OF LONG-TERM GEOSPHERE EVOLUTION

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ABSTRACT

A critical issue for building confidence in the long-term safety of geological disposal is to demonstrate the stability of the geosphere, taking into account its likely future evolution. An ongoing collaborative programme aims to establish comprehensive techniques for characterising the overall evolution of coastal sites through studying the palaeohydrogeological evolution in the coastal system around the Horonobe area, Hokkaido, northern Japan. Information on natural events and processes related to the palaeohydrogelogical evolution of the area have been integrated into the chronological tables and conceptual models that indicates the temporal and spatial sequences of the events and processes, such as climatic and sea-level changes, palaeogeography, and geomorphological and geological evolution in the area. The methodology for conceptualisation of the geosphere evolution will be applied to other analogous coastal areas on Japan's western seaboard to produce comprehensive techniques to support understanding the geosphere evolution of potential coastal sites for deep geological repositories.

Keywords: Geological disposal of radioactive waste, long-term geosphere evolution, palaeohydrogeology, coastal site, Japan, Horonobe

INTRODUCTION

A critical issue for building confidence in the long-term safety of geological disposal is to demonstrate the stability of the geosphere, taking into account its likely future evolution. This stability is broadly defined as the persistence of Thermal-Hydrological-Mechanical-Chemical conditions considered favourable for the long-term safety of a geological repository [1]. The geosphere is slowly, but constantly, evolving so that stability, in this case, does not imply that steady-state conditions exist. Stability, in terms of deep disposal, means that any changes will not significantly impact on the long-term safety of the repository.

In general, an understanding of the site evolution is gained by studying the palaeohydrogeological evolution of the area, defining temporal and spatial changes of various characteristics, events, and processes over geological time [2]. The site palaeohydrogeology refers to natural events and processes that have occurred in the past and contributed to the present state of the geosphere, which include sub-surface processes (e.g. crustal movement, diagenesis, etc.) and earth-surface processes (e.g. climatic and sea-level changes, geomorphological processes, etc.). An understanding of the palaeohydrogeological evolution of the site provides the firm foundation to describe the likely future evolution of the site.

In this study (see also [3-4]), the current status for the conceptualisation of the long-term geosphere evolution of coastal sites on the western seaboard of Japan is based on data from the Horonobe Underground Research Laboratory (Horonobe

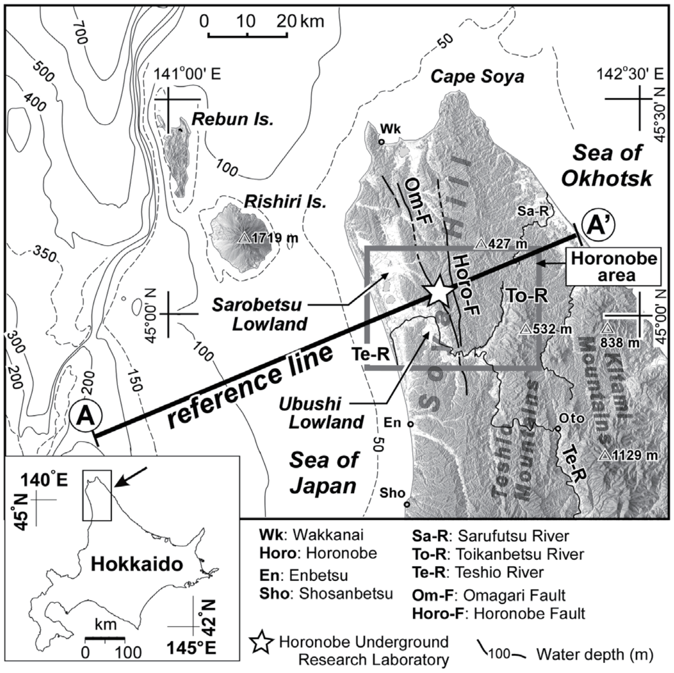


Figure 1. Present Geography of Northern Hokkaido
Shaded relief map is after [5].

URL; Fig. 1) project of the Japan Atomic Energy Agency (JAEA). This corresponds to the first to third steps of a geosynthesis methodology for the understanding of the geosphere evolution in a potential repository site which is described elsewhere in these proceedings [4].

The Horonobe URL project is a generic project conducted by 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 (see [6], for details). The project is proceeding in three overlapping phases, “Phase I: Surface-based investigation”, “Phase II: Construction”, and “Phase III: Operation”, extending over a period of about 20 years [6]. The following geoscientific information is mainly based on the results of the Phase I investigation of the project.

NATURAL EVENTS AND PROCESSES

The Phase I investigations for the geosphere evolution have been performed by the application of a geosynthesis methodology with the development of geosynthesis data flow diagrams [4, 6-8]. The geoscientific data have currently been synthesized into one conceptual model for a likely future evolution of the Horonobe area over the time-scale of the glacial-interglacial cycles (ca. 100 k.y.). This temporal scale was chosen as it marks the likely last significant change to the palaeohydrogeology of the area, beginning from the most recent sea-level minimum (e.g. Last Glacial Maximum) which would have led to a significant change to the salinity of the Sea of Japan (see discussion below). As noted in Amano et al. [3] and Ota et al. [4], the constantly changing sea-level of the Sea of Japan over this period would have had a significant impact on the site hydrogeology, impacting both groundwater fluxes and hydrochemistry. Changes in hydrogeological heads, as sea-level rose and fell, would impact flow across the study area just as sea-level would directly impact the chemistry of the infiltrating surface waters, changing from fresh to saline to fresh as the sea level rose and fell.

Groundwater flow simulation and particle-tracking analyses imply that, apart from shallow water less than ca. 75 m deep, the groundwater residence time would be in the order of a few millions of years [8]. This is supported by hydrochemical studies which indicate that the deep $Na\text{-}Cl\text{-}HCO_3$ dominant type groundwater is inferred to be of fossil seawater origin based on isotopic signatures and the groundwater age estimated by He and Cl radioisotopes is older than 1.5 Ma ([6], [9]). Therefore, geoscientific information should be collected in the order of millions of years for the description of the geosphere evolution in the Horonobe area.

Physical Geography in the Horonobe Area

The Horonobe area is situated in the eastern part of the Tenpoku Sedimentary Basin (e.g. [10]) and its geology is dominated by Neogene to Quaternary sedimentary sequences. The site lithostratigraphy, in ascending order, consists of the Soya (alternating beds of conglomerate, sandstone, and mudstone, intercalated with coal seams), Onishibetsu (sandstone intercalated with conglomerate and mudstone), Masuporo (alternating

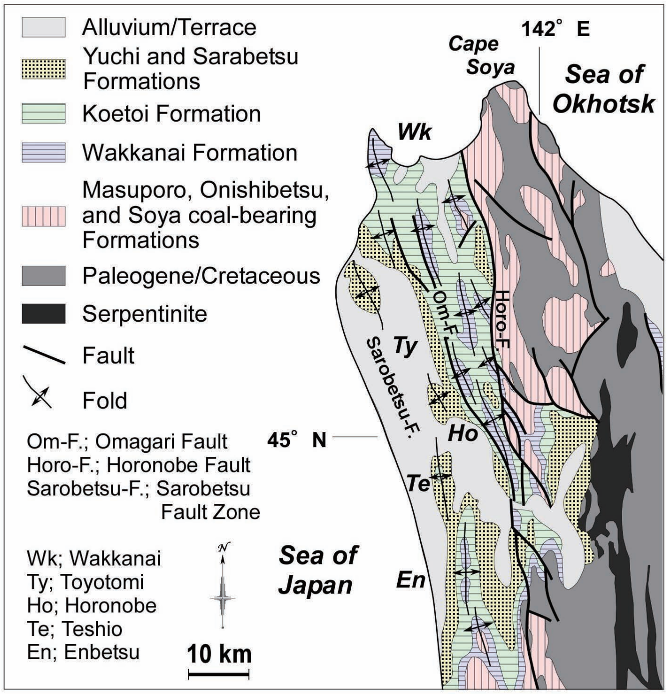


Figure 2. Geological Map of Northern Hokkaido
This map is partly modified from [14].

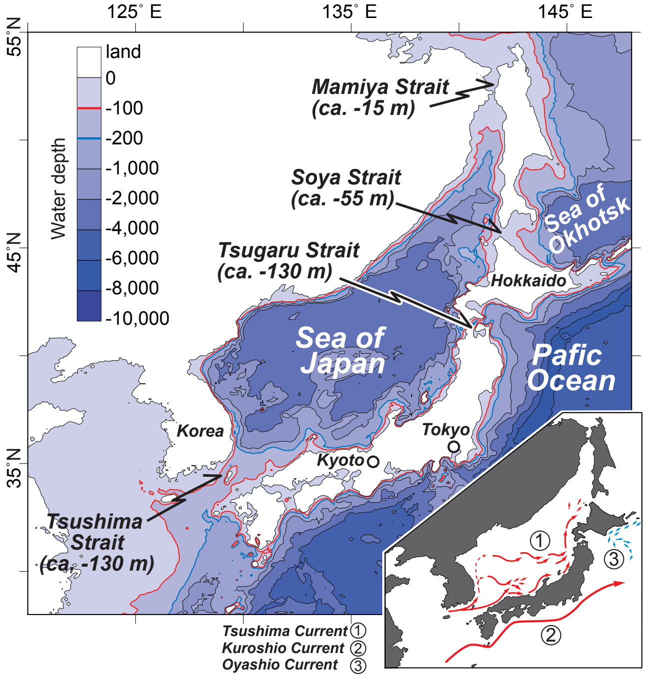


Figure 3. Present Geography and Surface Ocean Currents around Sea of Japan

Bathymetric data and generalized oceanic currents are after [21] and [22], respectively.

beds of conglomerate, sandstone, and mudstone), Wakkanai (diatomaceous and siliceous shale), Koetoi (diatomaceous and siliceous pebbly mudstone), Yuchi (fine- to medium-grained sandstone), and Sarabetsu (alternating beds of conglomerate, sandstone, and mudstone, intercalated with coal seams) Formations, (e.g. [11-14]; Fig. 2). 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 (e.g. [15]). In the area currently above sea-level, the basin has two main faults and one main fault zone called (from east to west) the Horonobe and Omagari Faults, and Sarobetsu Fault Zone, respectively ([11], [16]). Of these faults, the currently active structure is the Sarabetsu Fault Zone with deep-seated and ramp-flat geometry of low-angle thrusts (i.e. detachments). In addition, existing studies (marine seismic and geological surveys) indicate that three major fault and fold systems with north to south trend are located to the west of the Horonobe area (Sea of Japan) [17]. 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 (Tables 1 and 2). It can be also pointed out that the present geomorphological distribution of uplands and lowlands reflects the geological structures and lithologies of the area (Figs. 1 and 2).

Based on stratigraphic and sedimentalogical analyses, the structural development of the region has resulted in westward migration of the depositional area in the Tenpoku Basin ([11], [18]). In addition, the distribution 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 [11].

The area has a widespread distribution of marine terrace deposits, which are correlated to the marine oxygen isotope stages (MIS) 7 through 5.5. Column 5 of Table 1 shows the palaeogeography of the area, from MIS5.5 (ca. 125 ka) to the present, on the basis of the age and distribution of these deposits, global sea-level changes, and sea-floor topography [11]. The former shorelines of interglacial stages (e.g. MIS5.5) 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 to the west of the Horonobe area.

Additionally, key natural phenomena which have potential impacts on geosphere evolution can be identified and these include:

- 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 [19].
- The relationship between geology and geomorphology (hill morphology, drainage pattern, etc.) suggests that geomorphological processes are different for each geological formation [6].
- Changes in porosity of the sedimentary formations due to consolidation during burial have also changed their hydraulic conductivity and mass transport properties. This phenomenon will proceed on a time frame of tens of thousands to millions of years.

Two periods of mountain glacier development are reported in the mountain range of Hokkaido at ca. 50-40 and 20-10 ka based on geomorphological evidence ([20]; Table 1). However, in the Horonobe area, there is no geomorphological evidence of past glacial influence.

Palaeogeography of the Sea of Japan

Based on the microfossil biochronology, ages of igneous rocks, palaeobathymetry estimated from the benthic foraminiferal and the molluscan assemblages, and the regional correlation of the terrestrial and marine sediments, the northern part of the Sea of Japan had been connected to other seas [23], such as the Pacific Ocean, where the cold current could flow into the Sea between early Late Miocene (ca. 10 Ma) and 3.5 Ma [24]. Based on the palaeogeographic map of Iijima and Tada [23], the Tsushima Strait would appear to have been above sea level during the same period.

Currently, the Tsushima Warm Current flows into the Sea of Japan through the Tsushima Strait with ca. 130 m water depth in the present highstand conditions (Fig. 3). This compares with past glacial lowstands of up to -150±10 m over the last 500 k.y.(e.g. [25]) when the straits surrounding the Sea of Japan emerged above sea level and the Sea became almost isolated. At this point, the salinity of the surface seawater (mixed layer; ca. 150 to 200 m deep) of the restricted Sea of Japan probably decreased due to excess input of fresh water over evaporation and limited re-supply of saline water through the straits [26-27].

Estimated salinity of the surface seawater during the last glacial period is ca. 28 ‰, assuming the salinity of the surface water was the same as present (34 ‰) and the injected fresh water was -15 ‰ [26]. The isolation of the Sea occurred periodically during the glacial periods, at least since 800 ka [27] and it is possible that the Sea became even fresher during MIS10 and MIS12 (ca. 340 ka and 434 ka, respectively) when sea levels dropped to -150±10 m around the world [25]. Note that sea-levels higher than present have also been reported (see reviews [28-29]) with +7±4 m at MIS5.5 and up to +20 m during MIS11.3 (ca. 406 ka). All of the information described above is summarised in Table 1 (for the past 130 k.y.) and Table 2 (for the past 2.6 m.y.).

CONCEPTUALISATION

Information on natural events and processes has been integrated into a chronological conceptual model which indicates space-time sequences of the events and processes in the area over geological time. Spatial scale for the conceptualisation is ca. 100 km in the East-West direction through the locations of the URL and of the borehole investigations on the coast in the Horonobe area. Temporal conceptualisations over the last several hundred thousand years focused on the changes caused by earth-surface processes through the glacial-interglacial cycle and over the last few million years are focused on the spatial and temporal changes of the geosphere caused by sub-surface processes. Regarding the conceptualisation in the future glacial period (Fig. 4), it assumes that future natural events and processes will behave much as they did in the past. From the viewpoint of the evolution of the regional hydrochemistry, the Horonobe area is divided into three sub-areas (sea, coastal, and hill areas: Fig. 4). The main change to these sub-areas over the last 214 ka has been the oscillation of the position of the coast in response to sea-level changes. Clearly, the biggest impact of this oscillation will be changes in the chemistry (from marine to fresh and back) of the infiltrating surface waters [3].

A topographically driven groundwater flow would be expected since 1.5±0.1 Ma (Fig. 5), when the present location of the Soya Hill was considered to have been at a reasonably high altitude based on a provenance analysis of the Sarabetsu Formation [11].

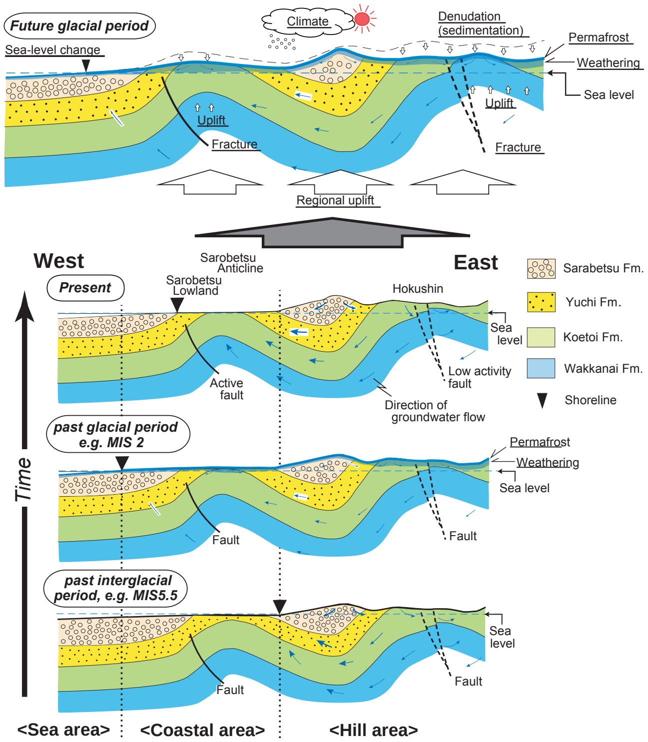


Figure 4. Conceptualisation for the Hydrogeological Evolution in the Horonobe Area through the Glacial-interglacial Cycle

The natural phenomena underlined in figure are those considered important for developing the geosphere evolution in the area.

DESCRIPTION OF UNCERTAINTIES

In building palaeohydrogeological models, it must be understood that data (and conceptualisation) uncertainties have to be considered in detail (cf. [32]). What is perhaps different from most scientific analysis is that the uncertainty in palaeohydrogeology must be considered in 4-dimensional space. There are also differences between the degree of uncertainty in data for the Sea of Japan area when compared to the Horonobe area. First, the data density is much greater around Horonobe and so conceptual uncertainty is generally much less. Second, the confidence in the data around Horonobe is generally greater as the programme has followed a state-of-the-art QMS (quality management system; e.g. [33]) whereas it is often difficult to assess the quality of data for the Sea of Japan, especially for older academic publications. As an example, the parameters building this 4-D volume for the Sea of Japan would include:

- Inhomogeneous nature of spatial distribution of uplift and subsidence
- Variations in the rate of uplift and subsidence
- Height of mountain range in the past period
- Recharge rate
- Changes in porosity and hydraulic conductivity over geological time
- Uncertainties about sea-levels in the Sea of Japan
- Uncertainties about location of former shoreline through the past glacial-interglacial cycles
- Variations in seawater chemistry (especially salinity and

Table 1. Natural Events and Processes in the Coastal Field in the Horonobe Area, Hokkaido, Japan since 130 ka
LGM; Last Glacial Maximum, LIG; Last Interglacial.

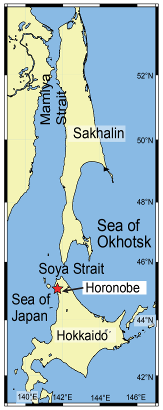
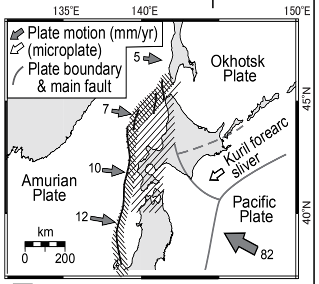
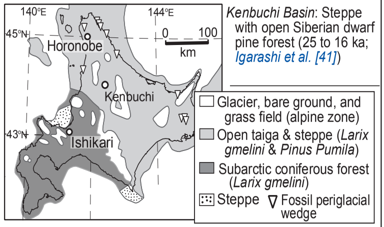
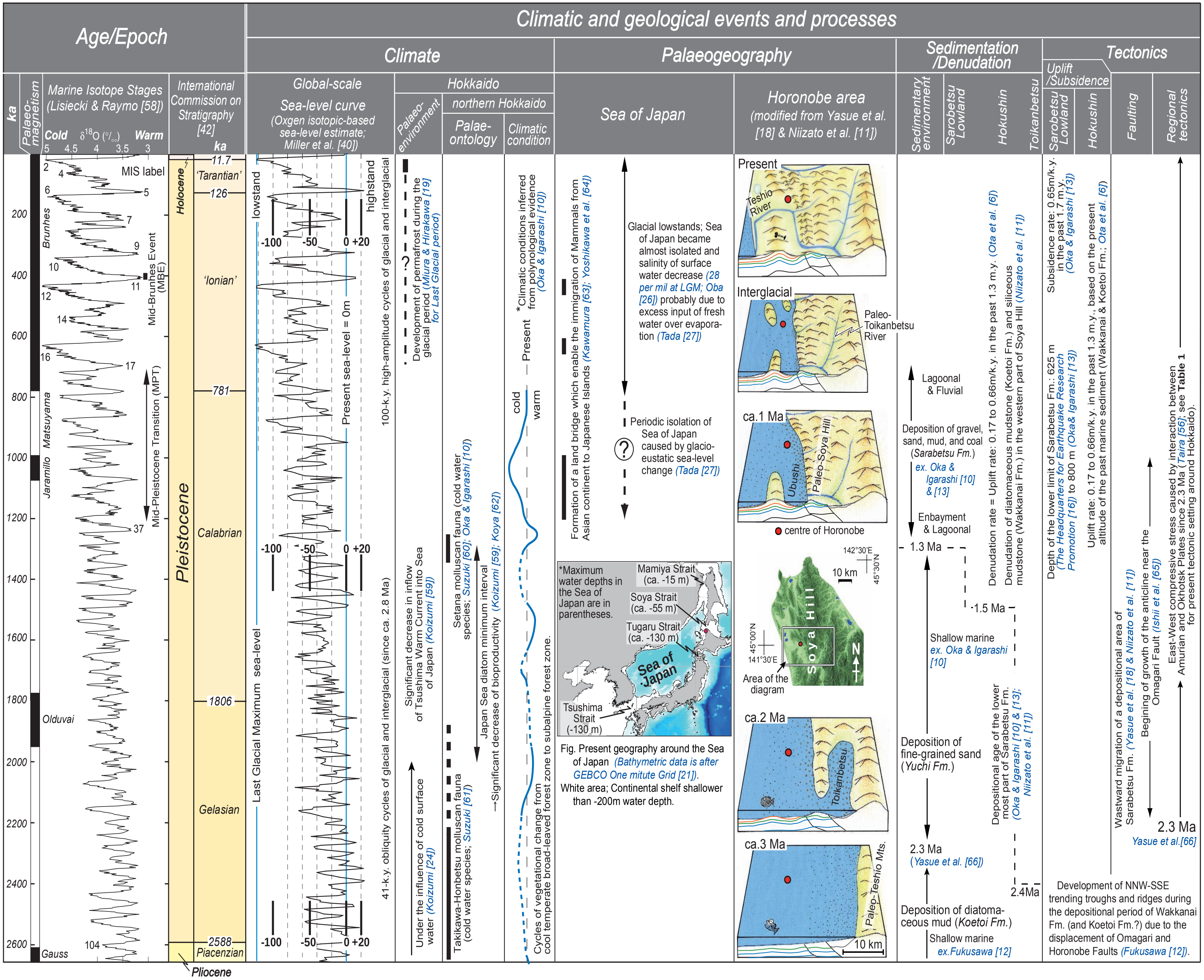
Age						Climatic and geological events and processes											
						Climate					Palaeogeography	Sedimentation / Denudation		Tectonics			
						Global-scale Sea-level		Hokkaido						Uplift /Subsidence			
ka (Gibbard & Kolfschoten [36] Umitsu [37])	Marine Oxygen Isotope Stages; MIS (Martinson et al. [38])	Glacial - interglacial cycle		(Gibbard & Kolfschoten [36] ; Umitsu [37])	Pollen zone of northern Europe (Umitsu [37] Machida,et al. [39])	Sea-level curve (Miller et al., [40])	Sea-level (meter to the present)	Climatic condition	Permafrost & periglacial environment	Vegetation	Horonobe area	Sarobetsu Lowland & Sarobetsu Anticline	Hokushin district	Sarobetsu Lowland	Sarobetsu Anticline	Faulting	Regional tectonics
Present	MIS1	Postglacial	Holocene	🟪 Temperate (interglacial) ▥ Cold (glacial) 🟧 Warm (interstadial) ▥ Cool (stadial)			present; 0 m Anthropogenic sea-level rising; 1.8±0.5 mm/yr *(after 1961; IPCC [42])*	Annual precipitation; ca.1,300～1,600 mm（Aug.～Nov., 2005）* Average annual air temp.**; 5.9°C ･Jan. average air temp.**; -7.7°C ･Aug. average air temp.**; 19.4°C **Ota et al. [6]* ***Weather condition of Horonobe Town (1998-2005)*		Pan-mixed forest (mosaic-like mixed forest with broad-leafed and coniferous trees; *Igarashi [49]*)		Downward erosion by river: 0.3 to 0.8 m/k.y. (Depth of dissection valley on MIS5.5 marine terrace by geomorphometry) Sedimentation rate: 6.6 m/k.y. (Sedimentation curve after LGM in the Sarobetsu Lowland) *(Horonobe-Rise [53])* ca. 5,000 years ago; Coastal sand dunes in the Sarobetsu Lowland *(Kitazawa [54])* ca. 1,900 to 670 years ago; southward migration of the river mouth of Teshio River *(Kitazawa & Tokiwa [55])*	Denudation rate : 0.17 to 0.66m/k.y. in the past 1.3 m.y. (Present altitude of the past marine sediment (Wakkanai Fm. & Koetoi Fm. ; *Ota et al. [6]*) *Hokushin district have been an land area since 1.3 Ma *(Niizato et al. [11])*	Subsidence rate: same as sedimentation rate after LGM ? (Sarobetsu Lowland)	Uplift rate: 0.3 m/k.y. based on the altitude & age of MIS5.5 marine terrace *(Ota et al. [6])*	? Activity of Sarobetsu Fault Zone in the coastal zone of Horonobe area. Average rate of slip: over 0.7m/k.y.; Recurrence interval: 4 to 8 k.y. *(The Headquarters for Earthquake Research Promotion [16])*.	East-West compressive stress obtained by borehole survey and GPS measurement *(Ota et al. [6])*
5 ~ 7.8 (ca.7 in Japan)				Jomon trans-gression	Atlantic (Hypsithermal interval)		+3 to 4 m *(Sakaguchi,et al. [43])*	Sea-surface temp.(SST); +5 °C warmer than present (molluscan fossil in northern Hokkaido; *Matsushima & Ohshima [47]*) Air temp.; +1 to +2 °C warmer than present *(Umitsu [37])*									
ca. 10							- 40 m *(Sakaguchi, et al. [43])*	Air temp.; -2 to -3 °C colder than the present *(Umitsu [37])*									
ca.10 ~ 11	MIS2	Late Glacial	Late Weichselian	Kenbuchi Stadial *(Igarashi et al. [41])*	Younger Dryas		?			*Kenbuchi Basin*: increase in Dahurian larch and decrease of Sakhalin fir *(Igarashi et al. [41])*	 Fig. Present geography around the Horonobe						
ca.11 ~ 11.8					Allerød		- 40 m *(Sakaguchi, et al. [43])*										
ca.11.8 ~ 12.1					Older Dryas		?	**< 14 to 12 ka >** Annual precipitation*: -750 to -1,000 mm lower than the present Average annual air temp.*: -8°C colder than present ･Jan. air temp.*: -12°C colder than present ･Aug. air temp.*: -6°C colder than present **These estimations are based on a pollen analysis of peat layer in the Horonobe area *Niizato et al. [48]*	**< 42 to 12 ka >** Discontinuous permafrost (northern part of Hokkaido) *(Miura & Hirakawa [19])* Development of discontinuous permafrost with ca. 20 m in thickness in Horonobe area *(Niizato et al. [11])*	*Horonobe*: decrease in the numbers of Dahurian larch and substantial increase of Betula (ca. 12ka; *Niizato et al. [48]*) *Kenbuchi Basin:* Significant drop in the numbers of Dahurian larch and Siberian pine *(Igarashi et al. [41])* *Horonobe:* Steppe with Dahurian larch(14 to 13 ka; *Niizato et al. [48]*)							 ▨ Tectonic zones I and VI *(Oka & Igarashi [13])* ▧ The tectonic belt of eastern margin of Japan Sea *(Taira [56])* Fig. Present tectonic setting in and around Hokkaido (plate motion and its velocity are after *Wei & Seno [57]*)
ca.12 ~ 13					Bølling												
ca.15					Oldest Dryas												
ca.20		LGM		Tottabetsu Stadial - Maximum expansion of alpine glacier reached down to 1,500 m above sea-level *(Sawagaki et al. [20])*			Max. -150 m based on the distribution of sand-layer on the sea-bottom surface of Sea of Japan *(Ikehara et al. [44])* -127±30 m based on the analysis of sediment core in Sea of Japan *(Oba [45])*	 **Fig. Vegetation of the Last Glacial Maximum in Hokkaido with locations of fossil periglacial wedges** *(Igarashi [49]; Miura & Hirakawa [19])*		*Kenbuchi Basin*: Steppe with open Siberian dwarf pine forest (25 to 16 ka; *Igarashi et al. [41]*)	 Soya and Mamiya Strait were land area in the Last Glacial Maximum. Present water depth ･Soya Strait; ca.-55 m ･Mamiya Strait; ca.-4 to -20 m						
30			Middle Weichselian														
42	MIS4 ~ 3			Poroshiri Stadial - Maximum expansion of alpine glacier reached down to 750 m above sea-level *(Sawagaki et al. [20])*			< 85 to 20 ka > *No inflow of warm Tsuhima Current into Sea of Japan* *(Oba et al. [26])*										
ca.70 ~ 110	MIS5		Early Weichselian				Interstadial; ca. -20 m Stadial; ca. -50 m →global-scale sea-level change *(Siddall et al. [28])*	**< MIS5.5 >** Isotopic temparature: +2 °C warmer than present（Vostok ice core in Antarctica; *Petit et al. [50]*) Average air temp. (Central and Eastern Europe, Pollen analysis; *Velichko et al. [51]*) ･The warmest month: +2 to °C warmer than present ･The coldest month; +2 to +10 °C warmer than present									
ca.110 ~130	MIS5.5 (or 5e)	LIG	Eemian				+7±4 m based on multi-proxy investigations using sediment core collected off Central Japan *(Oba et al. [46])*			**< MIS5.5 >** *Ishikari Plain*: Cool temperate forest of Oak, elm, and walnut (warmer and wetter condition than present; *Igarashi [52]*)	*(Niizato et al. [11])*  🟨 Land 🟦 Sea 🔴 Horonobe Town						East-West compressive stress caused by interaction between Amurian and Okhotsk Plates since 2.3 Ma. *(Taira [56])*

Table 2. Natural Events and Processes in the Coastal Field in the Horonobe area, Hokkaido, Japan since 2600 ka



Development of permafrost during the glacial period (Miura & Hirakawa [19] for Last Glacial period)

Significant decrease in inflow of Tsushima Warm Current into Sea of Japan (Koizumi [59])

Under the influence of cold surface water (Koizumi [24])

Setana molluscan fauna (cold water species; Suzuki [60]; Oka & Igarashi [10])

Japan Sea diatom minimum interval

→Significant decrease of bioproductivity (Koizumi [59]; Koya [62])

Takikawa-Honbetsu molluscan fauna (cold water species; Suzuki [61])

*Climatic conditions inferred from polynological evidence (Oka & Igarashi [10])

Cycles of vegetational change from cool temperate broad-leaved forest zone to subalpine forest zone.

Formation of a land bridge which enable the immigration of Mammals from Asian continent to Japanese Islands (Kawamura [63]; Yoshikawa et al. [64])

Glacial lowstands; Sea of Japan became almost isolated and salinity of surface water decrease (28 per mil at LGM; Oba [26]) probably due to excess input of fresh water over evaporation (Tada [27])

Periodic isolation of Sea of Japan caused by glacio-eustatic sea-level change (Tada [27])

*Maximum water depths in the Sea of Japan are in parentheses.

Fig. Present geography around the Sea of Japan (Bathymetric data is after GEBCO One mitute Grid [21]). White area; Continental shelf shallower than -200m water depth.

Deposition of gravel, sand, mud, and coal (Sarabetsu Fm.) ex. Oka & Igarashi [10] & [13]

Deposition of fine-grained sand (Yuchi Fm.)

Deposition of diatomaceous mud (Koetoi Fm.)

Denudation rate = Uplift rate: 0.17 to 0.66m/k.y. in the past 1.3 m.y. (Ota et al. [6])

Denudation of diatomaceous mudstone (Koetoi Fm.) and siliceous mudstone (Wakkanai Fm.) in the western part of Soya Hill (Niizato et al. [11])

Depositional age of the lower most part of Sarabetsu Fm. (Oka & Igarashi [10] & [13]; Niizato et al. [11])

Subsidence rate: 0.65m/k.y. in the past 1.7 m.y. (Oka & Igarashi [13])

Depth of the lower limit of Sarabetsu Fm.: 625 m (The Headquarters for Earthquake Research Promotion [16]) to 800 m (Oka& Igarashi [13])

Uplift rate: 0.17 to 0.66m/k.y. in the past 1.3 m.y., based on the present altitude of the past marine sediment (Wakkanai & Koetoi Fm.; Ota et al. [6])

Wastward migration of a depositional area of Sarabetsu Fm. (Yasue et al. [18] & Niizato et al. [11])

Begining of growth of the anticline near the Omagari Fault (Ishii et al. [65])

East-West compressive stress caused by interaction between Amurian and Okhotsk Plates since 2.3 Ma (Taira [56]; see **Table 1** for present tectonic setting around Hokkaido).

Development of NNW-SSE trending troughs and ridges during the depositional period of Wakkanai Fm. (and Koetoi Fm.?) due to the displacement of Omagari and Horonobe Faults (Fukusawa [12]).

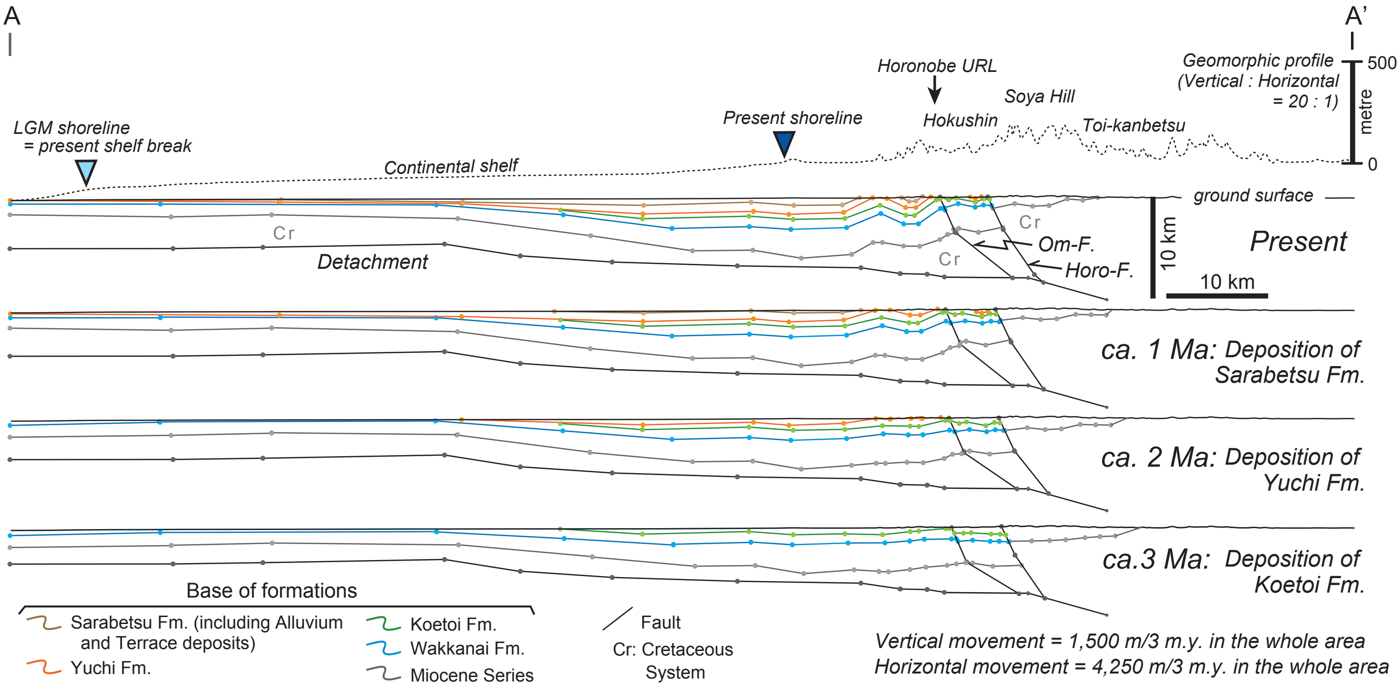


Figure 5. Conceptualisation for the Evolution of Geological Structure since ca. 3 Ma along A-A' line

This conceptualisation takes into consideration of a conservation of bed length in the cross section along the A-A' line. See Fig. 1 for A-A' line. Present geological cross section is based on [30]. Horizontal and vertical movements are after [31], and Tables 1 and 2, respectively. Om-F.: Omagari Fault, Horo-F.: Horonobe Fault.

stable isotopes)

- Degree of coverage of the permafrost (i.e. just how discontinuous is discontinuous?) around the northern end of the Sea of Japan

and, of course, the 4th dimension, namely uncertainties about the actual timing of these events. Work on establishing the degree of uncertainty in the main parameters is currently ongoing, but it is instructive to consider one here in detail: salinity. Salinity is a favoured tool of palaeohydrogeologists because it is a relatively stable parameter, little altered by reaction of groundwater with the host rock. This fact has been used by researchers around the world to elucidate the impact of climate and sea-level change at coastal sites (e.g. [34]). For example at Posiva's Olkiluoto site and SKB's Forsmark and Laxemar sites, changes in the salinity of the nearby Baltic Sea over the last 125 k.y. have been used to interpret the evolution of the hydrochemistry of these sites in quite some detail.

This is somewhat more difficult for the Sea of Japan as two of the four straits (Tsushima and Tugaru; Fig. 3) which supply Pacific seawater to this enclosed basin have sill depths (ca. -130 m) which lie within the error margin of the likely maximum lowstand over the last 125 kilo years. Clearly, this could have a significant impact on the assumed salinity of the Sea of Japan and therefore on the salinity of infiltrating surface waters on Japan's western seaboard. However, in the Horonobe area, which would have been some 50 km to the east of this low shoreline, the infiltrating surface water would have been freshwater and it would have remained so until the next transgression.

This being the case, it is perhaps better to visualise the overall uncertainty as a 4-D volume of uncertainty where the degree of uncertainty generally increases with distance away from the data-rich, QMS-influenced enclave around the Horonobe URL and with time (both forwards and backwards) away from the present day. Perhaps the most difficult part of this process is adequately addressing the paucity of QMS information for areas away from the URL – how can the data be weighted in comparison with that from Horonobe? This is a novel approach in Japanese palaeohydrogeology, but is one which will undoubtedly be utilised more in the future as potential repository sites are investigated in detail, beginning with the older, possibly non-quality assured data available in the literature and comparing this with data being produced in real time by the investigation programme.

CONCLUSIONS

An understanding of a palaeohydrogeological evolution of a potential repository site provides the firm foundation to describe the likely future evolution of the site and to support an identification of scenarios that illustrate the range of possibilities for the evolution of the geological disposal system under consideration. The evolution described in this paper is focused on the geosphere, which is one of the system-components in the geological disposal system. To describe the whole system behaviour, it is necessary to collect and to integrate the information about every system-component as far as possible, and to construct a consistent conceptual model for the evolution of the whole system. Therefore, in the future, it will be necessary to combine the palaeohydrogeological approach with a framework for examination of the long-term safety of a HLW repository [35]. Such a total assessment methodology will support building confidence in a safety case of a HLW geological disposal system in a coastal environment.

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NOMENCLATURE

ka	kilo-annum; 10^3 years before the present (the age of a strata or the time of a geological event)
k.y.	kilo (10^3) years (the duration of an interval of geologic time)
Ma	Mega-annum; 10^6 years before the present (the age of a strata or the time of a geological event)
m.y.	millions (10^6) of years (the duration of an interval of geologic time)

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