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Synthesized Research Report in the Second Mid-term Research Phase

－ Mizunami Underground Research Laboratory Project, Horonobe Underground Research Laboratory Project and Geo-stability Project －
(Translated Document)

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We have synthesized the research results from the Mizunami/Horonobe Underground Research Laboratories (URLs) and geo-stability projects in the second mid-term research phase. This report can be used as a technical basis for the Nuclear Waste Management Organization of Japan/Regulator at each decision point from siting to beginning of disposal (Principal Investigation to Detailed Investigation Phase). High-quality construction techniques and field investigation methods have been developed and implemented, which will be directly applicable to the National Disposal Program (together with general assessments of hazardous natural events and processes). Acquisition of technical knowledge on decisions of partial backfilling and final closure from actual field experiments in the Mizunami/Horonobe URLs will be crucial as the main theme for the next phases.

Keywords: Mizunami Underground Research Laboratory, Horonobe Underground Research Laboratory, Long-term Stability of Geological Environment, Second Mid-term Research Phase, Geological Disposal of HLW

This document is the English translation of "Synthesized Research Report in the Second Mid-term Research Phase" (JAEA-Research 2015-007).

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第 2 期中期計画期間における研究成果取りまとめ報告書
ー深地層の研究施設計画および地質環境の長期安定性に関する研究ー
（翻訳資料）

日本原子力研究開発機構
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（2016 年 5 月 27 日受理）

国立研究開発法人日本原子力研究開発機構は，高レベル放射性廃棄物の地層処分の実現に向けた国の第 2 期中期目標（平成 22～26 年度）に基づき中期計画を策定し，処分事業と国による安全規制の両面を支える技術基盤を整備するため，地層処分研究開発と深地層の科学的研究の 2 つの領域において研究開発を進めている。今般，本中期計画期間における深地層の科学的研究分野（超深地層研究所計画，幌延深地層研究計画，地質環境の長期安定性に関する研究）の成果を取りまとめるにあたり，処分事業におけるサイト選定から処分開始に関する意思決定ポイントまでに必要な技術情報を事業者・規制機関が活用し易い形式で体系化し，所期の目標の精密調査（前半）の段階に必要となる技術基盤として整備した。

本成果で体系化された調査解析技術は，地層処分場の許認可段階にある国外の地層処分事業（スウェーデン，フィンランド）での適用技術と比肩しうる網羅性と品質を有しており，地震・断層，火山などの天然現象の高精度調査解析技術との組み合わせにより，わが国の地質環境に適応したより幅広い地質環境特性のシナリオに対応可能である。

今後は，部分的埋め戻しや廃棄体定置終了，最終閉鎖に関する意思決定ポイントに必要な技術基盤を整備するために，これらに関する先進的な研究開発を深地層の研究施設において実施し，世界をリードする地層処分技術として国内外に広く発信していく。

本報告書は，「第 2 期中期計画期間における研究成果取りまとめ報告書－深地層の研究施設計画および地質環境の長期安定性に関する研究」（JAEA-Research 2015-007）を英訳したものである。

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1. Introduction

1.1 Background and current status of the Underground Research Laboratory project and research on geosphere stability for long-term isolation of radioactive waste

The Japan Atomic Energy Agency (JAEA) has conducted R&D programs on the Underground Research Laboratory (URL) project and geosphere stability research during the second mid-term program (fiscal years 2010–2014). Specific goals were set on the basis of past research achievements and the government's research policy, as listed below:

- Evaluation of applicability of investigation techniques and modeling methodologies through excavation of underground facilities up to approximately 500 m depth at Mizunami and up to approximately 350 m depth at Horonobe.
- Verification of the applicability of engineering technologies in the deep underground.
- Development of prediction and evaluation technologies for understanding the long-term evolution of the geological environment in terms of important natural phenomena during site characterizations of the planned geological disposal program.

With regard to the URL project, excavations over a five-year period and relevant investigations were conducted. At the end of September 2014, two shafts with a depth of 500 m and horizontal tunnels with a length of 430 m at that depth had been excavated at the Mizunami Underground Research Laboratory, and three shafts with a depth of 350 m and investigation tunnels with a length of 760 m at that depth had been excavated at the Horonobe Underground Research Laboratory (Fig. 1.1-1). In these laboratories, the geological environment data required to achieve the goals were obtained and analyzed/evaluated in parallel with the excavation. In addition, R&D on geological disposal, including validation of engineering technologies such as engineered barrier systems (EBS), was conducted in Horonobe. With regard to the geosphere stability research, more detailed R&D items were focused on (a) development and systematization of investigation techniques; (b) development of models for long-term estimation and effective assessment; and (c) development of dating techniques, in order to consolidate investigation and analysis technologies and the related knowledge and skills applicable to the Japan-specific geological environment within the mobile belt.

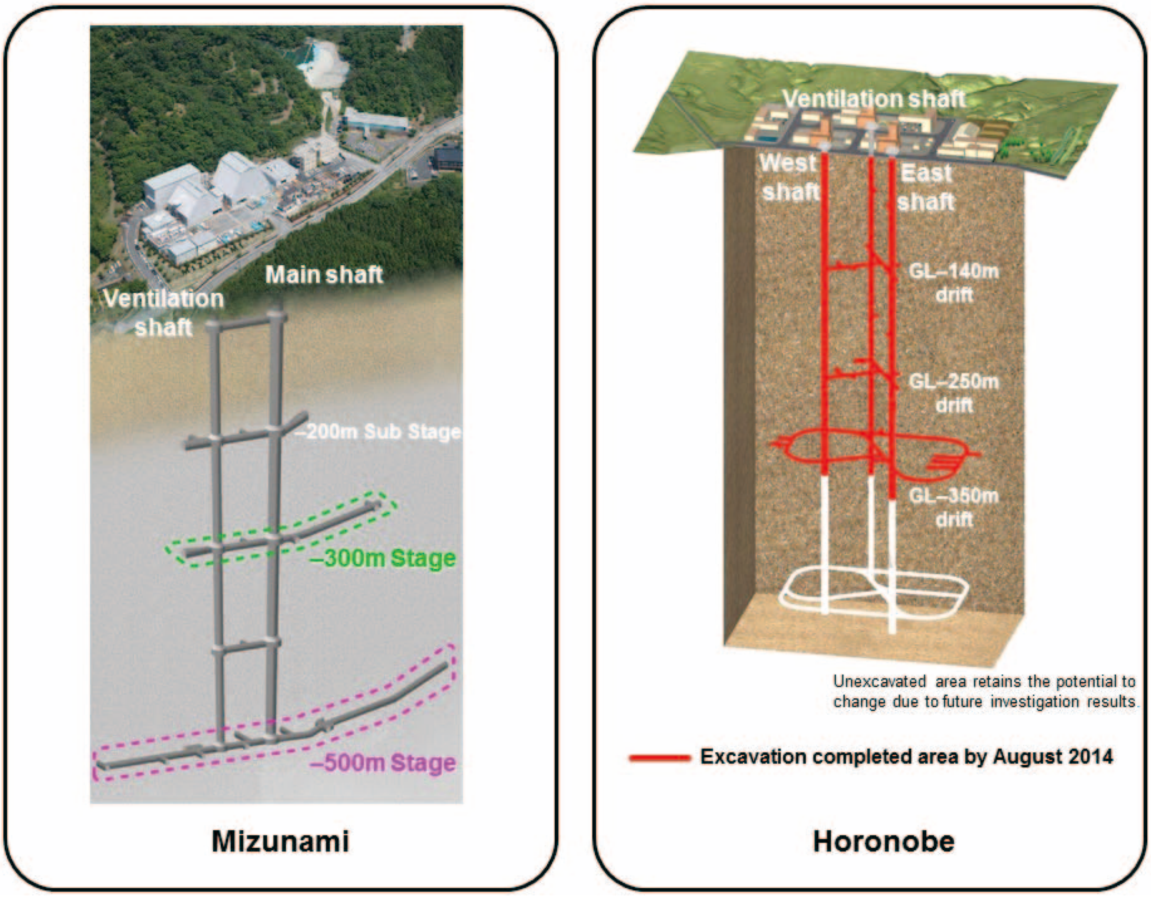

Fig. 1.1-1 Bird's-eye/cutaway view of the Underground Research Facilities (Mizunami and Horonobe; prepared in September 2014)

1.2 Integration of research results and chronological framework for reporting

1.2.1 Integration of research results

The results of R&D on geological disposal technologies were reported on the JAEA website after integration to form a knowledge base to support safety cases for geological disposal in order to allow readers to utilize the results easily[1)]. This newly invented reporting system was employed after the first mid-term research program was issued (CoolRepH22). This system allows presentation of the meaning and significance of the results of different areas of R&D to support the construction of safety cases, by which utilization of the results will be promoted and timely communication of information will become possible. The total number of visits to the website of CoolRepH22 was over 39,000 by August 2014. This number indicates that the site has played an important role as a tool to communicate with and provide information on R&D results to a variety of public groups.

In this kernel, specific utilization of the results of site characterization, particularly the site characterization techniques applicable to the early stages of siting processes in the planned geological disposal program, were compiled, with a focus on the systematic processes involved in the construction of a safety case (Fig. 1.2.1-1). More specifically, instead of the conventional message that "technologies required for constructing a site description model were developed," this kernel shows where and when to incorporate the results, and what points should be noted in incorporating the results (e.g., limitations of the investigation) as specifically as possible. In addition, a knowledge management system (JAEA KMS)[2] and a next-generation site characterization data integration system (ISIS) developed by JAEA were merged to provide a more convenient environment for the main end-users, i.e., the Japanese implementer (NUMO: Nuclear Waste Management Organization of Japan) and the Japanese regulator (NRA: Nuclear Regulation Authority).

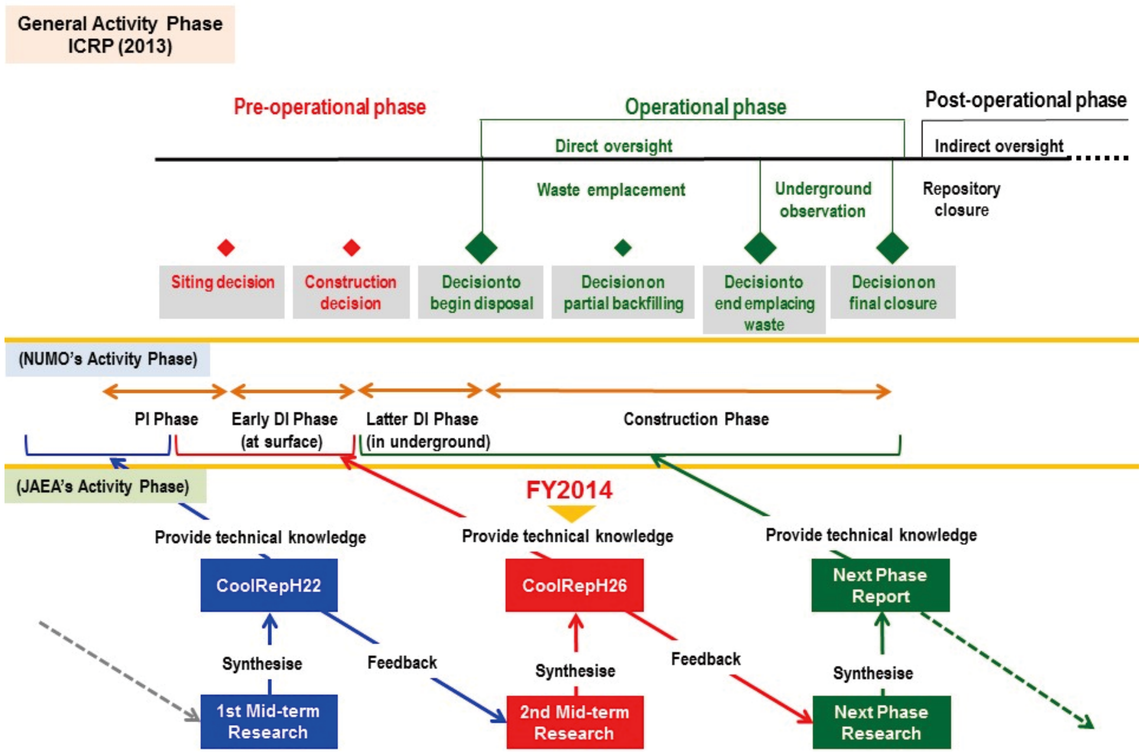

Fig. 1.2.1-1 Chronological history of CoolRep

1.2.2 Chronological framework

The research results were compiled considering each decision-making step of the geological disposal project (Fig. 1.2.1-1) and were described as a hierarchy in order to make the purpose of the reflection clear. The decision-making steps were divided into three groups: group A1 (understanding the initial state of the geological environment); group A2 (understanding the short-term evolution and recovery behavior of the geological environment); and group A3 (understanding the long-term evolution and recovery behavior of the geological environment), based on the general activity phases of projects defined by ICRP and NEA[3),4)]. Results relating to the period from before starting the tunnel excavation to the time of starting the tunnel excavation were assumed to belong to group A1; those for the period from completion of the tunnel excavation to tunnel closure to group A2; and those for the period after the closure to group A3. The results of the development of tools to integrate each result were defined as group B (development of tools to integrate the knowledge obtained in each R&D activity). In addition, construction of a structured system was attempted for gaining knowledge and information on geological disposal that could be complex and divided into a variety of disciplines with respect to time (lateral axis) and description level (vertical axis) (Fig. 1.2.2-1), wherein individual results for each R&D area and summaries of each result were collected as "results digests" a meaning was assigned to the results digests in each project and a total meaning was assigned as a core message.

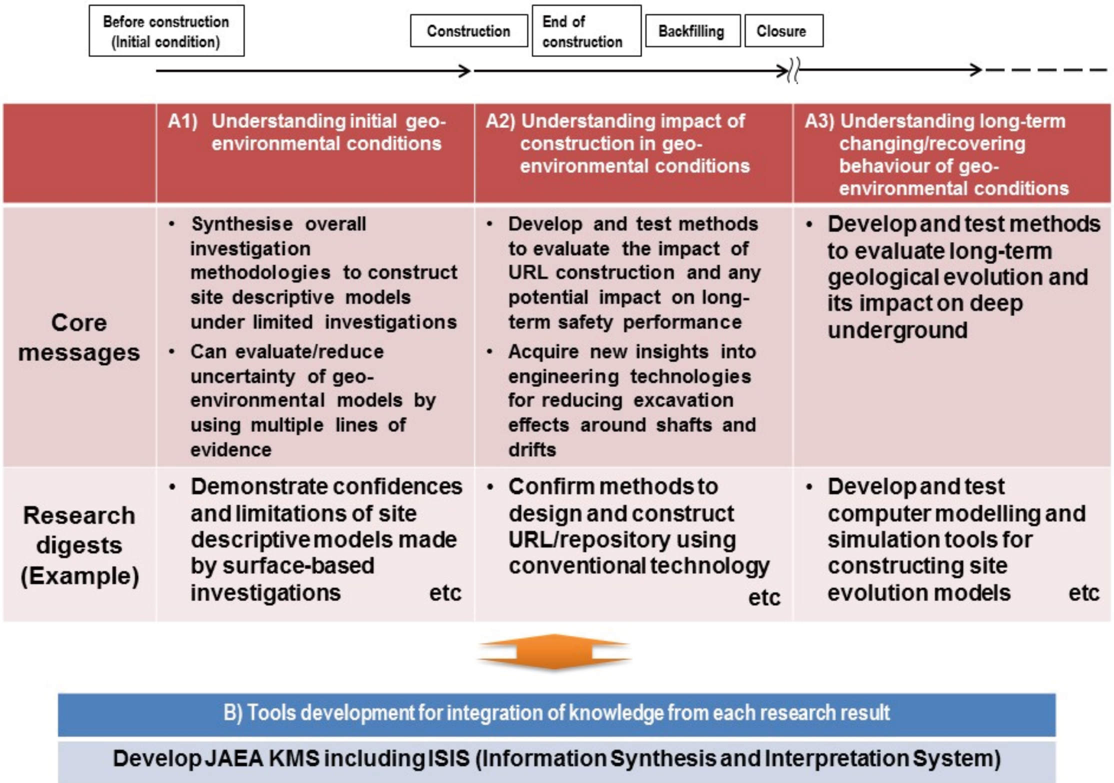

Fig. 1.2.2-1 Structure of the kernel of the URL project and research on geosphere stability

This type of structure allowed the contribution of individual research results to the overall goals to be more specifically shown and the knowledge base to support the construction of a safety case more easily referred to. Compilation using this format is expected to be useful in extracting issues to be addressed with priority in the future, streamlining of research topics, and creation of new research topics.

1.3 Core messages of major research results in the second mid-term research phase

The core messages and their meaning for groups A1 to A3 and group B as described above (section 1.2.2) are listed in Table 1.3-1, and their relationship with the results digest that supports the basis of the core message is mapped in Fig. 1.3-1 (only part of the total map is illustrated). These messages will help to clarify the significance of the results in the decision-making points for each project phase and allow easy and accurate identification of relationships between individual results and issues, which could not be sufficiently elicited from conventional compilation.

Table 1.3-1 Core messages of the research result from the URL project and research on the geosphere stability kernel

	Core message	**Technical meaning in decision points**
Understanding initial state of geological environment (A1 Group)	➢ Synthesize overall investigation methodologies to construct site descriptive models under limited investigations ➢ Can evaluate/reduce uncertainty of geo-environmental models by using multiple lines of evidence	✓ Be compatible with a complex geological environment and a resource-constrained environment based upon the developed techniques and the obtained technical knowhow ✓ Exemplify important investigation techniques and their combinations including investigation limitations
Understanding impact of construction in geo-environmental conditions (A2 Group)	➢ Develop and test methods to evaluate the impact of URL construction and any potential impact on long-term safety performance ➢ Acquire new insights into engineering technologies for reducing excavation effects around shafts and drifts	✓ Can utilize technical information for characterizing Excavation Damaged Zone (ex. functionally-useful investigation techniques, effective investigation layout and optimized planning scheme etc.)
Understanding long-term changing/recovering behavior of geo-environmental conditions (A3 Group)	➢ Develop comprehensive evaluation methodology for understanding long-term geological evolution and its impact on deep underground	✓ Can evaluate long term geo-environmental evolutions and their impact process by multidisciplinary approach ✓ Understand tolerant and resilient function of geo-environmental system to some degree
Tools development for integration of knowledge from each research result (B Group)	➢ Develop tools that can share and transfer expert knowledges on site characterization/engineering techniques, repository design and safety assessment	✓ Can transfer expert knowledge in a traceable manner for constructing safety case

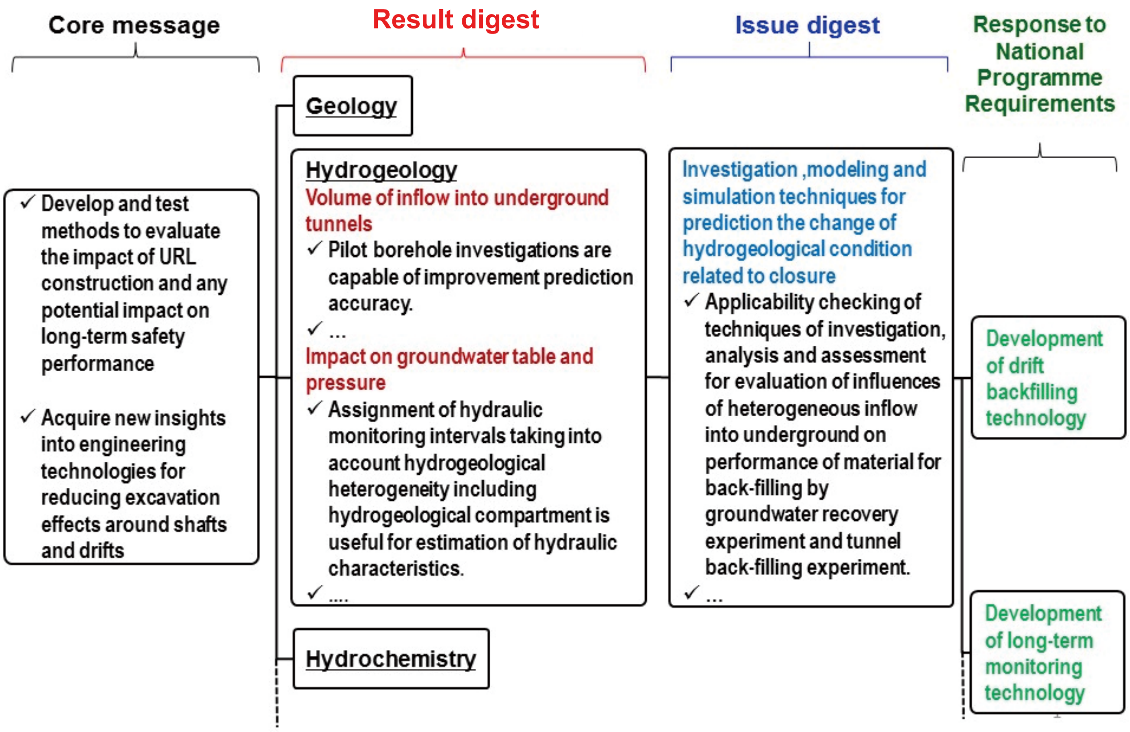

Fig. 1.3-1 An example of core messages in the results and issues digest map (part of the A2 group)

These core messages are also considered to be summaries of the R&D results obtained over a five-year period in the second mid-term program (146 technical reports, 124 academic publications, and 268 conference abstracts). In section 2 and the subsequent sections in this kernel, more specific explanations will be provided with respect to individual research results to be used as a basis for the core messages of groups A1 to A3 and group B.

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2. Understanding of the initial geo-environmental conditions

2.1 Geology

2.1.1 Introduction

Since both the geology and geological structure could control the capability of a site to act as a repository, the understanding of these fields of study is essential for understanding groundwater flow, hydrochemistry and mass transport conditions, as well as for the design of underground facilities. Therefore, we proceeded with the investigation, analysis and assessment of the distribution of geological structures from the ground surface in terms of safety assessments[1),2)], including an understanding of the following:

(1) distribution and shape of the targeted rock mass,
(2) geological inhomogeneity of rock mass, and
(3) important structures acting as paths for mass transport.

2.1.2 Objectives in the second mid-term research phase

The following studies as shown in Table 2.1.2-1 have been carried out to reach the performance target of R&D for perceiving three-dimensional geological structure, which was confirmed by the surface-based investigation performed during the first mid-term research phase.

Table 2.1.2-1 Performance target of R&D for perceiving three-dimensional geological structures (baseline condition)

Focus	Performance target of R&D	Tasks
Siting decision	Enable to select a geologically favorable domain	• Demonstration of technique to understand three-dimensional distribution of geological structure from ground surface
Construction decision	Enable to judge appropriateness of construction of underground facility taking into account important geological structure which acts as path for mass transport	• Demonstration of technique of investigation and interpretation to confirm distribution of fault in deep underground from ground surface • Demonstration of technique of investigation and modeling to confirm distribution of geological structure which acts as path for groundwater and mass transport • Demonstration of technique of investigation and interpretation to estimate distribution of fault around shaft/gellery

2.1.3 Project details and outcomes

(1) Understanding of the distribution and shape of the targeted rock mass

As a result of the surface-based investigation (Phase I), characteristics of the geological environment and processes important for deep geological disposal have been understood by stepwise investigations including existing data analysis, airborne and surface based investigations, and borehole investigations in the region, including URL construction sites. A technical basis has been also established through the iteration of investigation, interpretation, assessment and construction of geological models[3),4)].

In the second mid-term research phase, we accumulated all technical knowledge regarding the distribution and shape of the targeted rock mass and confirmed the validity of the geological model established in the Phase I investigation through the understanding of the rock mass distribution, and of geological structures such as fractures by observations in and around the URL site and by borehole and geophysical investigations from galleries.

1) Mizunami

As a result of the Phase I investigation, the distribution of the Toki Granite (late Cretaceous) and overlying Mizunami Group (Miocene) and the faults were estimated through stepwise investigations such as the interpretation of existing geological maps, surface geological and geophysical surveys (seismic reflection survey) and borehole investigations[3)]. Two structural domains, named the upper highly-fractured domain (UHFD) and lower sparsely-fractured domain (LSFD), were recognized by surface-based borehole investigations. The distributions of the domains were modeled based on the results of the borehole investigations and seismic reflection survey[3)]. We investigated the distribution of the UHFD and LSFD, and the obtained results are described below.

The thickness of the UHFD is related to the thickness of the overlying Mizunami Group, and is thicker in areas where the Mizunami Group is thick[5)]. The Mizunami Group is very thick in the Mizunami URL site, because the Group buried a channel structure developed on the granite. Thus, the UHFD was estimated to be located at G.L. −467 m[3),6)].

The pilot borehole drilled from the bottom of Ventilation Shaft[7)] revealed that the lower limit of the UHFD was located at approximately G.L. −460 m. Observations of the walls in the Ventilation Shaft[8)] revealed that the frequency of fractures decreased at approximately G.L. −460 m (Fig. 2.1.3-1)[9)]. These results implied that two structural domains were confirmed by the surface-based investigations with an error of approximately 10 m.

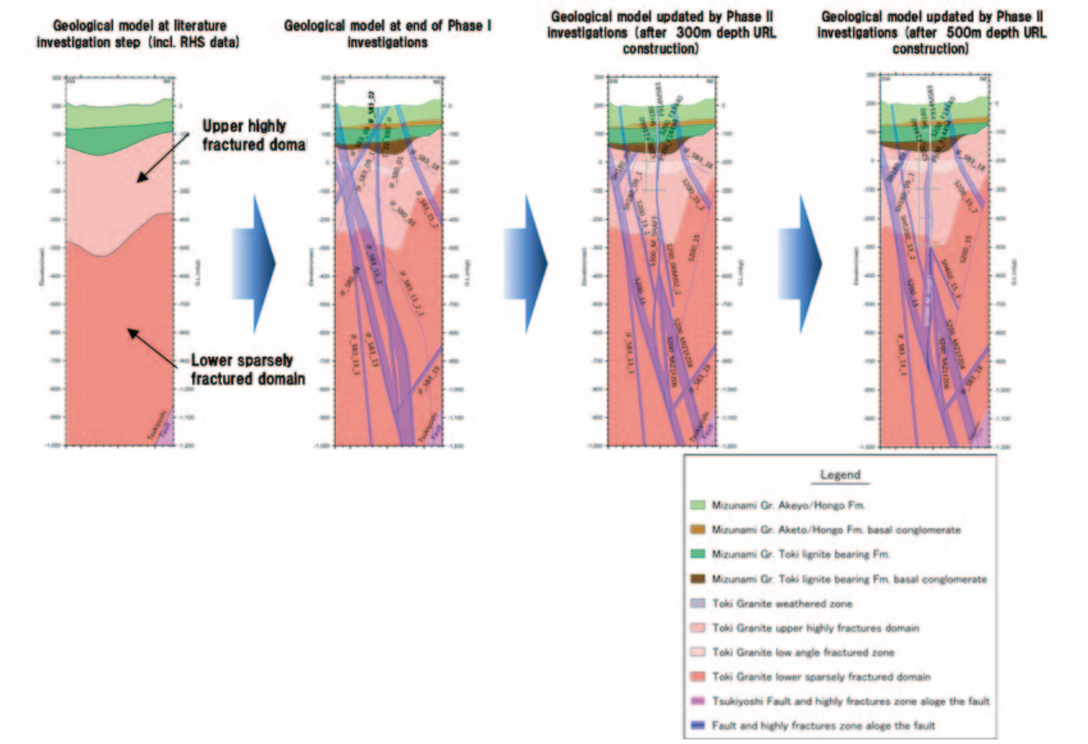

Fig. 2.1.3-1 Comparison of the geological models constructed during the surface-based investigation phase (Phase I) and in the second mid-term research phase

2) Horonobe

The distribution of the Neogene Koetoi and Wakkanai Formations, overlying Yuchi and Sarabetsu Formations and major faults have been confirmed by stepwise investigations such as interpretations of existing geological maps, surface geological and geophysical surveys (seismic reflection survey and audiomagnetotelluric (AMT) survey) and borehole investigations[4]. The boundary between the Koetoi and Wakkanai Formations is indicated by the occurrence of a silica mineral phase[10]; that is, the Wakkanai Formation contains Opal-CT which formed by the diagenesis of diatom remains (Opal-A), while the Koetoi Formation does not contain Opal-CT[11]. The boundary of the two formations estimated by the Phase I result was determined within a few meters, compared with the Phase II result obtained by the geological observation of the shaft walls and mineralogical analysis of drill core samples obtained from research galleries (Fig. 2.1.3-2 and Table 2.1.3-1)[12].

From the above mentioned points, we concluded that the geological model established by the Phase I result contained enough information to understand the stratigraphy in and around the URL, and that the estimation of the distributions of each geological formation on the basis of the Phase I result[4] was reasonable.

Based on the results of the previous investigations, we established a methodology to confirm the distribution and thickness of each formation in sedimentary rock and less fractured domains in granite. Thus, geological classification of the target rock in terms of the distribution of faults and frequency of fractures was achieved by a combination of surface geological, geophysical and borehole investigations. We also prepared a flow diagram to establish the geological model summarized by the result of various kinds of investigations on the basis of a "top-down" approach from "investigation" through to "data," and "interpretation/data set" to "conceptualization /modeling"[13].

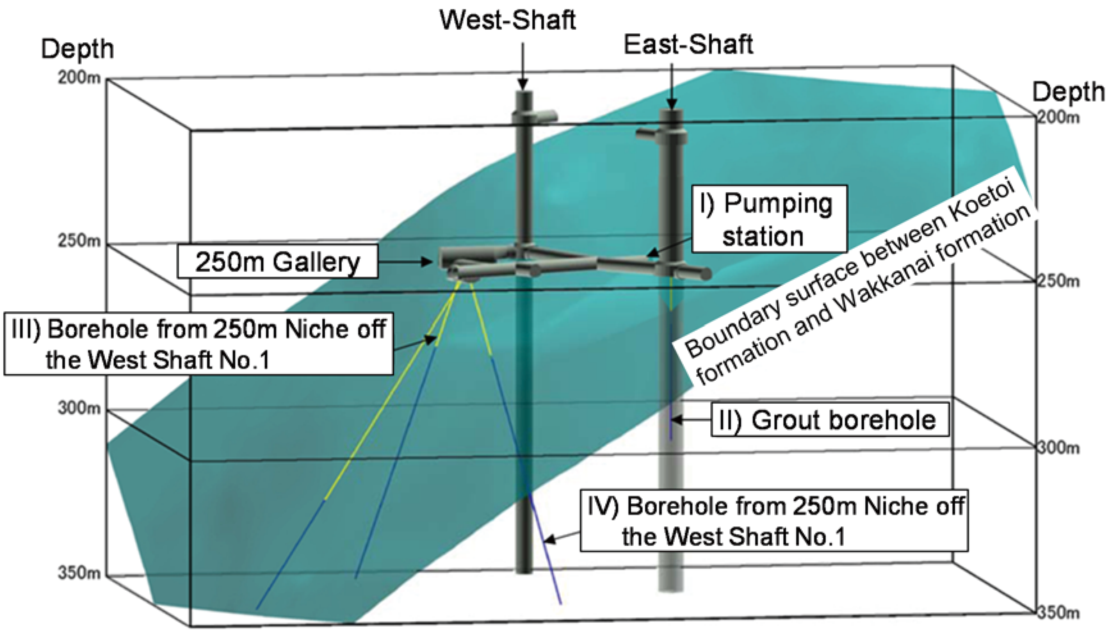

Fig. 2.1.3-2 Confirmation of the boundary the between Koetoi and Wakkanai Formations

Table 2.1.3-1 Depth of the boundary surface between the Koetoi and Wakkanai Formations

No.	Investigation/Location	Estimated depth	Observed depth
I	Geological mapping on the floor /250m pumping station	G.L. −249 m	G.L. −251 m
II	Analysis of Core /Grout hole in the East shaft	G.L. −260 m	G.L. −261 m
III	Analysis of core /Borehole from 250m Niche off the West Shaft No.1	G.L. −275 m	G.L. −274 m
IV	Analysis of core /borehole from 250m Niche off the West Shaft No.1	G.L. −276 m	G.L. −275 m

(2) Understanding the geological inhomogeneity of the rock mass

The geological inhomogeneity of the rock mass could result from variations in the rock facies and lithology (rock type, grain size and so on) and structural development (fracture frequency, distribution of faults and so on)[14]. We prepared a technical basis to understand the geological inhomogeneity by confirmation of the distribution of the rock mass and fracture zones on the basis of geological observations, as well as from borehole and geophysical investigations from research galleries.

1) Mizunami

Toki Granite has been lithologically divided into muscovite-biotite, hornblende-biotite and biotite granites on the basis of the petrography (mineralogical and modal compositions) of drill cores drilled from the ground surface[15]. These three litho-facies are systematically changed from biotite granite in the core of the rock mass through hornblende-biotite granite to muscovite-biotite granite in the rim[15].

A petrographic study of the MIZ-1 core revealed that hornblende-biotite and biotite granites are distributed above and below the G.L. −500 m point at the MIU site, respectively[15]. Hornblende is generally fine-grained and rarely contained in hornblende-biotite granite.

The granite observed in the shaft and galleries is generally equigranular and medium to coarse-grained with a long axis of 5 to 7 mm in each mineral, and is occasionally fine to medium-grained with long axis of 1 to 5 mm[9),16]. Pegmatite and aplite dykes are locally distributed in the granite and basic lamprophyre is distributed along the main-shaft fault[9),16]. Since these intrusions show limited distribution, we concluded that the rock mass was homogeneous as a whole.

In terms of fractures, a difference in the frequency of fractures was confirmed as mentioned in (1). The frequency of fractures is considered to be related to the cooling speed[17),18),19),20]. Based on statistical analysis and the response surface of the spatial relationship between regional geological structures and the fracture density, the fracture density may be interpolated in the uninvestigated area[21]. Spatial modeling of the regional geology and fracture density could be applied to understand the fracture density with each strike direction[22].

Some faults were confirmed by detailed surface geological investigations and were estimated by reflection seismic surveys[3] during Phase I[5]. Most of the faults around the URL site were not described in previous publications. The fault strikes indicate NS to NW-SE and EW to WNW-ESE with small displacements. Since some of the faults cannot be associated with the faults confirmed at the surface, such faults are not appeared at the surface, or are not presently active[3].

In Phase II (construction phase), we confirmed the locations and distributions of faults by geological observation of the walls in shafts and research galleries, borehole and geophysical investigations from research galleries. Based on the results of the Phase I and II investigations, we established a technical basis to understand the minor faults that were not described in previous publications (Fig. 2.1.3-3)[9),16]. In some cases, however, different faults were regarded as a single fault, and vice versa[6),9),16),23]. Estimations of the fault locations appear to contain a few tens of meters of error, because the position of some faults could not be confirmed by borehole investigations from galleries or reverse vertical seismic profiling surveys [24),25].

Strong alterations are pervasive around the main-shaft fault. The mode of occurrence of alterations in drill cores could be divided into white-colored clayey alterations in the entire core near the fault, and pale green to dark green-colored alterations along fractures [23),26].

The fault zone is generally fragile and thus core-loss often occurs. We developed a technology to estimate the location and characteristics of faults without core recovery by combining the data from geophysical loggings of the boreholes[27].

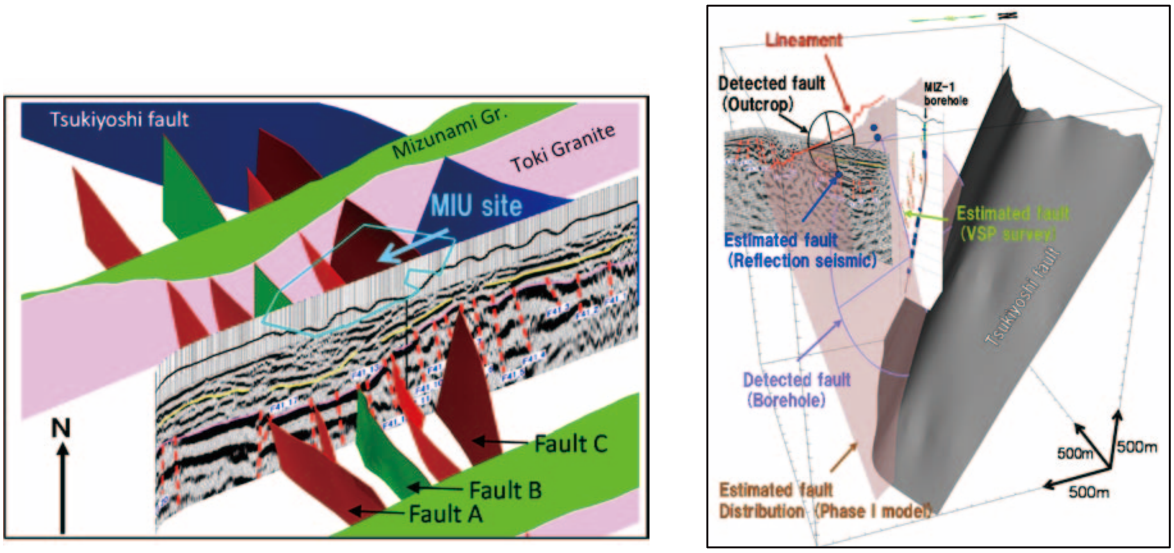

Fig. 2.1.3-3 Distribution of faults on the basis of geophysical investigation from ground surface (left), and the estimated distribution of Fault A (right)

2) Horonobe

The geological model established in Phase I contains the distributions of the target rock (Neogene Koetoi Formation: diatomaceous mudstone, and Wakkanai Formation: siliceous mudstone), Omagari Fault and minor faults (Fig. 2.1.3-4)[4].

The boundary between the Koetoi and Wakkanai Formations was determined by the occurrence of a silica mineral phase, as mentioned (1). In the Phase II investigation, we confirmed that the methodology applied in Phase I is adequate to distinguish between the two formations, and the physical properties obtained in the Phase II investigation such as porosity and hardness are concordant with those obtained in the Phase I investigation[12].

The apertures and interconnections of faults and fractures in the Koetoi Formation are less prevalent than those in the Wakkanai Formation[28]. The faults and fractures in the Wakkanai Formation are characterized by those crossing bedding planes at a high angle, and those that are parallel to bedding planes[29]. In the Wakkanai Formation, the faults mainly grew by linking with adjacent faults via numerous splay cracks, formed by tensile failures above roughly 400 m depth at the URL site[30]. In the Phase II investigation, geological observations of the shaft walls and floor revealed that the lengths of faults and fractures in the Koetoi Formation are generally less than a few meters and a few tens of centimeters, respectively (Fig. 2.1.3-5)[31),32].

Geological observations of the shaft walls and floor in the Wakkanai Formation revealed the development of a tensile failure crossing a bedding plane at a high angle (Fig. 2.1.3-6)[33]. Nineteen faults were confirmed in the Wakkanai Formation by borehole investigations from the ground surface. Six faults were estimated to be present at the G.L. −350 m gallery. Geological observations at this gallery indicated that the distribution of faults was concordant with results of the Phase I investigation[34]. As a result of the above mentioned points, the distribution and characteristics of faults and fractures could be estimated by surface based investigations.

As a result of the Phase I and II investigations, we confirmed the distribution and frequency of unknown faults in previous publications by a combination of surface geological, geophysical and borehole investigations, and classified target rocks in terms of the distribution of the fault and fracture density. Faults in granite that were difficult to confirm without borehole investigations could be estimated by reverse vertical seismic profiling surveys[35),36]. We developed a technology to estimate the location of minor faults by a combination of data from the geophysical loggings of boreholes. We also examined a method to show the change of understanding of the geological environment and the uncertainty in the geological model[37),38),39].

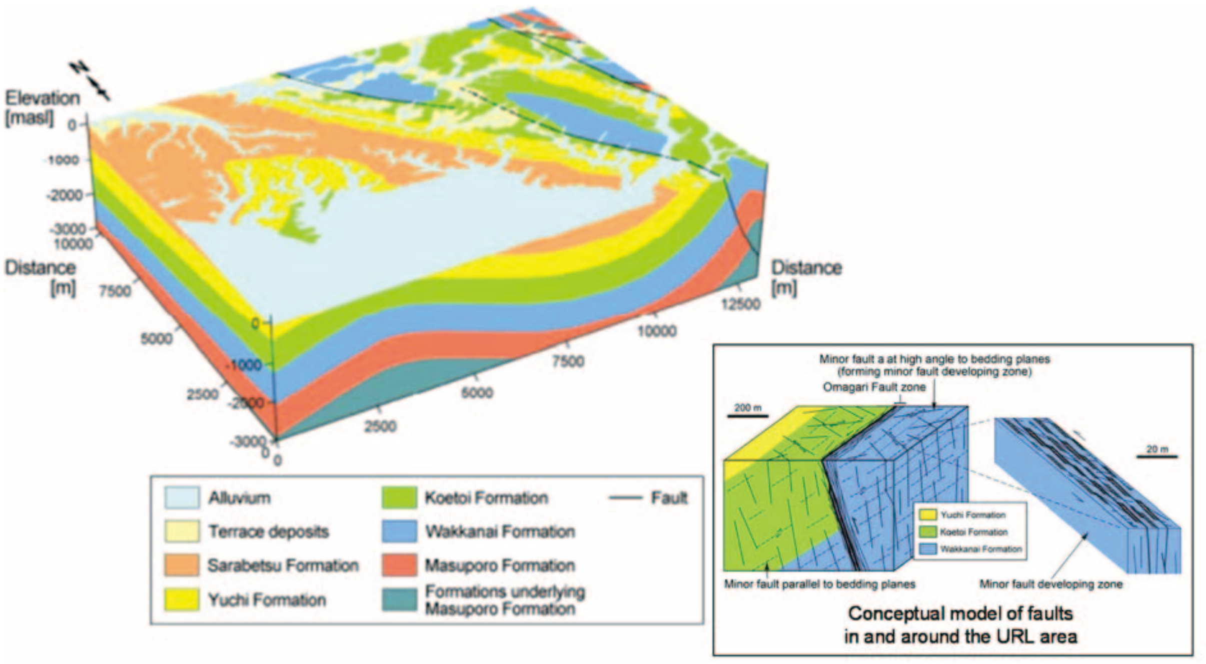

Fig. 2.1.3-4 Geological model of the Horonobe area prepared on the basis of the Phase I investigation results

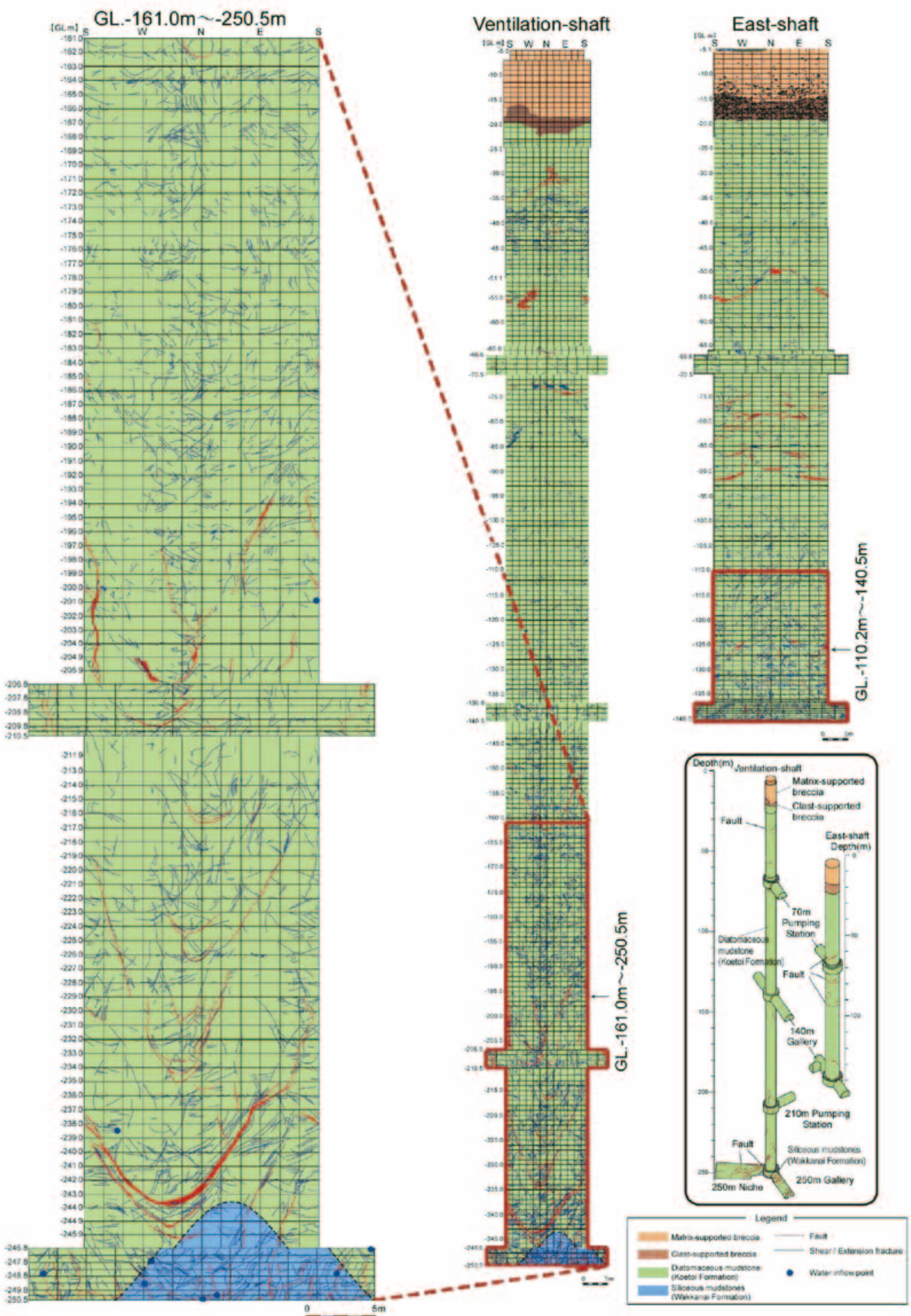

Fig. 2.1.3-5 Geological map of the ventilation and east shafts of the Horonobe URL

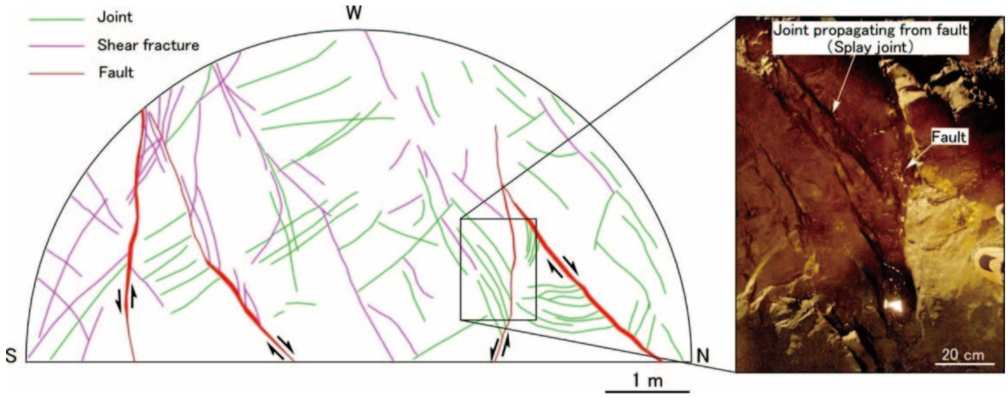

Fig. 2.1.3-6 Shear fractures related to faults in the upper Wakkanai Formation (G.L. −250 m in the ventilation shaft)

(3) Understanding of the important structures acting as paths for mass transport

Primary structures such as pores in grains, bedding planes, unconformities and schistose, and secondary structure such as fractures and faults are listed as the important structures that act as paths for mass transport[40]. We prepared a technical basis to understand these important structures through the investigation of discontinuities such as pores, fractures and faults by geological, borehole and geophysical investigations.

1) Mizunami

In the Mizunami URL, faults and flow-path fractures are the important structures that act as paths for mass transport. As mentioned in (2), we understood the distribution of the faults and extracted future issues to improve the accuracy of estimation.

We confirmed the flow-path fractures by geological observation of the gallery walls[8),9),16),41)]. We also discussed a technique to detect flow-path fractures on the basis of the mineral composition and mode of occurrence of fracture fillings[42)].

At the time of large inflow during the drilling of a pilot borehole at the G.L. −300 m Access/Research Gallery, a positive self-potential was observed at the northeastern side of the main-shaft fault (Fig. 2.1.3-7)[43)]. This result suggested the groundwater had flowed to the inflow point, and thus self-potential monitoring during shaft/gallery excavation could be used as a tool to estimate the distribution of structures influencing groundwater flow.

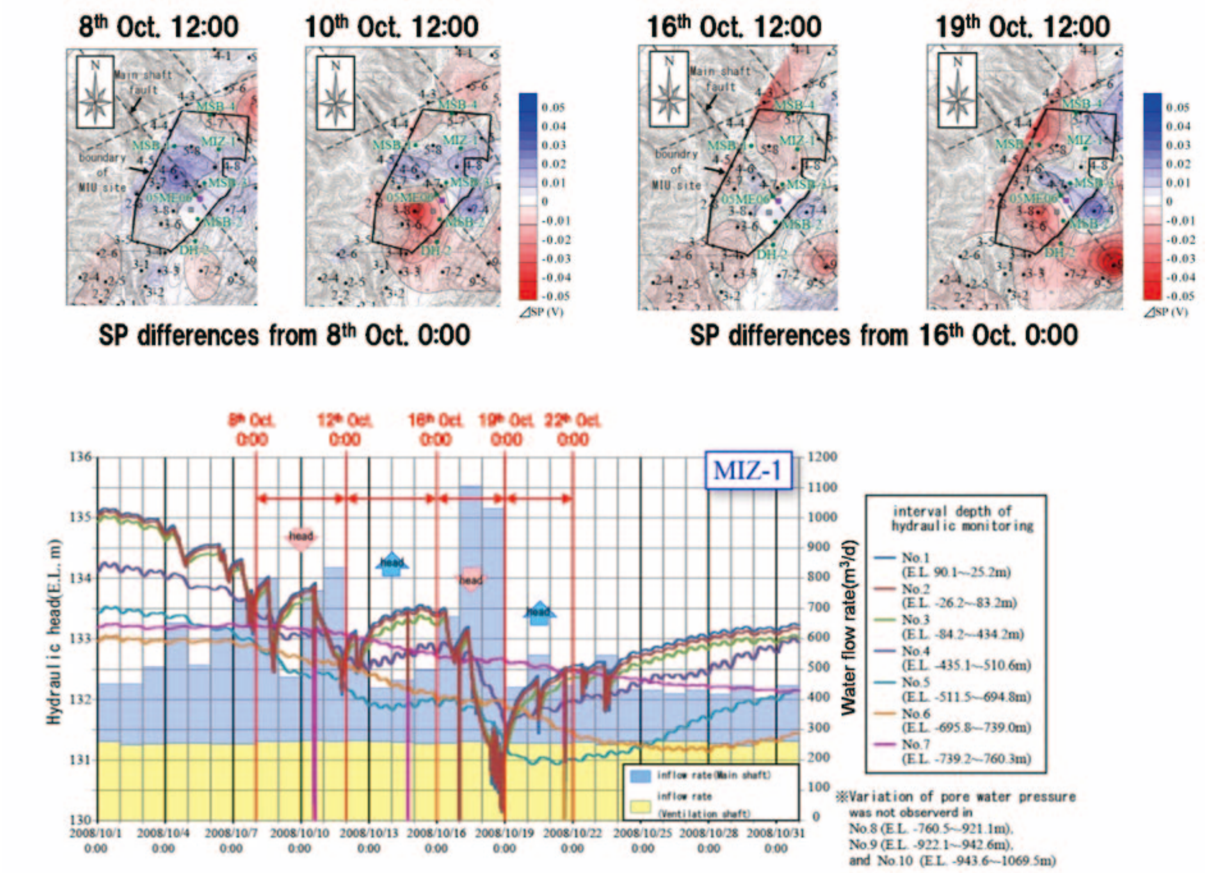

Fig. 2.1.3-7 Change in self-potential (upper) and hydraulic head in the MIZ-1 borehole with an inflow rate into the shafts (lower)

A positive self-potential was observed in the northeastern part of the main-shaft fault, suggesting the occurrence of groundwater flow to the inflow point.

2) Horonobe

In the Horonobe URL, discontinued structures such as faults and fractures are listed as the important structures acting as paths for mass transport[4)]. As a result of the Phase I investigation, a major fault (Omagari Fault) could be confirmed by a combination of surface geological and geophysical surveys (seismic reflection and AMT surveys) and borehole investigations (Fig. 2.1.3-8 and Fig. 2.1.3-9)[4),44)]. Minor faults and fractures are also listed, and their distribution and characteristics were estimated as mentioned in (2). In terms of permeability, the faults and fractures in the Koetoi Formation do not appear to act as major flow paths[28)], while some faults and fractures that cross a bedding plane at a high angle in the Wakkanai Formation act as a major flow path[29)]. In the Wakkanai Formation, the fault crossing a bedding plane at a high angle and tensile splay fault both possess high permeability[30)].

In the Phase II investigation, geological observations of gallery walls and floor revealed that most of the faults and fractures in the Koetoi Formation were not accompanied by water inflow (Fig. 2.1.3-5)[31),32)]. In the Wakkanai Formation, the fault crossing a bedding plane at a high angle and the accompanying fractures acted as major flow paths[33]. An increase in water inflow has been observed at the crossing point of faults crossing a bedding plane at a high angle and parallel to the bedding plane. Therefore, we performed the geological investigation at the surface exposure in a similar geological setting. As a result, we found evidence of past water flow in a fracture zone around the fault parallel to a bedding plane near the crossing point with a fault crossing the bedding plane at a high angle[34].

The differences in the density and permeability of faults and fractures in the Koetoi and Wakkanai Formations are estimated to result from differences in brittleness (Fig. 2.1.3-10)[45),46),47]. Based on this estimation, the target rock was divided in terms of permeability (Fig. 2.1.3-11)[48]. According to the estimation, the Wakkanai Formation below G.L. −500 m would have low permeability without developments of tensile faults (Fig. 2.1.3-11).

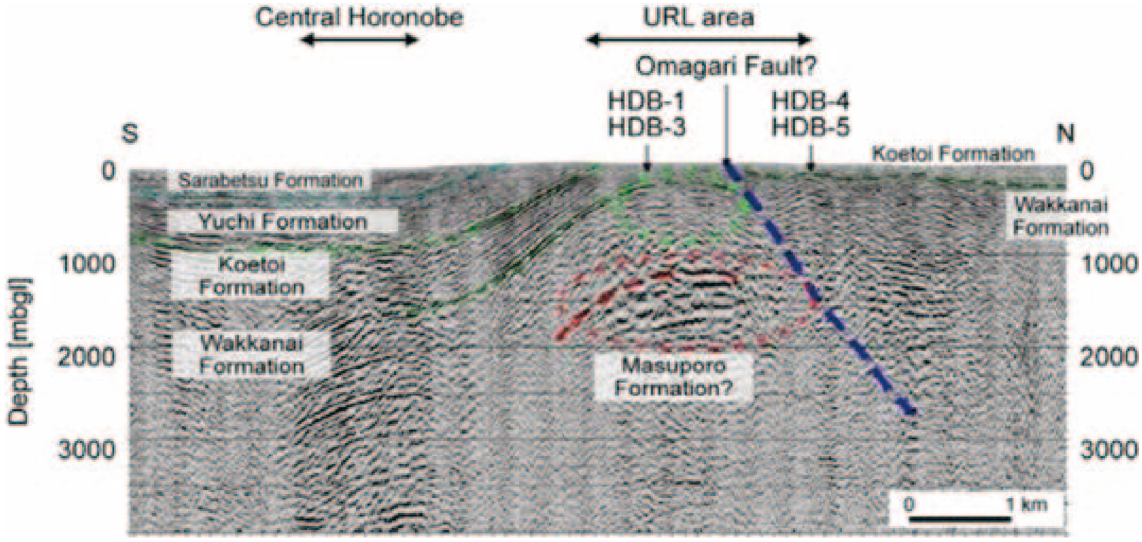

Fig. 2.1.3-8 Interpretation around the Omagari Fault by seismic reflection survey and borehole investigations

HDB-1,3,4 and 5 shows the location of boreholes projected to the survey line.

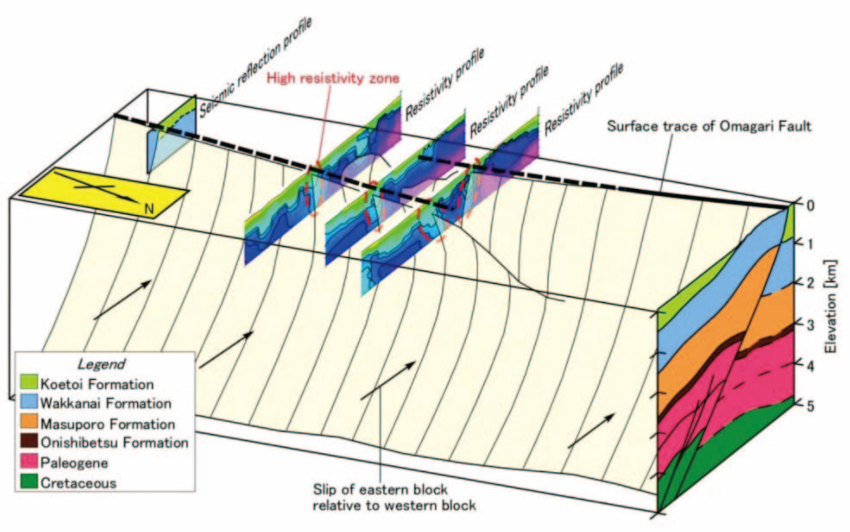

Fig. 2.1.3-9 Interpretation of the geological structure by AMT survey and borehole investigations

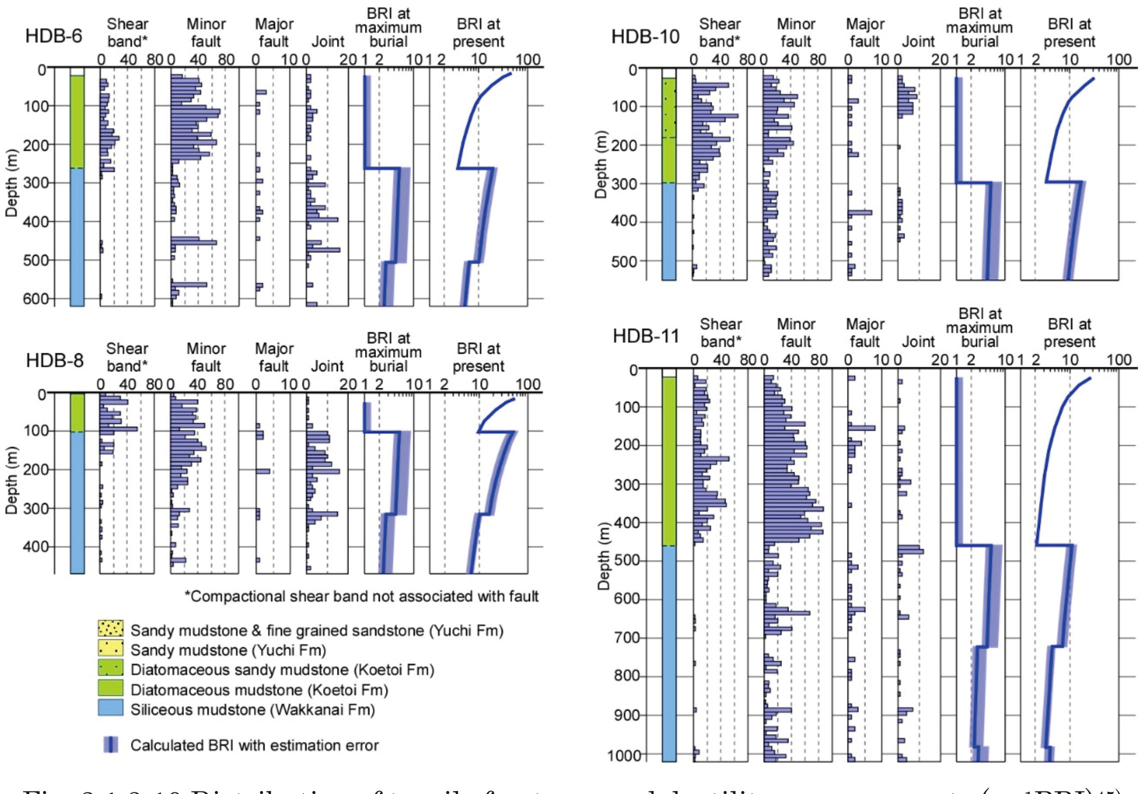

Fig. 2.1.3-10 Distribution of tensile fractures and ductility measurements ($\propto^{-1}$BRI)[45]

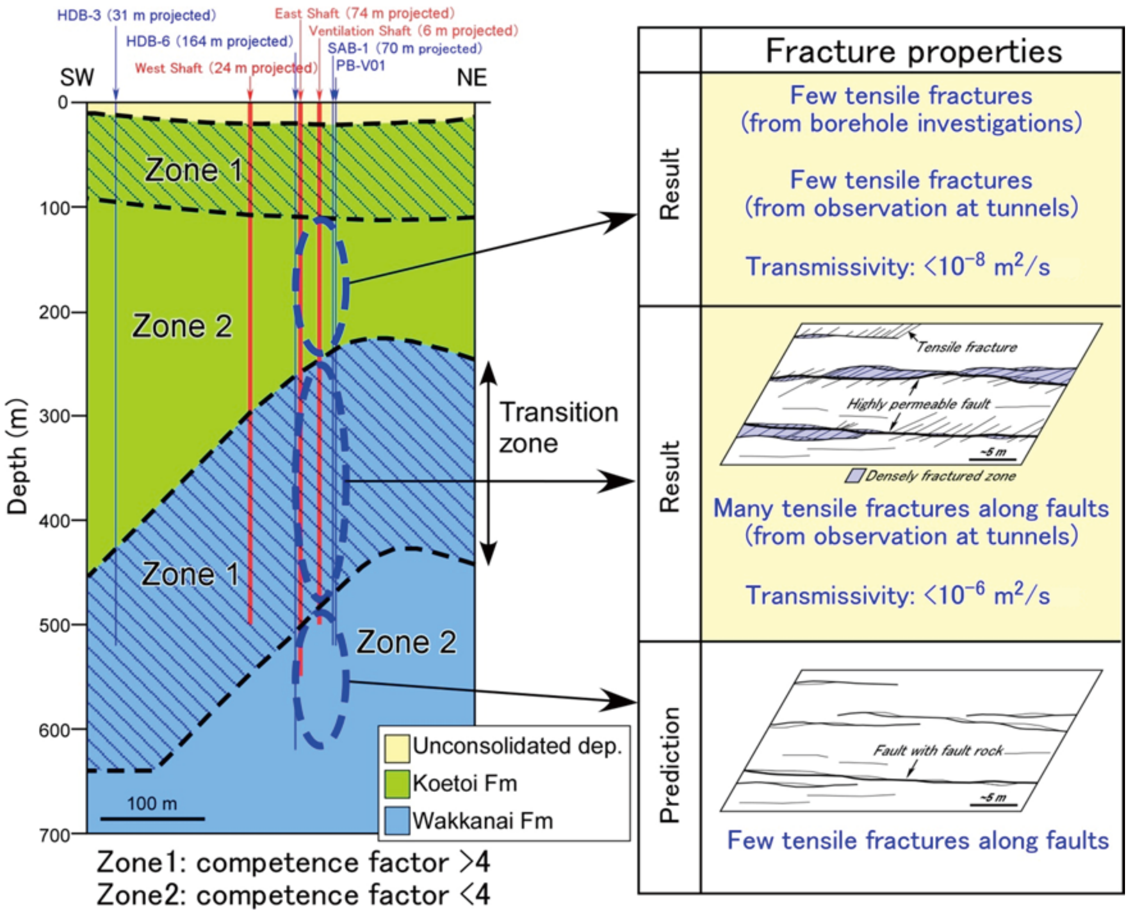

Fig. 2.1.3-11 Rock domain classified by the competence factor, and geological and hydraulic properties of fractures in each domain

2.1.4 Summary

The techniques and accumulated technical knowledge regarding the investigation, analysis, and assessment for understanding the three-dimensional distribution of geological structures in the Mizunami and/or Horonobe URLs are stated as follows:

(1) Understanding the distribution and shape of the targeted rock mass

- A technique to understand the distribution and shape of the target and surrounding rock was established by a combination of surface geological, geophysical, and borehole investigations (both URLs).
- A technique to construct the geological model was established by an arrangement of results obtained by each investigation using a "top-down" approach (both URLs).

(2) Understanding geological inhomogeneities of the rock mass

- A technique to classify the target rock on the basis of the distribution of the fault and fracture density was established by a combination of surface geological, geophysical, and borehole investigations (both URLs).

- A technique to estimate the distribution and strike of unknown faults was established by a combination of surface geological and borehole investigations (both URLs).
- A technique to understand minor faults in the deep underground was established by using a multi-dataset obtained by borehole investigations (both URLs).
- A technique to show the change in understanding of the geological environment and uncertainty in the geological model with an advance of the investigation phase was established (both URLs).

(3) Understanding the important structures that act as paths for mass transport

- A technique to model the rock domain with different permeabilities was established on the basis of the frequency of fractures (Mizunami URL; crystalline rock) and competence factor (Horonobe URL; sedimentary rock).
- A technique to obtain information about the hydrogeological conceptual model, such as the distributions of faults and fractures and permeability, was demonstrated in a case where the target rock had visible outcrops at the surface (both URLs).
- A technique to confirm the presence of faults in granite, which was difficult to confirm without borehole investigations, was demonstrated by a reverse vertical seismic profiling survey. This technique should be applicable to rocks without a large change in elastic wave velocity (Mizunami URL).
- An applicability of technique for wall rock observations was confirmed by an understanding of the detailed distribution and characteristics of faults and fractures by observation of the shafts and gallery (both URLs).
- A technique to confirm the distribution of geological structures influencing groundwater flow was demonstrated by self-potential monitoring during shaft/gallery excavation. This technique should allow for the detection of highly permeable structures such as fracture zones in granites and conglomerates (Mizunami URL).

As mentioned above, the techniques and procedures for understanding the distribution of the target rock and important structures acting as paths for mass transport have been prepared to date.

In further studies, an accumulation of knowledge on the heterogeneous distribution of fractures and their formative processes is needed through further studies on A2 and A3, as described in the following chapters. This knowledge will feed- back to the technique for surface-based investigation.

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2.2 Hydrogeology

2.2.1 Introduction

The objective of the study is to establish the following techniques:

- Comprehensive techniques of investigation, analysis, and assessment for characterization of groundwater flow conditions
- Techniques of investigation and analysis for prediction of the volume of inflow into underground facilities

From these hydrogeological points of view, the focused features and processes to be characterized and the resulting data requirements relevant to safety assessment, design, and construction were identified[1].

(1) Groundwater flow field

In order to estimate deep groundwater flow conditions on a scale of several kilometers using groundwater flow analysis, it is important to understand the following:

- The area containing a deep groundwater flow system within the recharge area to the discharge area
- State of groundwater flow conditions, such as advection or diffusion
- Type of driving force of the deep groundwater flow (potential flow, density flow, or thermal flow)

The major factors influencing groundwater flow are the topography and geological conditions.

(2) Spatial variability of groundwater flux

The three-dimensional spatial variability of groundwater flux is to be determined by spatial variability of hydraulic properties and hydraulic gradient. As the hydraulic properties show heterogeneity caused by faults, joints, and geological layers, it is important to estimate the 3D spatial variability of the hydraulic properties.

(3) Spatial variability of water fluxes in higher-permeability rocks and aquifers

Knowledge of the spatial variability of water fluxes in higher-permeability rocks and aquifers is important to understand dilution effects. The concentrations of solutes in the groundwater are diluted because of changes in the groundwater flux along groundwater flow paths from low-permeability rock zones to high-permeability zones or highly permeable structures. Therefore, thick aquifers with high hydraulic conductivities that extend over a large area and are associated with highly fractured zones were considered to be important for diluting solutes.

(4) Volume of inflow into underground facilities

Prediction of the volume of inflow into underground facilities from the viewpoints of design and construction of underground facilities is important. In particular, planning of grouting based on the prediction is necessary if a large volume of the inflow interferes with construction.

2.2.2 Objectives in the second mid-term research phase

The following studies have been carried out to reach the performance target of R&D for perceiving hydrological baseline conditions (Table 2.2.2-1):

- Monitoring of groundwater pressure and inflow volumes during construction of underground facilities

- Hydraulic tests using boreholes drilled at underground facilities
- Testing the prediction results of the surface-based investigation phase
- Examining the investigation and analytical techniques for prediction of the volume of inflow into underground facilities

Table 2.2.2-1 Performance target of R&D for perceiving hydrological baseline conditions

Focus	Performance target of R&D	Tasks
Siting decision	Enable to select a area with low groundwater flux and long flow path.	• Comprehensive techniques of investigation, analysis and assessment for characterization of groundwater flow condition • Method for groundwater flow modeling based on geo-synthesized information
Construction decision	Enable to judge appropriateness of construction and operation of underground facility taking into account groundwater flow.	• Techniques of investigation and analysis for prediction of volume of inflow into underground facilities

2.2.3 Project details and outcomes

(1) Groundwater flow field

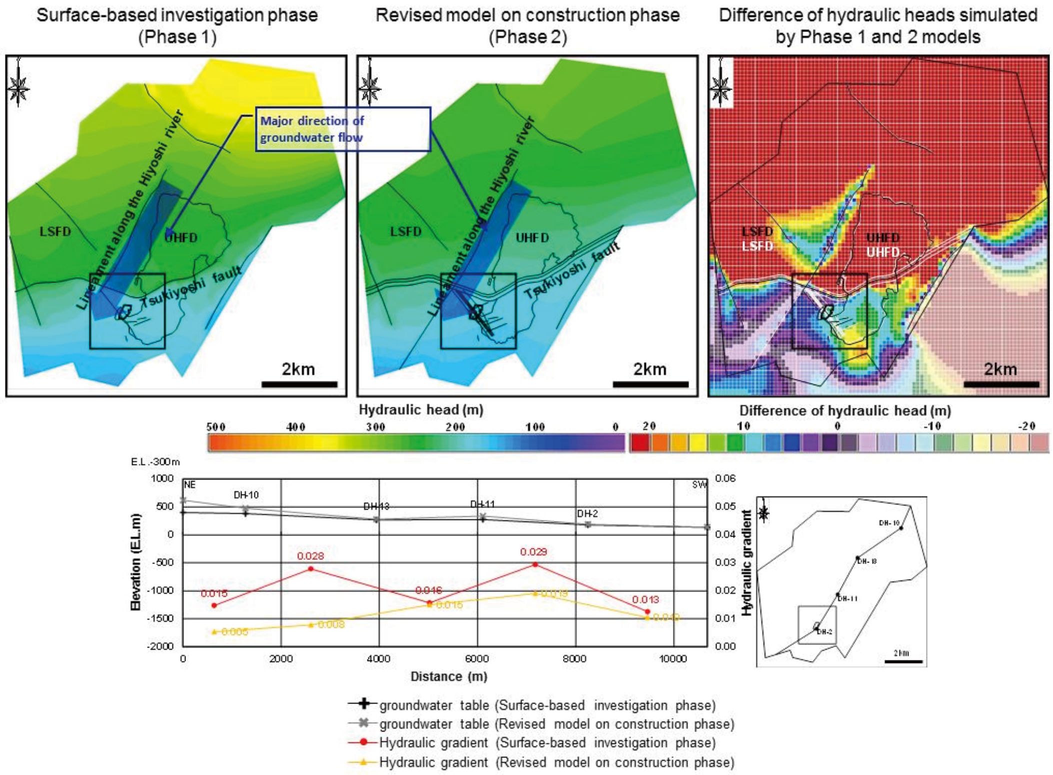
The hydrogeological model and boundary conditions for the groundwater flow analyses at the area from recharge area to the discharge area, which were constructed during the surface-based investigation phase (Phase I), have been modified and a groundwater flow analysis has been carried out. The results of the analysis will be used for assignment of boundary conditions for the groundwater flow analysis in the region measuring several km^2.

1) Mizunami

Low hydraulic heads, which are similar to river water levels, were observed at the MIU site[2)]. The river is located 1.5 km from the MIU site and the altitude is 50 m lower than that of the MIU site. Groundwater flow analyses at Phase I could not express the hydraulic head distribution. Therefore, improvement of hydrogeological model and analytical conditions taking into account the following uncertain points have been carried out in order to match the observed and analyzed hydraulic heads.

- Trace length and hydraulic parameters of large-sized discontinuities
- Trace length and hydraulic parameters of hydrogeological elements continuing from the MIU site to the river
- Side boundary conditions in the river part

The hydrogeological model of Phase I has been tested by comparison between the results of groundwater flow analyses obtained using the Phase I model and the improved Phase II model (Fig. 2.2.3-1). In detail, the analyzed distributions of the hydraulic head and hydraulic gradient were used for the comparison. Significant differences could not be recognized. This result indicates the reasonableness of the Phase I hydrogeological model.



Above: Hydraulic head distribution (Horizontal cross section on E.L. -300m), Below: Hydraulic gradient distribution (E.L. -300m)

Fig. 2.2.3-1 Stepwise evolution of the results of groundwater flow analyses (MIU)

2) Horonobe

Although the measured and analyzed hydraulic head distribution on the downstream side (west side) of the Omagari Fault was consistent, significant differences in the hydraulic head distribution were recognized at upper stream side (east side) of the fault[3]. Improvement of the hydrogeological model and analytical conditions taking into account the following uncertain points has been carried out to reduce the difference.

- Geometry and hydraulic parameters of the Omagari Fault
- Continuity of the Omagari Fault
- Recharge rate

As in the Mizunami case, the hydrogeological model of Phase I was tested by comparing the results of groundwater flow analyses obtained using the Phase I model and the improved Phase II model (Fig. 2.2.3-2). As significant differences could not be detected, the Phase I model was concluded to be reasonable.

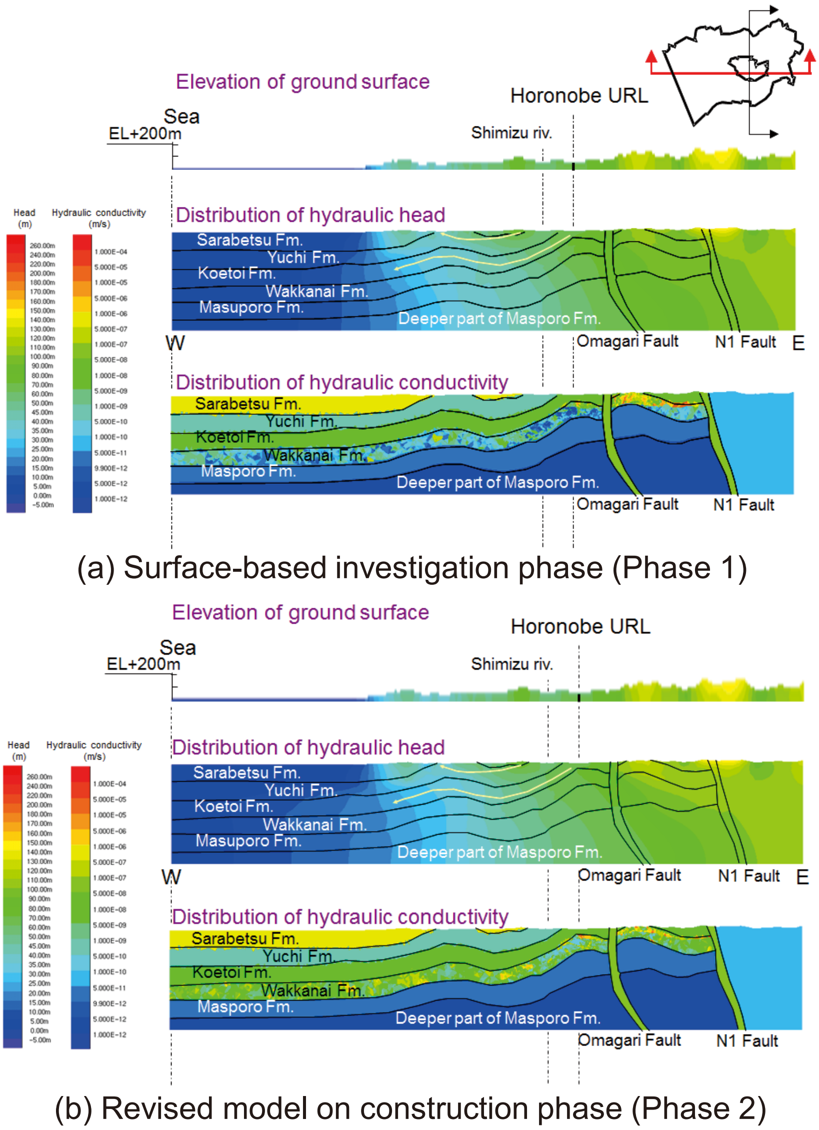


Fig. 2.2.3-2 Stepwise evolution of the results of groundwater flow analyses (Horonobe)

(2) Spatial variability of groundwater flux

The groundwater inflow rate into underground facilities and groundwater pressure responses during excavation and operation of the underground facilities have been monitored[4),5),6)]. Groundwater pressure monitoring was carried out using two types of multi-packer system, one that measures the groundwater pressure directly in the measurement interval and one that measures the groundwater level in a piezometer tube over a certain interval. The total inflow rate and depth profile of inflow rate were also monitored. In addition, tilt monitoring[7),8),9),10)] was conducted to complement the groundwater pressure monitoring. In advance of installation of the monitoring system, single-hole hydraulic tests were performed for hydrogeological characterization of the pilot borehole investigations[11)]. In addition, continuous surface hydrological investigations and meteorological observations were carried out to obtain the boundary conditions of groundwater flow analysis and to assess the changes in groundwater level resulting construction of underground facilities.

The hydrogeological models in the region measuring several km^2 were calibrated using the monitoring results. The hydrogeological model of Phase I has been tested by comparison of the results of groundwater flow analyses obtained using the Phase I model and the improved Phase II model. In particular, the analyzed hydraulic gradient, groundwater flux, and groundwater flow path were used in the comparison.

1) Mizunami

In addition to the investigations described above, a long-term pumping test was carried out using the boreholes drilled from underground facilities at the Mizunami site[12)].

The main achievements and technical findings from the investigations can be summarized as follows:

- The inflow rate increased during construction of facilities in the area of highly permeable structures (Fig. 2.2.3-3).
- The hydraulic responses differ for each hydraulic compartment that is formed with low-permeability structures (Fig. 2.2.3-4).
- The hydraulic conductivity of the lower sparsely fractured domain is one order of magnitude lower than that of the upper highly fractured domain.
- Fluid conductivity logging[13),14)], which can identify water-conducting features with transmissivity values higher than 10^{-9} to 10^{-8} m^2/s using boreholes drilled from the ground surface, is not applicable because of the larger inflow of water in the boreholes drilled from the underground facility.
- There is spatial variability in the recharge rate, which is affected by the location, the geological conditions of the ground surface, and the size of the catchment. The time variability of the recharge rate is also large because of fluctuations in the meteorological conditions[15)]. The results indicate that surface hydrological investigations in a catchment of similar size to that of the groundwater flow analysis is effective for obtaining accurate boundary conditions.

The main achievements and technical findings from the hydrogeological modeling and groundwater flow analysis can be summarized as follows:

- A hydrogeological conceptual model was constructed using the groundwater pressure responses[16)].
- The hydrogeological model was improved by taking into account the hydraulic heterogeneity caused by the water-conducting features in the fractured domain[17),18)] (Fig. 2.2.3-5).
- A procedure for improvement of the hydrogeological model during Phase II was developed (Fig. 2.2.3-6).
- The hydrogeological model has been improved using data on inflow rate and hydraulic responses during construction of underground facilities and long-term cross-hole hydraulic tests (Fig. 2.2.3-7, Fig. 2.2.3-8).

- The hydrogeological model could be improved step-wise as site characterization proceeds (Fig. 2.2.3-9).
- During the model improvement, geochemical changes during the construction of underground facilities as well as groundwater pressure changes were simulated[19] (Fig. 2.2.3-10).
- The reasonableness of the Phase I model was confirmed by comparing the models before and after improvement (Fig. 2.2.3-11). Significant differences could not be recognized.

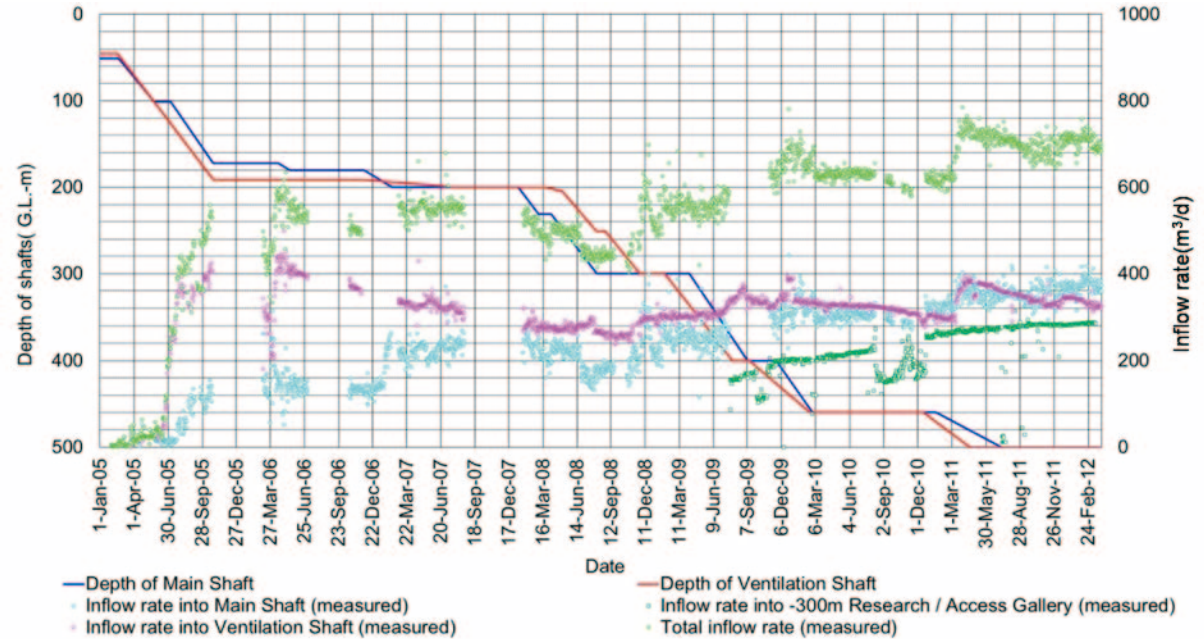


Fig. 2.2.3-3 Groundwater inflow rate into the underground facilities (MIU)

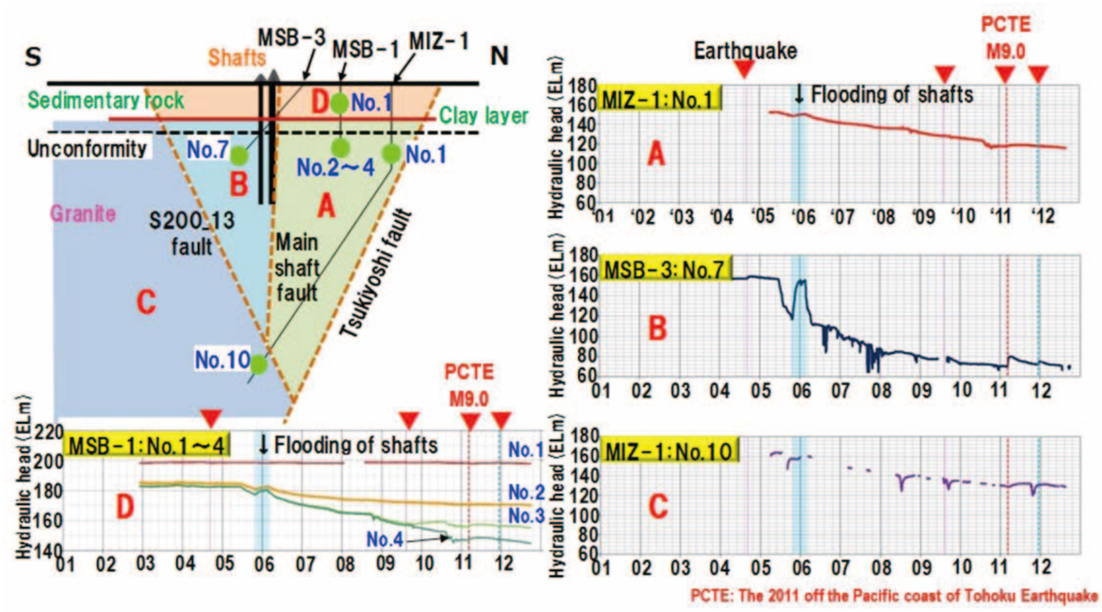


Fig. 2.2.3-4 Hydraulic responses caused by construction of underground facilities (MIU)

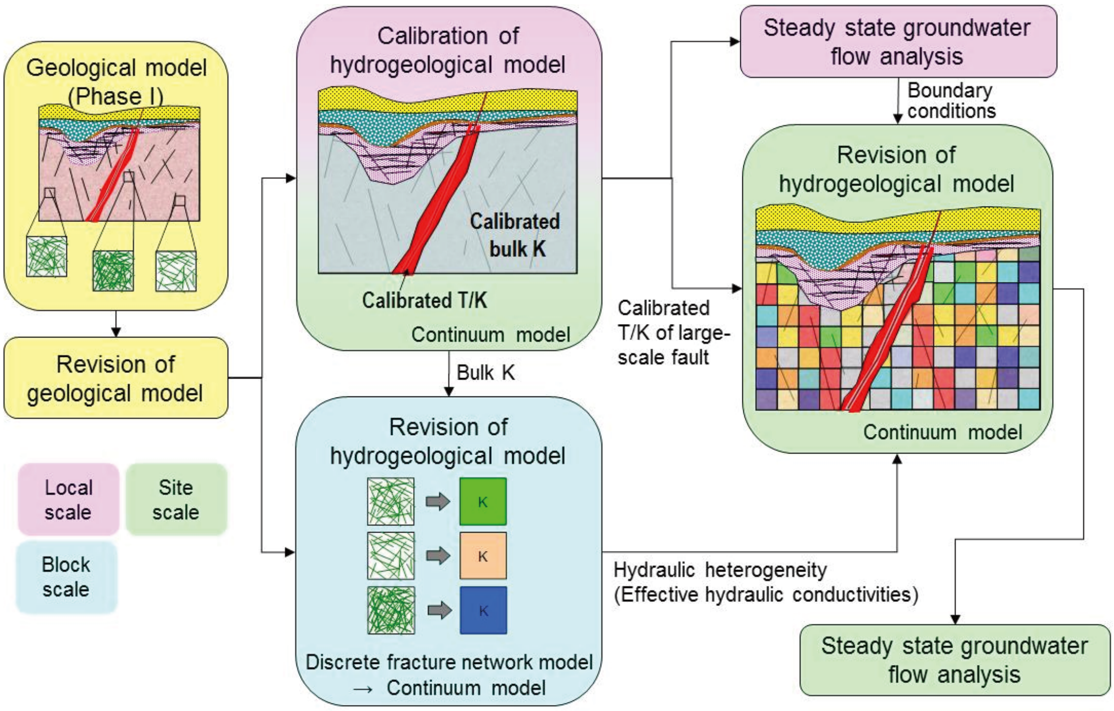


Fig. 2.2.3-5 Concept of hydrogeological modeling taking hydrogeological heterogeneity into account (MIU)

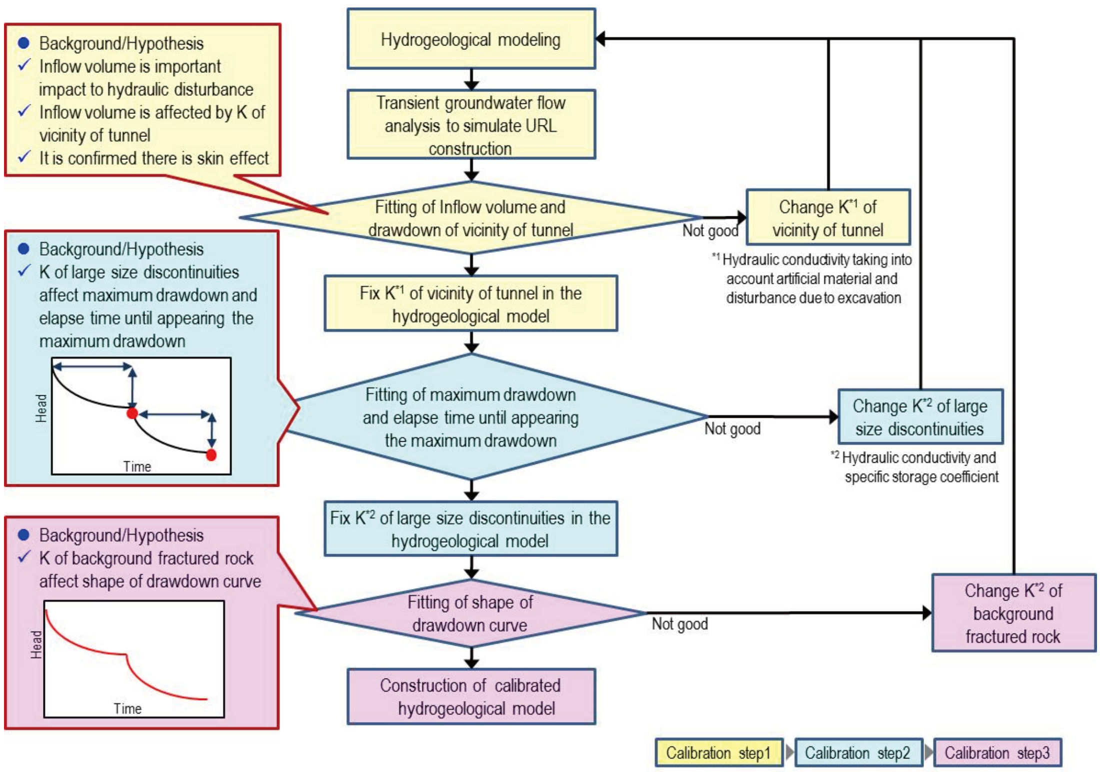


Fig. 2.2.3-6 Procedure for revising the hydrogeological model

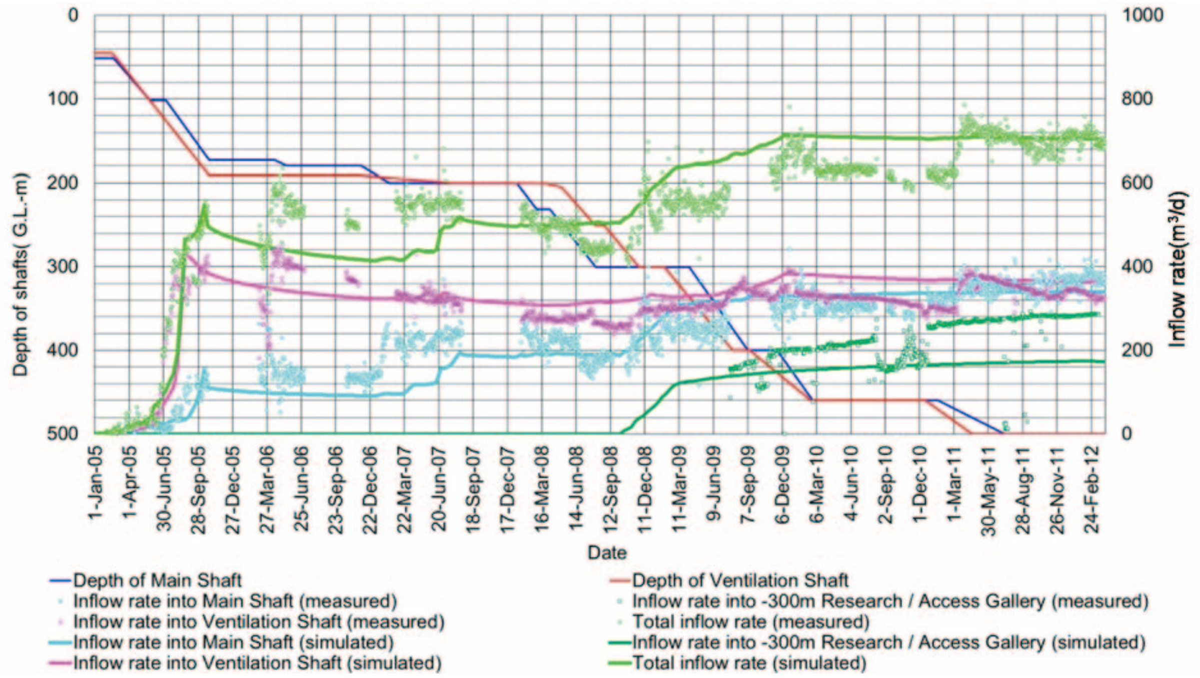


Fig. 2.2.3-7 Comparison of measured and modeled groundwater inflow rates (MIU)

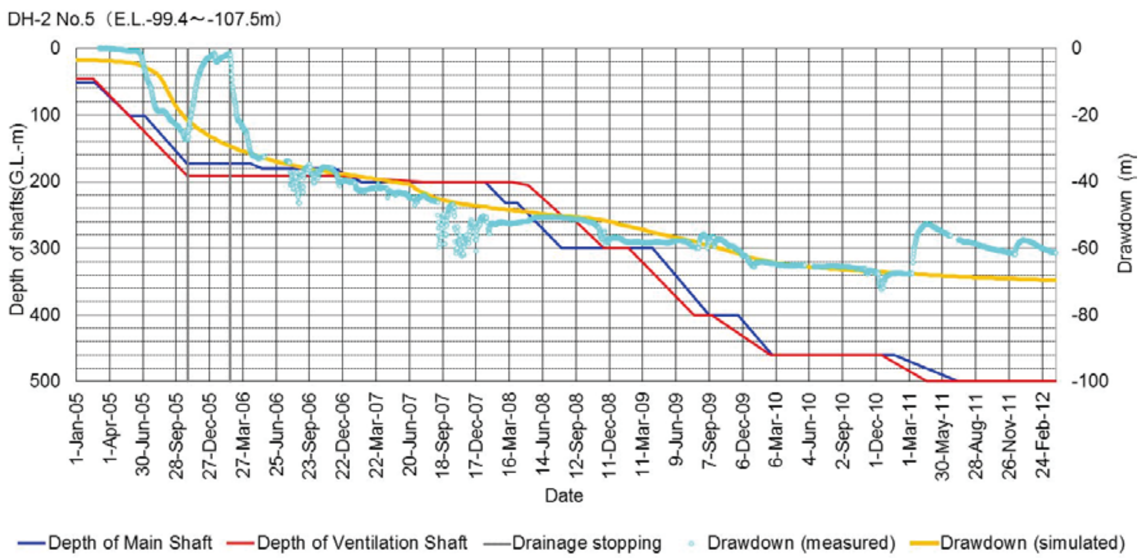


Fig. 2.2.3-8 Comparison of measured and modeled hydraulic responses (MIU)

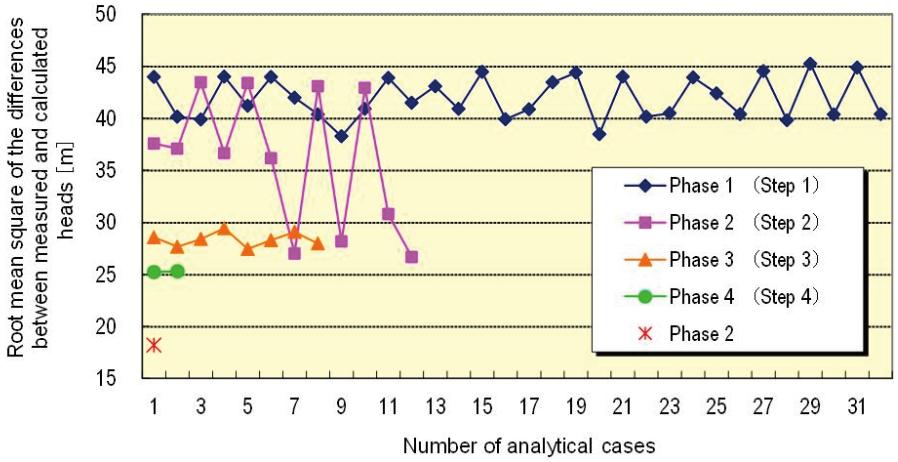


Fig. 2.2.3-9 Improvement in understanding of groundwater flow conditions with stepwise progress of the investigations

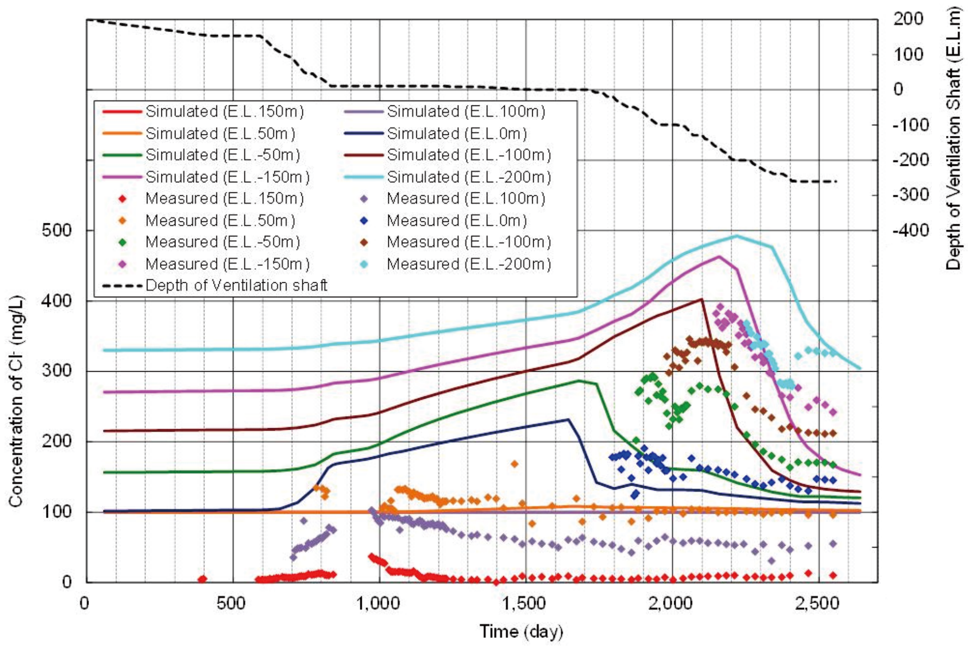


Fig. 2.2.3-10 Changes in Cl^- concentrations based on advection–dispersion analysis

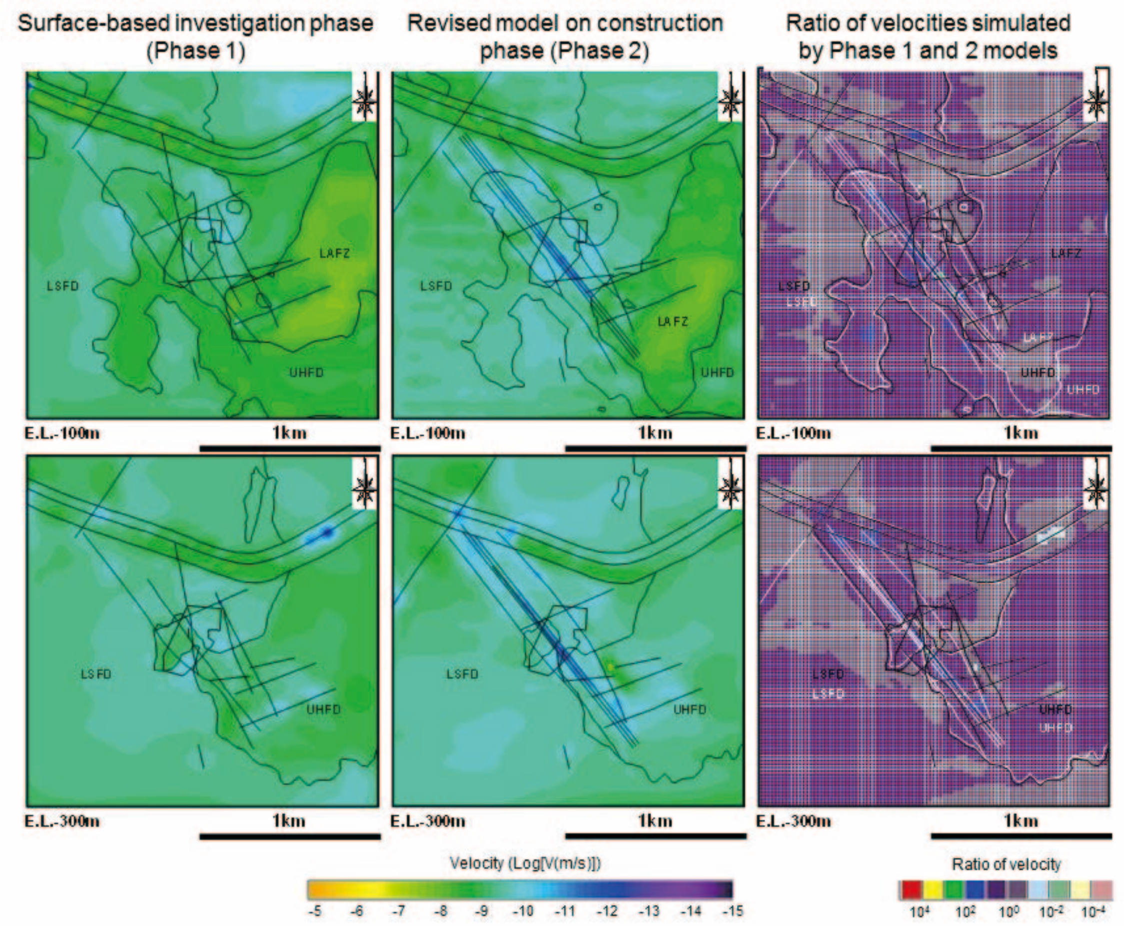


Fig. 2.2.3-11 Stepwise evolution of the results of groundwater flow analyses (MIU)

2) Horonobe

The main achievement and technical findings from the investigations are summarized as follows:

- The inflow rate increases during construction of facilities in the area with highly permeable structures (Fig. 2.2.3-12).
- Clear hydraulic responses were recognized in the zone of water-conducting fault with tensional fractures (Fig. 2.2.3-13).
- The network of splay fractures of fault in the upper part of the Wakkanai Formation forms a high-permeability zone[9].
- The recharge rate is affected by the geology and spatial distribution and the hydrogeology of the fractured zone rather than the topographic conditions and vegetation. The characteristics of recharge in snowy cold region are identified, which are: 1) 40%–50 % of the annual amount of precipitation is snowfall; and 2) the maximum recharge occurs during the snowmelt season[20),21)].

The main achievements and technical findings from the hydrogeological modeling and groundwater flow analysis are summarized as follows:

- A hydrogeological conceptual model was constructed using the groundwater pressure responses[10).
- The improved model could comprehensively simulate the changes of inflow rate into underground facilities and groundwater pressure responses (Fig. 2.2.3-14, Fig. 2.2.3-15).
- Based on the models, which underwent step-wise improvements as the site characterization proceeded, the relationship between accuracy of prediction results and number of boreholes could be clarified (Fig. 2.2.3-16).
- By comparing the models before and after improvement, it was confirmed that the hydrogeological model in the Wakkanai Formation is different (Fig. 2.2.3-17). In particular, the Wakkanai Formation has been divided into a shallow part with high-angle fractures and a lower part.

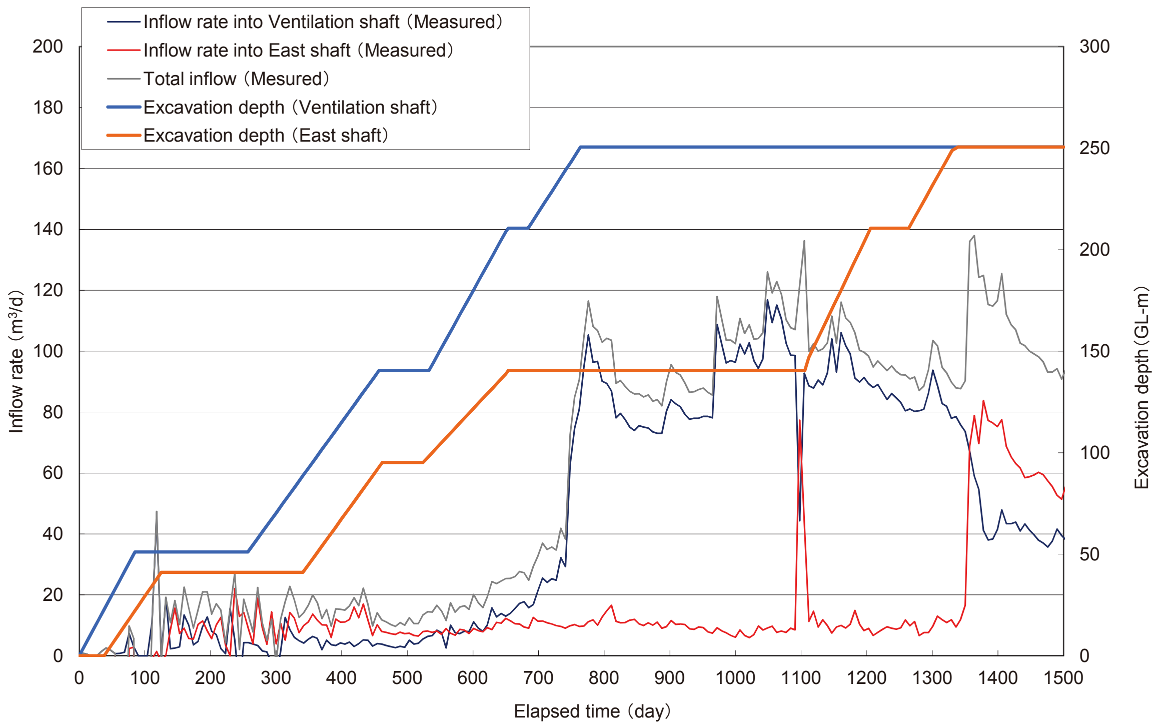


Fig. 2.2.3-12 Groundwater inflow rate into the underground facilities (Horonobe)

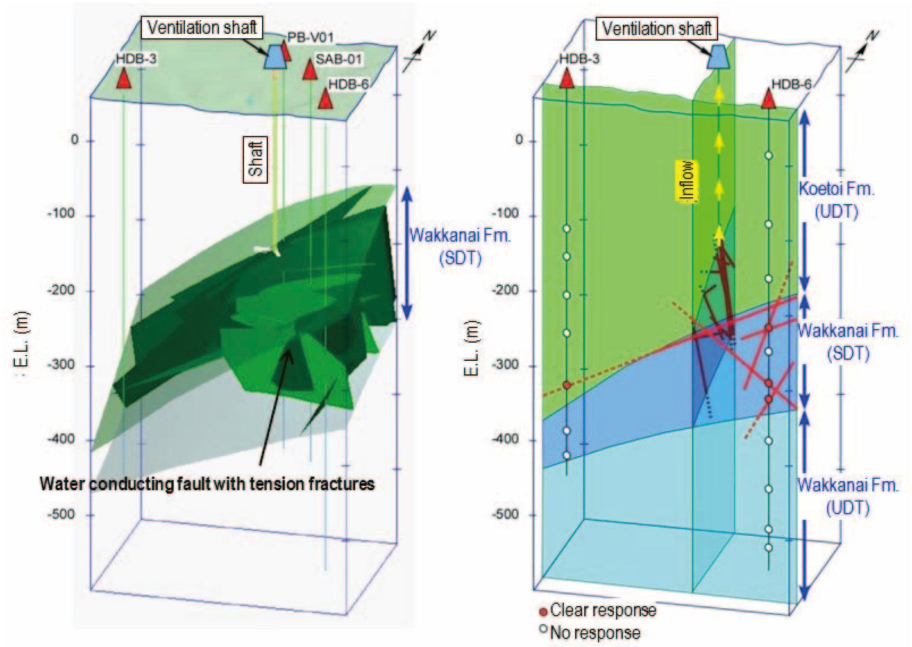


Fig. 2.2.3-13 Hydraulic responses because of inflow into the ventilation shaft and hydrogeological model (Horonobe)

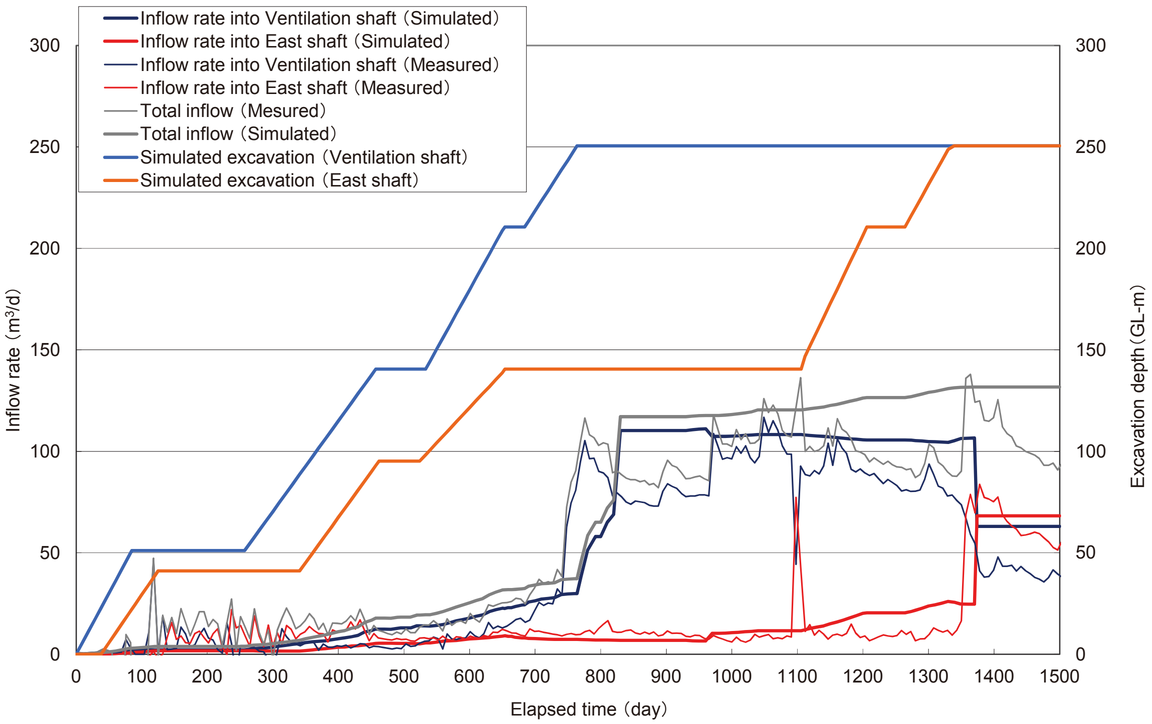


Fig. 2.2.3-14 Comparison of measured and modeled groundwater inflow rates (Horonobe)

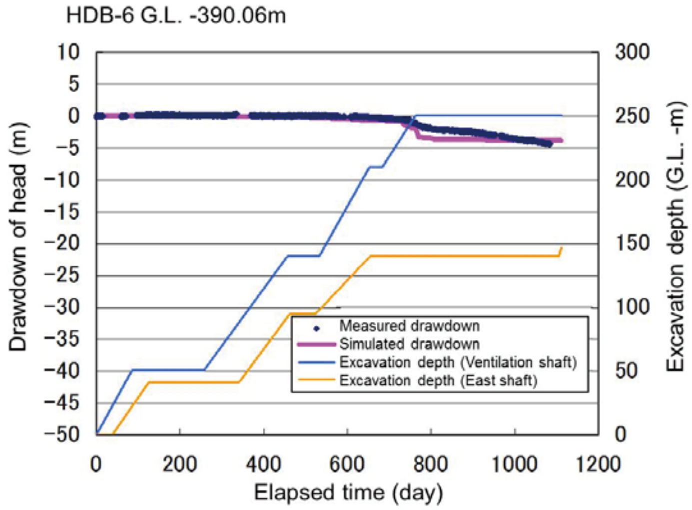


Fig. 2.2.3-15 Comparison of measured and modeled hydraulic responses (Horonobe)

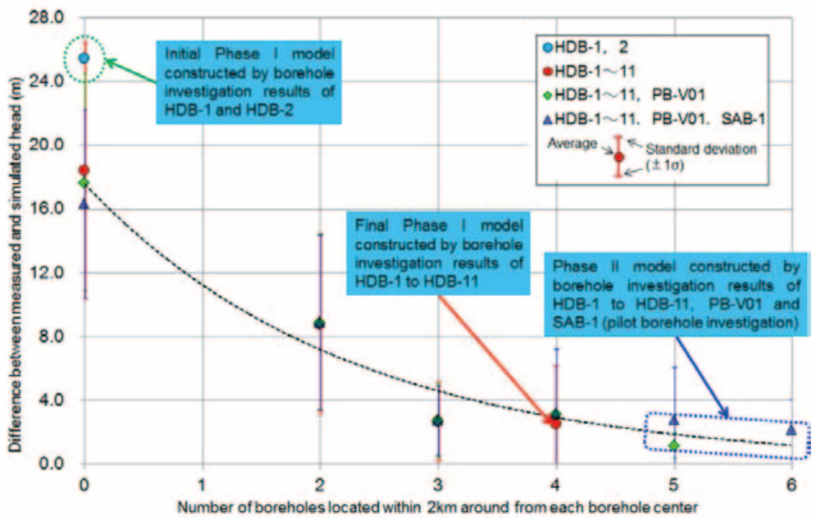


Fig. 2.2.3-16 Improvements in understanding of the groundwater flow conditions with stepwise progress of the investigations (Horonobe)[22]

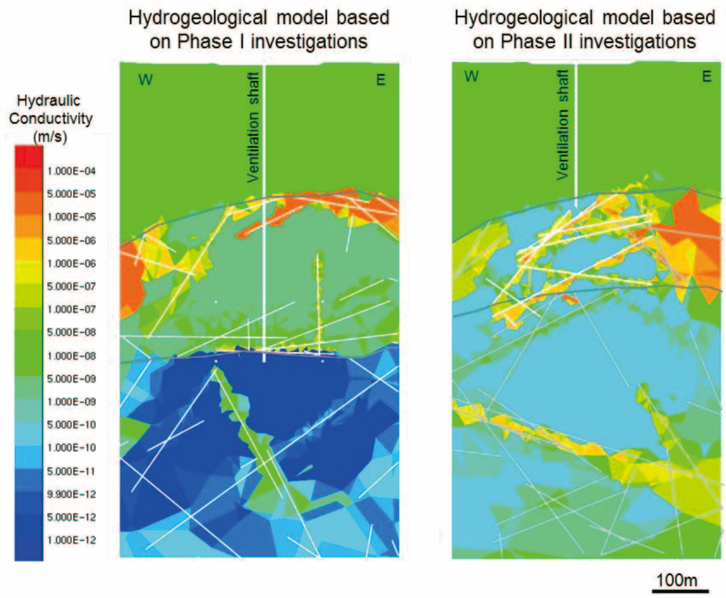


Fig. 2.2.3-17 Evolution of the hydrogeological model around the shafts (Horonobe)

(3) Spatial variability of water fluxes in higher-permeability rocks and aquifers

The dilution effect was estimated by comparing the distribution of the Darcy velocity in the hydrogeological units assumed to form the aquifer that extends over a large area in Phase I[23]. The Darcy velocity was also calculated using the improved hydrogeological model of Phase II. The reasonableness of the estimation result in Phase I has been confirmed by comparison with the Phase II result. Significant differences between the estimation results could not be recognized for both Mizunami and Horonobe.

(4) Volume of inflow into underground facilities

Groundwater flow analyses with the aim of predicting the inflow rate into the underground facilities were conducted using the hydrogeological model taking into account hydraulic heterogeneity[24]. Pilot borehole investigations were carried out to predict the inflow rate and to specify inflow points. Based on the investigation results, inflow reduction measures have been planned[24,25,26,27,28,29,30,31].

An overview of the prediction results using groundwater flow analyses are summarized as follows:

- The inflow volume rapidly increases in the zone crossed by a high-permeability fault.
- The highly permeable structures were found to affect the volume of the inflow significantly.
- The number and locations of the highly permeable structures intersecting the underground facilities will be influenced strongly by uncertainties in the geometry of those structures.

Overview of the pilot borehole investigation results are summarized as follows:

- Pilot borehole investigations could be used to specify inflow points.
- The geological and hydrogeological characteristics of the inflow points were described.
- The actual inflow volume could be reduced by grouting that was planned based on the pilot borehole investigations.

The probability of generation of water inflow has been estimated based on a stochastic discrete fracture network model. The relationship between the amount of information because of the progress of the investigations and the risk regarding cost variation for the countermeasures has been studied[32),33),34),35),36),37)] (Fig. 2.2.3-18, Fig. 2.2.3-19). The main achievements are summarized as follows:

- Pilot borehole investigations are effective for understanding the geological and hydrogeological characteristics.
- It is important to characterize the water-conducting features located around the underground facilities as well as in the vicinity of the facilities.
- For rational characterization of water-conducting features, an effective method is to conduct detailed borehole investigations following investigations on a wider area using techniques that yield 2D information to identify the open issues for which more detailed information is required.

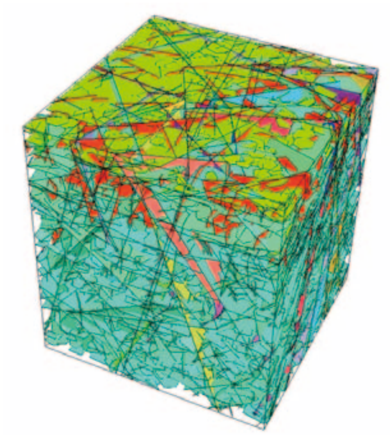


Fig. 2.2.3-18 Discrete fracture network model for estimation of the inflow rate into underground facilities

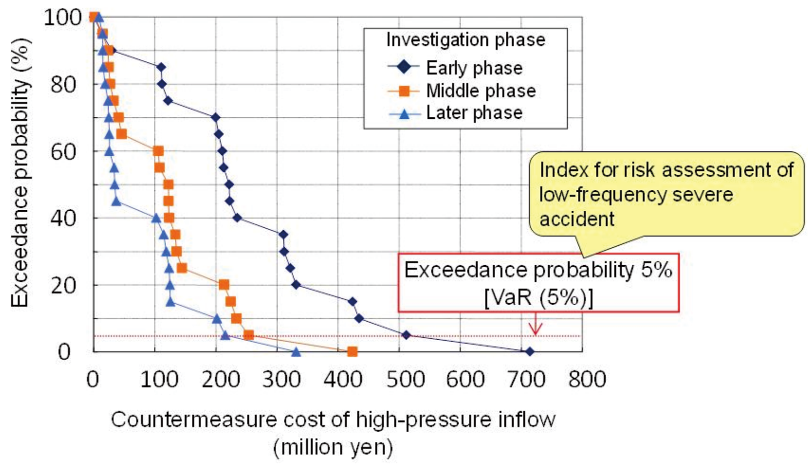


Fig. 2.2.3-19 Example of a risk curve showing the risk regarding cost variation for the countermeasures

(5) Tools developed and adopted

The system for geological and hydrogeological modeling and visualization has been developed to provide an efficient modeling platform that allows users to modify their models quickly in response to the acquisition of new data[38] (Fig. 2.2.3-20). This system has the advantages that the modeling and numerical analysis are integrated and both discontinuities and rock matrix zones can be considered simultaneously. Using the system, the 3D grid of groundwater flow analysis is constructed automatically, even for complex geological models. The automatic generation function of the discrete model is particularly effective in reducing the effort required for modeling complicated geological structures and conducting groundwater flow analyses based on the model, and also for developing a number of models (e.g., for sensitivity analysis). The visualization of the results obtained by the groundwater flow analysis allowed effective evaluation of the analytical results.

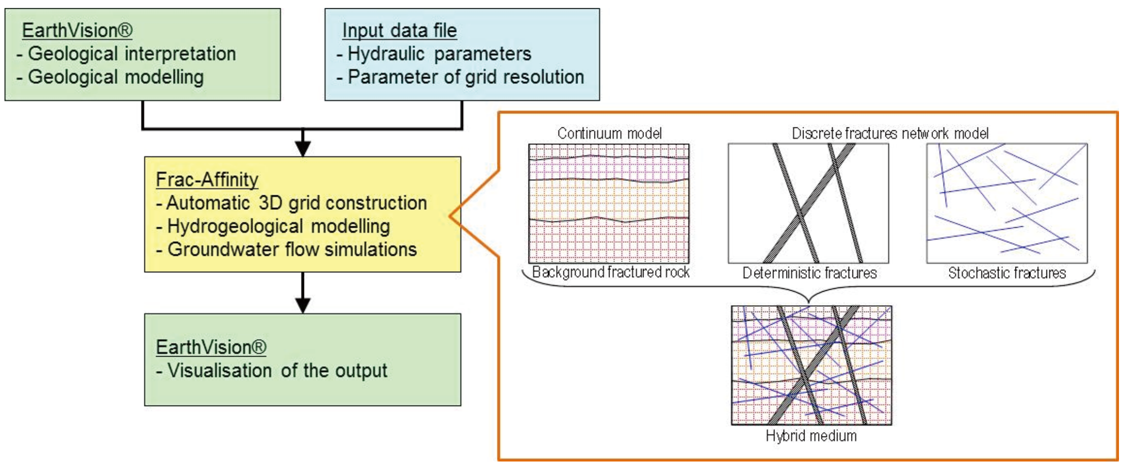


Fig. 2.2.3-20 Tools for supporting the rapid construction of geological environmental models

2.2.4 Summary

Techniques and accumulated technical knowledge regarding investigation, analysis, and assessment for characterization of groundwater flow conditions and for prediction of volume of inflow into underground facilities are listed below.

(1) Generic techniques

- The procedure described below is effective to characterize the hydrogeological environment.
    - Preliminary characterization of hydrogeological structures affecting groundwater flow field in a wider area using techniques providing 2D information
    - Identification of open issues requiring more detailed information
    - Borehole investigations addressing the investigation items
- Preferentially investigating the uncertain items identified by groundwater flow analysis with sensitivity analysis is effective.
- A modeling system allowing users to quickly construct and modify models in response to the acquisition of new data was developed.
- The technical findings for hydrogeological characterization are summarized and are available for inspection[23),39),40)].

(2) Groundwater flow field

- In order to characterize the groundwater flow field, preferential investigation of the hydraulic characteristics of faults across to the major groundwater flow direction is necessary.
- The major groundwater flow direction is in line with the overall topography.

(3) Spatial variability of groundwater flux

- The spatial distributions of hydraulic head are different in the areas divided by faults with low hydraulic conductivity across to the major groundwater flow direction. The hydraulic gradient in the areas bounded by such faults with low hydraulic conductivity tends to be low.
- Monitoring of hydraulic responses in the hydrogeological compartment is useful to characterize the connectivity and hydrogeological characteristics of hydrogeological structures forming hydrogeological compartments.
- In order to ensure sufficient quality of test data for rocks with a wide range of hydraulic characteristics, a series of improvements was successfully undertaken on packer test equipment, and efficient testing procedures and data evaluation methods were developed[41),42)] (Fig. 2.2.4-1, Fig. 2.2.4-2).
- The fluid electrical conductivity logging method is capable of detecting water-conducting features with a transmissivity two orders of magnitude lower than that detected by the flow-meter logging method using impellers or electric-magnetic flow-meters (Fig. 2.2.4-3).

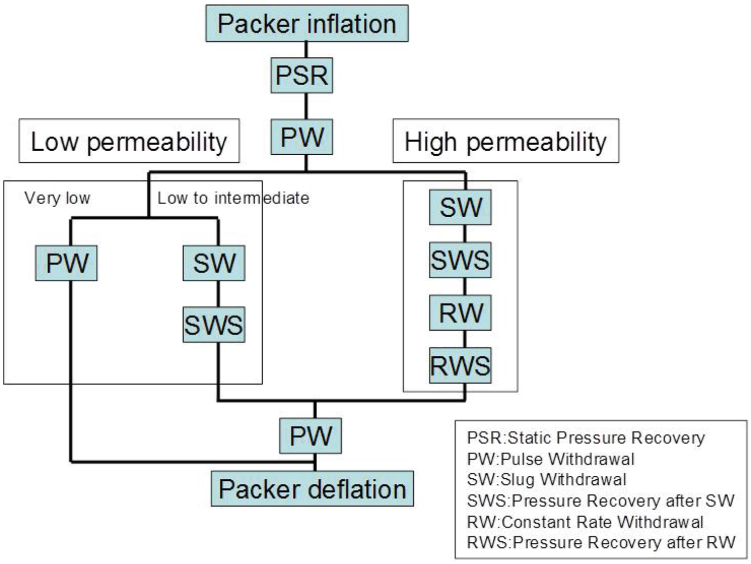


Fig. 2.2.4-1 Sequential hydraulic testing procedure (MIU)

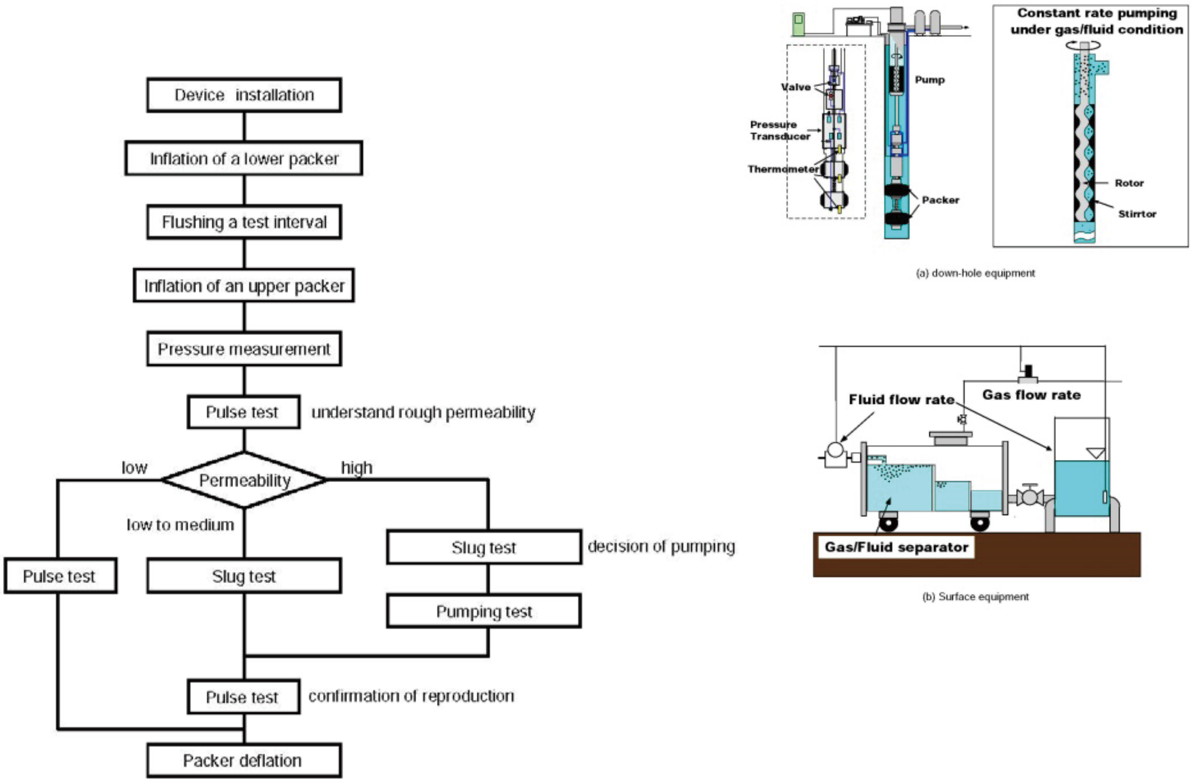


Fig. 2.2.4-2 Sequential hydraulic testing procedure (Horonobe)

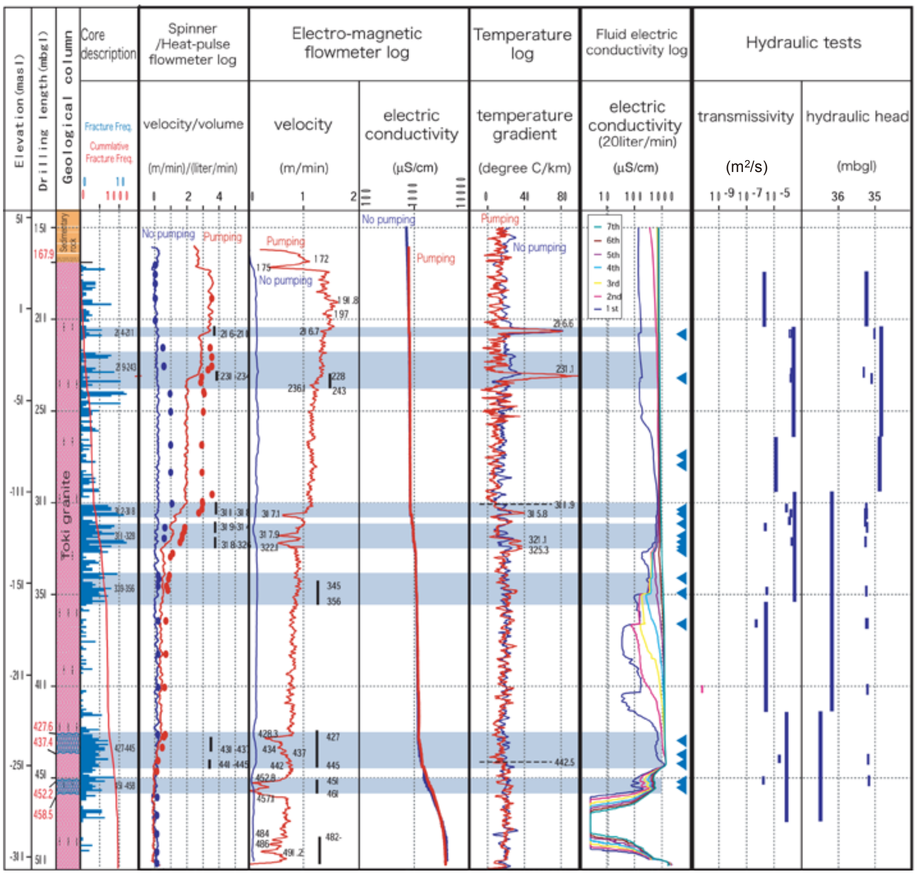


Fig. 2.2.4-3 Example of fluid logging (MIU)

(4) Spatial variability of water fluxes in higher-permeability rocks and aquifers

- Techniques of investigation, analysis, and assessment to characterize the spatial variability of water fluxes in higher-permeability rocks and aquifers are the same as those used to characterize the spatial variability of groundwater flux.

(5) Volume of inflow into underground facilities

- Pilot borehole investigations are useful for the improvement of prediction accuracy.

In further studies, development of effective investigation techniques for continuous data acquisition on fractures with a wide range of hydraulic characteristics in a continuous manner will be performed in A2-1 and fed back to A1-1. The development of the discrete fracture modeling methodology is also important.

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2.3 Hydrogeochemistry

2.3.1 Introduction

Aspects of groundwater chemistry such as the chemical composition (salinity), pH, and redox potential are indispensable parameters for safety assessment of HLW disposal. Knowledge of these parameters is necessary for decision-making during site selection and the subsequent underground facility construction. Investigation of groundwater chemistry needs to be conducted considering the three-dimensional geology, hydrogeological structure, and groundwater flow, because the chemistry evolves by the mixing of chemically distinct waters and water–mineral–microbe interactions. This chapter provides basic knowledge on surface-based investigation techniques to evaluate the hydrogeochemical conditions prior to the construction of underground facility.

2.3.2 Objectives in the second mid-term research phase

Most of the surface-based investigations were conducted during the first mid-term plan. The reliability of the estimated hydrogeochemical preliminary condition was confirmed by observations during the facility construction. The performance target of R&D in the second mid-term research phase is listed in Table 2.3.2-1.

Table 2.3.2-1 Performance target of R&D for the hydrochemistry

Focus	Performance target of R&D	Tasks
Siting decision	To provide an investigation technique and determination method to determine chemically favorable or unfavorable domains.	• Methodology for borehole layout and observation to identify spatial groundwater chemistry • Methodology for data traceability and transparency • Analysis and modeling procedure
Construction decision	To provide an investigative technique and determination method to judge; • Whether drainage during facility construction satisfies environmental law • Hydrochemical changes during facility construction and operation	• Borehole investigation methods to estimate chemical composition of drainage • Approach on design and layout of gallery to suppress hydrochemical disturbance • Technique for estimating hydrochemical disturbance caused by long-term drainage

2.3.3 Project details and outcomes

Groundwater was sampled from three boreholes (MSB-2, MSB-4: 100–200 m deep in sedimentary rocks; MIZ-1: 1,200 m deep in granitic rock) at the Mizunami URL site. In addition, data obtained from the regional hydrological study (DH-2: 500 m deep in granitic rock; DH-15: 1,000 m deep in sedimentary and granitic rocks) were used to estimate the spatial distribution of groundwater chemistry and its evolution. The results are summarized in Fig. 2.3.3-1.

Hydrogeochemical data were obtained from water collection rings in the shafts, inflow from the excavation wall, and boreholes drilled from galleries and the ground surface. Based on comparison of the newly obtained data with the results of previous surface-based investigations[1)], the investigation techniques and procedures to understand the hydrogeochemical baseline conditions were confirmed.

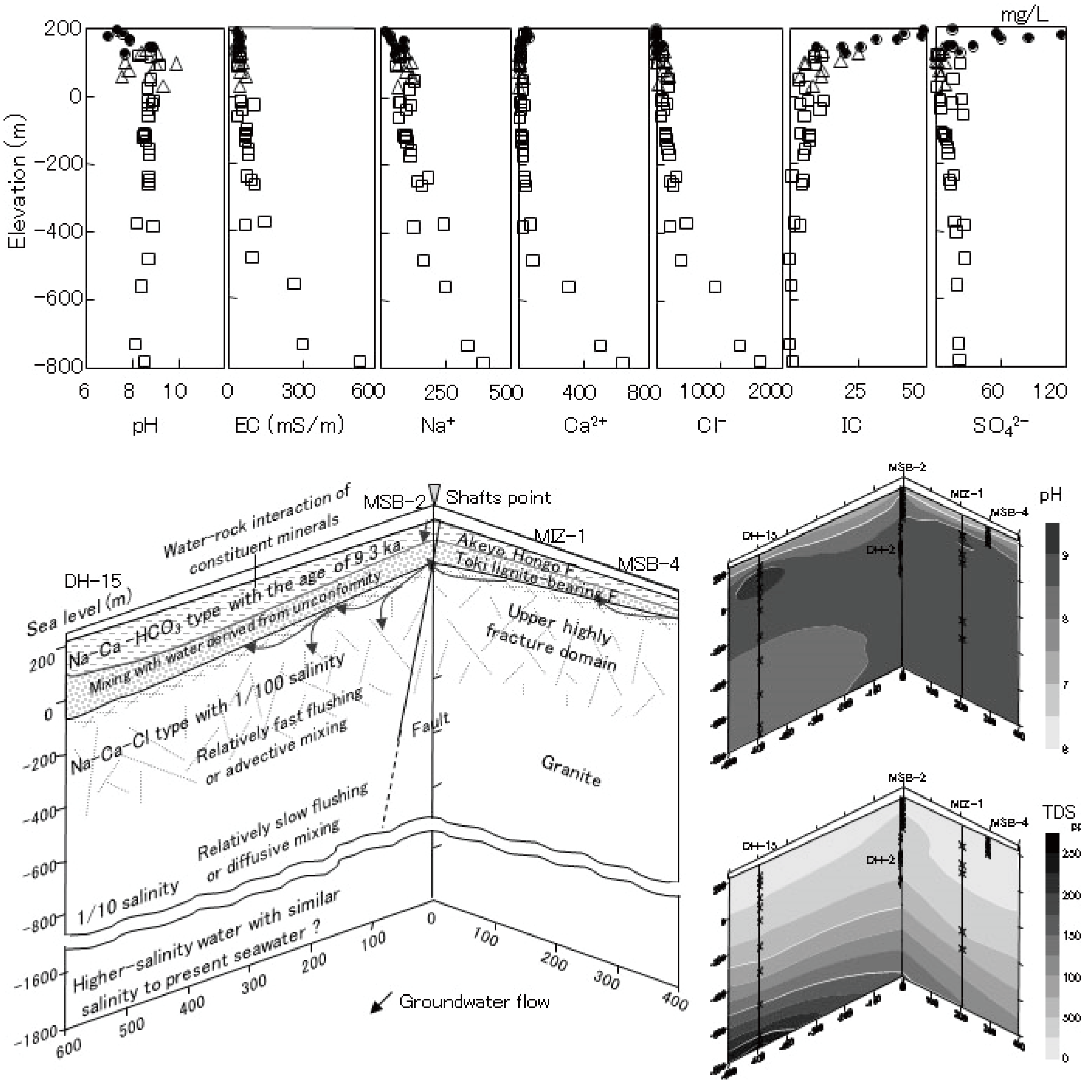


Fig. 2.3.3-1 Distribution of groundwater chemistry and the hydrochemical model constructed from surface-based investigations (MIU)

Groundwater chemistry around the MIU is classified into three types: 1) Na–Ca–HCO_3–SO_4 type in the shallower sedimentary rocks; 2) Na–Ca–Cl type with relatively low salinity in the deeper sedimentary rocks and shallower granite; and 3) Na–Cl type with relatively high salinity in deeper granite. The hydrochemical spatial distribution is controlled by mixing of these groundwater types[1)].

In the Horonobe area, groundwater was pumped from 11 deep boreholes (HDB-1 to -11, with borehole lengths of approximately 500 m to 1,000 m), which were drilled from the surface. In addition, pore waters were also squeezed from core samples of each borehole. In collaboration with other research organizations such as National Institute of Advanced Industrial Science and Technology (AIST) and Central Research Institute of Electric Power Industry (CRIEPI), pumped waters and pore waters were also collected from additional boreholes such as HCD-1 (300 m depth) and SAB-1 (500 m depth). Chemical analyses of pumped and pore waters were performed to identify the variation and evolution of groundwater chemistry (e.g., salinity) in the Horonobe area. Salinity distribution and a hydrochemical model based on the results obtained through surface-based investigation phase are illustrated in Fig. 2.3.3-2. According to the hydrochemical model, the followings are considered to have been important processes in the evolution of groundwater chemistry in Horonobe: diagenetic processes forming the fossil seawater during sedimentation, mixing processes affecting the salinity distribution (mixing between the fossil seawater and young meteoric water), and dilution processes derived from water of dehydration from biogenic silica during diagenesis. Based on the measurements of physicochemical parameters (pH and oxidation–reduction potential: ORP), appears to be slightly alkaline and weakly reducing (approximately −100 mV value of Eh).

In the second mid-term research phase plan, the applicability of prediction methods developed in the surface-based investigation phase has been confirmed. For validation of the prediction methods, comparative studies for the predicted parameters (e.g., pH, ORP, and probable groundwater salinity) and the measurements obtained from the shafts/boreholes during the construction phase of the URL until G.L. −350 m were performed.

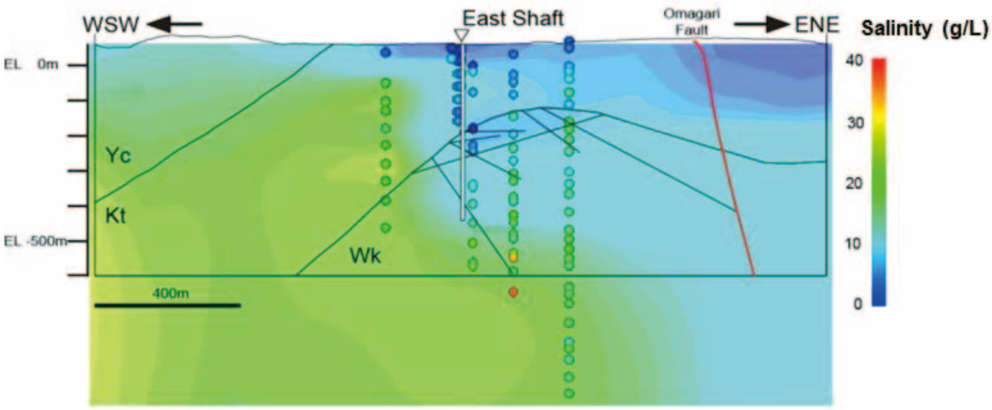


Fig. 2.3.3-2 Distribution of groundwater chemistry (salinity) and the hydrochemical model constructed from surface-based investigations (Horonobe)

The groundwater in the Horonobe area is considered to have originated as fossil seawater trapped during sedimentation. The spatial distribution of hydrochemistry could have been controlled by mixing of fossil seawater, meteoric water, and water of dehydration from biogenic silica during diagenesis.

(1) Groundwater chemistry (salinity)

1) Mizunami

Chlorine is not susceptible to water–mineral interaction. The Cl concentrations in WRs up to the depths of 500 m are shown in Fig. 2.3.3-3. The groundwater chemistry that was identified immediately after facility construction was almost the same as the results of surface-based investigations. Thus, the investigation techniques and procedures applied during surface-based investigation phase are suitable for understanding the hydrochemistry. The chemical type of the groundwater and the salinity distribution was influenced by specific hydrogeological structures (e.g., faults, low-permeability layers, and fracture zones). A borehole layout taking these structures into account is essential during surface-based investigations to confirm the relationship between the hydrogeological structure and the three-dimensional hydrochemical distribution. The investigation techniques and procedures for surface-based investigations are summarized by Saegusa et al. (2011)[2].

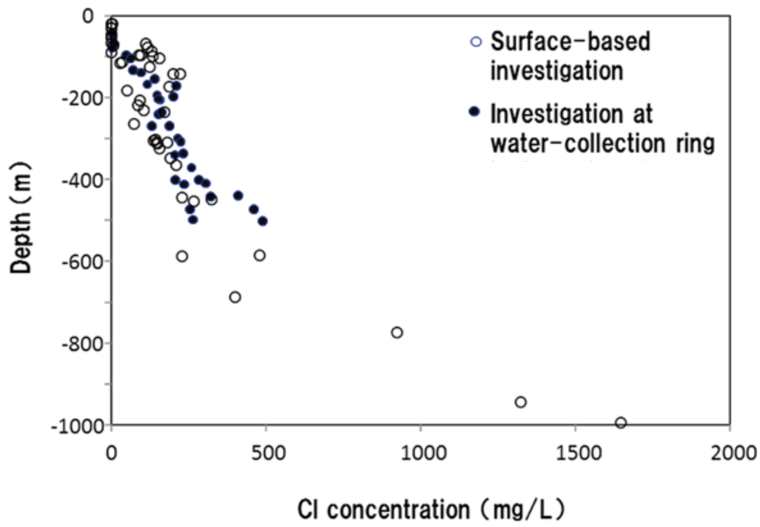
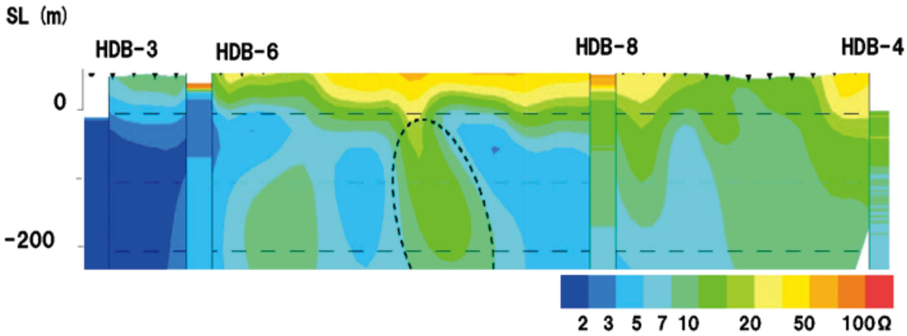


Fig. 2.3.3-3 Comparison of Cl concentrations in groundwater estimated by surface-based investigations and by investigations during the construction phase

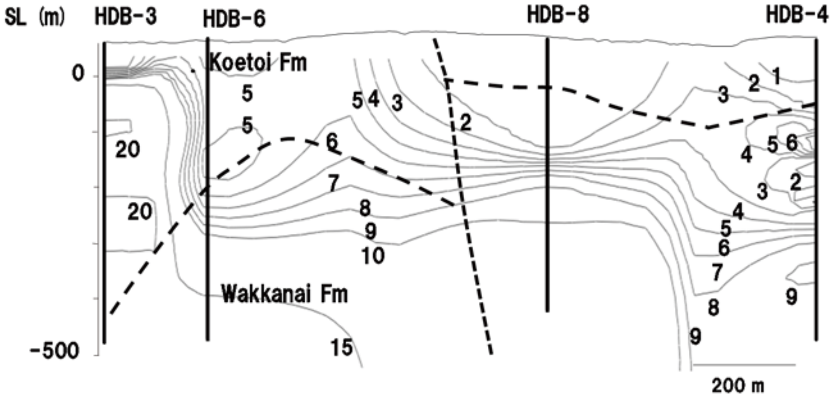
2) Horonobe

Comparison between the measured salinity variations of groundwater during the surface-based investigation phase and the relevant data obtained through the construction phase of the URL until G.L. −350 m level was performed. The results show that the groundwater salinity in a lower-permeability zone was almost identical to the predictions obtained during the surface-based investigation phase. Therefore, it was suggested that the method of predicting the salinity distribution used in the surface-based investigation phase is an appropriate technique. In addition, multivariate statistical analysis could be considered as a suitable method for comparison of data obtained in the surface-based investigation and construction phases of the URL, excluding data affected by engineering materials used in the drifts/shafts. Because the groundwater chemistry can change in higher-permeability zones after the construction of URL, it should be noted that determination of variations in salinity corresponding to the hydraulic properties and geological structures may be a key issue in the surface-based investigation phase.

Furthermore, the efficiency of using electric resistivity surveys to evaluate the salinity distribution has also been demonstrated by the good agreement between the results of extrapolation of salinity variations based on the chemical analysis and resistivity logging data obtained from deep boreholes (Fig. 2.3.3-4). The reason for this good agreement might be the correlation of the electric resistivity and salinity. This empirical knowledge implies that the results of geophysical exploration would be useful to complement the lack of salinity distribution data between the boreholes by extrapolation. Electric exploration at the surface could obtain variations in the specific resistivity in the depth of 200 m as a maximum; however, certain conditions might be necessary in order to evaluate the salinity distributions appropriately: 1) a significant contrast in electric resistivity between rock matrix and groundwater; 2) homogeneity of electric resistivity in the rock matrix.



Comparison of electrical survey and resistivity logging



Salinity distribution

Fig. 2.3.3-4 Results of surface-based electrical surveys and resistivity logging using boreholes (upper), and the distribution of Cl concentrations in groundwater (lower)

(2) pH and redox conditions

The pH and redox conditions can be measured by installing in situ sensors into boreholes during the surface-based investigation phase. The observed values can be evaluated using theoretical calculations based on the chemical composition of groundwater. However, it is difficult to investigate at a large number of sites because of limitations of the budget and the schedule of the surface-based investigation phase[2]. Moreover, formation of iron-compound films, possibly of redox-controlling material, has been observed on the walls of several boreholes[3] (Fig. 2.3.3-5). Thus, the quality of the redox data observed from the surface is uncertain.

During construction phase, pH and redox values were directly measured under pressurized and anaerobic conditions in the boreholes drilled from the gallery to confirm the redox conditions. In addition, periodic redox measurements were obtained in the borehole contaminated by iron-compound films to understand the influence of this contamination during borehole drilling.

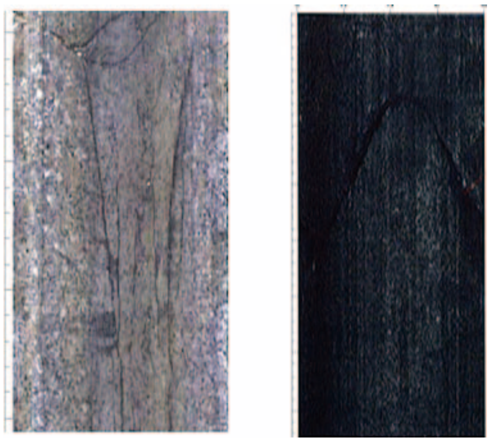


Fig. 2.3.3-5 Contamination by iron compounds on a borehole wall caused by drilling (left: immediately after drilling, right: after formation of films)

1) Mizunami

The redox potentials measured in the surface-based investigation phase and construction phase are illustrated in Fig. 2.3.3-6[3]. The redox potentials measured immediately after interrupting borehole drilling from surface tend to correspond with the values measured at the gallery. Measurement of groundwater immediately after drilling is probably important to minimize contamination. The pH and redox potential plots for near the calcite/bicarbonate ion boundary, ferric iron/ferrous hydroxide, and ferric iron/sulfide minerals are illustrated. These reactions may control the pH/redox conditions of groundwater.

In the periodic redox measurement in the borehole with iron-compound films at MIZ-1, redox potential approached the initial reducing value obtained immediately after drilling (approx. −300 mV) with an increase in the pump-out water volume (Fig. 2.3.3-7). This would have been because the contamination by iron compounds was removed by flushing with a large volume of groundwater. There are many outstanding questions about the formation process of the iron compound. Iron derived from the drill bits used for borehole drilling may be reduced and absorbed on the borehole wall. The elucidation of this process and development of a removal method for the iron compound are future tasks.

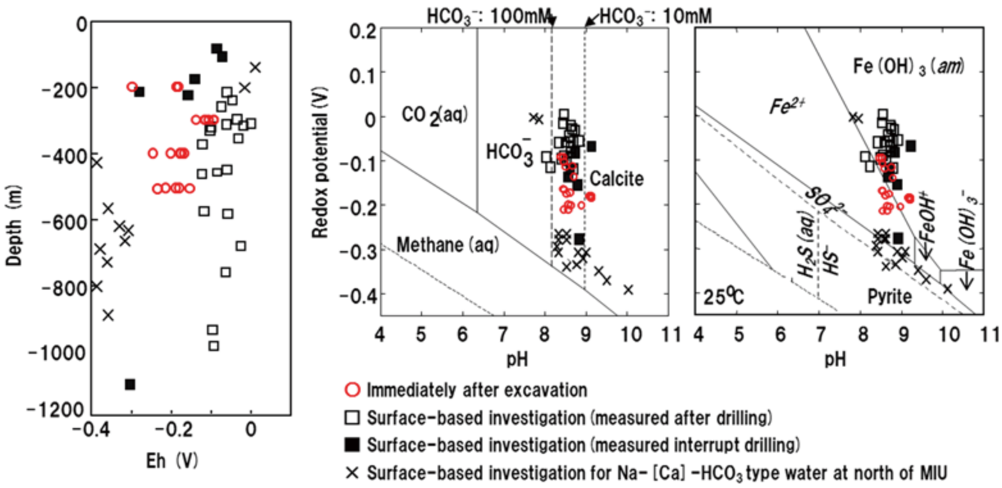


Fig. 2.3.3-6 pH and redox conditions of groundwater obtained by surface-based investigation and by investigation during the construction phase (MIU)

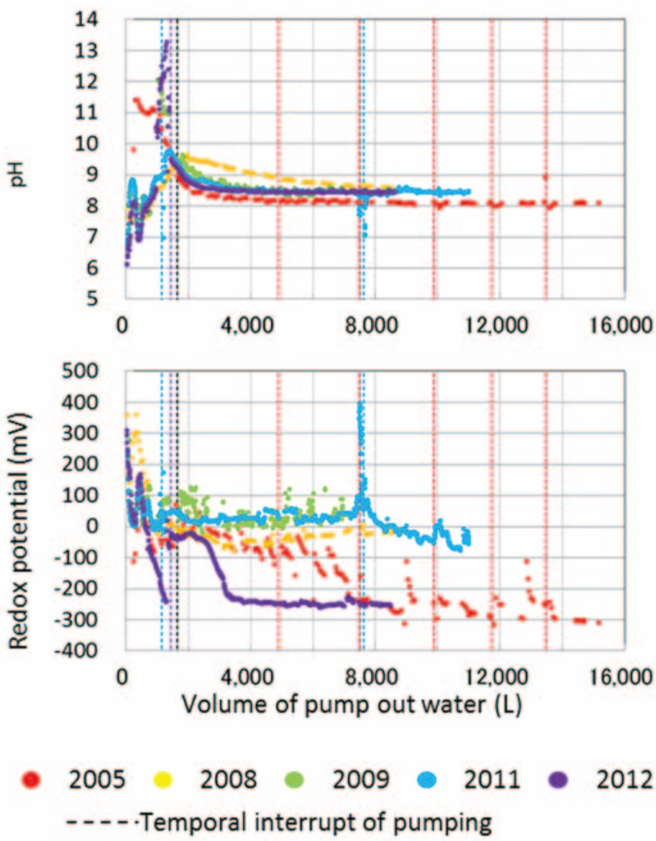


Fig. 2.3.3-7 Variation in physicochemical parameters during pumping at borehole MIZ-1, Section 9 (1150 mabh(meter along borehole))

2) Horonobe

Fig. 2.3.3-8 shows pH–Eh diagrams including data obtained both at the surface and underground. Dissolution/precipitation reactions of calcite might control the pH of groundwater because of the fact that the measured partial pressure of CO_2 (P_{CO2}) and the pH of groundwater showed good agreement with the theoretically calculated value assuming calcite equilibrium. Moreover, the effect of CO_2(g) degassing on the pH of pumped water has been evaluated for the groundwater sampled from the borehole at 500 mbgl (meter below ground level). The measured pH of groundwater at the surface was higher by approximately 0.4 compared to the in situ pH value. A correction method for pH changes caused by CO_2(g) degassing has been proposed; this method involves measuring the amount of degassed CO_2(g) and calculating the P_{CO2}, which corresponds to the in situ condition[4)]. Fig. 2.3.3-8 (a) shows the pH and redox conditions of the groundwater measured in deep boreholes. Data obtained at a depth of around 500 mbgl are plotted on the equilibrium lines of redox reactions related to sulfate ions and ferric sulfide or pyrite (lines 2 and 3 in Fig. 2.3.3-8 (a)). In contrast, data derived from a depth of around 600 mbgl are plotted on the equilibrium line of sulfate ions and hydrogen sulfide ions (line 1 in Fig. 2.3.3-8 (a)). The results obtained in the tunnel at 140 mbgl are plotted in Fig. 2.3.3-8 (b). Although the data in Fig. 2.3.3-8 (b) were obtained from depths different from those in Fig. 2.3.3-8 (a), the measured values are also plotted around the line of bicarbonate ions and pyrite and/or that of sulfate ions and pyrite. Therefore, it is suggested that these reactions are important in the redox reactions of groundwater in the sedimentary rocks in the Horonobe area[4)].

(a) Surface-based investigation (b) Investigation during shaft construction

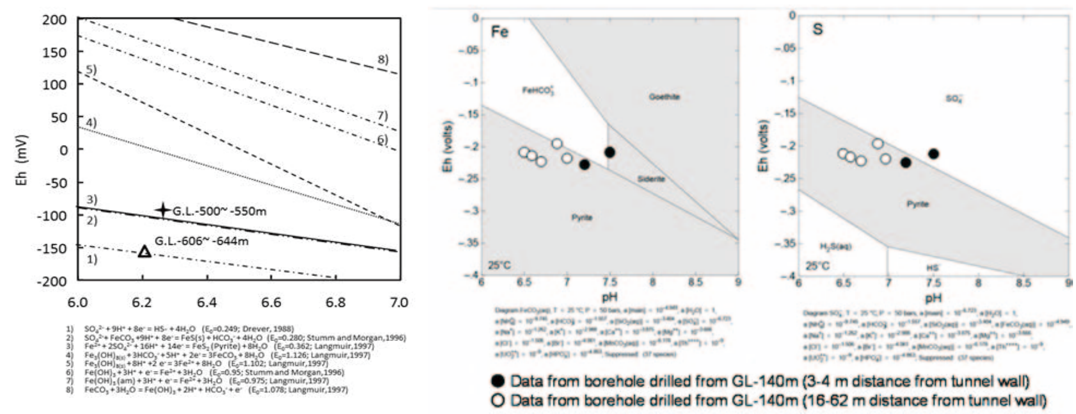


Fig. 2.3.3-8 pH and redox conditions of groundwater obtained during the surface-based investigation and the construction phases (Horonobe)

(3) Groundwater residence time

The practicability of using chemical tracers (e.g., ^{14}C, ^{36}Cl, ^{37}Cl, and ^{4}He) to estimate groundwater residence time was confirmed for various hydrogeological conditions (e.g., rock type and groundwater flow conditions)[5)].

1) Mizunami

Groundwater dating using the ^{14}C concentration in dissolved inorganic carbon (DIC) has primordial uncertainty due to contamination by "dead" (^{14}C-free) carbon derived from carbonate minerals. In the crystalline rock (MIU) without solid organics, a ^{14}C dating method using dissolved organic matter (DOM) was developed. In this method, a procedure for separating artificial organics (e.g., fluorescent dyes) from natural DOM was also presented[6].

2) Horonobe

A method of groundwater dating using radioactive chlorine (^{36}Cl), helium (^{4}He), and radioactive iodine (^{129}I) was developed to allow more precise estimation of residence time of groundwater (Fig. 2.3.3-9). In deeper locations, where the contribution of meteoric water infiltration is faint, the groundwater age showed a good agreement with the sedimentation age of geological formation. In consequence, the estimated age of the groundwater supports the scenario of groundwater evolution in which the present-day groundwater was formed from mixing of fossil altered seawater that was trapped in sedimentary rocks from the time of sedimentation and meteoric water. In addition, several notations regarding the applications of these geochronological methods (i.e., attention to the correction of the degassing effect of helium at the time of sampling) were summarized.

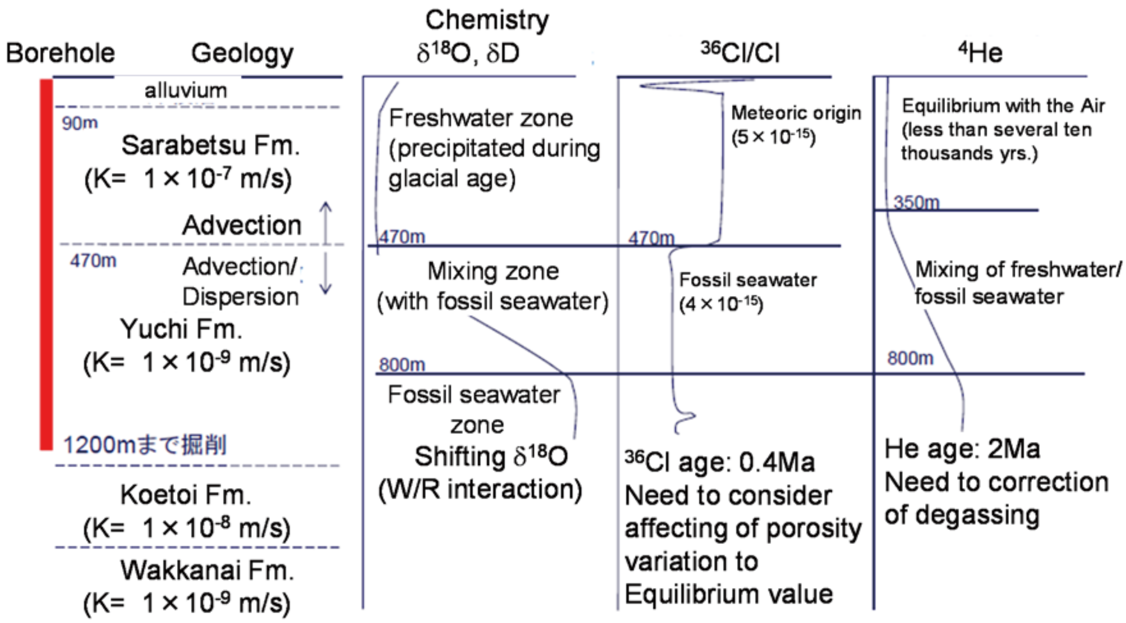


Fig. 2.3.3-9 Groundwater residence time estimated based on ^{36}Cl and ^{4}He, and groundwater evolution process estimated from $\delta^{18}O$ and δD depth profiles (Horonobe)

2.3.4 Summary

The techniques and procedures for understanding the hydrochemical baseline conditions prior to facility construction have been prepared to date (Fig. 2.3.4-1). R&D will be completed by performing feedback of knowledge relevant to the facility closure into surface-based investigations in future.

The messages in this section are summarized as follows:

- Make a plan of monitoring taking the hydrogeological compartments and potential permeable zones (e.g., conglomerates, faults, unconformities, and fractured zones) into consideration.
- For areas with homogeneous geology and saline water, the spatial distribution of groundwater salinity between boreholes can be interpolated based on electric and electromagnetic surveys at the ground surface and electrical logging in boreholes.
- New redox-controlled secondary minerals may precipitate on borehole walls during borehole investigations. Borehole walls should be observed using BTV observation prior to redox measurement. The preliminary measurements of redox conditions at the surface should be observed by measurements in the gallery.
- The measured redox values should be checked using theoretical calculations (with particular attention paid to carbonates and sulfide minerals–water interactions).

Data for ^{3}H and ^{14}C are available for piston-flow conditions in homogeneous sedimentary rocks. Several isotopic measurements (^{36}Cl, ^{4}He, and oxygen isotope shifts) are indexes of long-term residence conditions of seawater. Data for ^{14}C of DOM are available for non-piston-flow conditions in fractured granite.

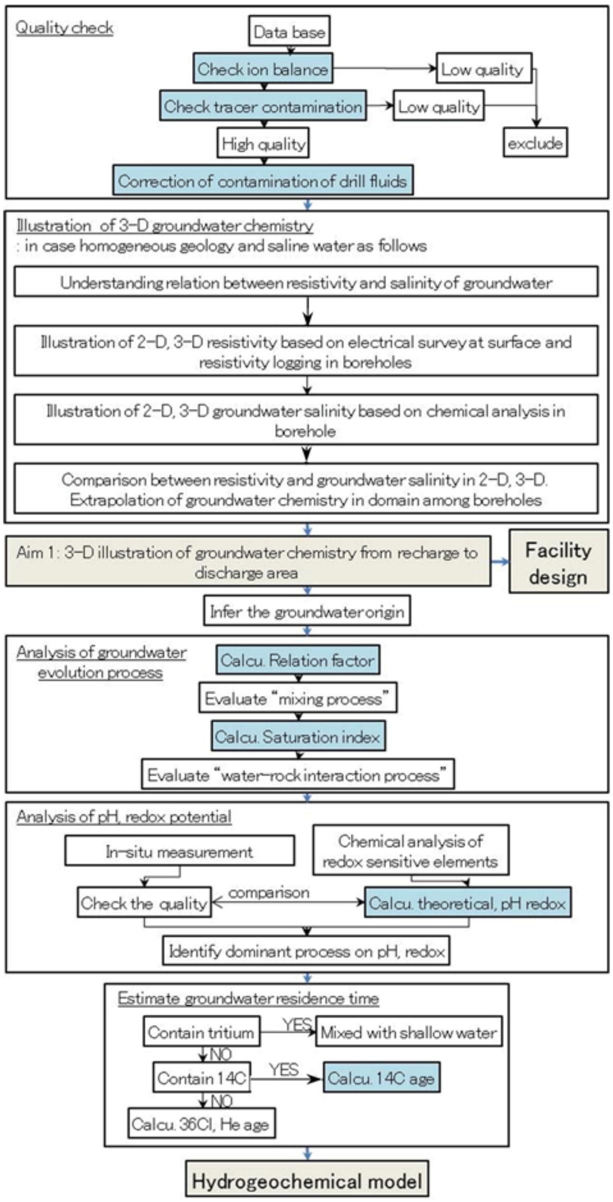


Fig. 2.3.4-1 Procedure for hydrogeochemical modelling during surface-based investigations

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2.4 Rock mechanics

2.4.1 Introduction

In situ stress and rock properties are important in the design and construction of large and deep underground structures. In fact, in situ stress is recognized as the primary factor in the development of an excavation damaged zone (EDZ). An EDZ is likely to be less stable than the undisturbed rock mass and to provide higher-permeability pathways for groundwater flow in the vicinity of excavations. Thus, development of an EDZ is recognized as a key issue both for the design and construction of disposal facilities and for safety assessment. In Phase I, it is necessary to understand the initial state of the rock conditions using borehole investigations and laboratory tests using core samples. In Phase II, it is necessary to obtain detailed information by investigation from the shaft and gallery and to compare with the information obtained during Phase I.

The subjects of rock mechanical studies are as follows:

- In situ stress
- Rock properties
- Thermal gradient
- Thermal properties

2.4.2 Objectives in the second mid-term research phase

The objectives of rock mechanics investigations during construction phase (Phase II) is to understand the detailed in situ stress conditions and rock mechanical properties by borehole investigations from the shaft and gallery, and laboratory tests during extension of the shaft and gallery at depths of 500 m (Mizunami) and 350 m (Horonobe). Also, it is necessary to confirm the validity of the conceptual model and analysis technique applied in Phase I. Table 2.4.2-1 lists the target level of R&D, achievement items, and reflection of the results of R&D. In Phase I, the thermal gradient and thermal properties of rock were also obtained.

Table 2.4.2-1 Performance target of R&D for rock mechanical characterization

Focus	Performance target of R&D	Tasks
Siting decision	Decision-making for selection of good rock conditions.	• Technology of rock mechanical investigation from the surface • Technology of modeling and numerical analysis to estimate the regional stress field

2.4.3 Project details and outcomes

(1) In situ stress conditions

1) Mizunami

During the surface-based investigation phase (Phase I), hydraulic fracturing tests were performed in borehole MIZ-1 and core-based in situ stress measurements (AE (Acoustic Emission) /DRA (Deformation Rate Analysis), ASR (Anelastic Strain Recovery), DSCA

(Differential Strain Curve Analysis)) were also obtained[1]. A conceptual model for rock mechanics was developed on the basis of the data obtained, and numerical analysis was performed to estimate the regional stress and excavation damaged zone (EDZ). In Phase II, the Compact Conical-ended Borehole Overcoring (CCBO) technique was performed in each gallery to understand the 3D in situ stress state. Based on the results of these investigations, the conceptual model and analysis technique applied in the Phase I was confirmed[2),3),4),5),6)]. The conclusions are as follows:

- The direction of horizontal maximum principal stress is NW–SE based on the results of hydraulic fracturing tests in the MIZ-1 borehole. The results correspond to the regional stress state estimated from movement of plates and GPS surveys. The stress state is reverse-fault type in the upper part to a depth of 400 m and normal-fault type to strike-slip-fault type in the lower part to a depth of 600 m, estimated from vertical stress and horizontal stresses[1)].
- The direction of horizontal maximum principal stress is NW–SE based on the CCBO results in the G.L. −100 m, 200 m and 300 m galleries. The results show good agreement with the hydraulic fracturing tests in borehole MIZ-1 (Fig. 2.4.3-1)[2),3),4),6)].
- For individual elemental technology, a high-compliance system of hydraulic fracturing was applied and the quality of data for the maximum principal stresses improved compared to that from the ordinary system[7)]. We developed a groundwater inflow countermeasure tool and applied it to in situ stress measurement using the CCBO technique[8)] (Fig. 2.4.3-2). The applicability of the core-based method (DSCA: Differential Strain Curve Analysis) was tested against the hydraulic fracturing tests and overcoring method[9)].
- To estimate simultaneously the regional stress fields and the elastic modulus of the rock mass from the in situ stress measurements, back-analysis based on three-dimensional finite element analysis and the boundary element method were developed; subsequently, the direction and principal stress magnitudes at MIU were predicted[10),11),12),13)]. The trend in the analyzed results coincides with the results obtained from hydraulic fracturing tests performed in the MIZ-1 borehole and using the CCBO technique in the G.L. −200 m and −300 m galleries[14)].

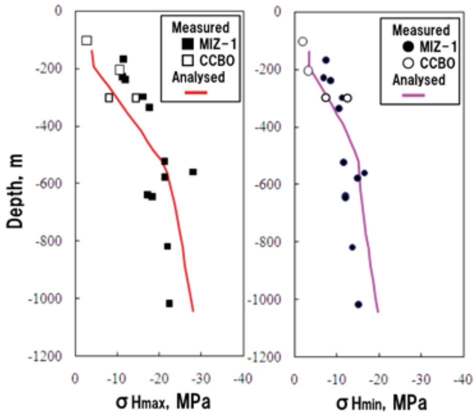


Fig. 2.4.3-1 Comparison of the in situ stress distributions from measured and analyzed values (Mizunami)

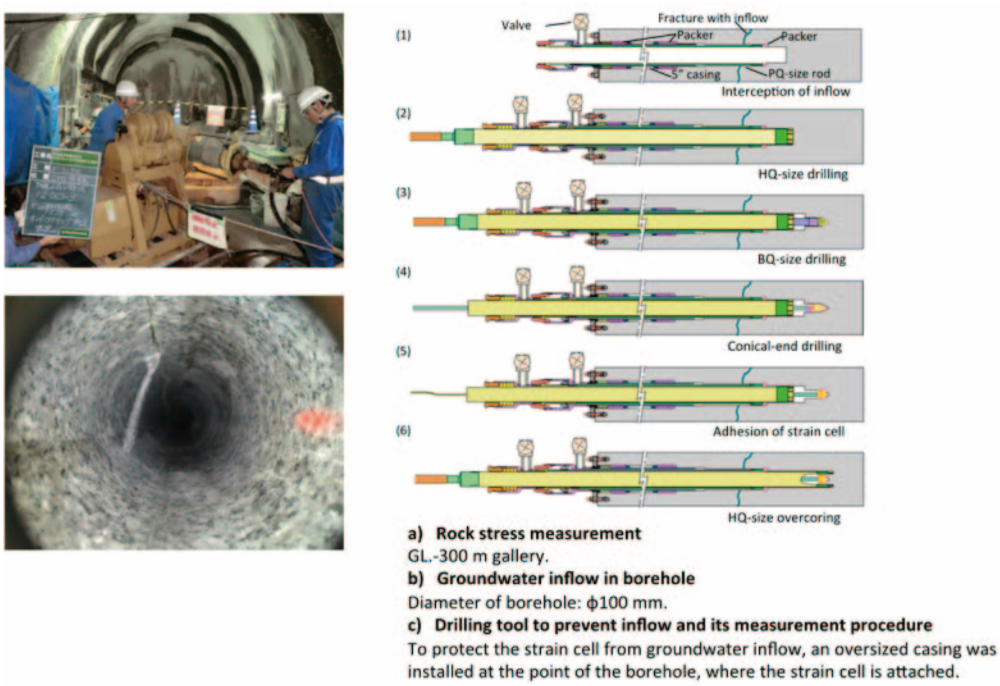


Fig. 2.4.3-2 Countermeasures against inflow during initial stress measurement by compact conical-ended borehole overcoring technique

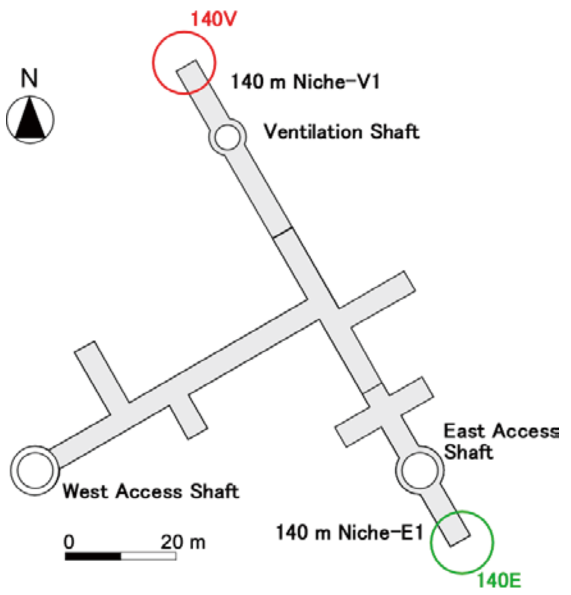
2) Horonobe

Hydraulic fracturing tests and observations of the breakout were conducted in the boreholes around the URL (Phase I), and in the G.L. −140 m, 250 m, and 350 m galleries in the URL during Phase II (Fig. 2.4.3-3). In each location, three boreholes, 76 mm in diameter and 20 m in length, were drilled. The orientation (trend and plunge) was different for each borehole. Hydraulic fracturing tests in the galleries were conducted using a high compliance hydraulic fracturing system in order to obtain reliable values of the fracture reopening pressure. The conclusions obtained from the results can be summarized as follows:

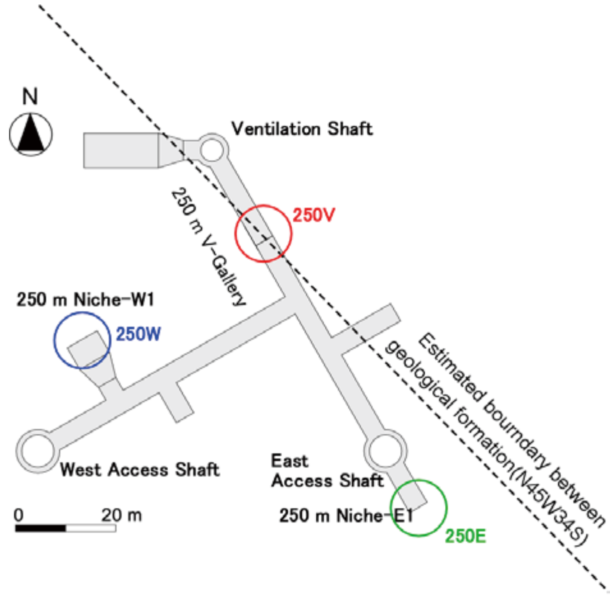
- The values and orientations (trend and plunge) of in situ stress in the G.L. −140 m galleries (Fig. 2.4.3-4(a)) showed good agreement with each other[15].

- The values and orientations of in situ stress are scattered in the G.L. −250 m galleries, which are located near the transition zone of the Koetoi and Wakkanai Formations (Fig. 2.4.3-4(b)). No principal stresses act in the vertical direction[15].
- The maximum principal stress is oriented NNW–SSE, plunging about 45° to the north in the G.L. −350 m pumping gallery[16]. In the G.L. −350 m loop gallery east, the orientation of one of the principal stress was vertical; the value of the maximum and intermediate principal stress was almost identical. The values of the stress in the 350 m galleries were smaller than the results from the surface-based investigation (Fig. 2.4.3-4(c)).
- The ratio of the maximum horizontal stress measured in the gallery to that obtained in the surface-based investigation was 0.4 to 0.9. On the other hand, the ratio of the minimum horizontal stress in the gallery to that obtained in the surface-based investigation was 0.5 to 0.6 (Fig. 2.4.3-5)[15]. This phenomenon is considered to be the result of decreased pore pressure resulting from shaft sinking and excavation of galleries[16].

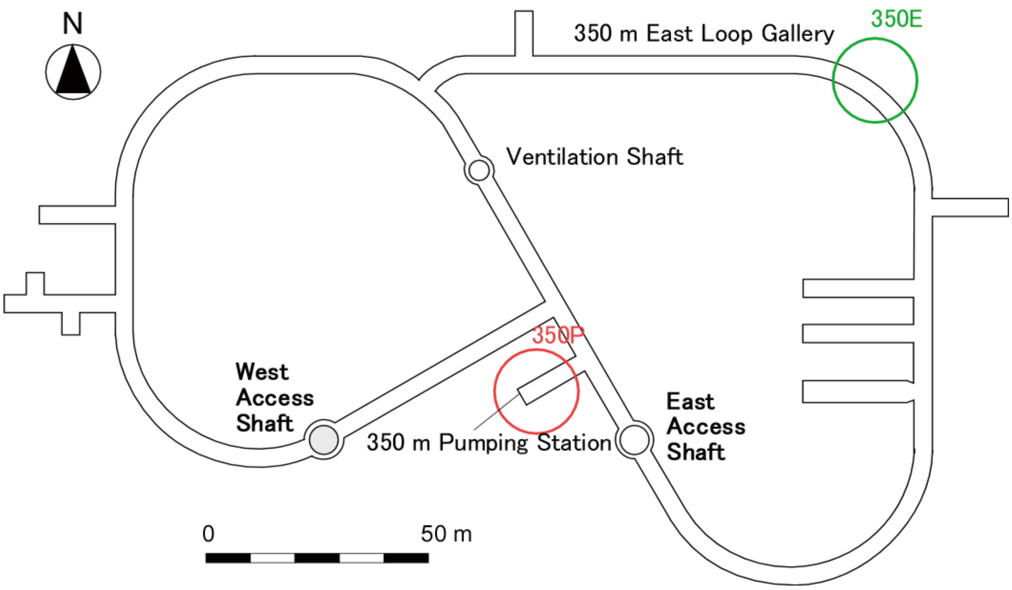
It is estimated that geological structures such as faults and folds affect the direction of in situ stress (Fig. 2.4.3-6). Therefore, for the assessment of in situ stress, it is essential to integrate the results of other measurement method such as analysis of borehole breakouts or measurement methods using rock specimens from cores[15,16].



(a) G.L. −140 m gallery



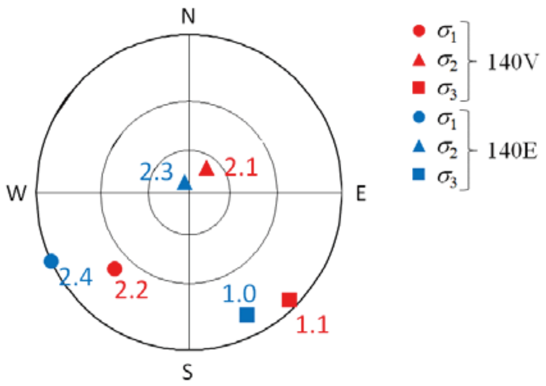
(b) G.L. −250 m gallery



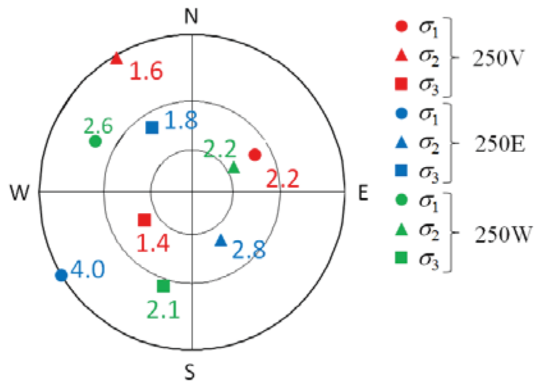
(c) G.L. −350 m gallery

Fig. 2.4.3-3 Locations of the stress measurements in the galleries

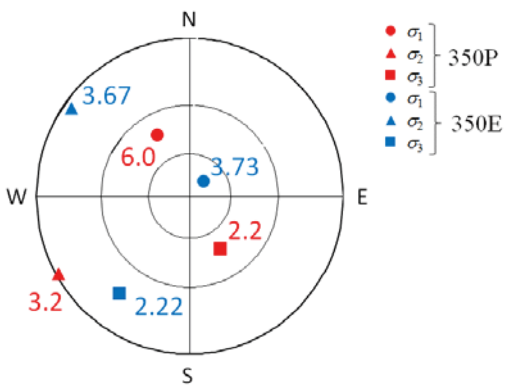
Circles indicate measurement locations. The colors of the circles correspond to the colors used in Figs. 2.4.3-4 and 5.



(a) G.L. −140 m gallery



(b) G.L. −250 m gallery



(c) G.L. −350 m gallery

Fig. 2.4.3-4 Stress magnitudes and orientations obtained in the galleries indicated on Wolf net diagrams, lower-hemisphere projections

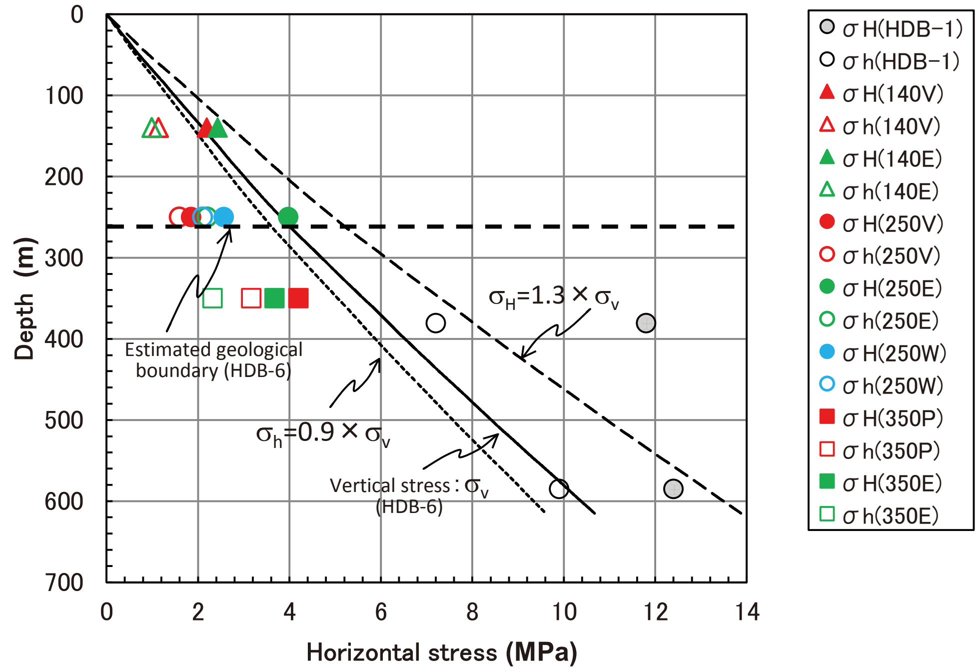


Fig. 2.4.3-5 Values of maximum and minimum horizontal stress measured in the galleries and HDB-1

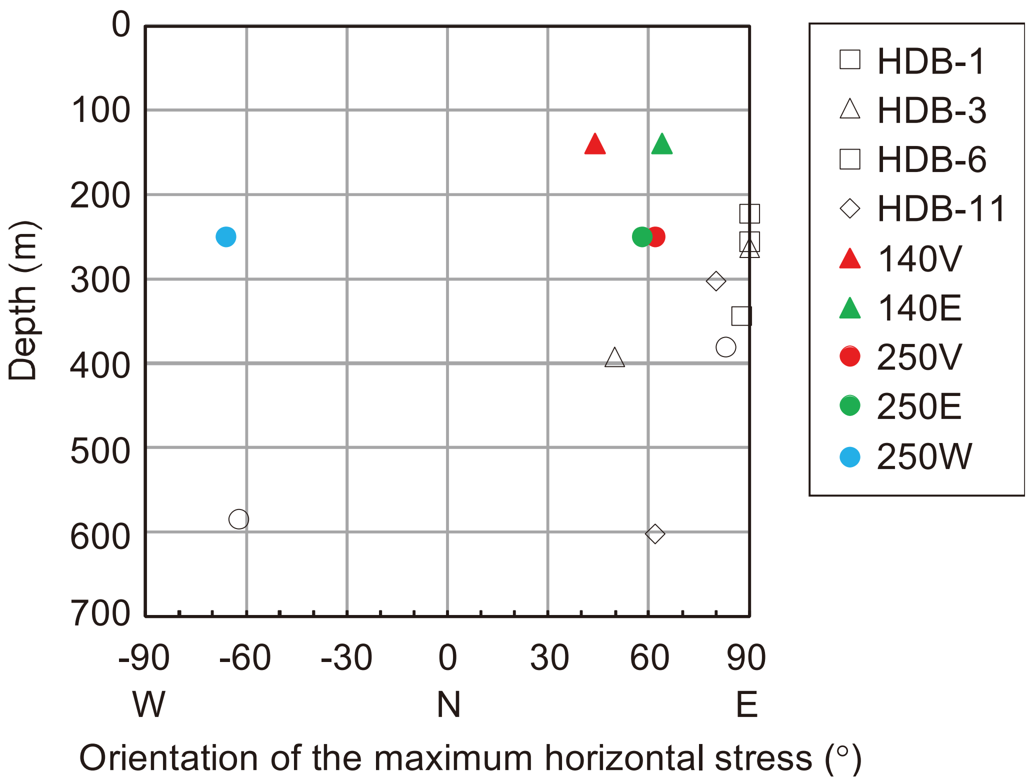


Fig. 2.4.3-6 Orientations of the maximum horizontal stress measured in the galleries and HDB-1, 3, 6, and 11

As the strength of the rock is different between Mizunami and Horonobe, there are limitations in the use of in situ stress measurements because the former is in hard rock and the latter in soft rock. It is difficult to apply in situ measurements because of the occurrence of borehole wall collapses in the soft rock. Hydraulic fracturing tests cannot be used in collapsed boreholes. Moreover, overcoring techniques cannot be used in this type of borehole as the technique assumes elastic behavior. In the case of collapse, borehole breakout can be used to estimate direction of maximum stresses. Although the CCBO technique can be used in many rock types, the strain gauge cell could not be glued to the sedimentary rocks in Horonobe.

(2) Physical and mechanical properties of rock

1) Mizunami

The physical and mechanical properties of rock were obtained by laboratory tests (e.g., uniaxial compressive test, triaxial compressive test, and Brazilian test) in Phase I (Fig. 2.4.3-7). Based on the results of these tests, a conceptual model was developed. Laboratory tests were also performed using cores obtained from boreholes drilled from the galleries and waste rock from shaft excavation in Phase II, and a conceptual model was revised[2),3),4),5)]. The conclusions are as follows:

- The physical and mechanical properties of rock obtained from MIZ-1 in the surface-based investigation show good consistency with those obtained in Phase II and the corresponding geological conditions.
- A conceptual model was developed on the basis of laboratory test results (Fig. 2.4.3-8). A comparison of the statistical properties of Toki Granite obtained from MIU and those obtained from the literature survey of the second progress report[17)] was performed[4)].

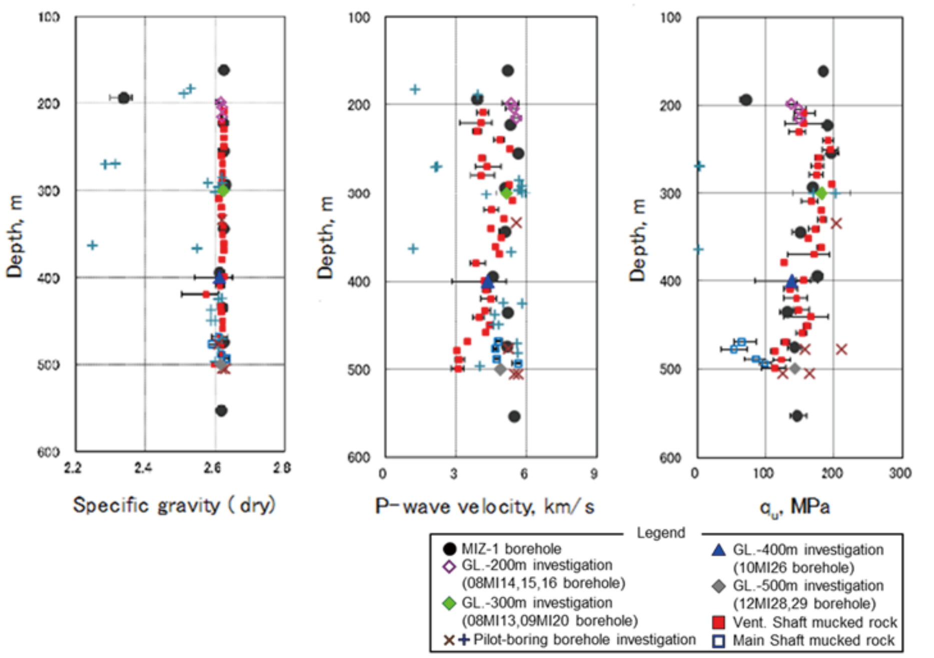


Fig. 2.4.3-7 Depth distribution of the physical and mechanical properties of rock (Mizunami)

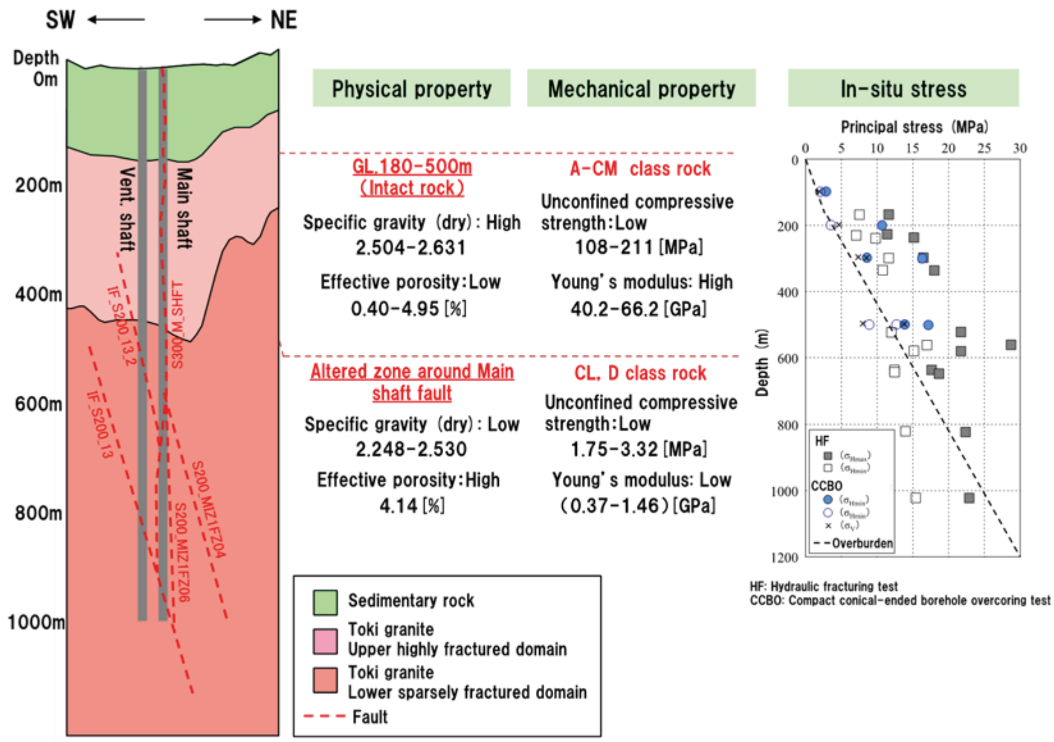


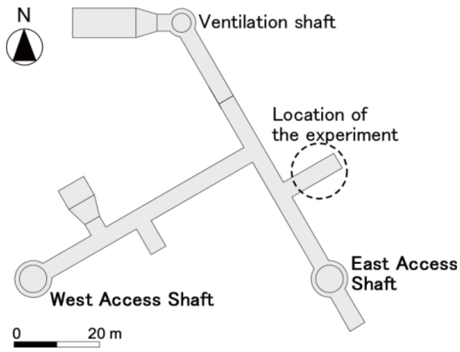
Fig. 2.4.3-8 Conceptual model of rock mechanics (Mizunami)

2) Horonobe

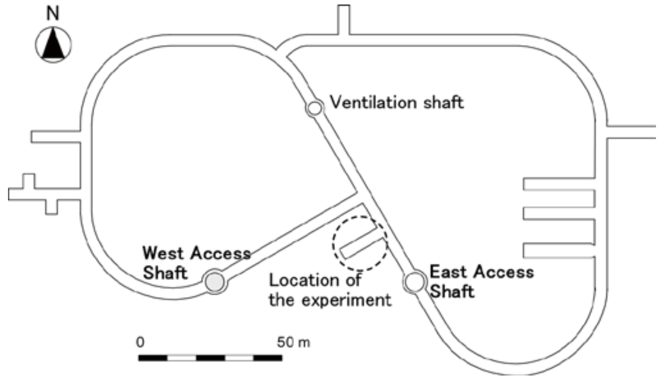
To investigate the rock mass properties on the scale of the disposal facility, plate-loading tests and direct shear tests were conducted in the G.L. −250 m and G.L. −350 m galleries (Fig. 2.4.3-9). In the direct shear tests, specimens 600 mm long, 600 mm wide, and 300 mm high were prepared on the floor of the gallery, then a vertical load and a shear load were applied to the specimen to obtain the failure stress state. In the plate-loading tests, a loading plate with a diameter of 600 mm was set on the floor and a vertical load was applied. The deformation modulus and elastic modulus were obtained from the tests. On the basis of these in situ tests, the properties of the rock mass were evaluated. The results can be summarized as follows:

- In the plate-loading tests (Fig. 2.4.3-10), the deformation modulus and elastic modulus of the Koetoi Formation in the G.L. −250 m gallery were almost same values as detected in surface-based investigation. On the other hand, in the G.L. −350 m gallery, the values of the two moduli were larger than those from the surface-based investigation. From the perspective of designing facilities, the estimation of the deformation characteristics of rock was almost valid[18].

In the direct shear tests (Fig. 2.4.3-11), the shear stress of failure at low vertical stress was almost the same as the failure criterion detected in the surface-based investigation[18].

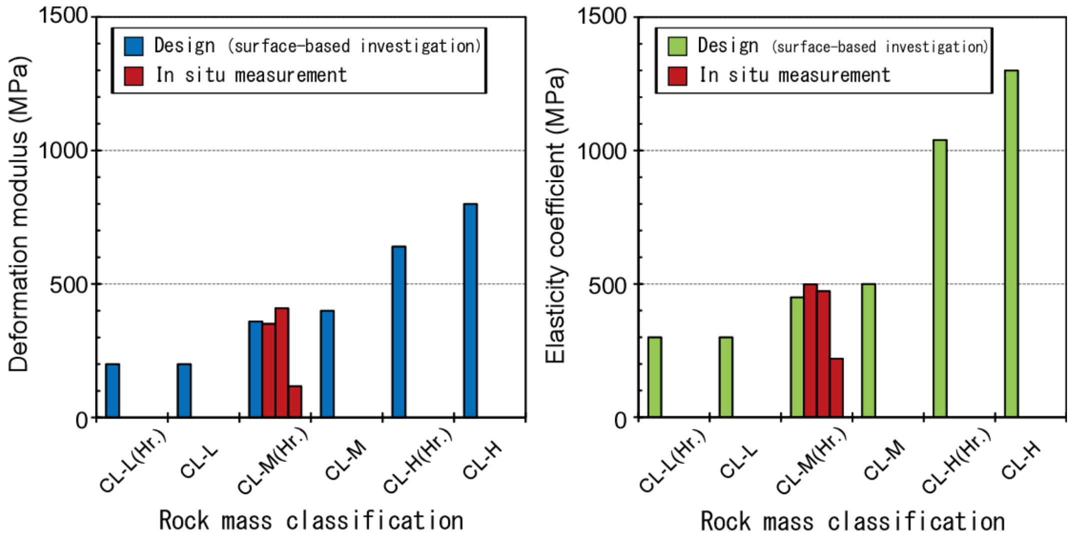


(a) GL−250 m gallery

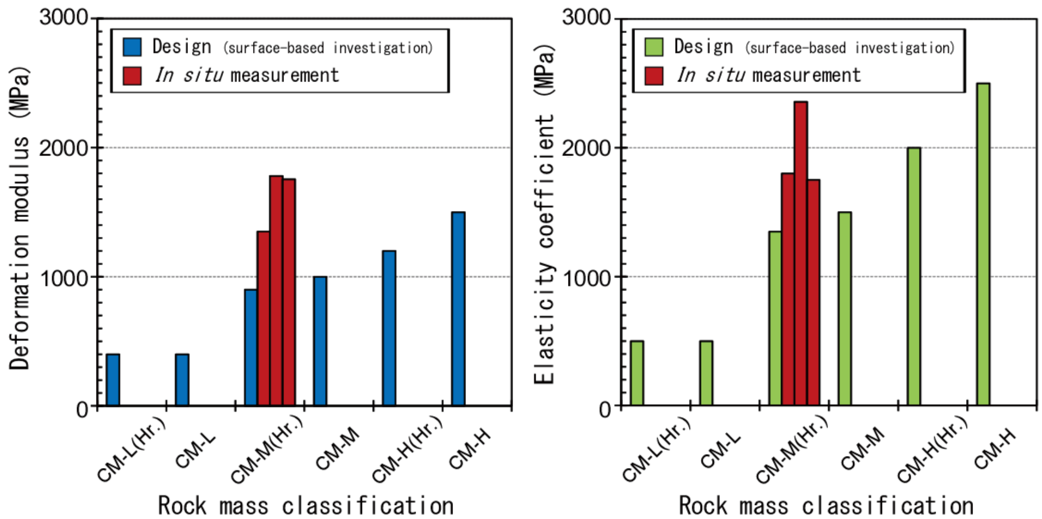


(b) GL−350 m gallery

Fig. 2.4.3-9 Locations of the plate-loading tests and direct shear tests

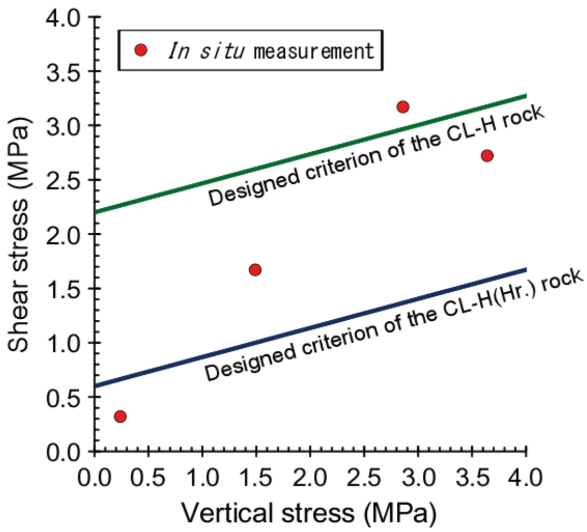


(a) GL−250 m gallery

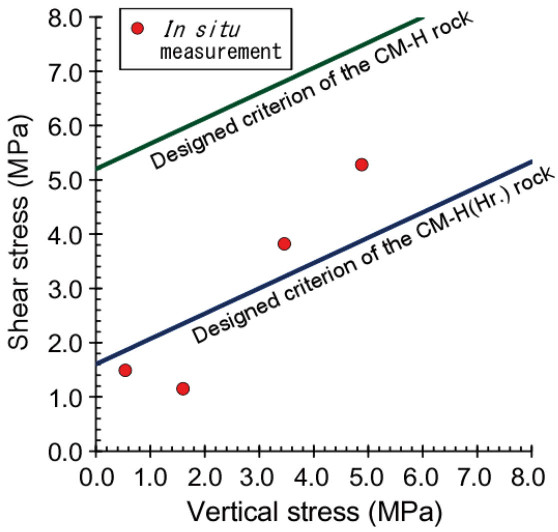


(b) GL−350 m gallery

Fig. 2.4.3-10 Results of the plate-loading tests



(a) GL−250 m gallery



(b) GL−350 m gallery

Fig. 2.4.3-11 Results of the direct shear tests

The investigation methods, modeling, and analysis techniques for the rock mechanical field are not dependent on the rock type.

(3) Thermal gradient distribution

1) Mizunami

Temperature logging was performed in borehole MIZ-1, which was drilled from the ground surface. The calculated thermal gradient was approximately 1.9°C /100 m, in good agreement with the value obtained from boreholes around MIU (about 2.0°C /100 m)[19].

2) Horonobe

After the surface-based investigation, a long-term hydraulic monitoring system was inserted in borehole HDB-3. The temperature was measured using the system at various depths. The results showed that the geothermal gradient around the Horonobe URL is approximately 4.6°C /100 m[17].

(4) Thermal properties of rock

1) Mizunami

The thermal properties of Toki Granite obtained from borehole MIZ-1 were: thermal conductivity 2.77–3.04 W/m・K; specific heat 0.74–0.93 J/g・K; and thermal expansion coefficient 4.0–5.6 × 10^{-6} /°C[20]. Comparison of the statistical properties between Toki Granite obtained from MIU and those obtained from the literature survey was performed. It was confirmed that there was no great difference between them.

2) Horonobe

In the surface-based investigation, the thermal properties of the rock mass were also obtained. The results showed that the thermal conductivity of the Koetoi Formation was 0.88 to 1.17

W/m·K and the value for the Wakkanai Formation was 1.24 to 1.61 W/m·K. The specific heat in saturated conditions of the Koetoi Formation was 1.88 to 2.67 J/g·K; that of the Wakkanai Formation was 1.34 to 1.53 J/g·K. In dry conditions, the specific heat values of both formations were 1.34 to 1.53 J/g·K. The thermal expansion coefficients were about 5 to 7 × 10^{-6}/°C in the Koetoi Formation and 9 to 14 × 10^{-6}/°C in the Wakkanai Formation. The coefficients of thermal expansion decrease as temperature increases[21).

Techniques to understand the thermal properties of rock by laboratory tests using core specimens are applicable to many rock types.

2.4.4 Summary

The principal stresses and the directions were understood by in situ stress measurements, and the applicability of the techniques and analysis methods was tested at Mizunami and Horonobe. An analysis method for regional stress field was developed. The statistics and depth distribution of physical and mechanical properties of rock were understood. In situ loading tests and direct shear tests were conducted at Horonobe.

It was shown that evaluation of the in situ stress field and mechanical properties of rock are possible using in situ and laboratory tests together with numerical analysis.

Accumulation of knowledge about the in situ stress and mechanical properties of rock is necessary to provide information for the design of the underground facility at a disposal site.

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2.5 Mass transport

2.5.1 Introduction

As part of the study of mass transport conducted for understanding the retardation effects on mass transport in rock masses and groundwater, we have been working toward understanding the initial conditions of the geological environment as assessed by surface-based investigations, with the aim of developing and applying investigative, analytical, and evaluation techniques with a focus on the properties and processes in the geological environment as shown in (1) and (2) below[1),2)] (Fig. 2.5.1-1).

(1) Understanding the sorption and diffusion properties of rock mass

From the perspective of safety assessment of geological disposal, it is important to understand the initial conditions of a rock mass in terms of sorption and diffusion properties. Moreover, it is essential to establish techniques to obtain reliable data for such properties, in addition to the techniques for analyzing and evaluating them.

(2) Understanding the effects of colloids, organics, and microbes

As the presence of colloids, organics, and microbes in the geological environment affects the mass transport properties of a rock mass in various ways, it is necessary to develop individual elemental techniques that can be used to understand the factors in a specific given geological environment as well as to systematize the investigation, analysis, and evaluation techniques. These tools are essential to understand the initial conditions of the geological environment.

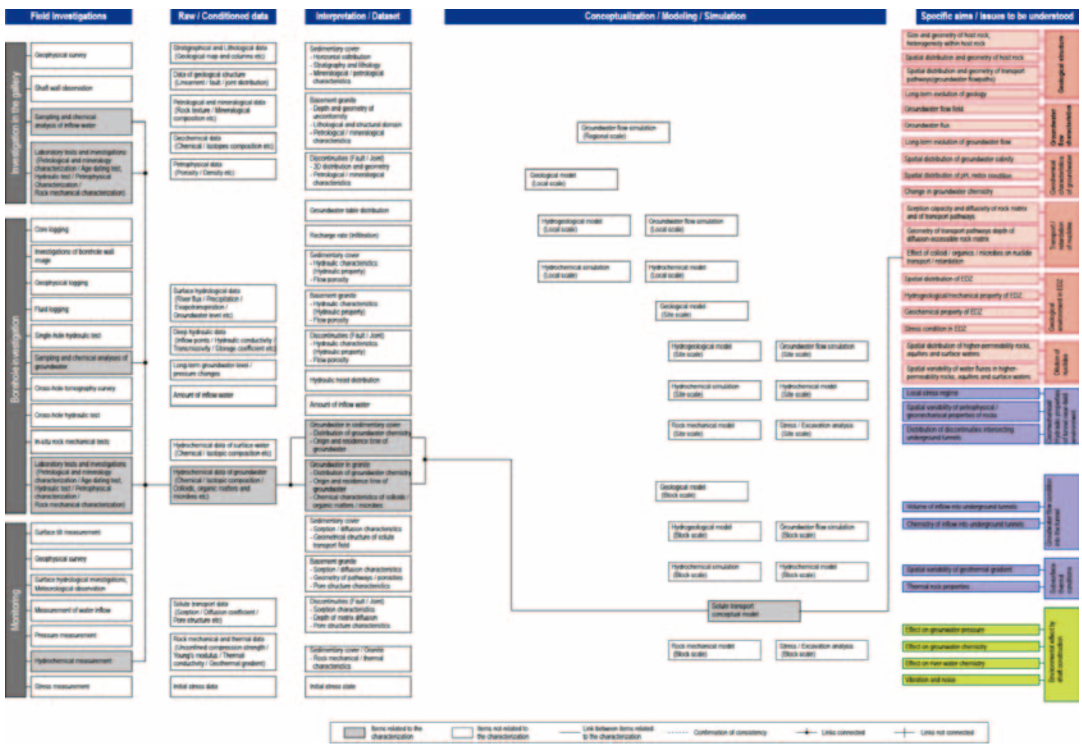

Fig. 2.5.1-1 Geosynthesis data flow diagram (mass transport study)[2)]

2.5.2 Objectives in the second mid-term research phase

Research in the underground facilities must produce outcomes and scientific knowledge that can be reflected in the decision-making concerning site selection, construction of facilities, commencement of disposal, completion of placement of waste packages, and final sealing in the actual disposal operation. The level of technical development in the context of understanding the initial conditions of the geological environment, is the establishment of investigation and evaluation techniques for identification of favorable environmental conditions in terms of mass transport in a rock mass by means of surface-based investigations and the confirmation of the applicability of such techniques, as well as the systematization of the series of techniques from investigation to analysis/evaluation (Table 2.5.2-1).

During the second mid-term research phase, we conducted investigations and studies addressing themes (1) and (2) described in 2.5.1. These investigations and studies were conducted using the boreholes drilled from the surface, drillcore and groundwater samples, and vertical shafts and horizontal galleries reaching depths of 500 m at Mizunami and 350 m at Horonobe. We conducted laboratory tests, analyses, and evaluations concerning mass transport to establish investigation techniques and accumulate data/knowledge.

Table 2.5.2-1 Performance target of R&D for the mass transport study

Focus	Performance target of R&D	Tasks
Siting decision	To identify the domain that is favorable for the mass transport study.	Sorption capacity and diffusivity of rock matrix and of transport pathways • Development of high-reliability technologies and methods for investigation, analysis and evaluation • To obtain mass transport parameters by laboratory experiment
		Effect of colloid/organics/microbe on nuclide transport/retardation • Development of investigation technologies for understanding phenomena affecting mass transport by laboratory experiment

2.5.3 Project details and outcomes

(1) Understanding rock mass sorption and diffusion properties

Sorption and diffusion in the geological environment are important phenomena controlling the retardation of nuclide transport. The sorption and diffusion phenomena vary greatly depending on the solid-phase mineral composition and pore structure, the groundwater chemistry and porewater chemistry, the state of dissolved nuclides in water (chemical species), and other physicochemical conditions. From this perspective, we performed various analyses and laboratory tests to obtain basic data such as chemical composition and mineral composition of the rock masses selected for study and to understand the sorption and diffusion properties of rock.

1) Mizunami

We acquired lithological and mineralogical data such as whole-rock chemical composition and mineral composition using rock samples obtained from boreholes drilled from the surface[3]. In addition, we started laboratory through-diffusion tests using the drillcore samples, with the aim of obtaining a detailed understanding of the relationship between fracture characteristics and mass transport parameters. In intact Toki Granite, we determined that the effective diffusion coefficient for substances such as non-sorbing tracer uranine (a fluorescent dye) ranged from 10^{-14} to 10^{-13} (m^2/s)[4,5] (Fig. 2.5.3-1).

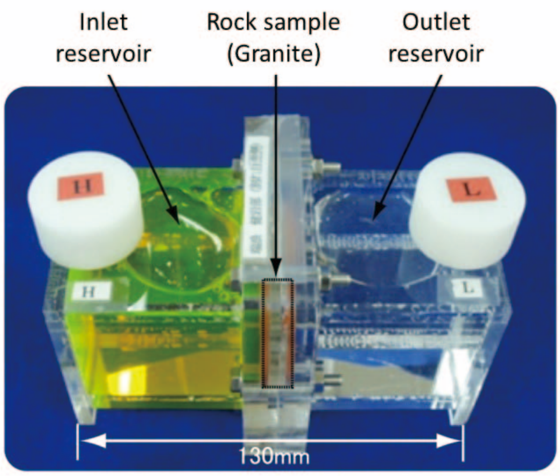

Fig. 2.5.3-1 Laboratory through-diffusion testing equipment

2) Horonobe

We acquired lithological and mineralogical data such as whole-rock chemical composition and mineral composition using rock samples obtained by surface geological investigations and surface-based borehole investigations[6),7),8], and also acquired data concerning mass transport properties, including porosity, pore size distribution, and other physical properties[9,10]. In addition, using core samples obtained from surfaced-based borehole investigations, we performed laboratory mass transport tests and determined the effective diffusion coefficient[11,12,13,14,15]. Furthermore, we developed methods for laboratory mass transport tests to obtain highly reliable sorption and diffusion parameters for a variety of elements and environmental conditions, and the measured sorption and diffusion parameters using non-sorbing tracers (Cs, I, and HTO) and highly sorbing tracers (e.g., Ni, Np, Am, Th, and Se)[16,17] (Fig. 2.5.3-2). The laboratory test methods employed were the batch method and the newly developed expanded through-diffusion/reservoir depletion method[18,19] (Fig. 2.5.3-3).

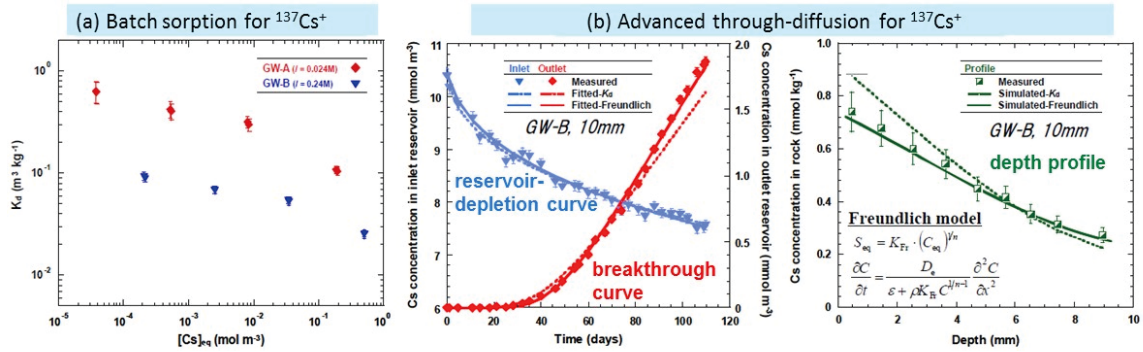

Fig. 2.5.3-2 Results from the laboratory experiment
(a) batch sorption, (b) advanced through-diffusion experiments

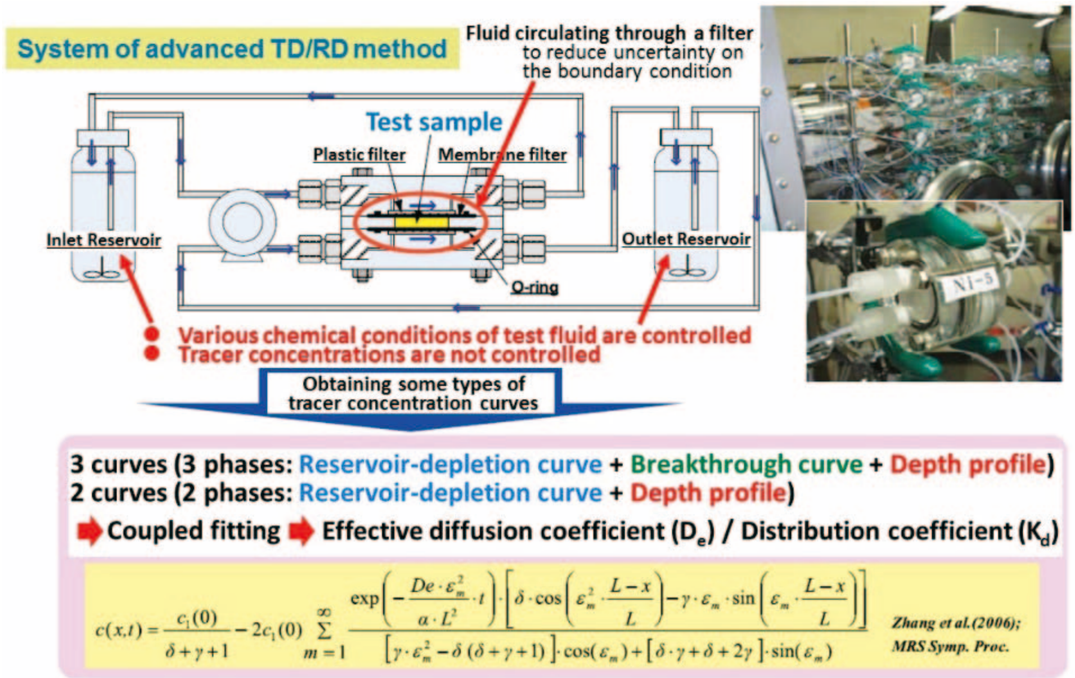

Fig. 2.5.3-3 Advanced through-diffusion/reservoir-depletion method

(2) Understanding the effects of colloids, organics, and microbes

We developed investigative techniques to understand the effects of colloids, organics, and microbes on mass transport in the underground environment. Because the mass transport in a rock mass depends on fluid media, and one of these fluids is groundwater, we conducted investigations and analyses to understand the phenomena that occur in the geological environment, focusing on groundwater–rock–colloids/organics/microbes interactions and the characteristics of mass transport. This enabled us to confirm the presence of colloids, organics, and microbes in the geological environment, demonstrating the necessity of future studies of their possible effects on the characteristics of mass transport and evaluation of these effects.

1) Mizunami

Confirmation of the presence or absence of microbes in groundwater and measurement of viable cell counts for sulfate-reducing bacteria and iron bacteria were performed using groundwater obtained from boreholes drilled from the surface. The results showed a total cell count of approximately 10^6 cells/ml, which is comparable to the abundance of marine bacteria[20]. In addition, it was demonstrated that sulfate-reducing bacteria were only found at particular depths, suggesting the formation of a microbial community structure reflecting the geochemical conditions[20),21)] (Fig. 2.5.3-4).

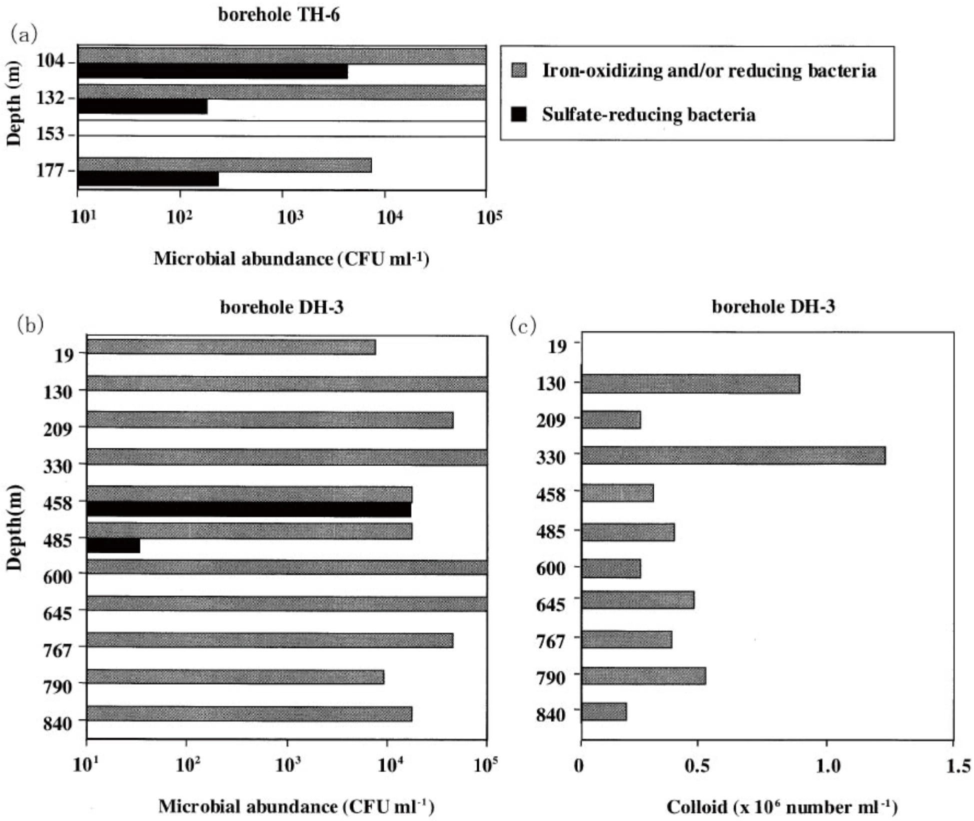

Fig. 2.5.3-4 Depth profiles of (a) sulfate-reducing bacteria, (b) iron-related bacteria, and (c) colloidal particles in the groundwater in the Mizunami area[20]

2) Horonobe

We examined the composition of natural colloids in groundwater and their interactions with substances such as rare earth elements in order to understand the forms and transport behavior of colloids in groundwater. The results showed that colloidal particles in groundwater mainly consisted of silicate minerals, phosphate minerals, carbonate minerals, and sulfate minerals. In addition, it was determined that lighter rare earth elements became incorporated in colloids more readily than heavier rare earth elements.

Groundwater from this site had a total organic carbon concentration between several and several tens of mg/l[22]. The concentration of dissolved organic matter at the Horonobe site is higher than that in groundwater in crystalline rocks (such as the groundwater at Mizunami), and hence the influence of mass transport behavior on organic matter is likely to be obvious. The study of the properties of organic matter (mainly humic substances) in groundwater from shallow and deep layers conducted for this reason indicated that the molecular weight distribution of humic substances may be uneven[23)]. In addition, a study using dissolved humic substances isolated and purified from groundwater from the Koetoi and Wakkanai Formations (Fig. 2.5.3-5) showed that those humic substances had low molecular weights (similar to those from other locations in Japan[24)]), were rich in aliphatic carbon, and there were no differences in structural characteristics between the two formations. The structural characteristics resemble those of humic substances originating from organic matter derived from aquatic life (e.g., in Lake Biwa).

To assess the effects of microbes in groundwater, we conducted measurements of total cell counts and genetic analysis using groundwater obtained from boreholes drilled from the surface. The total cell count ranged from 10^4 to 10^6 cells/ml with no depth-dependence[22)]. In addition, the presence of microbes that influence degradation of aromatic compounds, ammonia oxidation, nitrite oxidation, sulfur oxidation, methane oxidation, nitrate reduction, sulphate reduction, and denitrification in the nitrogen cycle was confirmed, as well as the dominance of a single strain of methane-producing microbes[25)]. The results suggested a tendency for microbial composition to differ greatly across a fault[25)] and a possibility of a relationship between geological structure and the structure and activity of microbial communities[26)] (Fig. 2.5.3-6).

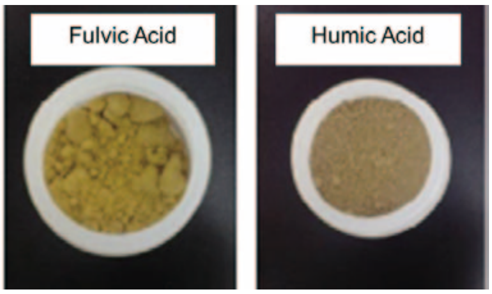

Fig. 2.5.3-5 Humic substances in groundwater at the Horonobe

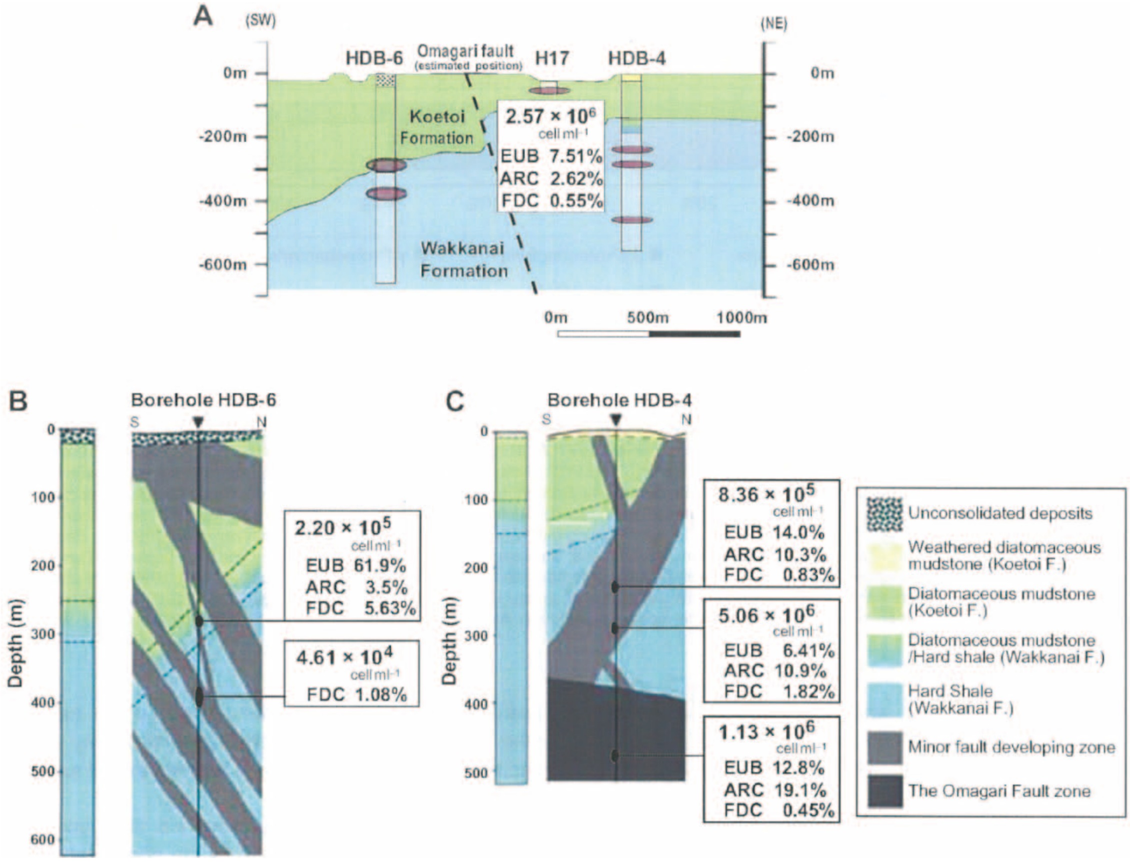

Fig. 2.5.3-6 Microbial populations related to geological setting in the Horonobe area[26)]

2.5.4 Summary

We obtained the basic information required to understand the characteristics of mass transport in the geological environment by means of surface-based investigations. The following list summarizes our technical findings.

(1) Understanding the sorption and diffusion properties of rock mass

- From the analysis of core samples, we obtained the whole-rock chemical composition, mineral composition, porosity, pore size distribution, and other data providing basic information concerning mass transport in rock masses (for both sites).
- Using laboratory mass transport tests, we obtained the sorption and diffusion parameters such as the effective diffusion coefficient (for both sites).
- Using the expanded through-diffusion/reservoir depletion method, we made it possible to obtain highly reliable sorption and diffusion parameters for various elements and environmental conditions (for Horonobe).

(2) Understanding the effects of colloids, organics, and microbes

- Colloid particles in groundwater mainly consist of silicate minerals, phosphate minerals, and sulfate minerals, and are considered to affect the mass transport behavior of substances such as rare earth elements (Horonobe).
- Although no relationship was detected between the organic matter concentration in groundwater and the major chemical concentrations, the influence of mass transport

behavior on organic matter concentrations is likely to become obvious (Horonobe).

- Because the humic substances in the groundwater from Horonobe are similar to those in the groundwater at other locations in Japan, it is necessary to evaluate the effects of organic matter in groundwater on mass transport as a generic property (Horonobe).
- The total cell counts of microbes in groundwater are comparable to the abundance of marine bacteria. As the microbial composition varies depending on fault structures and particular depths, it is possible that there are relationships linking geological structures and geochemical environments to the distribution and activity of microbes (Mizunami and Horonobe).

For understanding the sorption and diffusion properties of a rock mass, the concrete theme of a future study is to perform in situ tests in the galleries and laboratory tests for the purpose of establishing techniques and collecting data on mass transport in the rock mass as well as sorption and diffusion parameters.

With respect to the effects of colloids, organics, and microbes, which have been difficult to assess using surface-based investigations, the concrete theme for another future study is to assess these issues using samples of controlled quality.

From the perspective of safety assessment, it is extremely important to understand the characteristics of mass transport in the geological environment by surface-based investigations in decision-making concerning site selection. Therefore, an important theme is provision of examples of investigation, analysis, and evaluation techniques through the investigations and research at the Mizunami URL and the Horonobe URL.

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2.6 Engineering technology for deep underground applications

2.6.1 Introduction

The underground research laboratory projects will provide the opportunity to demonstrate the feasibility of safe and reliable construction, maintenance, and management of an underground research facility by applying conventional and state-of-the-art engineering technology in a deep geological environment. Engineering technologies, such as design, construction planning, construction, countermeasures, and safety management, have been applied to Mizunami and Horonobe.

2.6.2 Objectives in the second mid-term research phase

The objectives of engineering technology for deep underground application during the second mid-term plan are to test the applicability of construction and countermeasure technologies, maintenance technology during extensions of shaft and gallery at depths of 500 m (Mizunami) and 350 m (Horonobe). Design and construction planning technologies have been also estimated during this phase. Table 2.6.2-1 shows the performance target level of technical development for engineering technology.

Table 2.6.2-1 Performance target of R&D for engineering technology

Focus	Performance target of R&D	Tasks
Decision-making for start of construction	Decision and planning the construction of underground facilities.	• Design methodology of construction of underground facilities ◆Stability of underground operation ◆Design of support ◆Earthquake-resistant design • Technology of planning of underground facilities

2.6.3 Project details and outcomes

(1) Design and construction planning technologies

1) Mizunami

The shafts and galleries were excavated based on the results of the design and construction plan at the Phase I. Confirmation of the design and construction plan was carried out by evaluation of data obtained during excavation to a depth of 500 m. The conclusions are as follows[1),2),3)]:

- Parameters, such as rock mass classification, rock properties, and stress release ratio, which were used for numerical analysis of rock mass behavior of the Ventilation Shaft excavated in good rock conditions during the surface-based investigation phase, were variable (Fig. 2.6.3-1, Table 2.6.3-1).
- On the other hand, a fault with an altered zone was observed at the Main Shaft. The support system which was designed during Phase I were applied with minor changes to the specifications to the excavation of the Main Shaft. As deformation of the supports was

not observed, the design methodology applied to the Mizunami can be used in a wide range of geological conditions.

- Pilot borehole investigations are useful for both estimation of the applicability of the support system and also for planning countermeasures to water inflow at the Ventilation Shaft and the −300 m access/research gallery[4].
- It was observed that the intensity of earthquake motion increases from deep underground to the shallow surface. Numerical simulations were carried out to compare the analytical results with observed records. The calculated results agreed well with the observed values (Fig. 2.6.3-2, Fig. 2.6.3-3)[5].
- The excavation cycle time was recorded during Ventilation Shaft sinking and compared with the planned excavation cycle time for evaluation of the baseline design plan. The recorded results indicate that actual cycle time was longer than those listed in the plan because of safety matters and maintenance of the equipment[6),7].

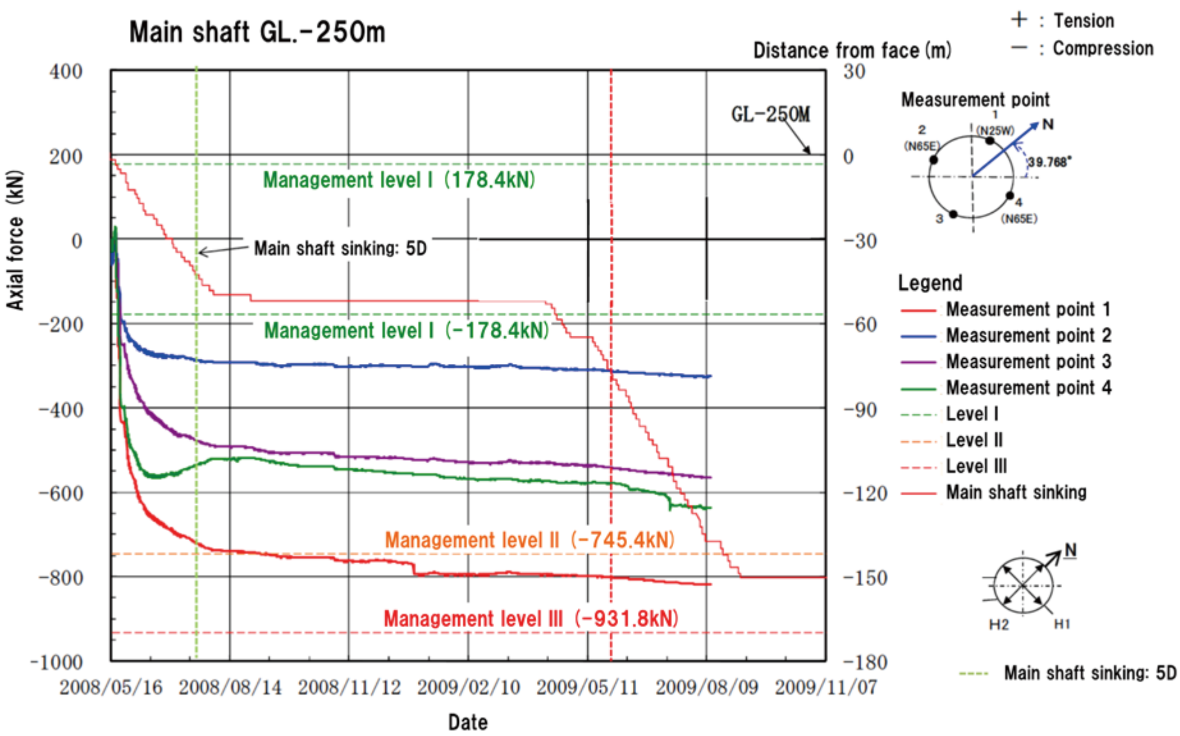


Fig. 2.6.3-1 Measurement results of the axial forces of the steel support for the Main Shaft (G.L. −250 m) (Mizunami)

Table 2.6.3-1 Evaluation of B-measurement results for the Main Shaft (Mizunami)

Measurement depth	G.L. −250 m	G.L. −450 m
Steel support	There were some data exceed management level II, steel support were functioning, in general.	There were some data exceed management level II, steel support were functioning, in general.
Concrete liner	All the data were within management level II.	All the data were within management level I.
Convergence	Anisotropic displacement closed to management level II, but it converged.	Displacement was within management level I, it converged.
Evaluation	Stress of concrete lining was 17N/mm^2. Shaft was stable, but it is necessary to monitor concrete liner.	Stress of concrete lining was 12N/mm^2. Shaft was stable, but it is necessary to monitor concrete liner.

Data No.	Date	Hypocenter	Seismic intensity at Site	Max. Acceleration (gal) of each direction		
				Ground surface	GL-100m	GL-300m
1	2008.11.24 06:15	East MINO, Gifu Depth 11km M:3.9	1	12.0 E-W	6.6 E-W	−
2	2009.5.25 20:26	West, SHIZUOKA Depth 26km M:4.7	2	5.6 E-W	3.1 E-W	1.8 N-S
3	2009.7.14 03:57	East MINO, Gifu Depth 50km M:3.5	2	6.5 E-W	3.2 E-W	1.9 N-S
4	2009.7.27 09:44	West, AICH Depth 41km M:4.0	2	8.2 N-S	3.1 N-S	1.9 E-W
5	2009.8.11 05:07	Suruga Bay Depth 23km M:6.5	3	30.8 E-W	14.7 N-S	6.6 E-W
6	2011.3.11 14:46	Sanrikuoki Depth 24km M:9.0	3	10.4 N-S	7.7 N-S	5.0 U-D
7	2011.12.14 13:01	East MINO, Gifu Depth 49km M:5.1	3	66.6 U-D	39.6 E-W	28.6 E-W

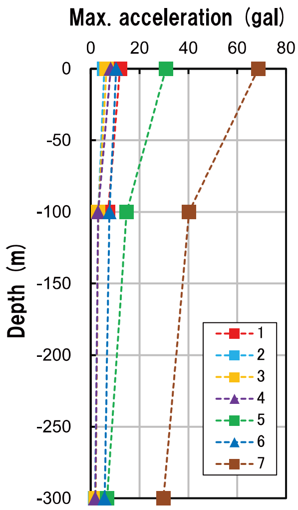


Fig. 2.6.3-2 Measured maximum acceleration values of earthquakes (Mizunami)

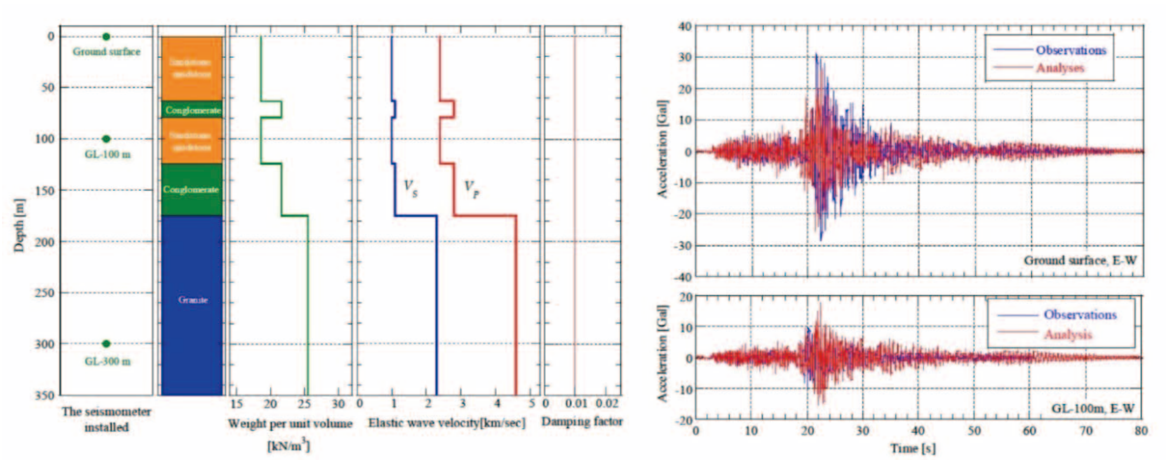


Fig. 2.6.3-3 Comparison of measured and analyzed motion of the Suruga Bay earthquake (2009.8.11)

2) Horonobe

In the Horonobe URL, the stability of the support and the mechanical behavior of the rock mass around shafts and horizontal galleries were analyzed on the basis of in situ measurements such as stress on lining, steel arch libs, and rock bolts, and numerical simulations (three-dimensional excavation analysis). In shaft sinking and excavations of horizontal galleries, consuming time for excavation and mucking, i.e., cyclic time was analyzed; then compared with geological observations and laboratory tests. On the basis of these investigations, the validity of the design and plan of construction were assessed. The results are summarized as follows:

- The relationship between the initial deformation rate, the final deformation, and the stress of the concrete lining was suggested for use as a practical guide in shaft sinking[8),9)].
- Analyses of the relationship between the initial deformation rate, observed deformation, ratio of the modulus of elasticity of rock mass to the initial stress, and magnitude of inelastic behavior of rock based on convergence measurements and investigation of rock mass properties on shaft walls were conducted to construct a classification of rock mass behavior in shaft sinking[8),10)]. This classification is useful to predict the rock mass behavior and stress on the lining caused by excavation work at the earlier stage.
- From analysis of the effects of rock bolts on the deformation of rock and lining in shaft sinking, a support pattern that omits the installation of rock bolts was suggested and applied in subsequent shaft sinking[11)].
- The results of three-dimensional stress analysis showed that the minimum and maximum stresses on the concrete lining occurred in the direction of the maximum and minimum horizontal stress, respectively (Fig. 2.6.3-4). Considering the result of stress analysis of a concrete lining, a stress meter for a concrete lining should be installed at an inner and lower position in the direction of the minimum horizontal stress in order to estimate the stability of the support system of a shaft (Fig. 2.6.3-5)[12),13),14)].
- Fractures were newly created and developed around the wall of the shaft during the excavation process. After the concrete lining was installed, these fractures would be closed. As a result of this behavior, it was determined that the concrete lining gradually deformed from an original cylindrical form to an elliptical shape with the long axis parallel to the direction of the minimum horizontal principal stress[15)].
- In shaft sinking, the mechanical behavior of the concrete lining and the rock mass around the shaft wall is affected by inhomogeneity of the stress conditions and construction procedures. For the design of a support pattern and planning of in situ measurements, it is necessary to understand the behavior of the support and the rock mass prior to excavation on the basis of the results of three-dimensional excavation analysis considering the stress conditions and construction procedure.
- The relationship between the progress of shaft sinking (cyclic time) and rock mass classification was analyzed. The results showed that the time required for shaft sinking by mechanical excavation and by the drill-and-blast method were almost identical. Also, the relationship between rock mass classification and cyclic time has a correlation[16)].

- In shaft sinking, analysis of the relationship between the specific energy required for excavation using a boom header and the mechanical properties of rock was conducted. As a result, the rock mass property will be determined using the measurement value of specific energy[17),18),19)].

The excavation of galleries perpendicular to the orientation of the natural fractures yielded faster excavation rates than the excavation of galleries parallel to the orientation of natural fractures when tunneling through the soft sedimentary rocks using an impact hammer in the Horonobe URL (Fig. 2.6.3-6)[20)].

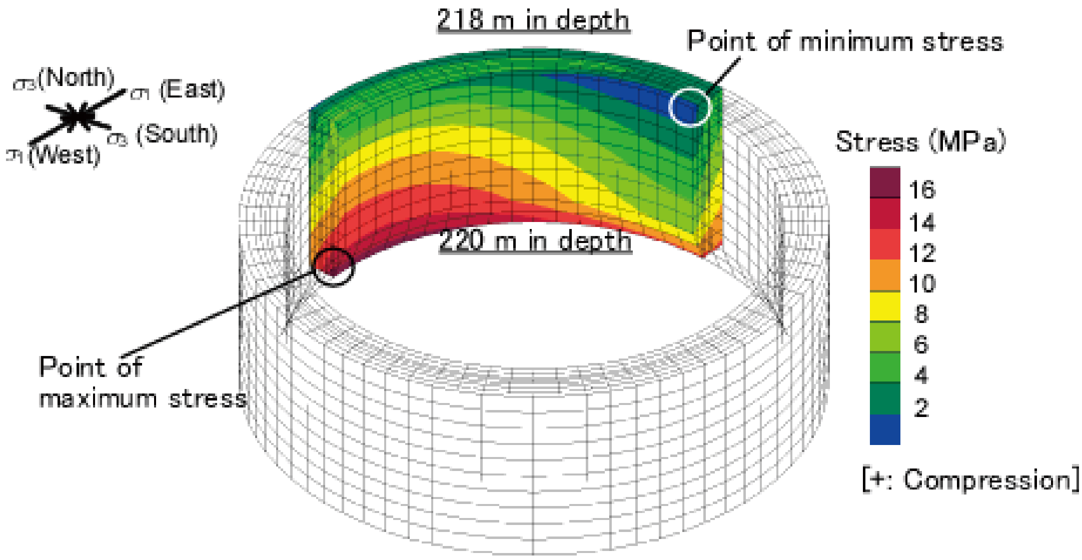
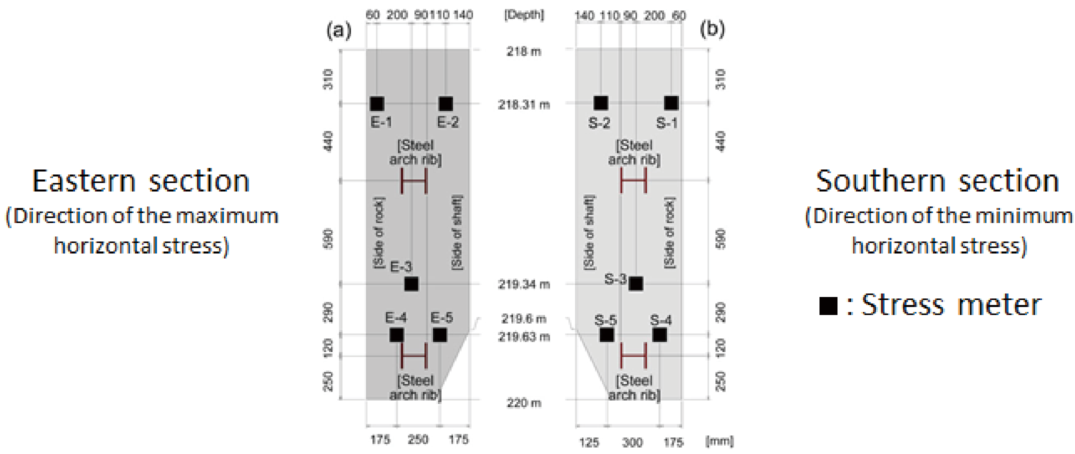
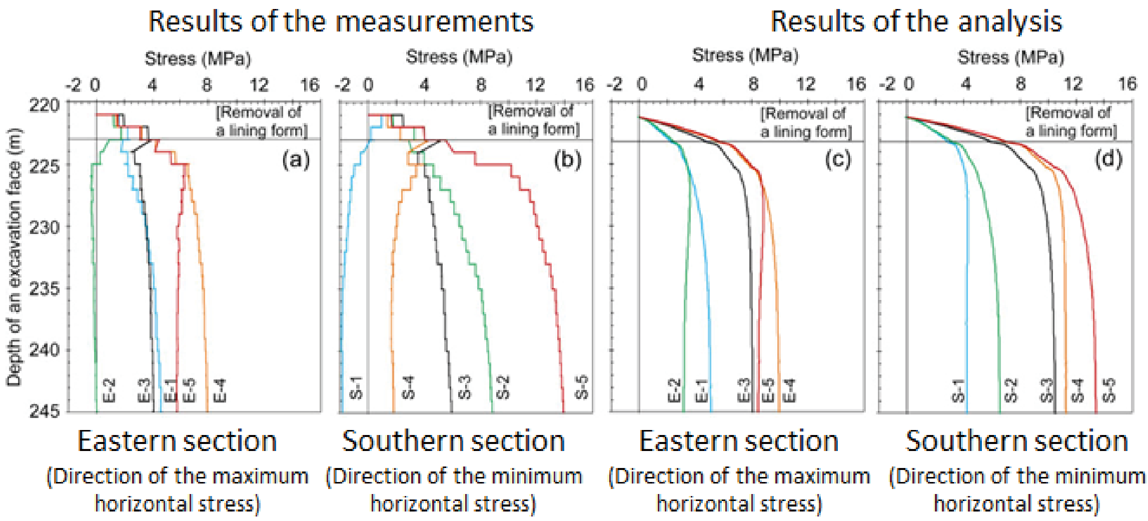


Fig. 2.6.3-4 Distribution of circumferential stress on concrete lining[14)]



(a) Layout of stress meters in the concrete lining between 218 m and 220 m depth



(b) Change in circumferential stresses as an excavation face advances

(+: compressive, −: tensile)

Fig. 2.6.3-5 Measured and analyzed results of circumferential stresses in a concrete lining[13)]

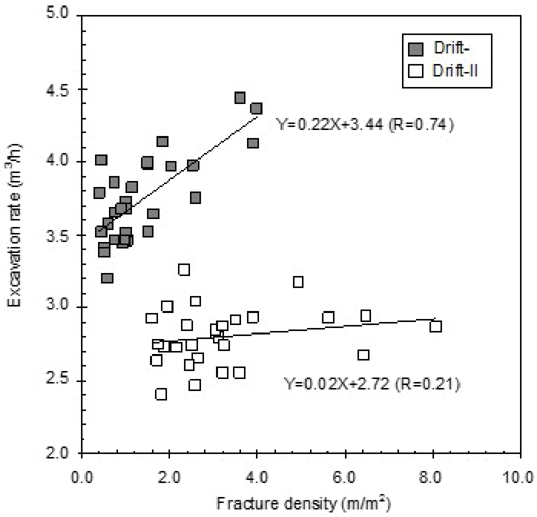


Fig. 2.6.3-6 Relationship between excavation rate and fracture density in Drifts I and II (Drift I: excavated perpendicular to the orientation of pre-existing fractures; Drift II: excavated parallel to the orientation of pre-existing fractures)[20]

The design and construction planning technologies applied during the excavation of shafts and galleries at Mizunami and Horonobe are considered as the generic engineering technology for road and railway tunnels and could be applied to the various kinds of rock types. These technologies should be treated carefully as countermeasures against large amounts of water inflow are required at Mizunami, and a mechanical stability and support system is necessary at Horonobe. However, insufficient preliminary investigations have been performed in excavations of road and railway tunnels. Pilotborehole investigations are useful for decreasing the uncertainty related to the geological environment. The results at Mizunami and Horonobe are recognized as good practice.

2.6.4 Summary

The effectiveness of estimation of the mechanical stability of underground openings and support systems and the earthquake-resistance design has been confirmed based on the results of excavation of shafts and galleries at Mizunami and Horonobe. It was determined that the intensity of earthquake motion increases from deep underground to the shallow surface. For construction planning technology, the excavation cycle time was recorded during shaft sinking then compared with the planned excavation cycle time for the purpose of evaluating the baseline design plan.

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2.7 Geosphere stability for long-term isolation of radioactive waste

2.7.1 Introduction

The framework of the research on geosphere stability for long-term isolation of high-level radioactive waste is structured into three categories to contribute to the site selection and the national safety regulation of the final disposal. These three categories are: development and systematization of investigation techniques; development of models for long-term estimation and effective assessment; and development of dating techniques. Development and systematization of investigation techniques aims to construct the technical bases whether the geological environments at the candidate disposal sites satisfy the stepwise site selection requirements of the Specified Radioactive Waste Final Disposal Act, the environmental requirements of safety regulations, and other considerations, through the preliminary investigation and the detailed investigation. This report documents the main results from the research and development.

2.7.2 Targeted level of technology development

The scientific program for fiscal years 2010–2014 was set taking into account the importance and urgency of the needs of the implementing bodies and the regulatory agencies[1),2),3),4),5)] with attention to acts and reports after having investigated the trend of basic research in universities as well as related research institutes (Table 2.7.2-1).

Table 2.7.2-1 Performance target of R&D on geosphere stability for long-term isolation

Focus	Performance target of R&D	Tasks
Decision on site selection	Enable investigation of faults with unclear tectonic landforms.	Investigation techniques for active faults with unclear tectonic landforms • Development of investigation technique using the geochemical characteristics of gas released from the fault
	Enable estimation of the presence or absence of an earthquake source fault and high-temperature fluid in deep underground.	Investigation techniques for earthquake source faults in the crust • Development of an investigation technique using the resistivity structure determined by the magnetotelluric method
	Enable understanding the activity of fault which can't apply the approach using cover sediments.	Investigation techniques for fault activity in basement rock • Development of an investigation technique with the material science and radiometric age of faulted materials infilling fractures
	Enable estimation of the uplift, subsidence, and erosion rates in inland areas that have poorly developed river terraces.	Investigation techniques for estimation of uplift and erosion rates in inland areas • Development of an investigation technique for erosion rate using an old river valley around a detached meander core • Development of an investigation technique for uplift and erosion rates based on thermochronology

2.7.3 Project details and outcomes

(1) Investigation techniques for active faults with unclear tectonic landforms

Earthquake faulting is one of the most important factors affecting the long-term stability of a geological disposal system, because a faulting could cause dynamic destruction of basement rocks. Recently, some large earthquakes have occurred in several areas where active faults with geomorphological signature[6),7)] have not been detected, implying the existence of concealed active faults. Therefore, we developed a geochemical approach based on terrestrial gases along faults to detect concealed active faults. In the second mid-term research phase, we observed a wide variety of chemical components (He, Ar, CO_2, and H_2) of terrestrial gases along faults, indicating that active faults may be major leaks or pathways in the crust for these gases[8)]. In particular, helium isotopes provide an excellent geochemical tracer to detect immature faults at an early stage of their evolution (i.e., concealed active faults without geomorphological and geological expression), as suggested by observations in and around the seismic source region of the western Tottori earthquake and the Itoigawa–Shizuoka Tectonic Line (ISTL).

An inland earthquake (M 7.3) with no noticeable surface expression of faulting occurred in western Tottori in 2000, where no active fault was related to the earthquake. Groundwater samples collected in the aftershock area are characterized by helium isotope ratios ($^3He/^4He$) several times higher than the atmospheric value. The helium isotope ratios decrease with distance from the inferred fault segments[9] (Fig. 2.7.3-1). In addition, magnetotelluric soundings were taken in the aftershock area in order to estimate the subsurface electrical resistivity structure. These measurements detected an anomalous conductive body, which may be attributed to latent magma and related fluids, on the southwestern side of the source fault. These findings indicate that mantle helium is leaking from latent magma through the concealed faults[10].

The ISTL fault system can be divided into three distinct segments: northern, middle, and southern. The northern and southern segments are characterized by reverse faults. The middle segment of the ISTL contains strike-slip faults. The spatial variation of the helium isotope ratios of groundwater samples along the ISTL revealed that a high helium isotope ratio can be detected along active faults[11),12)] (Fig. 2.7.3-2), which can be interpreted as leakage of mantle helium within the crust migrating upward through reverse and strike-slip faults. The central Nagano earthquake (M 5.4) occurred near the Gofukuji fault, located in the middle segment of the ISTL, in 2011. The helium isotope ratio of groundwater samples collected before and after the earthquake showed no significant change[11),13)], indicating stable leakage of mantle helium along the active faults.

In future studies, geochemical data in a different area with different tectonics should be collected. In addition, construction of a technique that jointly incorporates geomorphological, geological, and geophysical findings for detecting concealed active faults will also be important.

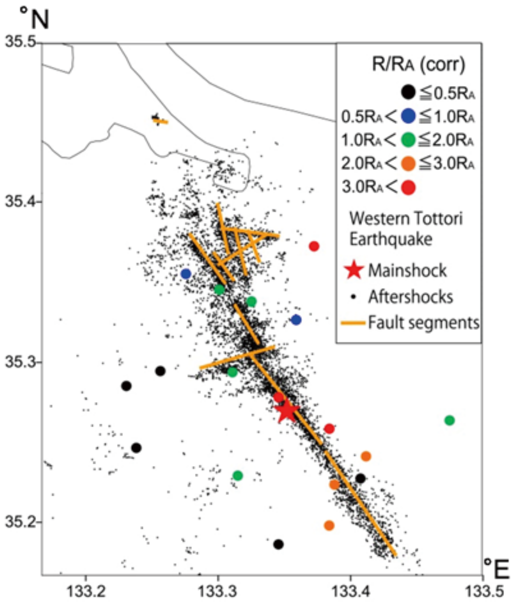

Fig. 2.7.3-1 Spatial distribution of $^3He/^4He$ ratios in groundwater around the source region of the 2000 western Tottori earthquake (after Umeda and Ninomiya (2009)[9]).

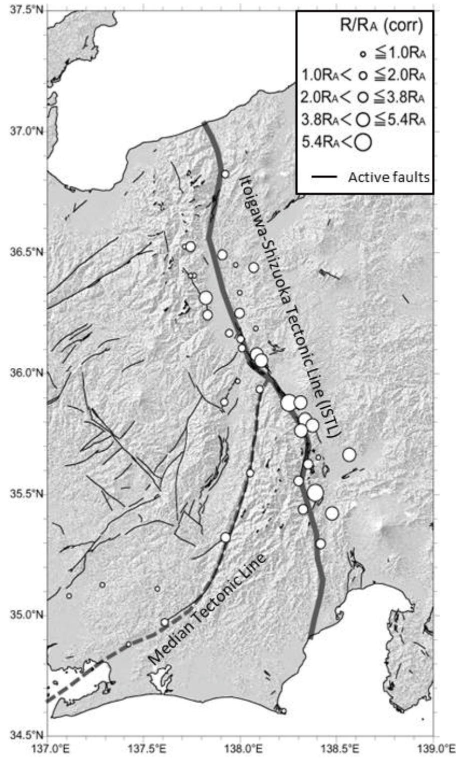

Fig. 2.7.3-2 Spatial distribution of $^{3}He/^{4}He$ ratios along the Itoigawa–Shizuoka Tectonic Line (ISTL) (after Umeda et al. (2013)[11])

(2) Investigation techniques for earthquake source faults in the crust

Earthquake faulting and volcanism are important factors affecting the long-term stability of geological disposal systems, because the intrusion of magma and fault movement could cause dynamic destruction of basement rocks. Recent studies have argued that the existence of aqueous fluids and melts in the crust may affect long-term fault evolution and earthquake generation[14] as well as volcanism. Magnetotelluric (MT) sounding is a powerful tool for detecting crustal fluids. However, there are several problems in correctly determining the crustal structure in Japan. The reliability of the resistivity structure determined by MT inversion analysis is affected by strong artificial noise, such as leakage currents from DC railways, and complicated three-dimensional (3-D) subsurface structure in and around the observation area.

We developed a weighted stacking method for use with data degraded by strong artificial noise, and demonstrated the validity of the method using synthetic and observed MT data[15),16] (Fig. 2.7.3-3). We also developed a 3-D MT inversion code with a heterogeneous smoothness-constrained least-squares method to allow modeling of resistivity boundaries in the subsurface structure[17]. In addition, we performed 3-D MT modeling in the source region of the 1997 Kagoshima earthquake doublet (M_j 6.5, M_j 6.3), where there have not been any obvious indications of active faulting at the surface prior to the events. A prominent conductive zone was revealed in the vicinity of the main shocks. The source faults of the earthquake doublet are located near the boundary between the conductive and the resistive part of the crust[18]

(Fig. 2.7.3-4).

These results indicate that the distribution of crustal fluids could contribute to detecting the existence of concealed source faults. A joint approach using the above-mentioned geochemical and geophysical techniques including MT sounding could reveal the distribution of partially melted zones [10),19),20),21),22)]. In future studies, seismological techniques such as seismic tomography should also be incorporated into this approach for detecting concealed source faults.

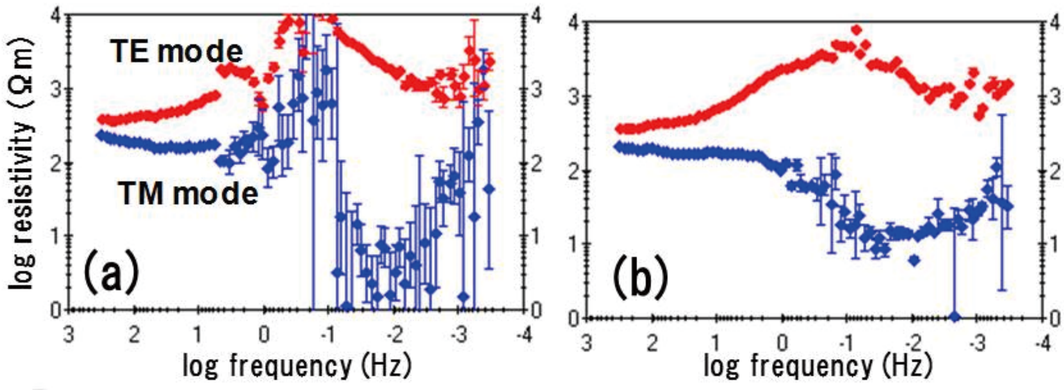

Fig. 2.7.3-3 An example of improvement in MT data quality. Observed (a) and stacked (b) apparent resistivity.

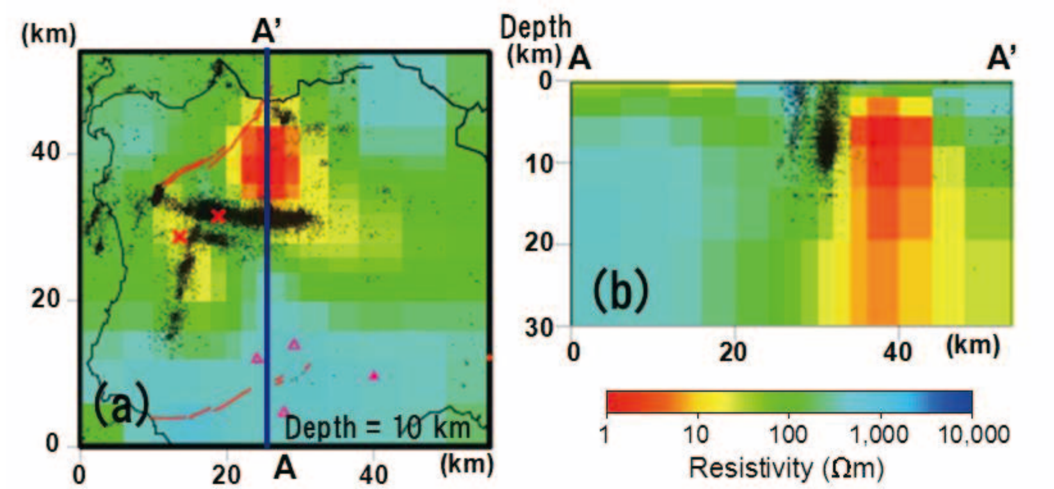

Fig. 2.7.3-4 3-D resistivity structure in the source region of the Kagoshima earthquake doublet (after Umeda et al. (2014)[18)]). Resistivity distribution at a depth of 10 km (a) and along cross-section AA' (b).

(3) Investigation techniques for fault activity in basement rock

Examination of fault activity is essential for safety assessment of a candidate site for geological disposal. In general, identification of recent fault activity is based on dating of faulted sediments, such as radiocarbon dating and tephrochronology. In that case, the age of undeformed sediments covering a fault provides information about the timing of the latest activity of the fault. However, this type of approach using cover sediments is not applicable to assessment of faults in basement rocks, for example, faults that are newly detected during borehole drilling or tunnel excavation[23),24)]. Mineralogical and chemical analyses of material infilling faults[25)] and radiometric dating of fault rocks[26)] have been proposed for the assessment of faults in basement rocks. During second mid-term plan, we carried out K–Ar dating of authigenic clay minerals formed as a result of fault activity.

JAEA possesses an installation for noble gas mass spectrometry that can be used for argon isotope analysis and flame photometry for measurement of potassium concentration. Specifically, the mass spectrometry in JAEA enables measurement of argon isotope ratios using the sensitivity method[27)], which is advantageous for precise dating for ages younger than 1 Ma. We collected <0.1 μm particle size fractions from fault gouge samples using a repetitive freezing and thawing technique and high-speed centrifugation[28)]. The particle size distribution of each fraction was examined using a laser diffraction-scattering particle size distribution analyzer. As a case study, we carried out K–Ar dating on clay fillings from fractures or faults in the Toki, Rokko, and Kojaku Granites of southwest Japan.

There are many faults in the Toki Granite, which is overlain by the Miocene Mizunami Group. K–Ar dating of two clay samples from these faults indicated that the finer fractions have younger K–Ar ages (Fig. 2.7.3-5). The K–Ar ages of the <0.1 μm fractions are 46.5 Ma and 42.7 Ma[29)]. These results suggest that the age of the finer clay minerals corresponds to the timing of more recent hydrothermal activity along faults, i.e., more recent fault activity. Thus, precise separation and collection of finer particle size fractions are important for identification of younger fault activity[28)]. The depositional age of the Mizunami Group (ca. 20 Ma) and the cooling history of the Toki Granite[30)] are consistent with the results of K–Ar dating[29)].

The K–Ar ages of fault gouge samples from the Arima–Takatsuki Tectonic Line in the Rokko Granite also indicated that finer fractions have younger K–Ar ages[31)]. The youngest age in the finest fractions is 23 Ma (Fig. 2.7.3-6). There is still a discrepancy between the K–Ar age and the age of the latest activity of the Arima–Takatsuki Tectonic Line. K–Ar dating may be difficult to apply to any determination of the timing of subsurface fracturing, at least in the studied area[28),32)]. However, K–Ar dating could be informative for assessment of coupling of main faults and subfaults, and estimation of the extent of fault damage.

The K–Ar ages of clay fillings in fractures in the Kojaku Granite in the Tsuruga Peninsula also show that finer fractions have younger K–Ar ages (Fig. 2.7.3-7). In electron microscopy, specular illite, which is typically formed as a result of fault activity and subsequent hydrothermal alteration, was invisible in the fine clay fractions. Most clay minerals are flaky or platy. These clay infillings could have been derived from hydrothermal alteration at ca. 50 Ma and subsequent weathering[33)].

As future work, application of radiometric dating to veins such as carbonates displaced by faults, as well as mineralogical and chemical analysis of faulted materials, are recommended.

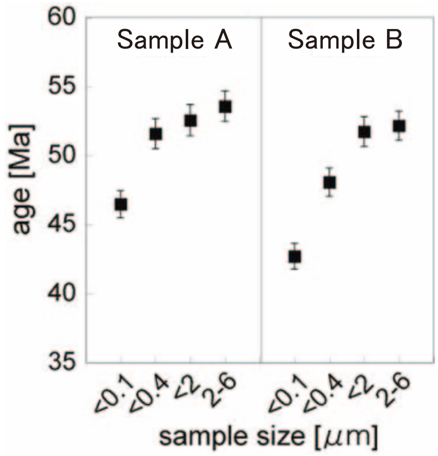

Fig. 2.7.3-5 Results of K–Ar dating for fault gouges from the Toki Granite
Error bars indicate standard deviation (2σ)[31].

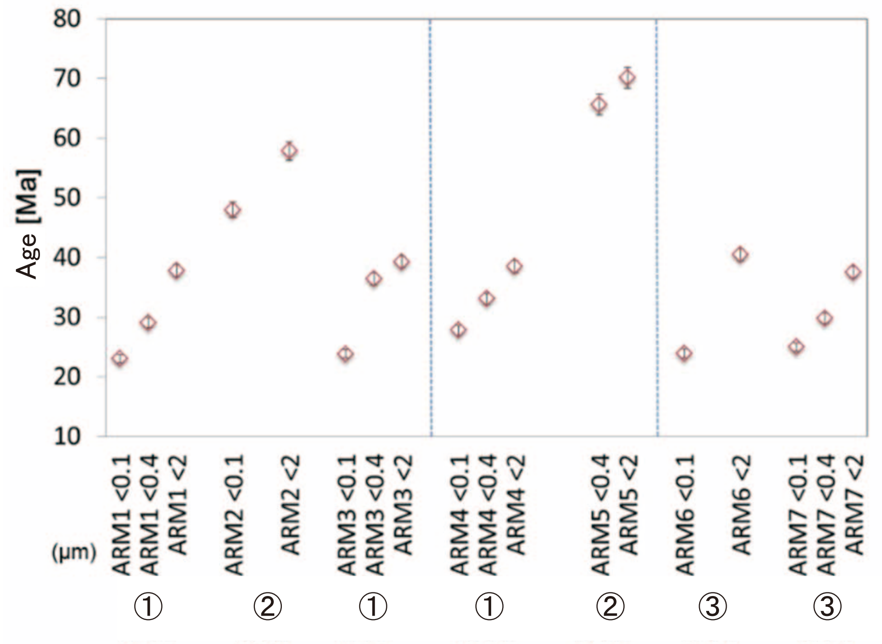

Fig. 2.7.3-6 Results of K–Ar dating for fault gouges from the Arima–Takatsuki Tectonic Line
Error bars indicate standard deviation (2σ)[31].

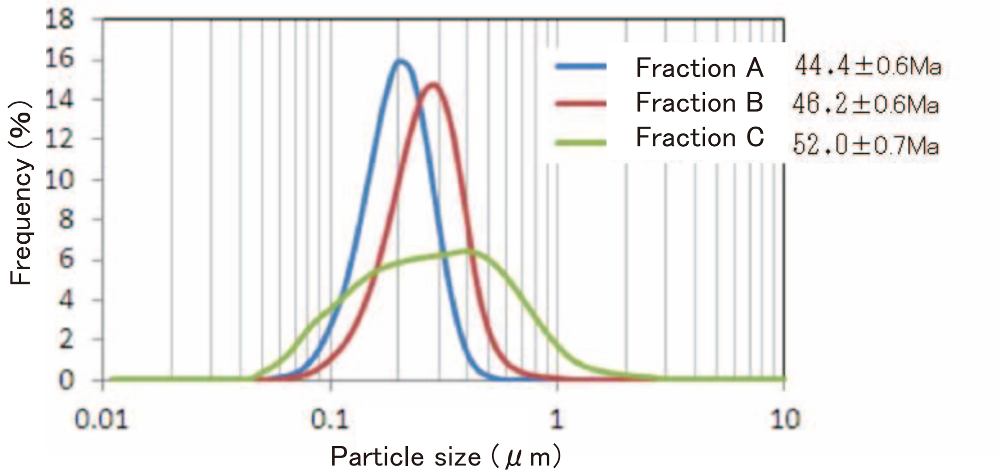

Fig. 2.7.3-7 Results of particle size distribution analysis and K–Ar dating for clay fractions from fractures containing clay infillings in the Kojaku Granite

(4) Investigation techniques for estimation of uplift and erosion rates in inland areas

The uplift and erosion rates for the past tens of thousands of years and the past hundreds of thousands of years can be calculated from the age and height of terrace surfaces, such as marine terraces along the shore and river terraces inland[34]. However, it is difficult to apply the calculation technique of the uplift rate using river terraces in the inland areas[35] of southwest Japan and the upper reaches of rivers, because terraces are lacking in these areas.

Therefore, a new investigation technique to clarify the uplift and erosion rates in inland areas is necessary. We focused on “circular abandoned channels”, which are old valleys around detached meander cores formed by the cut-off of incised meandering rivers in inland mountains with a small river terraces. We considered the estimation approach of uplift and erosion rates from the emergence age and elevation. Approximately 800 circular abandoned channels, interpreted from topographic maps with a scale of 1 to 25,000, were detected throughout the Japanese Islands. These channels can be useful for estimating uplift and erosion rates because they occur at a range of elevations throughout the Japanese Islands (Fig. 2.7.3-8)[36),37)]. We undertook a case study to determine the uplift and erosion rates using a circular abandoned channel in the middle reaches of the Kumanogawa (Totsukawa) River. The old river channel deposits that overlie the circular abandoned channel have been emergent since approximately MIS7 (i.e., 214 ka), based on analyses of the soil color and volcanic ash grains in the deposits, and the distribution of fluvial terraces around the Kumanogawa River[38]. The incision rate, as calculated from this age and the difference in elevation between the deposit and present channel (112 m), is about 0.5 m/ky or less. Matsushi et al. (2012)[39] calculated an incision rate of 4.4±0.3 mm/y from the ^{10}Be exposure ages of gravels on the abandoned channel in the uppermost reaches of the Totsukawa River. That rate is different from the rate calculated in this study.

It is necessary to study the reliability of the estimates of the uplift and erosion rates in inland mountains obtained using circular abandoned channels.

Thermochronometric methods using cooling ages and closure temperatures of multi-systems have conventionally been applied to estimate uplift and denudation histories on timescales of one million years or longer[40]. (U–Th)/He thermochronometry, which has a lower closure temperature, has been recently put to practical use[41),42] and applied to estimate later uplift and denudation histories[43]. We carried out fission-track dating and track length measurements of apatites in granites collected from the Suzuka Mountains as a case study of estimation of the uplift and denudation histories over the past few million years in medium-sized mountains (Fig. 2.7.3-9). The results showed that the thermochronologic methods were effective for obtaining an estimate of vertical crustal movement. On the other hand, the result showed that apatite FT thermochronometry cannot readily detect the Quaternary uplift and denudation histories of <1,000-m-high mountains in the Japanese Islands[31].

We are planning to measure exposure ages of bedrocks using in situ terrestrial cosmogenic nuclides, such as ^{10}Be and ^{26}Al, to estimate the amounts of uplift and denudation in inland areas over shorter periods.

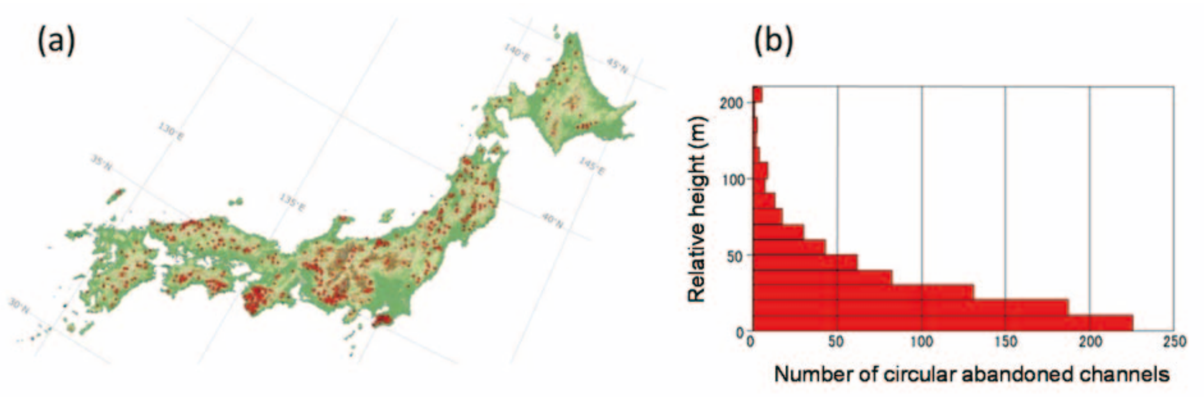

Fig. 2.7.3-8 (a) Distribution of circular abandoned channels in Japan interpreted from 1:25,000 topographic maps and
(b) Histograms of the heights of circular abandoned channels in Japan relative to present-day channels[37]

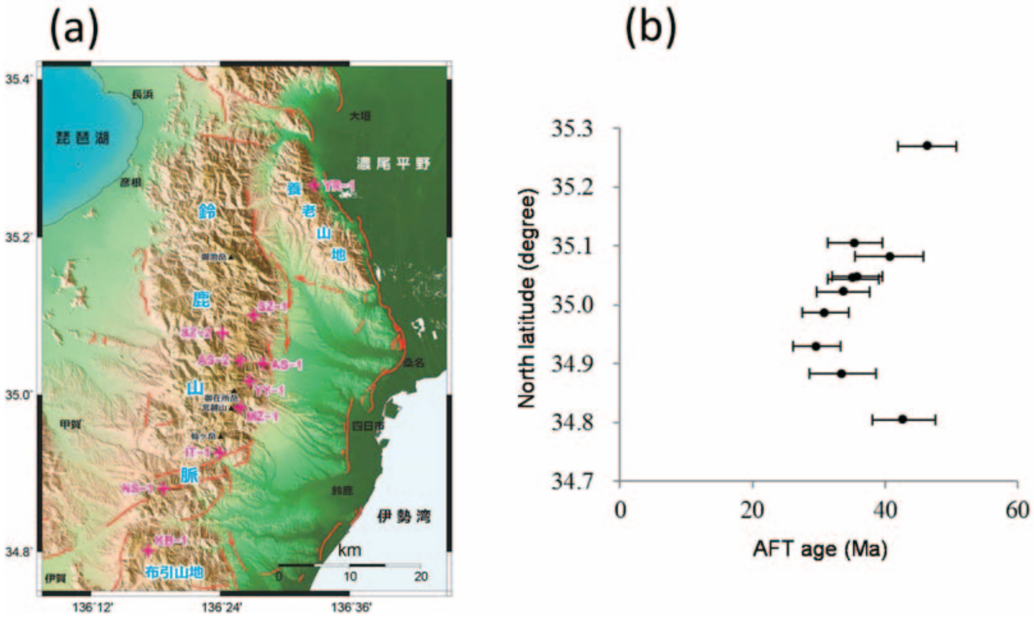

Fig. 2.7.3-9 (a) Topographical map of the study area showing the locations and sample codes around the Suzuka Mountains and
(b) Latitude versus apatite fission-track (AFT) ages across the Suzuka Mountains[31)]

2.7.4 Summary

We developed techniques to investigate past and present natural phenomenon that must be considered during the site selection phase in the final disposal. These investigation techniques cannot be used to observe faults directly, but instead are used to infer the existence of faults on the basis of indirect evidence. Therefore, in addition to the accumulation of examples, important themes include construction of a comprehensive investigation technique that incorporates different types of data.

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3. Understanding impact of construction in geo-environmental conditions

3.1 Geology

3.1.1 Introduction

Knowledge of the distribution and characteristics of the Excavation Damaged Zone (EDZ) induced by the excavation of underground facilities is important for understanding the short-term evolution and recovery behavior of the geological environment around the underground facility. In the construction phase (Phase II) and operation phase (Phase III), detailed information concerning the EDZ needs to be obtained by geological investigations at the shaft and galleries during and after the facility excavation. Therefore, we proceeded with R&D to identify the extent of the EDZ that should be characterized for the safety assessment[1),2)].

3.1.2 Objectives in the second mid-term research phase

Geological mapping of the excavated shaft and gallery walls and borehole investigations at the underground facilities were conducted to reach the performance target of R&D, in order to identify the extent of the EDZ induced by excavation of the underground facilities shown in Table 3.1.2-1.

Table 3.1.2-1 Performance target of R&D for perceiving the extent of the EDZ

Focus	Performance target of R&D	Tasks
Decision to begin disposal	Enable to understand an extent of EDZ around a gallery.	• Demonstration of technique to understand extent of EDZ induced by construction of underground facility

3.1.3 Project details and outcomes

(1) Understanding the extent of the EDZ

Fracture observations by geological mapping of the excavated shaft and gallery walls and borehole investigations at the underground facilities were carried out in the Horonobe URL to identify the extent of the EDZ in soft sedimentary rock. However, the EDZ that were induced by the excavation of granitic rocks in the Mizunami URL could not be identified by visual observations such as geological mapping. The results of the studies around the Horonobe URL are summarized as follows:

- Fractures observed on the floor of the Pumping Drift in the 250 m gallery could be divided into pre-existing fractures (shear fractures) and EDZ fractures (extension fractures). The EDZ fractures were not controlled by the orientation of the excavation, and could be classified into two sets by focusing on their orientation. The first set was from NW-SE to N-S strike, dipped slightly westward, and was parallel to the bedding plane. The second set was from E to W strike and dipped steeply north or south. This fracture set was parallel to the E-W shear fractures and weak planes inferred from the paleo-stress field. These EDZ fractures were terminated against the pre-existing shear fractures. The results suggested that the formation of the EDZ fractures occurred along weak planes including bedding and transgranular fractures, and was controlled by pre-existing fractures (Fig. 3.1.3-1)[3].

- Several pre-excavation grouting boreholes were drilled from the 250 m depth in and around the Ventilation Shaft, and grouting was carried out from 250 to 380 m depth. After grouting, the Ventilation Shaft from 250 to 350 m depth was excavated, and geological mapping was carried out. Based on the mapping results, EDZ fractures with grout were observed until several meters depth from the floor at the 250 m gallery (Fig. 3.1.3-2)[4]. These fractures with grout were assumed to be induced by the excavation of the 250 m gallery.
- The total trace length of the newly created fractures was small in the areas where the total trace length of the pre-existing fractures was large while the total trace length of the newly created fractures was large where the total trace length of pre-existing fractures was small[5]. Thus, there was a negative correlation between the total trace length of pre-existing fractures and that of the newly created fractures. The number of fractures around the gallery drastically increases after gallery excavation, and the resulting stress release and formation of the EDZ occur due to the formation of the newly created and pre-existing fractures. From these studies, conceptual models of the EDX showing characteristics of the formation of the newly created and pre-existing fractures around the gallery were constructed[5].

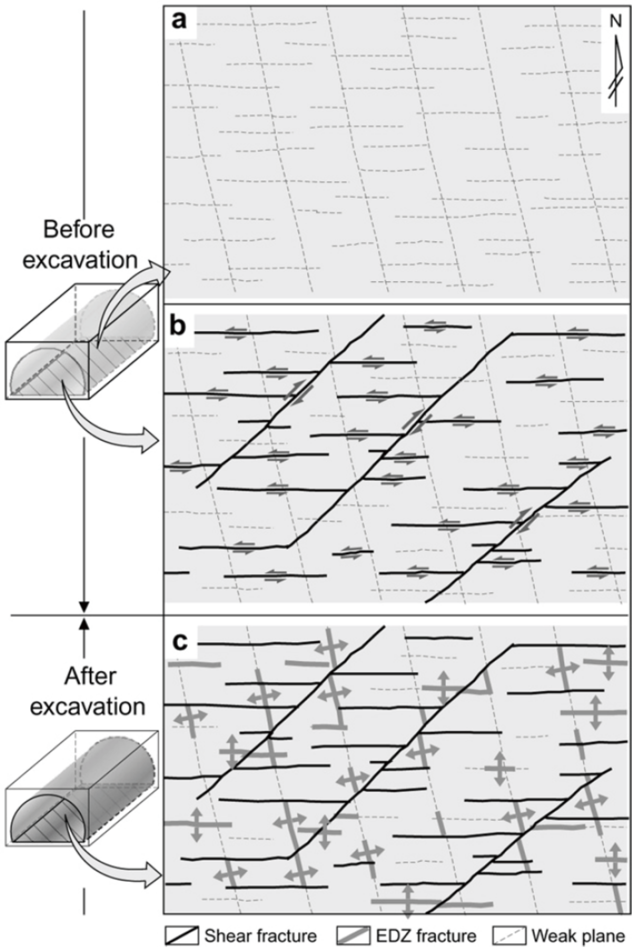

Fig. 3.1.3-1 Conceptual models showing the fracture formation process before excavation (a and b) and after excavation (c) on the floor of the gallery[3)]

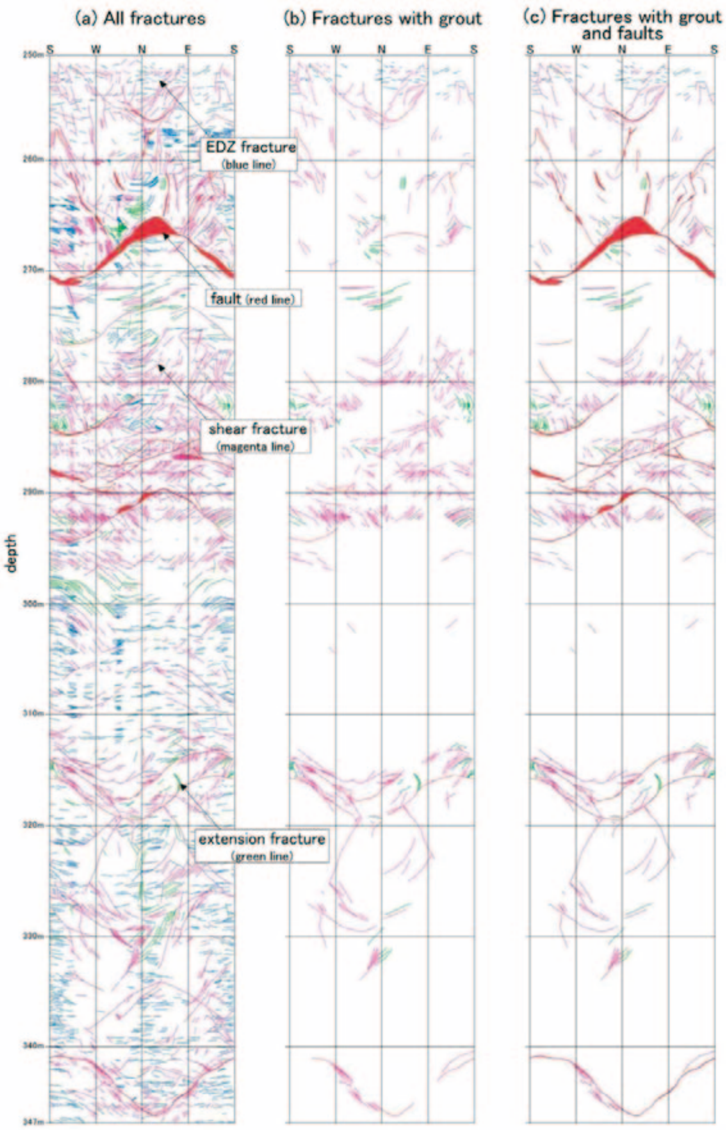

Fig. 3.1.3-2 Fracture mapping showing all fractures (a), fractures with grout (b), and fractures with grout and faults (c)[4)]

3.1.4 Summary

The common knowledge regarding the potential investigation techniques for understanding the extent of the EDZ induced by the construction of underground facilities is as follows:

- For soft sedimentary rocks such as those found in the Horonobe area, the distribution and characteristics of the EDZ could be identified, and a conceptual model of the formation of the EDZ could be constructed based on the results obtained from geological mapping and borehole investigations in the gallery. On the other hand, for granitic rocks such as those found in the Mizunami area, the EDZ induced by the excavation could not be easily identified from visual observations such as geological mapping investigations.

Future issues include the development of investigation techniques for understanding the evolution of the EDZ during construction and operation phases, which will require the following R&D:

- Development of investigation techniques for understanding the evolution of the extent and characteristics of the EDZ fractures
- Accumulation of data and knowledge regarding infilling and sealing of fractures during the post–closure gallery

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3.2 Hydrogeology

3.2.1 Introduction

The objective of the study was to establish the following techniques:

- Comprehensive techniques of investigation, analysis, and assessment, including a monitoring method, for characterization of the evolution of groundwater flow conditions during construction and operation of underground facilities
- Techniques of investigation, analysis, and assessment for characterization of groundwater flow conditions near the field of the disposal gallery

From these hydrogeological points of view, the focused features and processes to be characterized and the resulting data requirements relevant to safety assessment, design, and construction were identified[1].

(1) Volume of inflow into underground facilities

It is necessary to understand the volume of inflow into underground facilities from the following points of view:

- Design, construction, and maintenance of underground facilities
- Prediction of recovery behavior during backfilling of underground tunnels

(2) Impact on groundwater table and pressure

It is also necessary to understand the impact of construction and operation of underground facilities on the groundwater table and pressure from the following points of view:

- Design, construction, and maintenance of underground facilities
- Prediction of recovery behavior during backfilling of underground facilities
- Environmental impact assessment

(3) Spatial variability of groundwater flux

The three-dimensional spatial variability of groundwater flux is determined from the spatial variability of hydraulic properties and hydraulic gradient. In order to assess the mass transport and retardation characteristics, it is important to characterize the spatial variability of the groundwater flux near the field of the underground facilities, which includes the excavation damaged zone.

3.2.2 Objectives in the second mid-term research phase

The following studies were carried out to achieve the R&D performance target for perceiving the short-term evolution and recovery behavior of groundwater flow condition (Table 3.2.2-1):

- Monitoring of groundwater pressure and inflow volume during construction of the underground facilities
- Hydraulic testing using boreholes drilled at underground facilities to characterize the hydrogeological heterogeneity near the field of the underground facilities

Table 3.2.2-1 Performance target of R&D perceiving the short-term evolution and recovery behavior of groundwater flow conditions

Focus	Performance target of R&D	Tasks
Construction decision	Enable judging of appropriateness of construction and operation of underground facility taking into account groundwater flow.	• Method for measurement of inflow volume during construction of underground facility • Method for monitoring of changes of groundwater pressure during construction of underground facility
Decision to begin disposal	Enable estimation of recovery of feasible groundwater flow conditions post closure.	• Techniques of investigation and analysis for prediction of recovery behavior of groundwater flow conditions post closure
	Enable prediction and confirmation of the spatial variability of hydraulic characteristics and groundwater flux near field of disposal gallery.	• Techniques of investigation, analysis and assessment for prediction of groundwater flow conditions near field of disposal gallery

3.2.3 Project details and outcomes

(1) Volume of inflow into underground facilities

The total volume of inflow into the underground facilities has been monitored. In addition, the inflow rate monitoring was carried out at measured intervals along the shafts to understand the depth profile of the inflow volume[2)].

1) Mizunami

It is estimated that the influence of the hydrogeological characteristics near the tunnel on the inflow rate are significant, because artificial structural materials, such as lining concrete or drainage materials installed behind the lining or grout, may function as a skin. Therefore, data regarding the skin has been obtained[3)] as well as regarding the inflow volume.

The main achievements and technical findings from the investigations can be summarized as follows:

- The total and sectional inflow rates into the underground tunnel have been monitored. The inflow rate increased during construction of facilities at the area with high-permeability structures (Fig. 3.2.3-1, Fig. 3.2.3-2).
- The applicability of each technique for inflow rate monitoring was evaluated.

Steep hydraulic drawdown was recognized in the vicinity of shafts caused by skin effects (Fig. 3.2.3-3).

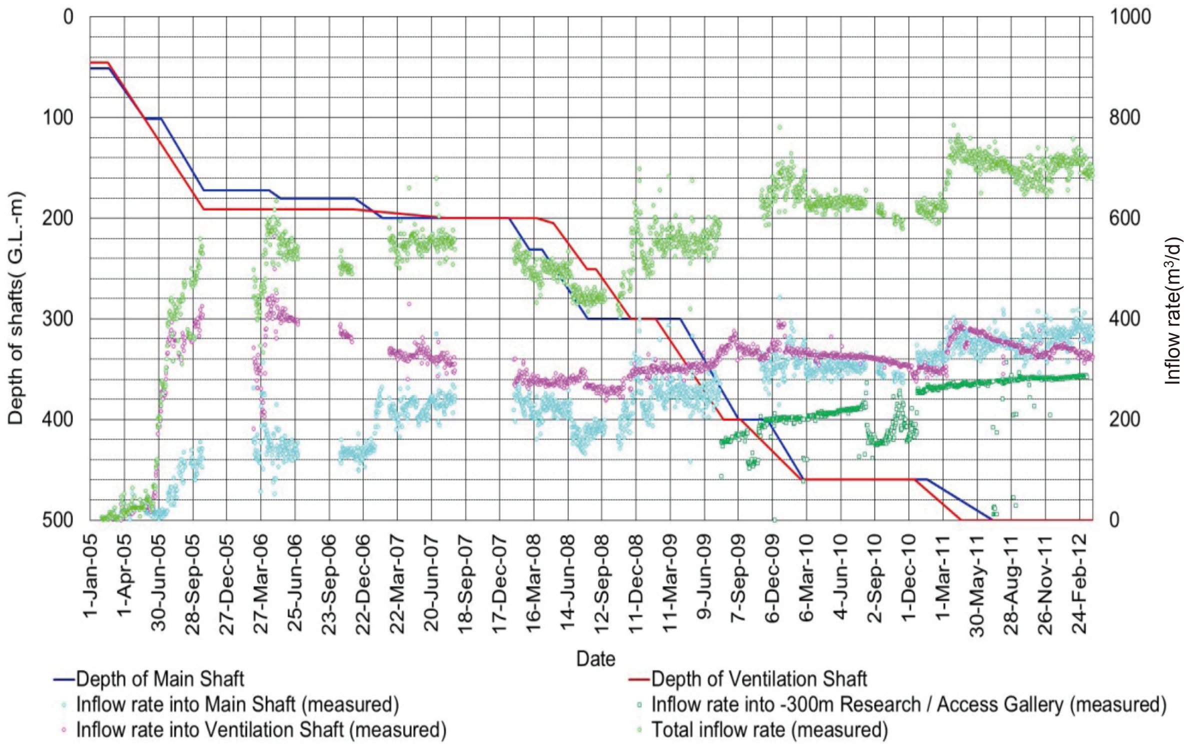
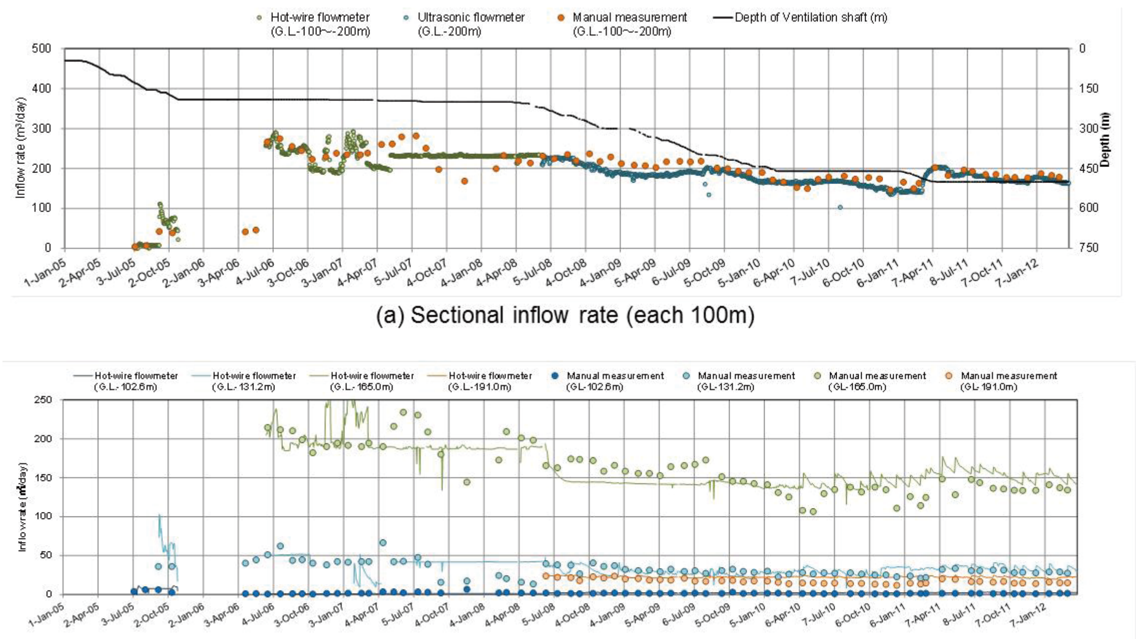


Fig. 3.2.3-1 Groundwater inflow rate into the underground facilities (MIU)



(a) Sectional inflow rate (each 100m)

(b) Inflow rate at water-ring

Fig. 3.2.3-2 Sectional groundwater inflow rate into the underground facilities (MIU)

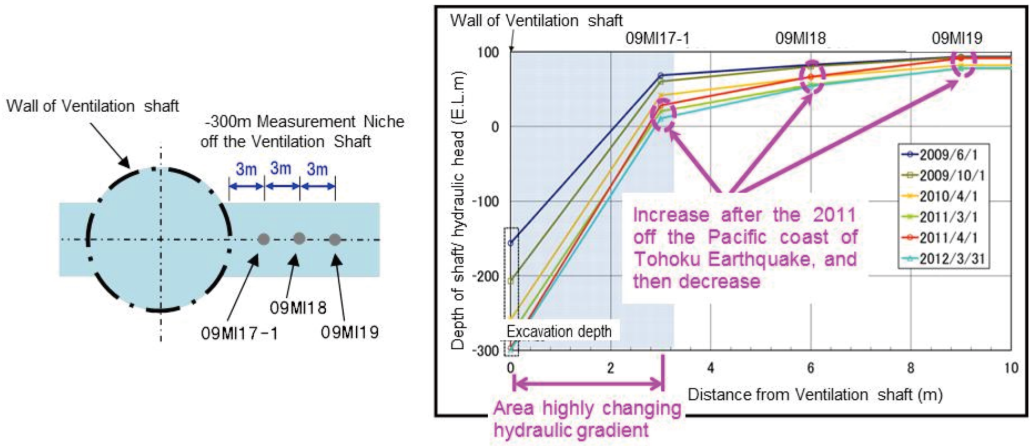


Fig. 3.2.3-3 Hydraulic head distribution in the vicinity of the shafts (MIU)

2) Horonobe

The main achievements and technical findings from the investigations can be summarized as follows:

- As it is estimated that the inflow rate into the underground tunnel is high in the high-permeability zone along the shafts, impermeable walls in the underground area have been constructed to reduce the inflow rate[4),5)].

The total inflow rate into underground tunnel has been monitored. The inflow rate increased during construction of facilities in the area with high-permeability structures (Fig. 3.2.3-4).

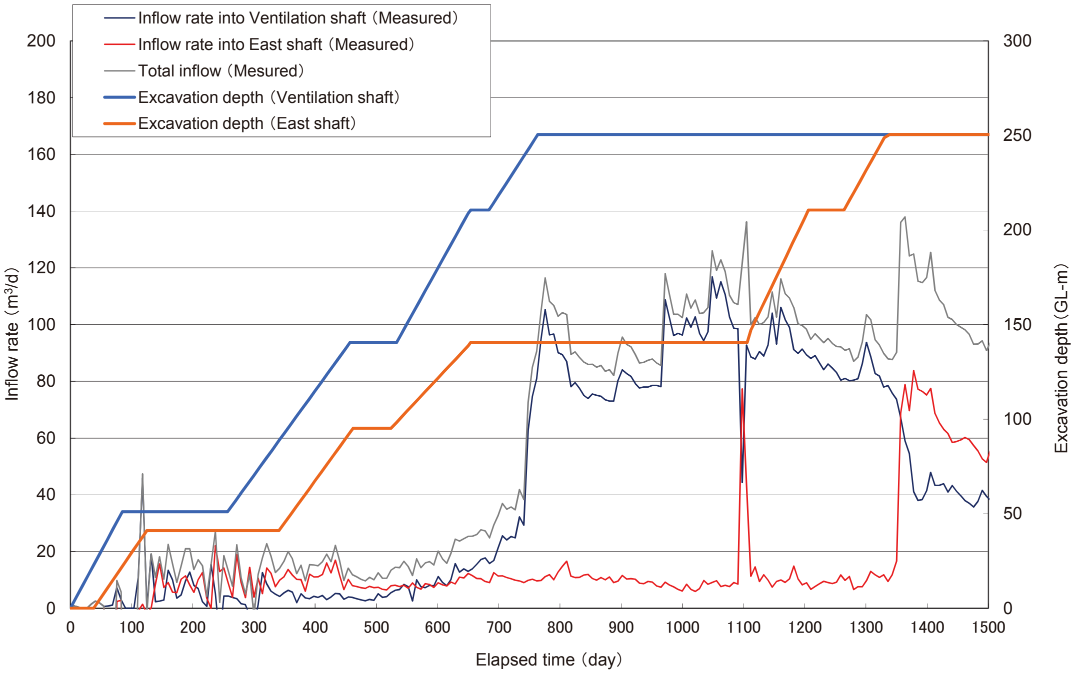


Fig. 3.2.3-4 Groundwater inflow rate into the underground facilities (Horonobe)

(2) Impact on groundwater table and pressure

Groundwater pressure has been monitored using several boreholes drilled from the surface and underground tunnels[6),7)]. Tilt monitoring[8),9),10),11),12),13)], self-potential monitoring[14)] (Mizunami only), and surface hydrological monitoring[15)] have also been carried out as supplementary methods of groundwater pressure monitoring.

1) Mizunami

The main achievements and technical conclusions from the investigations are summarized as follows:

- The hydraulic responses differ for each hydraulic compartment that is estimated to be formed by low-permeability structures (Fig. 3.2.3-5).
- Degassing of dissolved gas causes measurement errors if the piezometer tube is thin. A method was developed as a countermeasure.
- A method of data processing has been developed for specifying hydraulic changes resulting from construction of underground facilities and elimination of other components such as hydraulic changes caused by earth tides, atmospheric pressure variations, and earthquakes (Fig. 3.2.3-6).
- The groundwater level in the unconfined aquifer near the surface fluctuates synchronously with rain fall (Fig. 3.2.3-7).

Tilt monitoring and self-potential monitoring are useful methods to understand the hydraulic responses in the horizontal plane and can be supplementary methods of groundwater pressure monitoring.

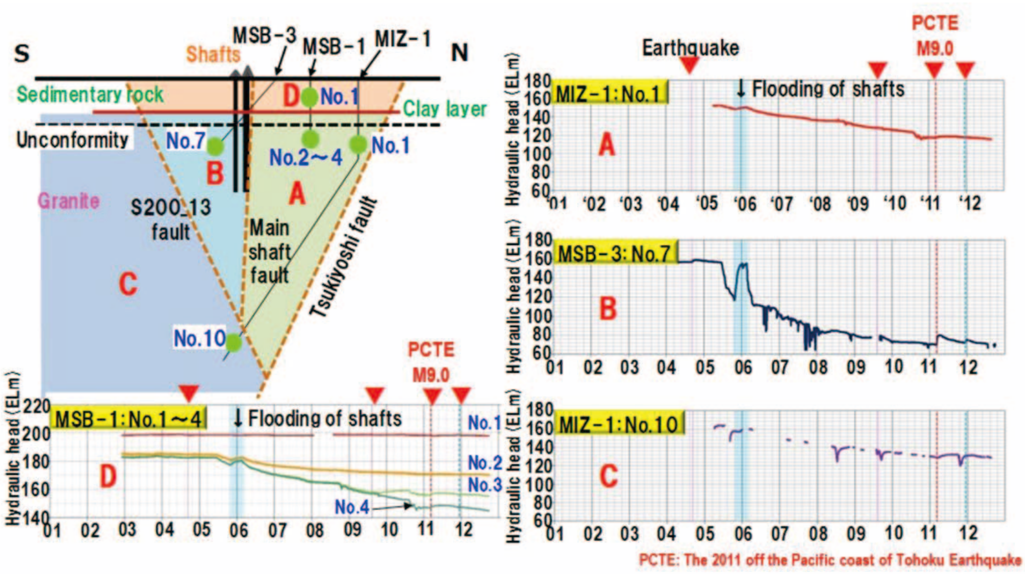


Fig. 3.2.3-5 Hydraulic responses caused by construction of underground facilities (MIU)

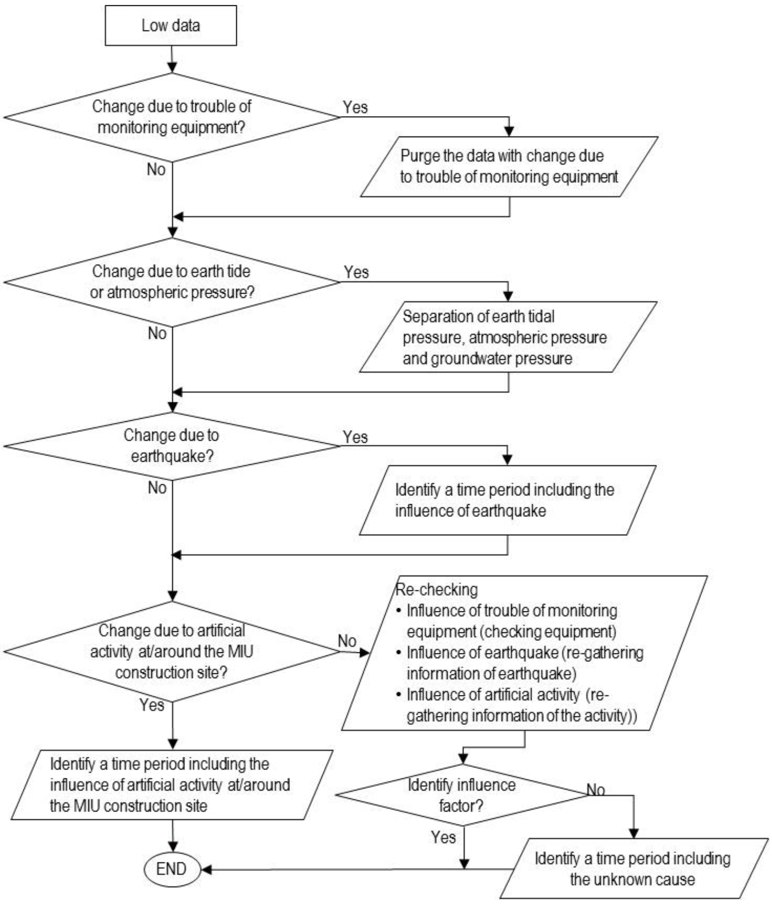


Fig. 3.2.3-6 Method of data processing for specifying hydraulic changes

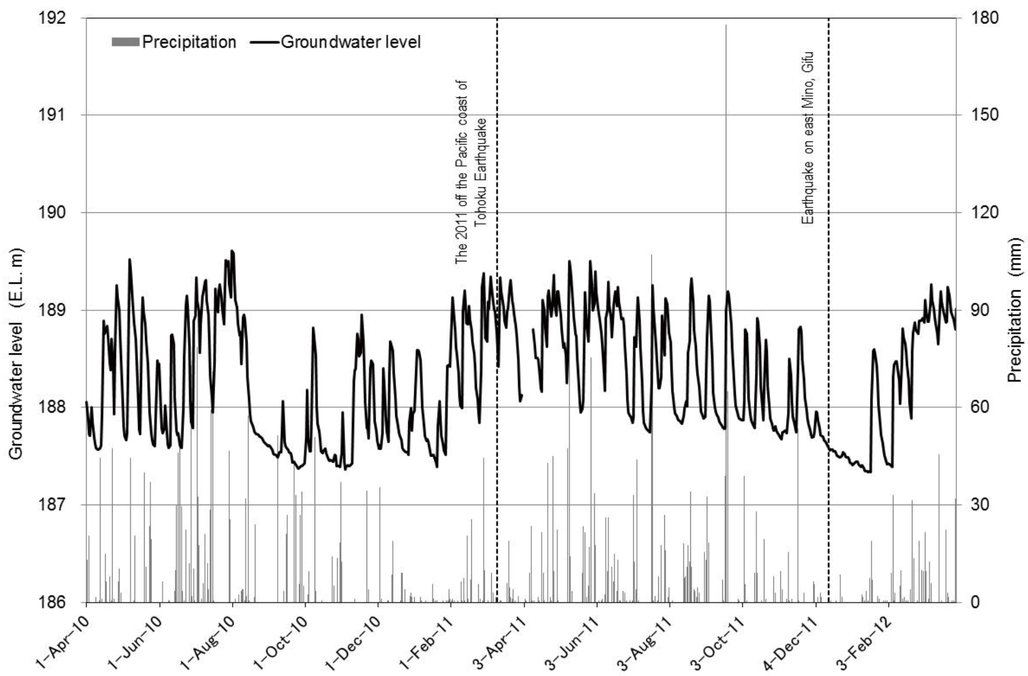


Fig. 3.2.3-7 Changes in the groundwater level of the unconfined aquifer (MIU)

2) Horonobe

The main achievements and technical findings from the investigations can be summarized as follows:

- Clear hydraulic responses have been recognized only in the zone of water-conducting faults with tensional fractures[16] (Fig. 3.2.3-8).
- The groundwater level in the unconfined aquifer near the surface fluctuates synchronously with rain fall[17] (Fig. 3.2.3-9).

Tilt monitoring is a useful method to understand the hydraulic responses in the horizontal plane and can be used as a supplementary method of groundwater pressure monitoring (Fig. 3.2.3-10).

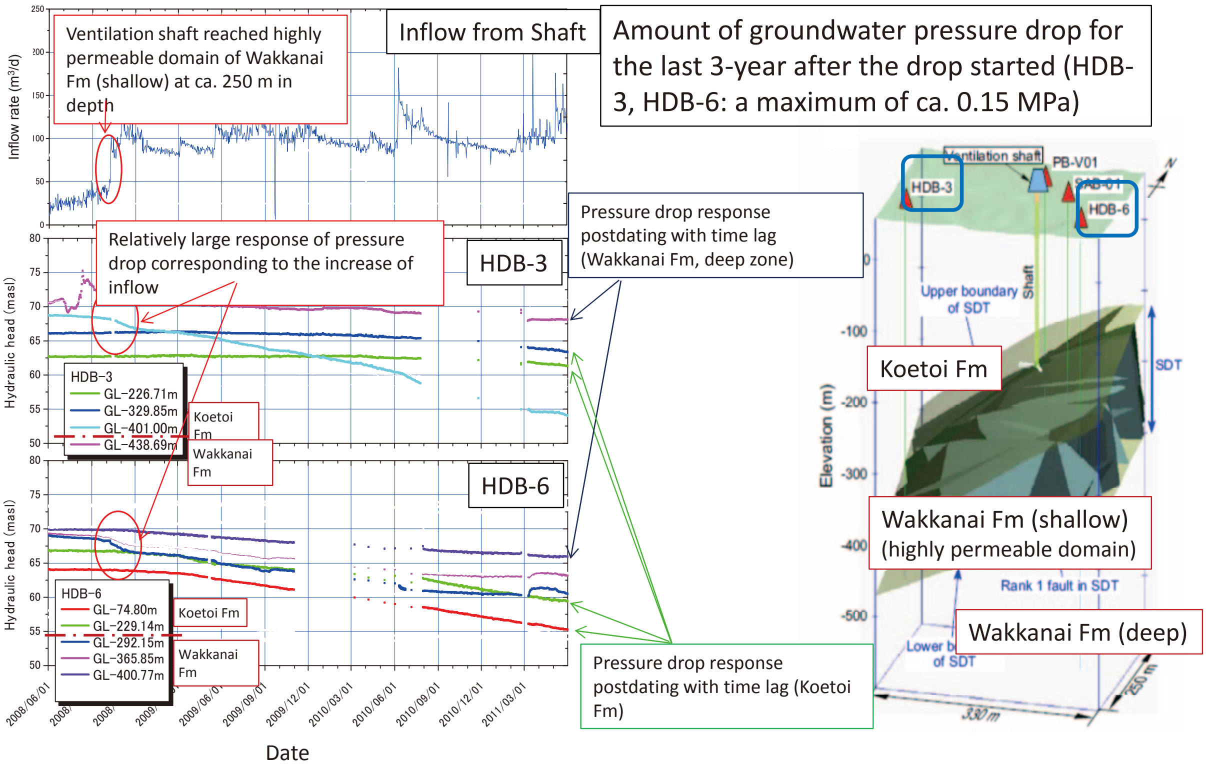


Fig. 3.2.3-8 Hydraulic responses caused by construction of underground tunnels (Horonobe)

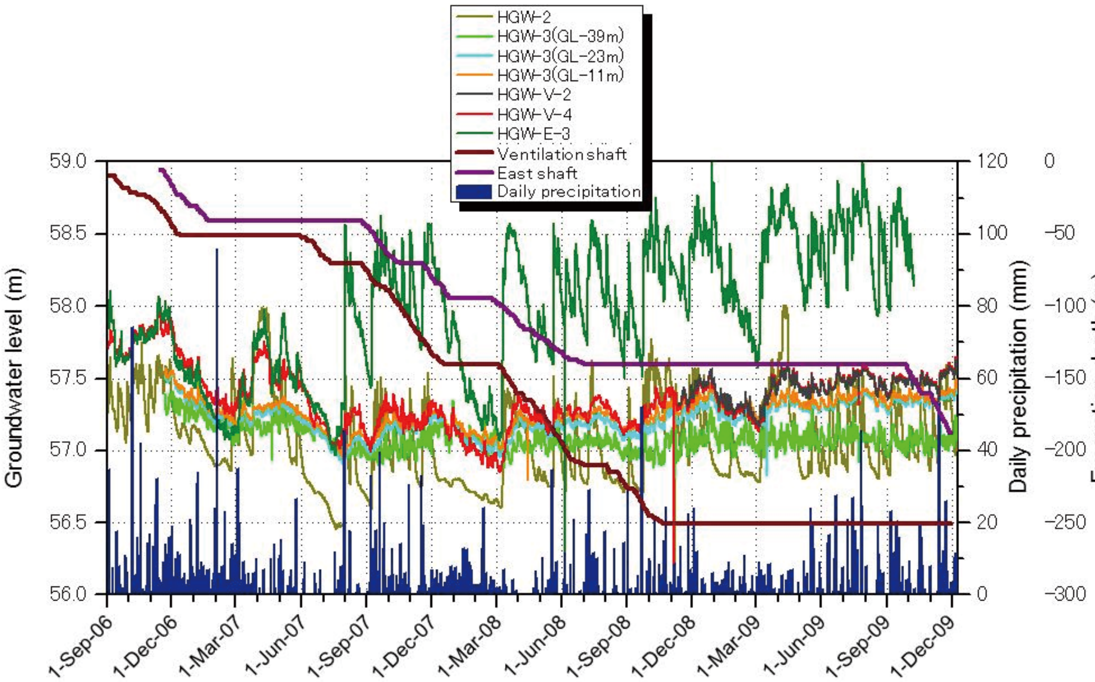


Fig. 3.2.3-9 Changes in the groundwater level of the unconfined aquifer (Horonobe)

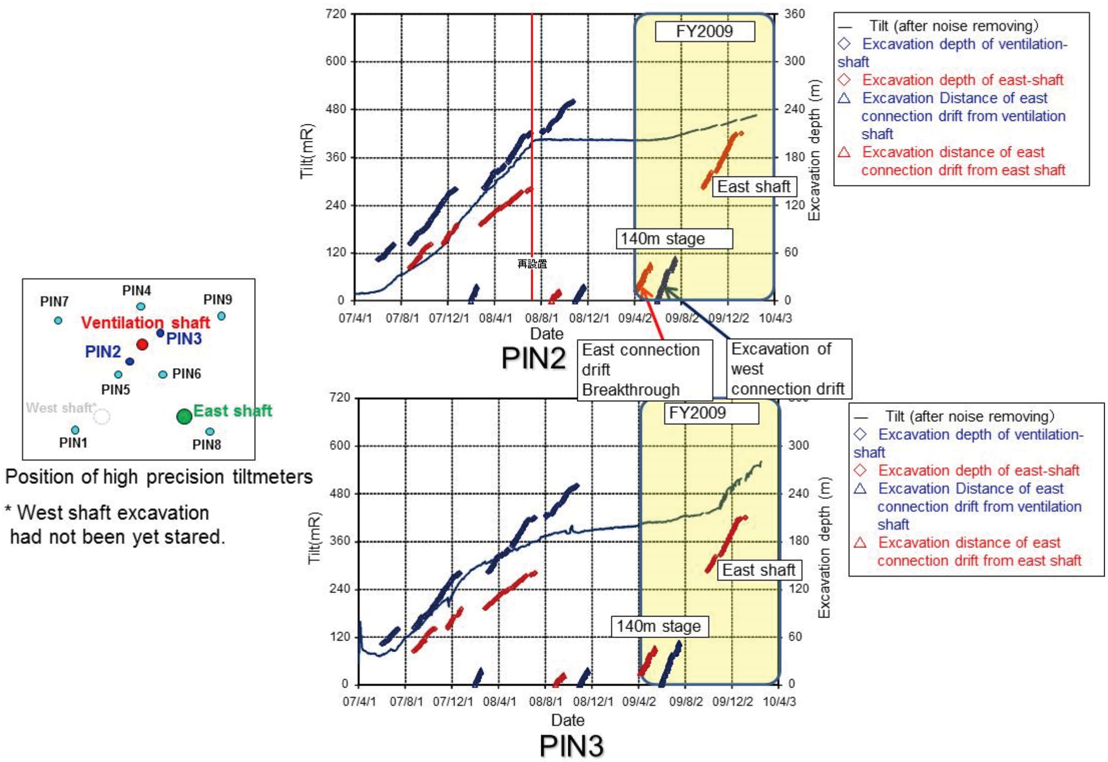


Fig. 3.2.3-10 Tilt changes during construction of underground tunnels (Horonobe)

(3) Spatial variability of groundwater flux

1) Mizunami

A hydrogeological model based on a discrete fracture network approach was constructed using data obtained from investigations at the underground facilities and from boreholes drilled underground[18),19)]. The main achievements and technical findings from the investigations can be summarized as follows:

- A method of discrete fracture network modeling and continuum modeling taking into account the hydraulic heterogeneity were developed.
- Sensitive parameters for discrete fracture network modeling were specified taking into account the influence of the geological and hydrogeological characteristics of fractures on groundwater flow and mass transport phenomena.
- Data acquisition for fractures with a wide range of hydraulic characteristics in a continuous manner was difficult because of the high groundwater pressure condition (it was difficult to replace borehole fluid for fluid logging) and time constraints (it was necessary to carry out short-interval hydraulic tests for a long time along the whole length of the borehole).

2) Horonobe

The short-term phenomena of geological and hydrogeological characteristics in the EDZ has been investigated to understand the spatial variability of groundwater flux[20),21),22)]. The main achievements and technical findings from the investigations can be summarized as follows;

- Changes in groundwater pressure stabilized within 1.5 years after construction of the underground facilities, and saturation also stabilized at 70% to 80% humidity (Fig. 3.2.3-11).
- Changes in the hydraulic properties and pore structure at distances greater than 3 meters from the wall of the underground tunnel were not recognized.
- A hydro-testing method has been developed for an environment in which degassing of dissolved gas occurs.

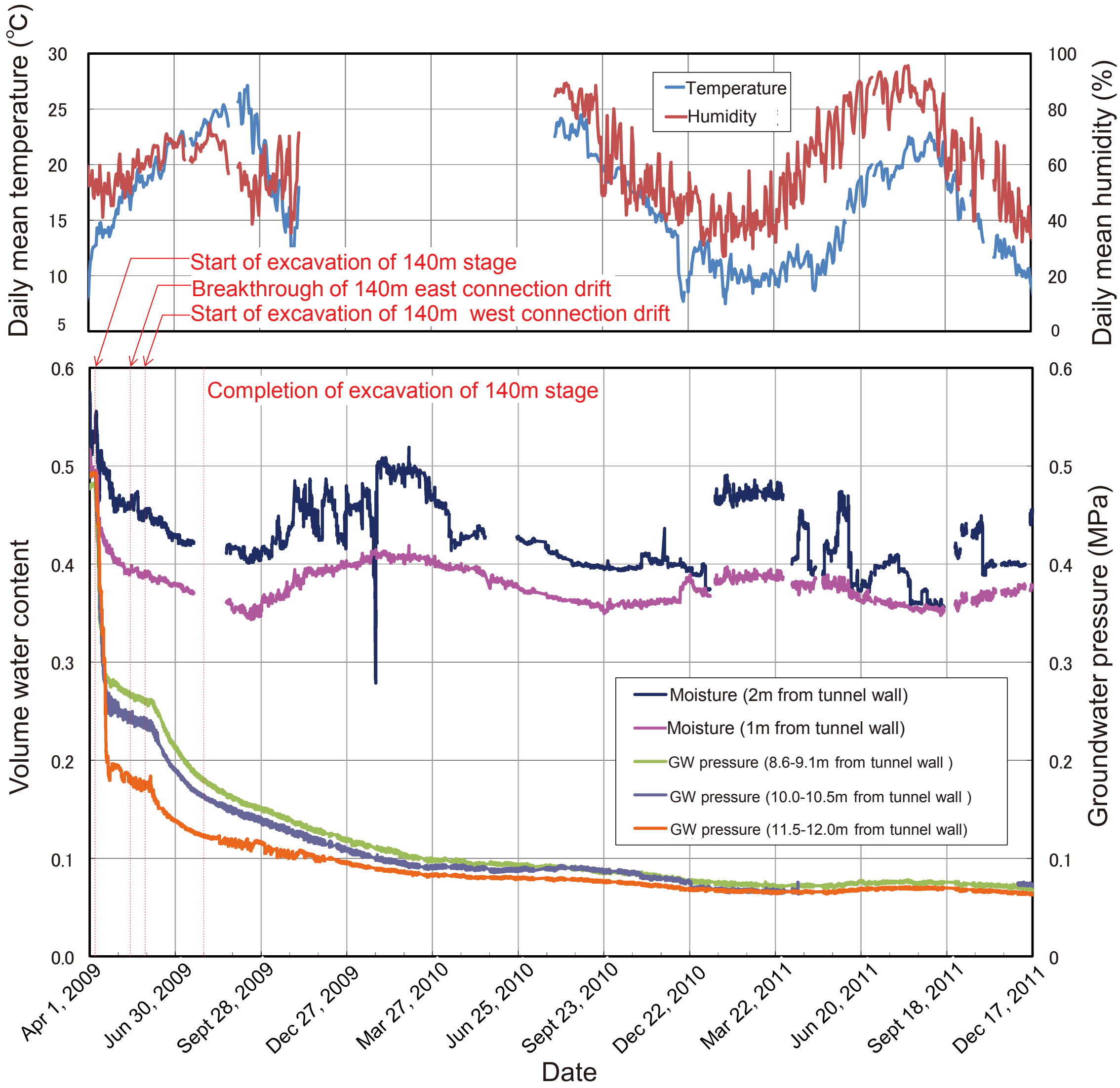


Fig. 3.2.3-11 Changes in groundwater pressure/moisture and temperature/humidity in the tunnel (Horonobe)

3.2.4 Summary

The techniques and accumulated technical knowledge regarding investigation, analysis, and assessment for characterization of the evolution of groundwater flow conditions during construction and operation of underground facilities and for characterization of groundwater flow conditions near the field of the disposal gallery are summarized below.

(1) Volume of inflow into underground facilities

- Pilot borehole investigations are capable of yielding improvements to the prediction accuracy.
- Measurement of the sectional inflow rate is useful for interpretation of hydrogeological heterogeneity.
- The influence of the hydraulic characteristics near the tunnel on the groundwater inflow

rate is quite significant, because artificial structural materials, such as lining concrete, grout, and drainage material, may function as a skin.
- A method for maintenance of measurement equipment has been established.
- The technical findings for the measurements have been accumulated, and a method for quality control of the measurements has been developed.

(2) Impact on groundwater table and pressure
- Assignment of hydraulic monitoring intervals, taking into account hydrogeological heterogeneity including hydrogeological compartmentalization, is useful for estimation of hydraulic characteristics.
- A method for maintenance of measurement equipment, including countermeasures against gas, has been established.
- The technical findings for the measurement have been accumulated, and a method for quality control of the measurements, under gaseous condition, has been developed.

(3) Spatial variability of groundwater flux
- The necessity to develop techniques of investigation, analysis, and assessment for characterization of hydrogeological heterogeneity and groundwater flow conditions in low-permeability domains using boreholes drilled from tunnels has been identified.

The future studies will be performed to solve the open issues described below:

1) Development of techniques of investigation, analysis, and assessment for prediction of the post-closure recovery behavior of groundwater flow conditions.
- Applicability checking of techniques of investigation, analysis, and assessment for evaluation of the influences of heterogeneous inflow into the underground on the performance of material for back-filling by groundwater recovery experiment and tunnel back-filling experiments.
- Durability enhancement of measurement equipment, development of a wireless monitoring technique, development of a method for maintenance of measurement equipment (including countermeasures against gas), accumulation of technical know-how, and development of quality control methods.
- Accumulation of technical knowledge regarding the post-closure recovery behavior of geological environments.

2) Development of effective techniques of investigation, analysis, and assessment for characterization of hydrogeological heterogeneity and groundwater flow conditions in low-permeability domains.
- Development of effective investigation techniques for continuous data acquisition on fractures with a wide range of hydraulic characteristics.
- Development of a method for discrete fracture network modeling taking into account the actual characteristics of fractures.

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3.3 Hydrogeochemistry

3.3.1 Introduction

The geological environment will probably be influenced for several decades by changes resulting from the construction and operation of a large underground facility. In the excavated damaged zone [EDZ], mechanically and chemically damaged rock properties will not recover after facility closure. In the excavated disturbed zone [EdZ] comprising EDZ, hydraulic and chemical disturbance may possibly recover over time after closure of the facility[1]. During the construction and operation of the facility, the tunnels have atmospheric pressure and groundwater inflow into the tunnel occurs depending on the hydrogeological properties of the rock. Large amounts of groundwater inflow will alter the hydraulic conditions as well as the groundwater chemistry around the facility[2].

3.3.2 Objectives in the second mid-term research phase

Basic knowledge of changes in the hydrochemical baseline conditions based on long-term monitoring is required during the construction, operation, and post closure around deep large underground facilities similar to HLW repository. The R&D listed in Table 3.3.2-1 has been conducted in both URLs.

Hydrochemical changes during the facility construction phase are mainly caused by the following processes. In an EDZ, the mechanical and hydrogeological properties of rock change intensely because of fracturing during excavation, and the chemical properties are modified by factors such as shotcrete, grouting, and air circulation. In an EdZ, the groundwater chemistry possibly changes because of mixing of chemically distinct waters induced by changes in the hydraulic conditions. The hydrochemical changes and their processes in the EdZ/EDZ were summarized based on hydrochemical monitoring during the facility construction phase.

Table 3.3.2-1 Performance target of R&D for the short-term evolution and recovery behavior of hydrochemical conditions

Focus	Performance target of R&D	Tasks
Start of isolation	To judge that favorable chemical conditions can be presumed after facility closure.	• Demonstrate the monitoring and simulation technique for hydrochemical changes during facility construction, operation, and post closure • Provide an appropriate design to facilitate recovery of favorable hydrochemical conditions post closure

3.3.3 Project details and outcomes

(1) Changes in groundwater chemistry (salinity)

1) Mizunami

Hydrochemical monitoring was conducted in and around the MIU during the shaft construction down to G.L. −500 m depth (Fig. 3.3.3-1, Table 3.3.3-1). Hundreds of cubic meters of inflowing groundwater have been draining every day. From October 2005 to February 2006, when the shafts had been excavated to 180 m depth (uppermost part of granite), groundwater discharge from the shafts had to be reduced while the effluent treatment facility was being expanded. As a result, the shafts were temporarily flooded by groundwater up to 50 m underground.

Water-collection rings (WR) were placed every 25 m in the shafts to direct the water inflow and reduce the water pressure on the concrete lining. The inflow rate was measured at each WR in the shafts (Fig. 3.3.3-2). The highest water inflow occurred from the conglomerate layer; this is probably the dominant groundwater flow path in the sedimentary rock. Water inflow increased in the weathered granite below the unconformity or low angle fractured zone (LAFZ), and at the G.L. −300 m access/research gallery. The connectivity and continuity of fractures of the LAFZ may be higher than those of the upper highly-fractured domain (UHFD). The water inflow volume at the G.L. −300 m access/research gallery, having a length of about 100 m, is relatively higher than that from both shafts in the granite part at depths of 170–500 m. The reason for this may be differences in the encounter rate of excavations and higher-angle fractures in granite. The volume of water inflow into the Main Shaft tends to be less compared to that into the Ventilation Shaft. Such differences are attributed to the low permeability of the Main Shaft fault.

The groundwater chemistry in the WRs is possibly affected by water–cement interactions caused by contact with the concrete liner. Incidentally, Cl is not susceptible to water–mineral interactions. The variations in chlorine (Cl) concentration in WRs and the water chemistry in boreholes drilled from the gallery are illustrated in Figs. 3.3.3-3 and 3.3.3-4, respectively. The Cl concentrations in the WRs and boreholes increased during the initial observation period but subsequently decreased with time. The groundwater chemistry at depth was affected by the upconing in the initial period. After the excavation of the shaft had advanced to deeper depths, the upconing point also moved to a greater depth. In the upper depths, upconing was reduced and the impact of shallower groundwater infiltration increased with time[3]. To assess shallow water infiltration, stable isotopes, tritium (^{3}H), and chlorofluorocarbons (CFCs) as tracers of shallow groundwater were monitored in granitic rock for 5 years (Fig. 3.3.3-5). The results showed that the shallow groundwater infiltrates into the groundwater at depths of 200–400 m after 10 years of drainage (hundreds ton/day). The mixing ratio of surface water in deep groundwater can be approximately estimated using CFC-12 data. The hydrochemical changes in groundwater were estimated by principal components analysis (PCA) (Fig. 3.3.3-6)[3]. It is presumed that deep groundwater will be replaced by shallow groundwater in the future.

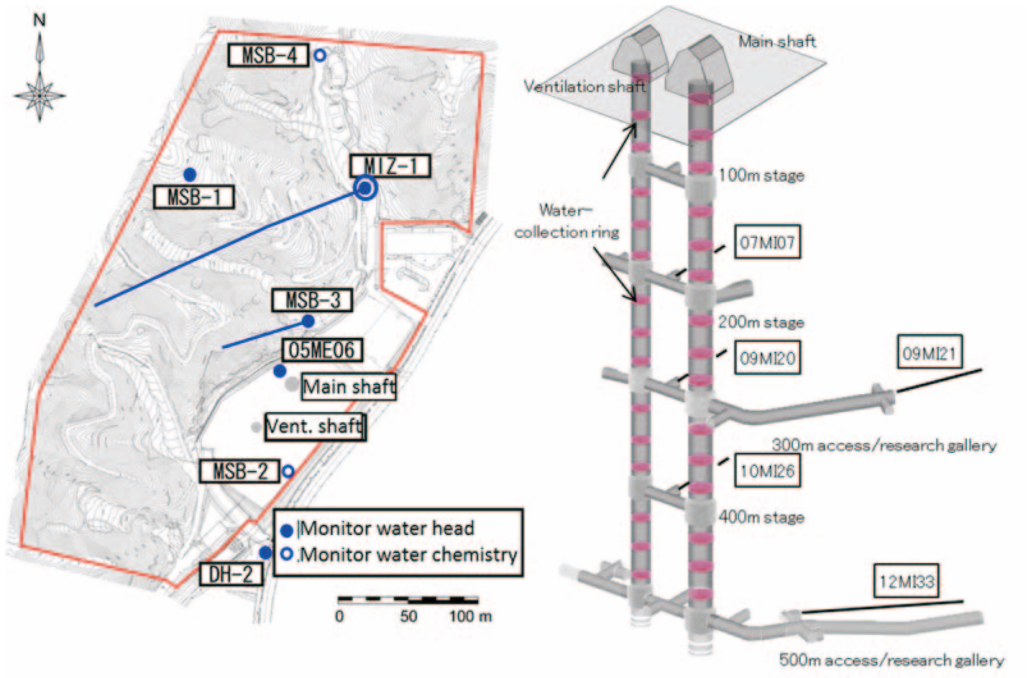


Fig. 3.3.3-1 Hydrochemical monitoring boreholes in and around the MIU

Drawdown occurred at the boundary between the conglomerate layer and the weathered granite (700–800 kPa below baseline conditions); and in the deep granite (1.0–1.5 MPa below baseline conditions). The drawdown values in the 09MI21 borehole on the G.L. −300 m access/research gallery drilled to the north of the Main Shaft fault were less than those in the 09MI20 borehole, and the drawdown was larger to the south of the Main Shaft fault compared to the north. Any potential hydraulic impact caused by the Ventilation Shaft was shielded by the Main Shaft fault from impacts on the north side of the fault.

Cl is not susceptible to water–mineral interaction. Variations in Cl concentrations in WRs are shown in Fig. 3.3.3-3; the Cl concentrations in these WRs increased during the initial observation period but subsequently decreased with time. The WRs were sequentially installed in the deepest part of the shaft as the excavation progressed; therefore, the observation at each WR was affected by upconing during the initial period. Increases in Cl concentrations from baseline levels because of upconing were observed to be of the order of several tens to hundreds mg l^{-1} in the Ventilation Shaft. Groundwater movement by upconing is illustrated using these groundwater chemistry data. For example, the Cl concentration at WR 13 (300 m depth) in the Ventilation Shaft was approximately 250 mg l^{-1} during upconing periods (December 2009). This value corresponds to the Cl concentration observed at approximately 450 m depth prior to shaft excavation. This finding implies that groundwater from approximately 150 m below moved upward to the bottom of the shaft. As excavation of the shaft advanced to deeper depths, the upconing point also moved to deeper depths. Meanwhile, in the upper depths, upconing was reduced and the impact of shallow groundwater infiltration increased with time[3].

Table 3.3.3-1 Hydrological/hydrochemical monitoring sections at the Mizunami

Borehole (Elevation)	Zone No.	Monitoring interaval: Meter along borehole		Elevation (m)		Geology	Method
MSB-2 (E.L.: 198.5m) Vertical borehole	1	18.8	22.7	179.7	175.8	Akeyo Fm. (Weathered zone)	Multilevel groundwater monitoring in a multiport system (Westbay MP system)
	2	23.6	38.9	174.9	159.6	Akeyo Fm. (Mudstone)	
	3	39.8	68.2	158.7	130.3	Akeyo Fm., Hongo Fm. (Mudstone)	
	4	69.1	77.4	129.4	121.1	Hongo Fm. (Conglomerate)	
	5	78.3	120.2	120.2	78.3	Toki lignite-bearing Fm.	
	6	121.1	130.4	77.4	68.1	Toki lignite-bearing Fm. (Basal conglomerate)	
	7	131.3	153.7	67.2	44.8		
	8	154.6	170.4	43.9	28.1		
	9	171.3	175.2	27.2	23.3	Toki granite (Weathered zone)	
MSB-4 (E.L.: 214.4m) Vertical borehole	1	15.8	25.6	201.6	191.8	Akeyo Fm. (Mudstone)	Multilevel groundwater monitoring in a multiport system (Westbay MP system)
	2	26.5	33.9	190.9	183.5	Akeyo Fm. (Mudstone)	
	3	34.8	62.1	182.6	155.3	Akeyo Fm., Hongo Fm. (Mudstone)	
	4	63.0	76.9	154.4	140.5	Hongo Fm. (Conglomerate)	
	5	77.8	81.7	139.6	135.7	Toki lignite-bearing Fm.	
	6	82.6	93.9	134.8	123.5	Toki lignite-bearing Fm.	
	7	94.8	99.0	122.6	118.4	Toki granite (Weathered zone)	
MIZ-1 (E.L.: 206.6m) Inclined borehole	3	290.8	647.3	-84.1	-434.1	Toki granite (UHFD/LSFD)	Stand-pipe multi packer systems (Solexperts SPMP system)
	6	916.3	960.8	-695.7	-738.9		
	9	1148.8	1169.8	-922.1	-942.5		
07MI07 (E.L.: 1.8m) Horizontal borehole	1	48.1	55.3	-2.1	-2.6	Toki granite (UHFD)	Continuous hydrochemical monitoring system (JAEA CHM system)
	2	38.7	47.2	-1.3	-2.0		
	3	31.3	37.8	-0.7	-1.2		
	4	26.9	30.4	-0.4	-0.6		
	5	16.9	26.0	0.4	-0.3		
	6	0.0	16.0	1.8	0.5		
09MI20 (E.L.: -97.8m) Horizontal borehole	1	96.1	101.9	-102.8	-103.1	Toki granite (UHFD)	Continuous hydrochemical monitoring system (JAEA CHM system)
	2	84.7	95.2	-102.2	-102.8		
	3	58.7	83.8	-100.9	-102.2		
	4	34.8	57.8	-99.6	-100.8		
	5	19.4	33.9	-98.8	-99.6		
	6	0.0	18.5	-97.8	-98.8		
09MI21 (E.L.: -98.2m) Horizontal borehole	1	0.0	66.1	-98.2	-101.7	Toki granite (LSFD)	Continuous hydrochemical monitoring system (JAEA CHM system)
	2	67.1	77.1	-101.7	-102.2		
	3	78.1	88.1	-102.3	-102.8		
	4	89.0	103.0	-102.9	-103.6		
10MI26 (E.L.: -197.4m) Horizontal borehole	1	52.8	70.6	-195.5	-194.9	Toki granite (UHFD)	Continuous hydrochemical monitoring system (JAEA CHM system)
	2 *	50.6	51.8	-195.6	-195.5		
	3	37.9	49.6	-196.0	-195.6		
	4	30.2	36.9	-196.3	-196.1		
	5	10.0	29.2	-197.0	-196.3		
	6	0.0	9.0	-197.4	-197.0		
12MI33 (E.L.: -297.8m) Horizontal borehole	1	105.40	107.00	-303.3	-303.4	Toki granite (LSFD)	Continuous hydrochemical monitoring system (JAEA CHM system)
	2 *	85.70	104.40	-302.3	-303.3		
	3 *	64.00	84.80	-301.1	-302.2		
	4 *	53.80	63.10	-300.6	-301.1		
	5	44.10	52.90	-300.1	-300.6		
	6	0.00	43.20	-297.8	-300.1		
Water collection ring (Elevation of shaft point: 200.9m)							
Main shaft	A-WR-1	190.9	Ventilation shaft	B-WR-1	189.3	Alluvium	Manual water collection in the shafts
	A-WR-2	158.4		B-WR-2	161.4	Akeyo Fm. (Mudstone)	
	A-WR-3	123.9		B-WR-3	132.4	Hongo Fm. (Conglomerate)	
	A-WR-4 *	106.5		B-WR-4	106.9	Toki lignite-bearing Fm. (Carbonaceous mud/sandstone)	
	A-WR-5 *	98.3		B-WR-5	98.3		
	A-WR-6	64.7		B-WR-6	69.7	Toki lignite-bearing Fm. (Basal conglomerate)	
	A-WR-6(1)	49.1					
	A-WR-7	33.5		B-WR-7	35.9		
	A-WR-8	6.5		B-WR-8	9.9	Toki granite	
	A-WR-9	-1.7		B-WR-9	0.9		
	A-WR-10	-35.3		B-WR-10	-30.3		
	A-WR-11	-63.9		B-WR-11	-64.1		
	A-WR-12 *	-93.5		B-WR-12	-93		
	A-WR-13	-101.7		B-WR-13	-101.7		
	A-WR-14	-135.3		B-WR-14	-130.3		
	A-WR-15	-171.1		B-WR-15	-164.1		
	A-WR-16	-193.5		B-WR-16	-193		
	A-WR-17	-204.3		B-WR-17	-201.7		
	A-WR-18	-235.3		B-WR-18	-230.3		
	A-WR-19	-263.7		B-WR-19	-264.1		
	A-WR-20	-293.5		B-WR-20	-292.1		

Elevation: above meter sea level, *: There are no data at the point where water inflow is low or recently installed monitoring system.

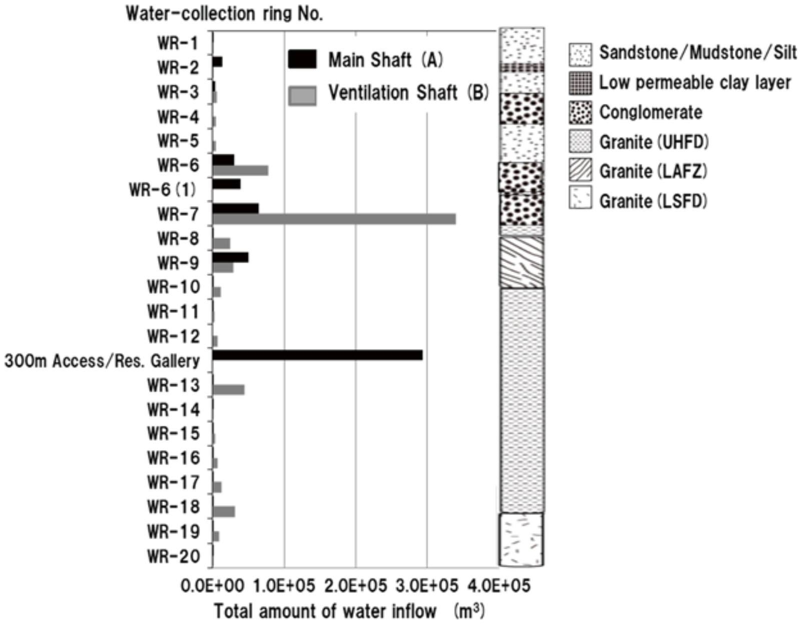


Fig. 3.3.3-2 Accumulated inflow in each water-collection ring (Apr. 2004–May 2012)

The groundwater in 07MI07, 09MI20, and 10MI26 initially had relatively high Na, Ca, and Cl and low DIC and SO_4 concentrations, which subsequently changed to relatively low Na, Ca, and Cl and high DIC and SO_4 concentrations (Fig. 3.3.3-4). This tendency was clearly observed near the borehole collars in the excavations (e.g., zones 5 and 6). Horizontal monitoring boreholes were drilled sequentially in the deepest gallery during excavation. Therefore, the observations at each borehole were affected by upconing during the initial period. In boreholes 07MI07, 09MI20, and 10MI26 on the south side of the Main Shaft fault, groundwater with relatively high levels of Na, Ca, and Cl and low DIC and SO_4 concentrations during early observations was representative of the upconed-water around the Ventilation Shaft. Since then, relatively shallow groundwater has infiltrated to the area around the Ventilation Shaft and is characterized by low levels of Na, Ca, and Cl, and high DIC and SO_4 concentrations. This process of groundwater replacement is most likely occurring at a faster rate on the south side of the Main Shaft fault than on the north side of the fault, reflecting the extent of hydraulic impact. However, such trends were not observed in borehole 09MI21 on the north side of the Main Shaft fault. Borehole 09MI21 is located approximately 100 m north of the Main Shaft fault and was drilled into LSFD. Hydrochemical changes in the groundwater here were most likely caused by mixing with groundwater at 300 m depth without having been influenced by the upconing along the shaft. In general, mixing with shallower groundwater became the dominant process on the south side of the Main Shaft fault whereas mixing with deeper groundwater dominated groundwater chemistry on the north side of the fault[3)].

To infer the infiltration of shallow groundwater as a result of the long-term drawdown into the shafts, measurements of tritium and chlorofluorocarbon (CFC) concentrations were used as an index of surface water infiltration (Fig. 3.3.3-5). Tritium was detected at several monitoring zones even though the concentrations dropped to zero at around 200 m depth prior to shaft excavations[3]. CFC-12 was first detected in 2010, and the concentrations gradually increased with time as observed in boreholes 07MI07 (200 m depth), 09MI20 and 09MI21 (300 m depth), and 10MI26 (400 m depth). This implies that surface water containing CFC-12 penetrated up to 400 m depth within a few years.

Principal component analysis (PCA) was performed to identify the chemical composition of groundwater end-members using the chemical data obtained from over 1,000 groundwater samples located below the low-permeability clay layer, but excluding the areas considered to have been contaminated during drilling or subsequently by cement materials.

The first principal component (PC 1) and second principal component (PC 2) values of groundwater are shown in Fig. 3.3.3-6. PC 1 is dominated by Na, Ca, and Cl concentrations, and PC 2 is dominated by DIC, SO_4, and F concentrations. The PCA results also indicated that groundwater displacement of high-salinity deep groundwater by infiltration of low-salinity shallow groundwater occurred.

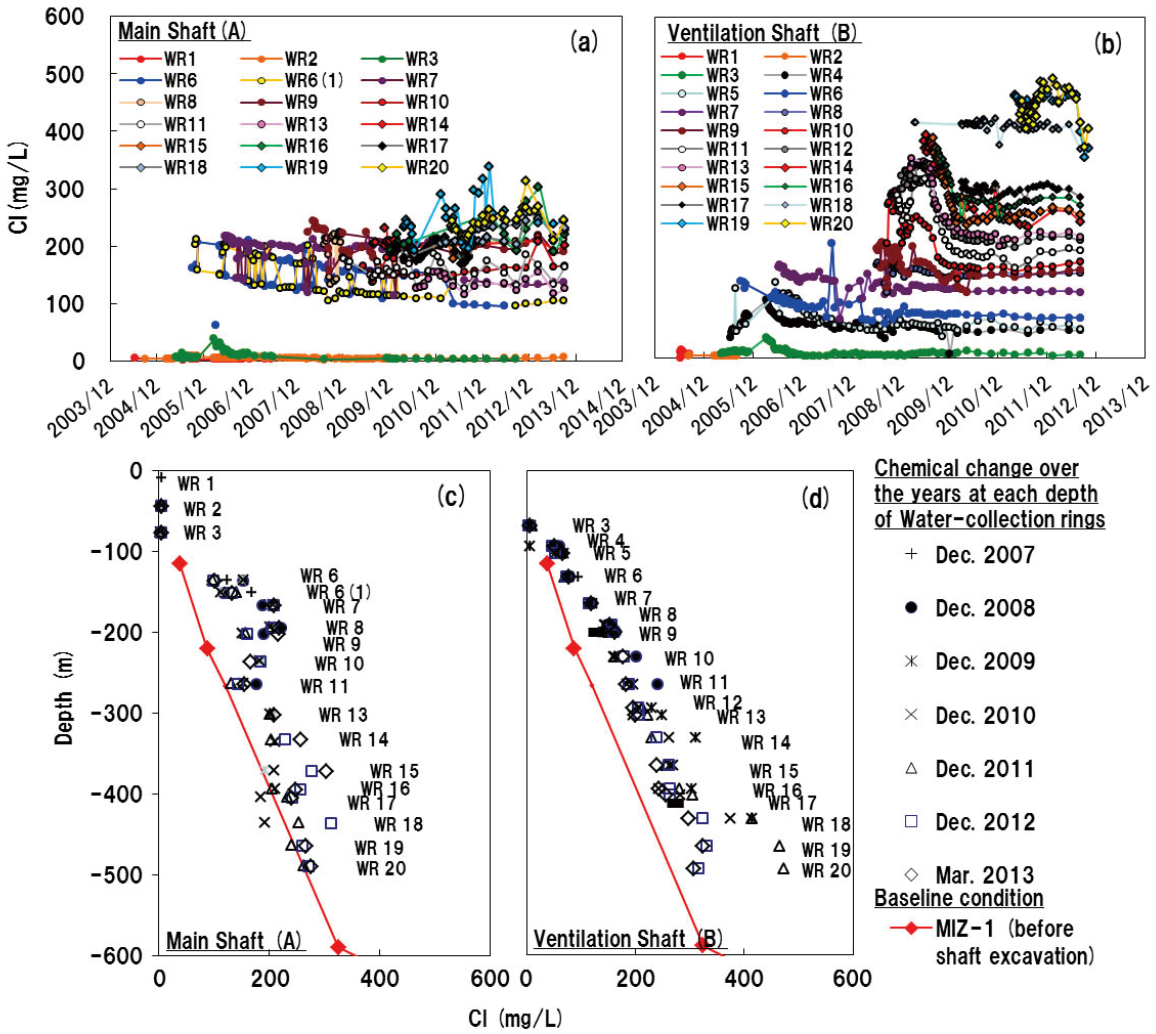


Fig. 3.3.3-3 Temporal variations of Cl concentrations in groundwater at the Main Shaft and the Ventilation Shaft

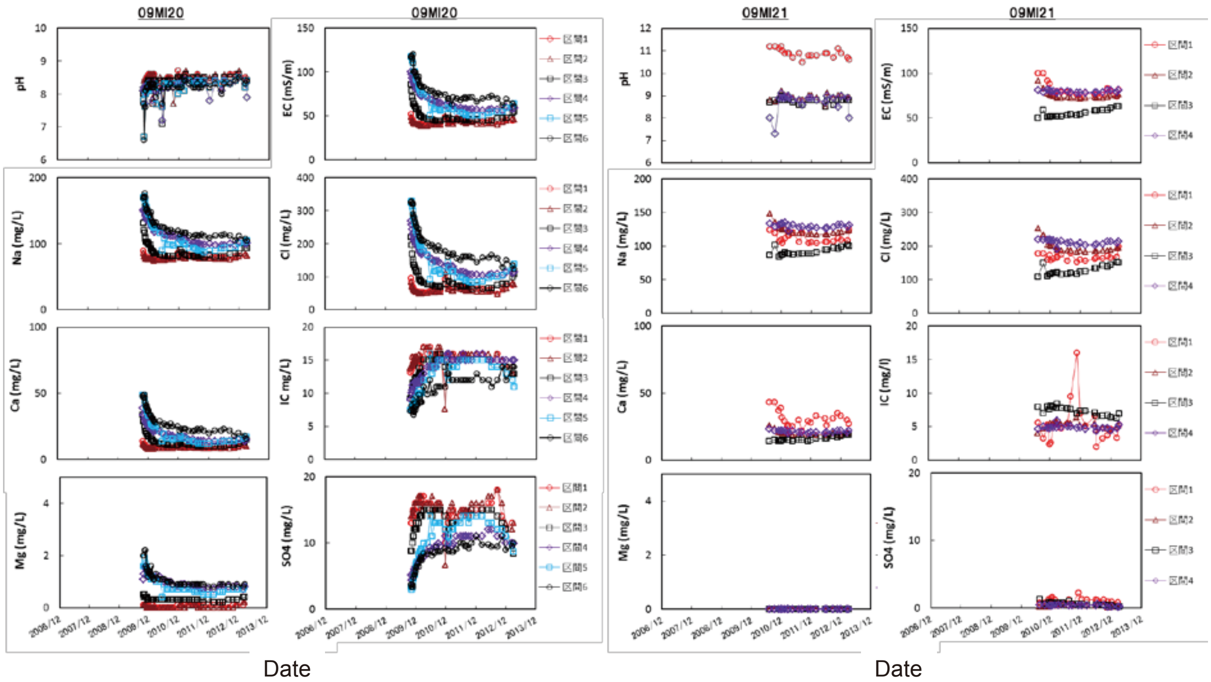


Fig. 3.3.3-4 Temporal variations of Cl concentrations in groundwater in the boreholes drilled from the gallery

Borehole 09MI20 has six monitoring sections (section 1 is located at the bottom of the borehole) and was drilled from the G.L. −300 m sub-stage. Borehole 09MI21 has four sections (section 4 is located at the bottom of the borehole) and was drilled from the G.L. −300 m access/research gallery.

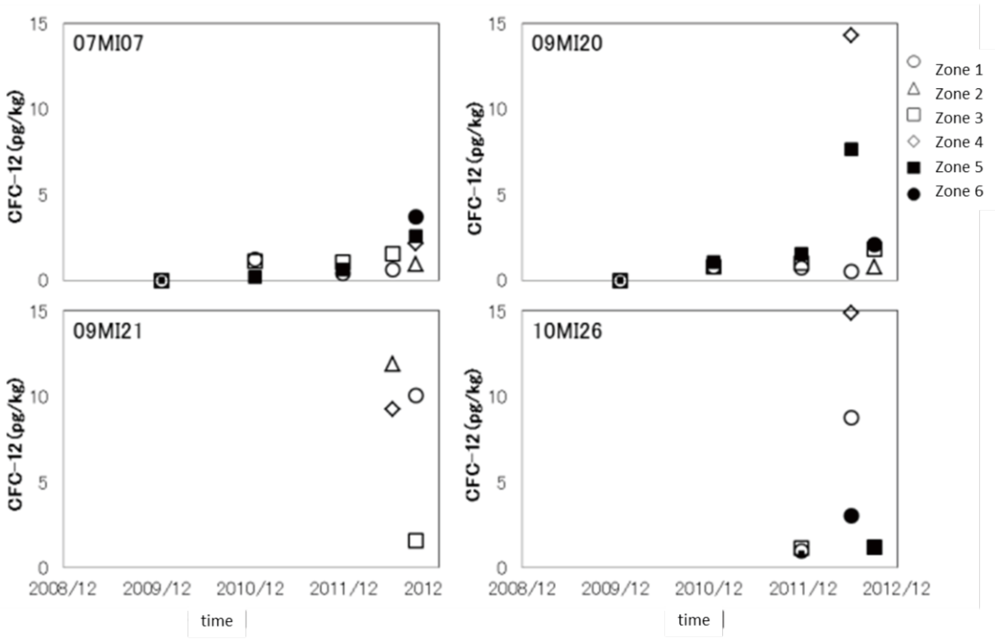


Fig. 3.3.3-5 Temporal variations of CFC gas in each monitoring section

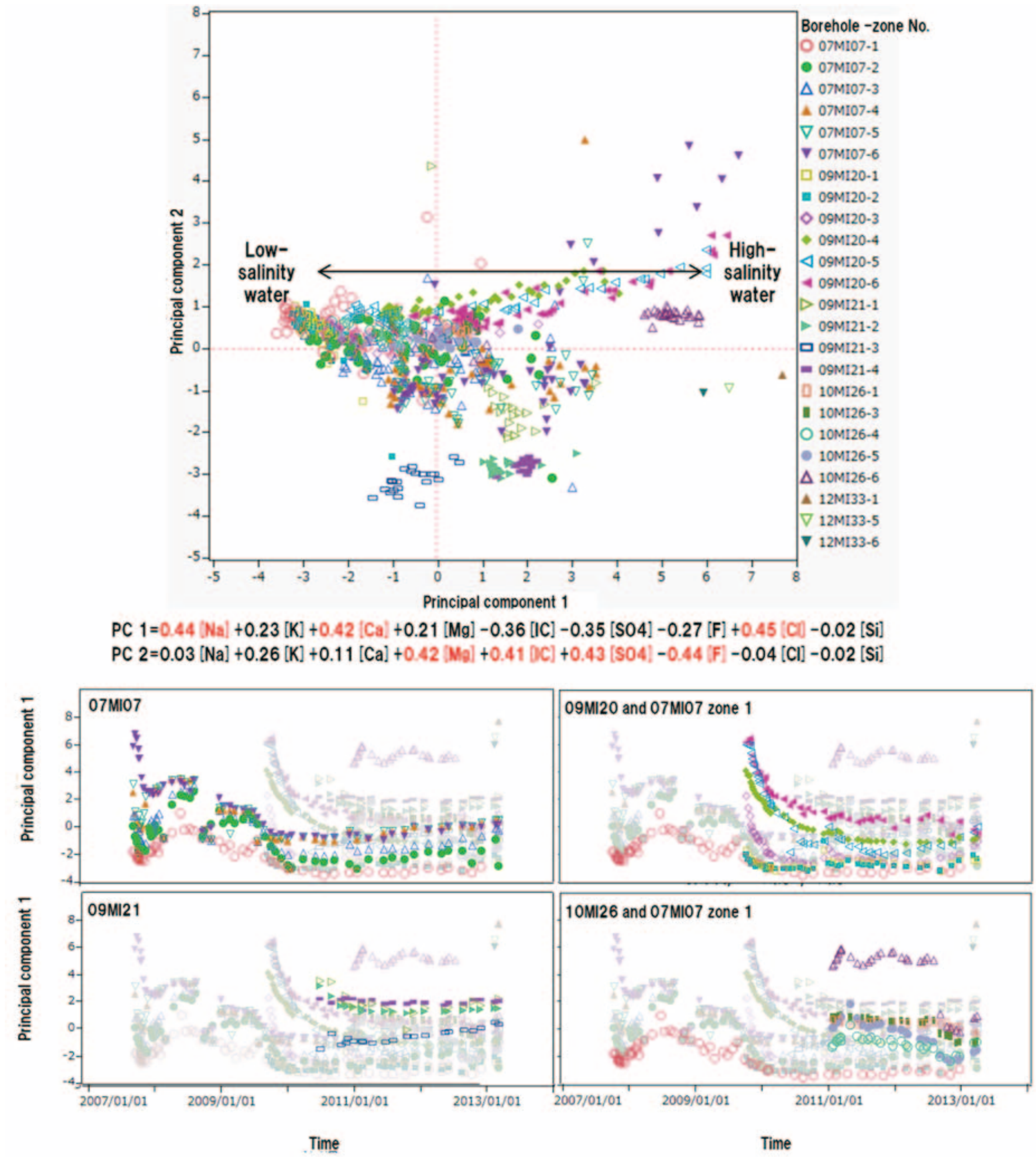


Fig. 3.3.3-6 Principal component analysis of groundwater chemistry related to shaft sinking

2) Horonobe

In the second mid-term research phase, three shafts (the East Shaft, the West Shaft, and the Ventilation Shaft) were excavated down to a depth of G.L. −350 m and the G.L. −350 m gallery was also constructed. The daily outflow rate of groundwater due to the shaft and drift excavation was normally less than about 200 m^3/day, except the period during the excavation of the G.L. −350 m gallery, which caused the maximum groundwater outflow (e.g., 700 m^3/day) in February, 2013.

The amount of groundwater outflow in the Horonobe URL is generally lower than that in the

Mizunami URL. This may be explained by 1) general differences in the permeability of the parent rocks (i.e., permeability of the sedimentary rock at the Horonobe URL is lower than that of the crystalline rock at the Mizunami URL) and 2) the effect of pregrouting on the permeable zone predicted before the construction of URL below the G.L. −250 m level in the Horonobe.

During the excavation of shafts, a hydrological response was observed in the surface-based borehole PB-V01 close to the Ventilation Shaft (borehole PB-V01 is located ca. 17 m north of the Ventilation Shaft). This response suggests that hydrological effects may be active in the part deeper than G.L. −350 m because a decrease in the hydraulic head in the packed-off section of G.L. −479 to −520 m was observed.

Additionally, similar hydrological responses were recorded both in the surface-based boreholes HDB-3 (located ca. 210 m west of the East Shaft) and HDB-6 (located ca. 160 m south of the Ventilation Shaft). In HDB-6, a decrease in salinity was identified in the monitoring zone around G.L. −500 m after shaft sinking. Based on these hydrological monitoring results, the extent of EdZ around the Horonobe URL seems to be several tens to hundreds of meters.

Sampling and analysis of groundwater (results shown in both Fig. 3.3.3-7 and Table 3.3.3-2) have been performed. For the groundwater collected from the water ring in the shafts, sampling and analysis have been conducted in both the East and Ventilation Shafts but not in the West Shaft. The groundwater sampling and analysis have been performed in the boreholes (e.g., borehole length from 20 m to 100 m) drilled from the G.L. −140 m and G.L. −250 m galleries.

Fig. 3.3.3-8 shows variations with time in the groundwater salinity for each sampling point in the drift from 2006 to 2013. The results of chemical analysis of groundwater indicate that there are different tendencies of salinity variations at the sampling points; at some points, the salinity increases with time (i.e., WR-V-98.0, WR-V-132.0, WR-V-202.0, WR-V-242.0, WR-E-63.8, and WR-E-202.0) and at others, the salinity decreases with time (i.e., WR-V-310.0, WR-V-343.9, WR-E-276.0, and WR-E-340.0). The maximum change in salinity observed was ca. 0.8 g/L. These changes in the groundwater salinity might be caused by a probable change in the mixing ratio between fossil sea water and meteoric water resulting from the URL excavation.

Fig. 3.3.3-9 shows the temporal variations around the URL during shaft construction. As shown in Fig. 3.3.3-9, the groundwater salinity in the west part of the URL and in the deeper part around the URL area was higher than that in the other part. During shaft construction, the groundwater salinity around the East Shaft appeared to change because of the intrusion of higher-salinity groundwater in the west part of the URL through the boundary between the Koetoi and Wakkanai Formations. To understand the process of salinity change, a multivariate statistical analysis (principal component analysis; PCA) was performed.

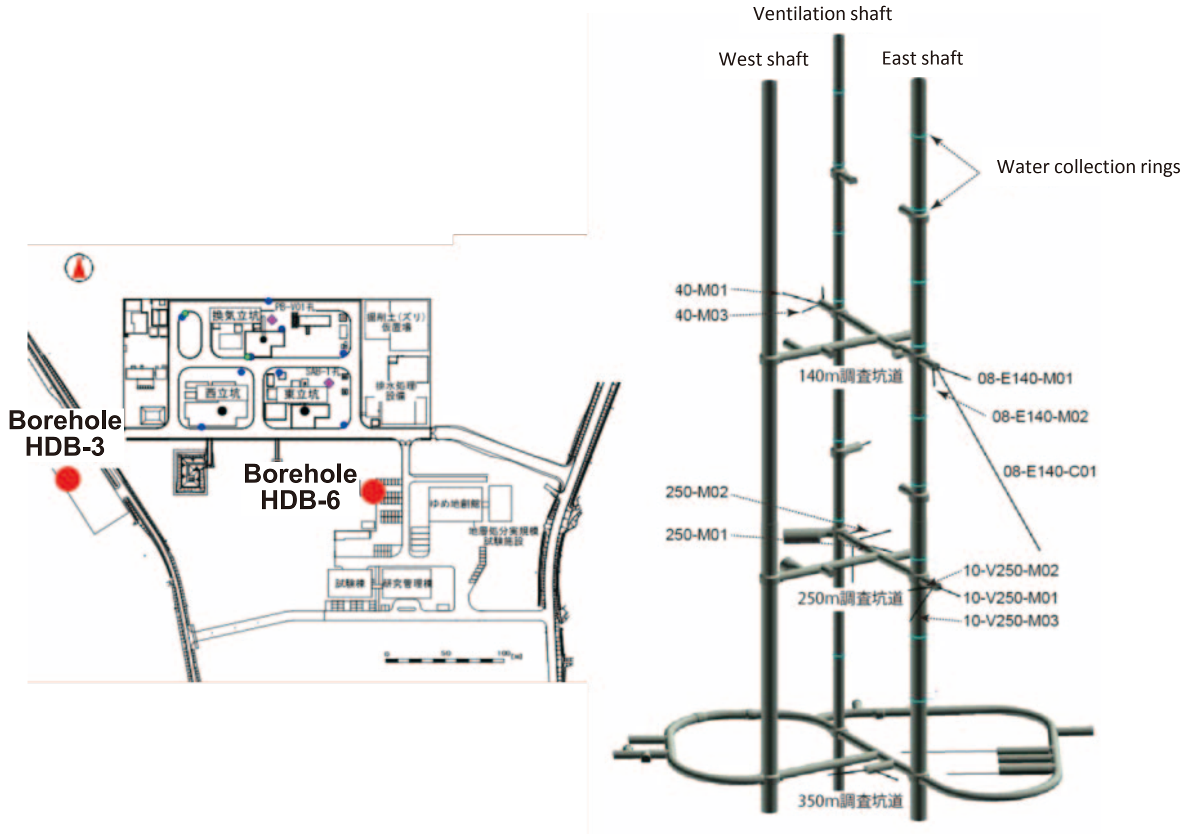


Fig. 3.3.3-7 Hydrological/hydrochemical monitoring boreholes at the Horonobe

Table 3.3.3-2 Hydrological/hydrochemical monitoring sections at the Horonobe

Borehole (Elevation)	Zone No.	Monitoring interval: Meter along borehole		Monitoring interval: Elevation (m)		Geology	Method
HDB-3 (E.L.: 60.21m) Vertical borehole	2	185.86	195.21	-125.65	-135.00	Koetoi Fm.	Multilevel groundwater monitoring in a multiport system (Westbay MP system)
	5	326.85	336.21	-266.64	-276.00	Wakkanai Fm.	
HDB-6 (E.L.: 60.21m) Vertical borehole	4	288.66	302.90	-228.45	-242.69	Wakkanai Fm.	Multilevel groundwater monitoring in a multiport system (Westbay MP system)
	6	362.39	385.70	-302.18	-325.49	Wakkanai Fm.	
07-V140-M01 (E.L.: -78.68m) Horizontal borehole		0.00	20.00	-76.88	-78.68	Koetoi Fm.	Simplified sampling equipment (open borehole and flange)
07-V140-M03 (E.L.: -79.67m) Horizontal borehole	1	15.00	20.00	-82.34	-90.09	Koetoi Fm.	Continuous hydrochemical monitoring sysytem (JAEA system)
	2	7.50	8.50	-81.34	-81.84	Koetoi Fm.	
08-E140-C01 (E.L.: -80.03m) Inclined borehole	1	90.00	101.00	-149.69	-158.70	Koetoi Fm.	Continuous hydrochemical monitoring sysytem (JAEA system)
	2	72.00	89.00	-135.00	-148.87	Koetoi Fm.	
	3	47.00	71.00	-115.13	-134.20	Koetoi Fm.	
	4	38.50	46.00	-108.62	-114.37	Koetoi Fm.	
	5	24.00	37.50	-97.55	-107.86	Koetoi Fm.	
08-E140-M01 (E.L.: -79.13m) Horizontal borehole		0.00	20.00	-79.13	-80.88	Koetoi Fm.	Simplified sampling equipment (open borehole and flange)
09-V250-M01 (E.L.: -189.15m) Horizontal borehole		0.00	20.00	-188.10	-189.15	Koetoi Fm.	Simplified sampling equipment (open borehole and flange)
09-V250-M02 (E.L.: -189.15m) Horizontal borehole	1	6.60	20.00	-188.10	-188.80	Koetoi Fm.	Continuous hydrochemical monitoring sysytem (JAEA system)
	2	4.60	5.60	-188.85	-188.91	Koetoi Fm.	
10-V250-M01 (E.L.: -188.76m) Horizontal borehole		0.00	15.56	-187.01	-188.76	Koetoi Fm.	Simplified sampling equipment (open borehole and flange)
10-V250-M02 (E.L.: -188.79m) Horizontal borehole		0.00	15.63	-187.04	-188.79	Koetoi Fm.	Simplified sampling equipment (open borehole and flange)
10-V250-M03 (E.L.: -188.83m) Inclined borehole		0.00	22.50	-188.83	-203.69	Koetoi Fm.	Simplified sampling equipment (open borehole and flange)
Water Collection rings							
Shaft	No.	Elevation (m)	Shaft	No.	Elevation (m)	Geology	Method
East Shaft	WR-E-27.0	33.00	Ventilation shaft	WR-V-28.5	31.50	Koetoi Fm.	Manual water collection in the shafts
	WR-E-63.8	3.80		WR-V-63.8	3.80	Koetoi Fm.	
	WR-E-100.0	-40.00		WR-V-98.0	-38.00	Koetoi Fm.	
	WR-E-132.0	-72.00		WR-V-132.0	-72.00	Koetoi Fm.	
	WR-E-168.0	-108.00		WR-V-168.0	-108.00	Koetoi Fm.	
	WR-E-202.0	-142.00		WR-V-202	-142.00	Koetoi Fm.	
	WR-E-239.0	-179.00		WR-V-242.0	-182.00	Koetoi Fm.(E)/Wakkanai Fm. (V)	
	WR-E-276.0	-216.00		WR-V-282.0	-222.00	Wakkanai Fm.	
	WR-E-310.0	-250.00		WR-V-310.0	-250.00	Wakkanai Fm.	
	WR-E-340.0	-280.00		WR-V-343.9	-283.90	Wakkanai Fm.	

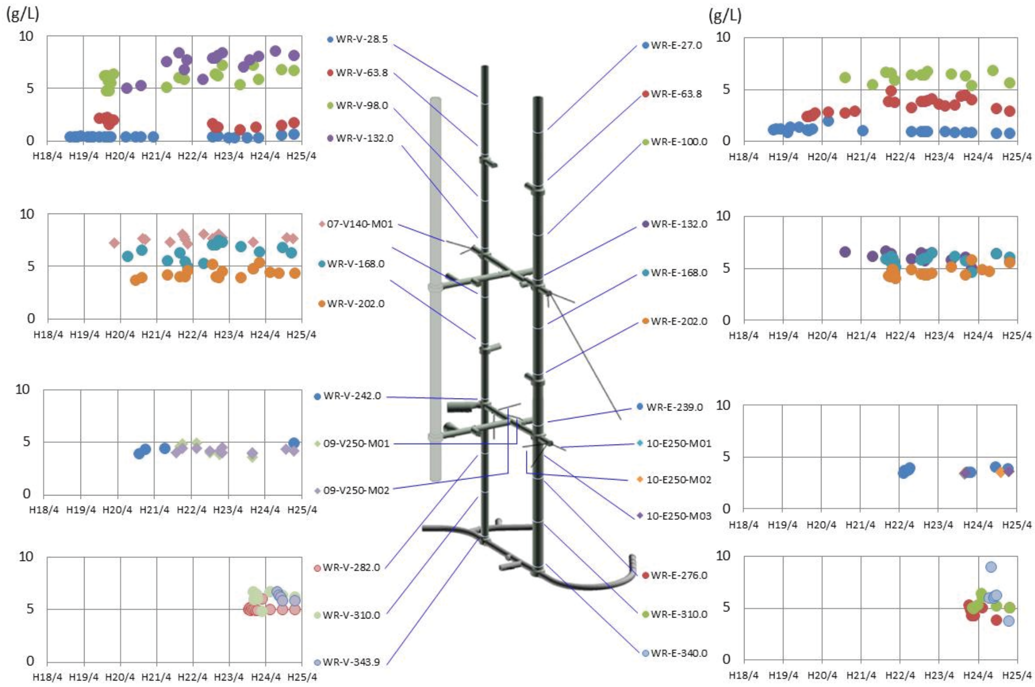


Fig. 3.3.3-8 Salinity distribution around the Horonobe

Fig. 3.3.3-10 shows the results of PCA including the 13 major components (Na^+, K^+, Ca^{2+}, Mg^{2+}, Si, Sr, Cl^-, Br^-, I^-, SO_4^{2-}, HCO_3^-, δD, and $\delta^{18}O$). The first principal component (PC 1) has loading factors dominated by Na^+, K^+, Ca^{2+}, Cl^-, Br^-, δD, and $\delta^{18}O$, which implies that its variation corresponds to differences in the mixing ratio of groundwaters with different salinity. In Fig. 3.3.3-10, the data are mostly plotted along the line between the data of WR-V-28.5 (water ring in the Ventilation Shaft) and of HDB-3 (surface-based borehole). Borehole HDB-3 is located in the west of the URL where the groundwater salinity is relatively higher (Fig. 3.3.3-9). On the other hand, the groundwater sampled from WR-V-28.5 is low-salinity and similar to meteoric water. Therefore, it is suggested that the Horonobe groundwater chemistry can be understood as mixing of these endmembers (Fig. 3.3.3-10).

In contrast, the second principal component (PC 2) has loading factors of Mg^{2+}, SO_4^{2-}, and HCO_3^-. Because these ions are common in major components of concrete material, PC 2 probably reflects the mixing proportions of the groundwater and the concrete material used for the construction of the URL. In the time variation of WR-V-28.5 in Fig. 3.3.3-10(a), for example, only PC 2 decreased while PC 1 showed small variation. Although the pH of groundwater sampled from WR-V-28.5 had an initial value of 10, the value decreased to pH 7–8 over four successive years. This result suggested that the groundwater was influenced by the surrounding concrete materials at the beginning of the monitoring, and the influence reduced with time. This is also consistent with the results of PCA analysis, because the decrease in groundwater pH corresponds to the decrease in the scores for PC 2 (Fig. 3.3.3-10(a)).

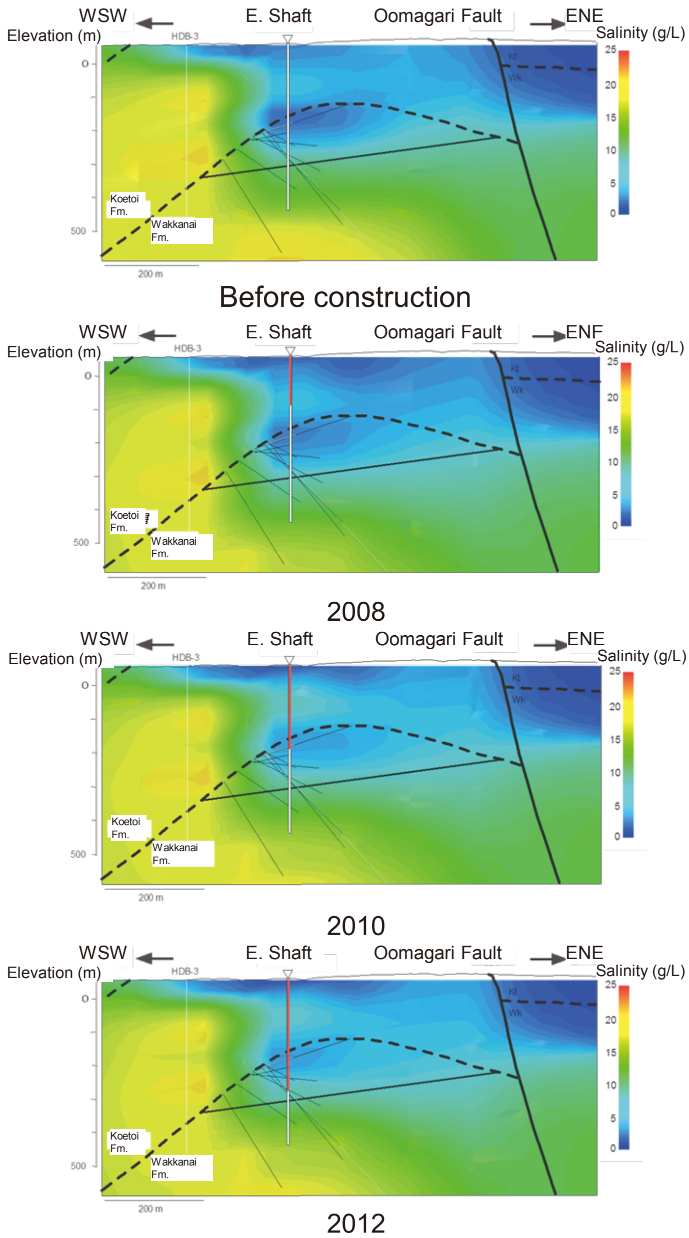
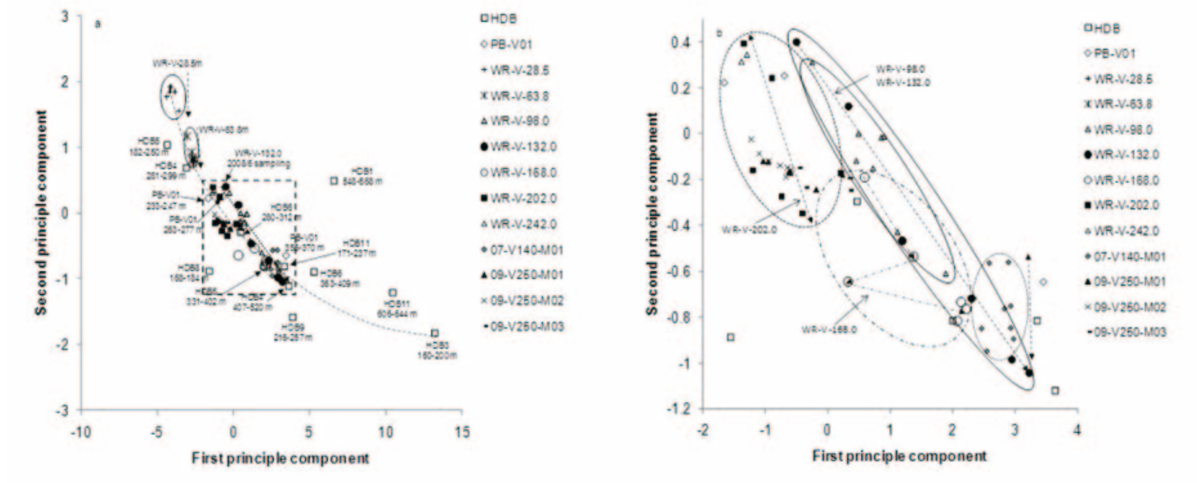


Fig. 3.3.3-9 Salinity evolution related to shaft sinking (Horonobe)

Additionally, the lack of major variation of score plots with time suggests no significant changes of groundwater chemistry in each sampling point. However, strictly speaking, the data belonging to the sampling points WR-V-98.0, WR-V-132.0, and WR-V-168.0 appear to shift with time from the left upper part to the right lower part on the PCA score plot. These trends reflect the decreasing effect of concrete degradation and increasing influence of groundwater salinity changes. This salinity increase can be interpreted as an increase in the mixing ratio of higher-salinity groundwater in borehole HDB-3.

The relationships between 1) the area of groundwater salinity change and the hydrogeological structure, and 2) the timing of groundwater salinity change and the hydrological conditions have not been well understood. The shallow part of the Wakkanai

Formation (just below the boundary of the Koetoi and Wakkanai Formations) has a high permeability where fractures are developed. When the construction of the URL reached the high-permeability zone (i.e., after September 2008), the groundwater outflow rate rose and the distribution of the groundwater salinity changed. Hence, the observed salinity changes probably had a close relationship to both the hydrogeology structure system and groundwater flow conditions. However, the range of variation of the groundwater salinity and its area will be limited in the future because the groundwater flow rate is relatively slower than at the Mizunami URL and the rock permeability in the Horonobe area is very low.



(a) (b)

Fig. 3.3.3-10 Principal component analysis based on hydrochemical data of Horonobe groundwater

(2) Change of groundwater chemistry (pH and redox conditions)

Possible processes to change the pH and redox conditions during facility construction and operation are: 1) groundwater alkalization by degassing in the EdZ; 2) groundwater mixing with relatively shallower water by drawdown in the EdZ; 3) alkalization by grout and shotcrete in the EDZ; and 4) oxidation by air circulation in galleries in the EDZ.

1) Alkalization by degassing

As an example, the pH value changed by approximately 0.2–0.4 by degassing of dissolved carbon dioxide (according to the decrease in water pressure from a depth of 500 m to the ground surface in the Horonobe). The pH changes depending on P_{CO_2} during degassing and the inorganic carbon concentration. In the Mizunami, groundwater drawdown by the facility construction ranged from 100 to 150 m, but the pH values were stable in the range 8–9 during facility construction[3]. In the Horonobe, the pH ranged from 6.5 to 7.5 during facility construction, excluding the area around the cement materials used. The amount of alkalization by degassing during the facility construction and operation appears to have been small.

2) Groundwater mixing subsequent to drawdown

Groundwater mixing has been mainly observed in the Mizunami[3]. The groundwater chemistry at depth tends to vary with time from high-Na, Ca, Cl, low-DIC, SO_4 type to high-DIC, SO_4, low-Na, Ca, Cl type. Though the pH and redox potential (weakly alkaline, reducing conditions) almost never show changes over time at the present day, long-term monitoring is required to evaluate the influence of shallow-water infiltration and the pH and redox buffer capacity of rock minerals. Groundwater chemistry at deep depths can change to that of the shallow depths because of long-term drainage. Changes in the pH and redox potential are controlled by chemical interactions in mixed groundwaters and buffer minerals. If sufficient levels of pH–redox buffer minerals are present in the bedrock, the pH–redox conditions can be inferred based on the future groundwater chemistry and dominant pH–redox buffer reactions.

The possible dominant buffer reactions at depths of 200–400 m are thought to be as follows:

$$Fe(OH)_3 + 3H^+ + e^- = Fe^{2+} + 3H_2O \ (E_0 = 0.95 \text{ V})$$

$$Fe(OH)_3(am) + 3H^+ + e^- = Fe^{2+} + 3H_2O \ (E_0 = 0.975 \text{ V})$$

$$FeCO_3 + 3H_2O = Fe(OH)_3 + 2H^+ + HCO_3^- + e^- \ (E_0 = 1.078 \text{ V})$$

Future pH–redox conditions can be theoretically inferred by substituting the chemical composition of these solutes. For instance, if the solute concentrations in the deep groundwater change to those of the shallow groundwater as follows:

pH: 7.5–8.5

Fe^{2+}: 0–3.6 μM (0–0.2 mg/L)

HCO_3^-: 1.3–1.7 mM (IC: 15–20 mg/L)

SO_4^{2-}: 0.17–0.21 mM (SO_4^{2-}: 15–20 mg/L),

the redox potential ranges from −230 to −10 mV at G.L. −200 m to G.L. −400 m and −250 to −180 mV at deeper than G.L. −400 m. However, the pH–redox conditions would markedly change if buffer minerals such as iron hydroxides on fracture surfaces are all used up in the reactions or the groundwater flow around the facility is faster than the buffer reactions between the groundwater and buffer minerals. Thus, long-term monitoring of groundwater chemistry and pH–redox conditions at the gallery is indispensable to demonstrate the natural buffer capacities of bedrock on the impact of facility construction and operation.

3) Alkalization by shotcrete and grout

For conditions of groundwater inflow and no inflow in Mizunami, the pH was 7–9 and 11–12 for several years, respectively. This implies a low pH-buffering capacity of granite for cement material. The pH values of ordinary Portland cement (OPC) and high fly-ash silica-fume cement (HFSC: low-alkaline cement) were observed in the HOR. In this monitoring, the pH did not increase in either cement for two years because of groundwater replacement.

These observations suggest that alkalization around drift occurs heterogeneously according to the extent of water inflow in various hydrogeological conditions. Additional alkalization of groundwater by cement may possibly occur in stagnant conditions after facility closure.

4) Oxidation by air circulation

The redox buffer capacity for air diffusion from gallery to rock was mainly researched in the

HOR. An infiltration experiment of O_2-saturated water into a borehole drilled from the gallery showed that the redox potential recovers to the baseline reducing condition within a few days as a result of water–mineral–microbe interactions. Organic-rich sedimentary rock has a sufficient redox buffer capacity for air infiltration. On the other hand, no obvious increase in redox potential was observed in the vicinity of the gallery in the granitic rocks of the MIU.

3.3.4 Summary

The R&D in the second mid-term research phase focused on demonstrating monitoring techniques during facility construction and operation. Based on the results from MIU/HOR, knowledge of the mid-term variations in the geological environment around the underground facilities is as follows.

Points to keep in mind for facility construction/operation and monitoring

- Based on comparison between Mizunami and Horonobe, chemical disturbance is lesser in low-permeability sedimentary rock with a smaller amount of water inflow.
- The hydrochemical conditions change markedly with time if a facility is constructed in fractured rock with a large volume of groundwater inflow. Design of gallery layout taking into account the low-permeability rock domain identified in the surface-based investigation is indispensable to avoid and reduce disturbance.
- Hydrochemical monitoring in each hydrogeological compartment during facility construction/operation enables assessment of a panel division that should be preferentially closed to prevent expansion of the disturbed zone.
- The mid-term changes in groundwater chemistry during the operation phase are predicted based on monitoring of the permeable zone and multivariate analysis such as principal component analysis. Shallow water is likely to infiltrate to depth in a facility with a large volume of groundwater inflow. Tritium and CFCs are essential tracers that should be observed from baseline conditions.
- During facility construction and operation, it is important not to disturb the performance of the natural barrier. It is essential to maintain minimum disturbance by predicting the distribution of high-permeability domains around the facility area. However, excessive water-tight grout may cause unanticipated inflow accidents. This is a trade-off with safety management.

Points to keep in mind for pH and redox conditions:

- During facility operation and after closure, alkalization around drift will occur heterogeneously according to the water inflow conditions. Geophysical surveys and hydrochemical integrated analyses are available to identify the area of alkalization.
- Sedimentary rock with abundant organic matter has an efficient redox buffer capacity for oxidation by air in drift.
- Replacement of the shallower groundwater infiltrated during facility operation to original deep groundwater is required for recovery of chemical conditions. Then the facility closure procedure should be considered based on data such as the groundwater inflow rate at each depth, chemical composition, and preliminary modeling of water pressure recovery.

- In the low-permeability rock domain, an unsaturated zone around gallery may persist locally and possess heterogeneous hydrochemical properties after closure.

Regarding the approach used to consider the variation of hydrochemical conditions, it is important to compare the magnitude relation between short-term and medium-term variation caused by facility construction/operation and long-term variation resulting from natural geological phenomena. The magnitude relations are listed in Table 3.3.4-1.

Table 3.3.4-1 Remaining R&D issues for perceiving the evolution and recovery behavior of the hydrochemical conditions

		pH		Redox		GW chemistry
Main process		Change with GW flow	Change with cement	Change with GW flow	Change with material transport from drift	Change with GW flow
Fracture medium	Construction/ operation	A>B	B>A	B>A ?	A>B	B>A
	Post closure	A>B	B>A	B>A ?	B>A ?	B>A ?
Porous medium	Construction/ operation	A>B	B>A	A>B	A>B	A>B
	Post closure	A>B	B>A	A>B	B>A ?	A>B
Importance		Small variation	A long-term steady state	Buffer capacity for infiltrated oxidizing water	Impact of backfilling material	GW replacement

A: long-term variation caused by natural geological phenomena

B: short-term and medium-term variation caused by facility construction/operation

The subjects denotes as A > B and B > A require R&D on the long-term phenomena and short, mid-tem monitoring for each geological medium. For instance, changes in the redox conditions caused by shallow-water infiltration during facility construction/operation in a fractured medium resemble accelerated testing of long-term infiltration of shallow oxidized water related to uplift/erosion. If no changes in redox conditions were identified by monitoring during facility construction/operation, the rock probably has a sufficient redox buffer capacity. In other words, the redox conditions do not change over the long term unless the impact of long-term geological phenomena is greater than the impact of facility construction/operation. On the other hand, pH changes caused by cement materials are much larger than changes from long-term geological phenomena. The long-term pH variation after closure is an important future problem.

R&D on the variation in the geological environment after facility closure, such as the recovery process and features are planned as indispensable subjects in the next research phase of Mizunami and Horonobe.

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3.4 Rock mechanics

3.4.1 Introduction

An EDZ (Excavation Damaged Zone) and an EdZ (Excavation disturbed Zone) are likely to be less stable than the undisturbed rock mass and to provide higher-permeability pathways for groundwater flow in the vicinity of excavations. Thus, development of an EDZ and EdZ is recognized as a key issue in both the design and construction of disposal facilities and safety assessment. Knowledge of the initial conditions of in situ stress and mechanical properties of the rock before shaft sinking is necessary in the surface-based investigation phase (Phase I). In the construction phase (Phase II) and operation phase (Phase III), the predicted geological conditions have been evaluated based on additional data obtained during these phases and information about the EDZ and EdZ around the shaft and gallery should be obtained. The subjects of study regarding rock mechanics are as follows:

1) Mechanical stability around openings
  - In situ stress
  - Physical and mechanical properties
  - Discontinuities

2) Thermal condition
  - Thermal gradient
  - Thermal properties

3) Geological environment of the EDZ
  - Width of the EDZ
  - Physical and mechanical properties of the EDZ
  - In situ stress state in the EDZ
  - Thermal properties of rock

The geological environment of the EDZ is discussed below.

3.4.2 Objectives in the second mid-term research phase

As shown in section 2.4, the objectives of rock-mechanics investigation during Phase II are to understand the detailed in situ stress conditions and rock mechanical properties by borehole investigations from the shafts and galleries and laboratory tests during extension of the shafts and galleries at depths of 500 m (Mizunami) and 350 m (Horonobe). Also, it is necessary to confirm the validity of the conceptual model and analysis technique applied in Phase I. An additional objective of this phase is to understand the geological changes caused by shaft and gallery excavation. Table 3.4.2-1 lists the performance target of R&D, achievement items, and reflection on the R&D results.

Table 3.4.2-1 Performance target of R&D for rock mechanical characterization

Focus	Performance target of R&D	Tasks
Decision-making for start of construction	Decision-making for excavation of underground facility.	• Technology for determining the width and properties of the EDZ

3.4.3 Project details and outcomes

(1) Geological environment of the EDZ

1) Mizunami

Two- and three-dimensional and numerical simulations using crack tensor model and an MBC (Micromechanics Based Continuum) model considering the EDZ were performed to predict the rock mass behavior based on the results of in situ stress measurements and laboratory tests during Phase I. The distribution of rock mass stress and strain, fracture openings, shear strain, and the local safety factor were predicted at depths of 500 m and 1,000 m.

Strain measurement during shaft sinking was performed to estimate the width of EDZ caused by blasting at the shaft wall[1)]. The simulation results were compared with measurements and the validity of the simulation was confirmed[2)]. The scale effect of the crack tensor calculated using the geometric properties of discontinuities based on geological mapping at the shaft wall was discussed to reflect the modeling method for fractured media[3)].

The conclusions are as follows:

- Based on the results of equivalent continuum analysis using information obtained from Phase I, the distribution of rock mass stress and strain, fracture openings, shear strain, and local safety factor were influenced by the in situ stress field, existing fractures, and the orientation and length of induced fractures. The changes in the hydraulic conductivity of the EDZ were assessed in terms of the relation between fracture opening and hydraulic conductivity (Fig. 3.4.3-1). An increase in hydraulic conductivity by two orders of magnitude of the EDZ was predicted as a result of opening of fractures parallel to the gallery wall.[4),5),6)]. Investigation of the length and spacing of fractures is important for modeling of the EDZ.
- Rock mass stress and strain were measured during Ventilation Shaft sinking at a depth of 200 m (Fig. 3.4.3-2). The magnitude of the rock strain was equal to the value predicted by elastic analysis, and slightly less than the limiting value. The measured lateral strain was compressive, but the predicted strain was tensional. Rock mass behavior caused by excavation was dominated by changes in fractures[1)] (Fig. 3.4.3-3).
- The relative error of the crack tensor calculated from the results of geological mapping of the shaft and gallery was estimated to examine the variation of relative error to the scale of observation areas for suitable modeling of the Toki Granite[3)] (Fig. 3.4.3-4, Fig. 3.4.3-5).

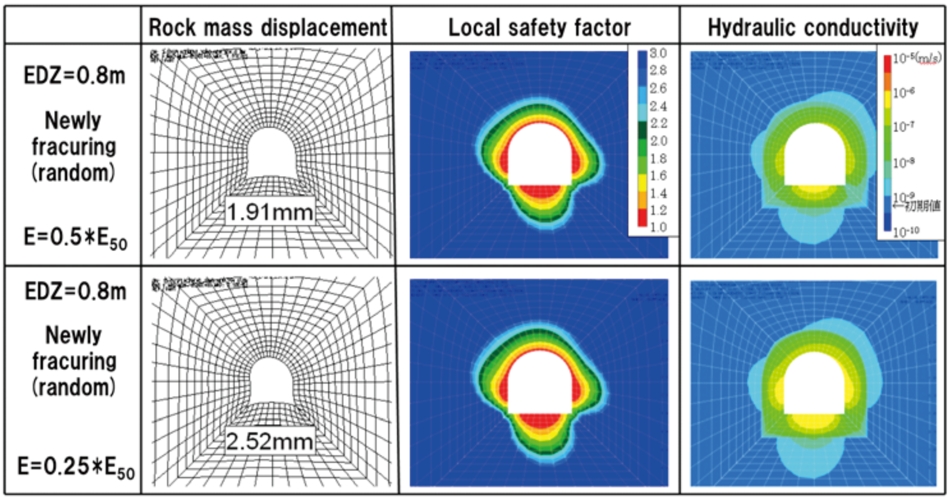

Fig. 3.4.3-1 Results of equivalent continuum analysis using the crack tensor model

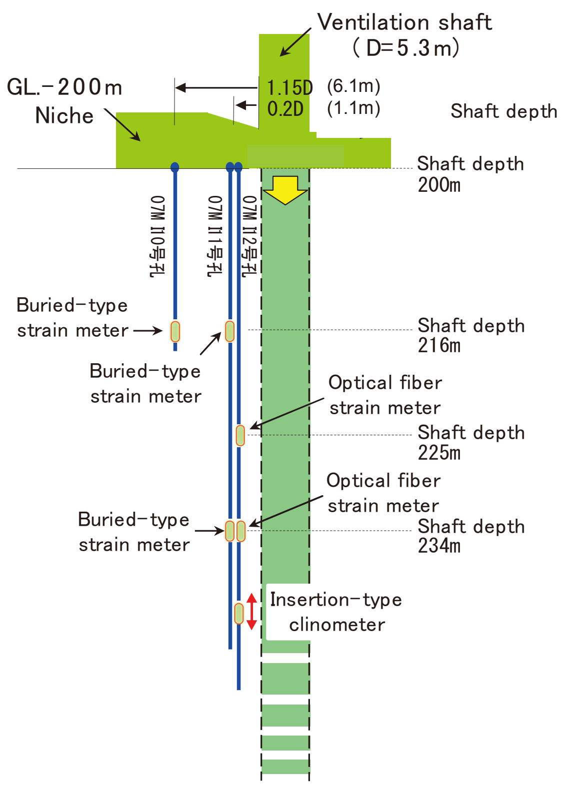

Fig. 3.4.3-2 Strain measurement during shaft sinking

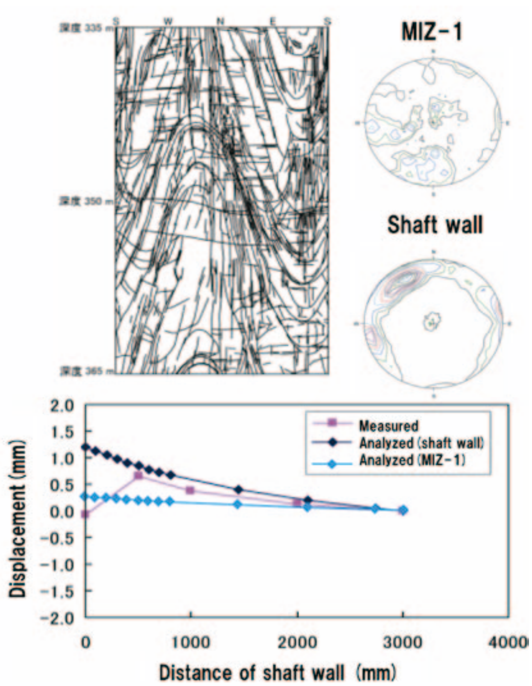

Fig. 3.4.3-3 Comparison of measured and analyzed rock mass displacement

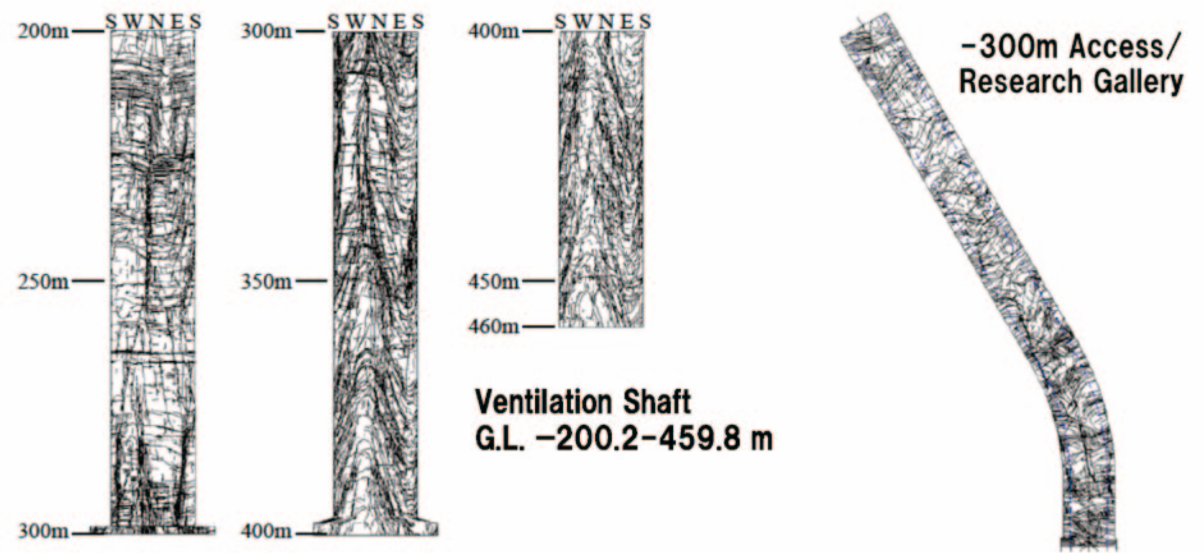

Fig. 3.4.3-4 Results of discontinuity observations obtained at the shaft wall

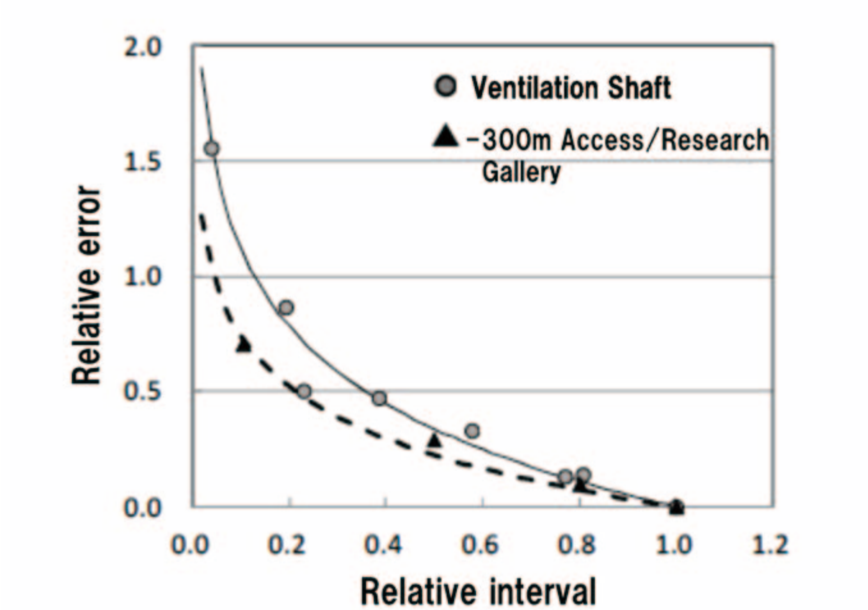

Fig. 3.4.3-5 Relative error of crack tensor vs. relative interval

2) Horonobe

Investigation of an EDZ was conducted in the G.L. −140 m and G.L. −250 m galleries and the East Access Shaft at 160 m depth. In the G.L. −140 m and G.L. −250 m galleries, seismic, resistivity, and acoustic tomography surveys had been conducted before excavation and during excavation of the tomography area. After excavation of the tomography area, these surveys have been conducted about two to four times a year. Fig. 3.4.3-6 shows the layout of the investigation conducted in the G.L. −250 m gallery. In addition, hydraulic tests and measurements of pore pressure, displacement, and pressure of a shotcrete were conducted to understand the hydrogeological properties in an EDZ in detail. In the East Access Shaft, hydraulic tests were conducted; then the hydraulic conductivity before and after excavation was compared. The results of these tests can be summarized as follows:

- For the tomography survey in the presence of flammable gases such as methane, the simplified seismic velocity survey system was developed. This system consists of a hammer to transfer seismic energy to receivers. In addition, this system is well suited to repetitive surveying[7),8)].
- In the G.L. −140 m gallery, a desaturation zone was detected from the measurements of water content and pore pressure[9)].
- In the G.L. −250 m gallery, the layer with low seismic velocity (LVL) has changed with time; however, the layer did not exceed the extent detected shortly after excavation (Fig. 3.4.3-7)[10),11)].
- From numerical analysis, microcracks were expected to be induced in the LVL (Fig. 3.4.3-8)[12)].
- In the LVL, hydraulic conductivity was increased by about two orders of magnitude compared with undamaged rock[13)].
- A conceptual model of the distribution of fractures in the G.L. −250 m gallery was constructed based on fracture mapping on the wall (Fig. 3.4.3-9)[14)].
- Hydraulic conductivity within approximately 1 m of the East Access Shaft wall increased by one order of magnitude[15)].
- A multi-interval displacement sensor using Fiber Bragg Grating (FBG) technology was developed to measure the long-term deformation behavior of the rock mass[16)]. Using comparison with measurement data from conventional extensometers, the applicability of the FBG sensor was investigated.

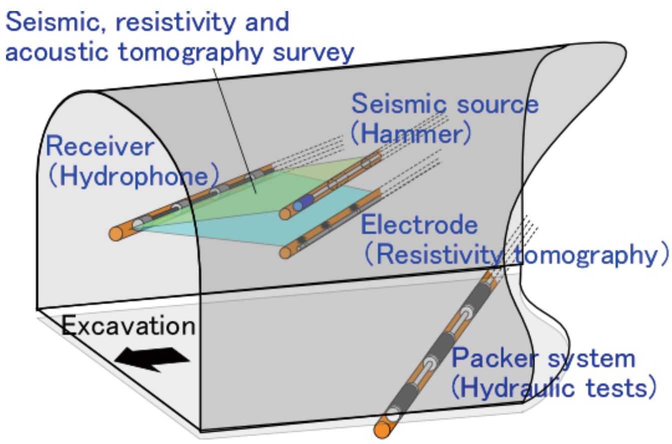

Fig. 3.4.3-6 Image of the layout of the in situ surveys used for determining the EDZ in the gallery

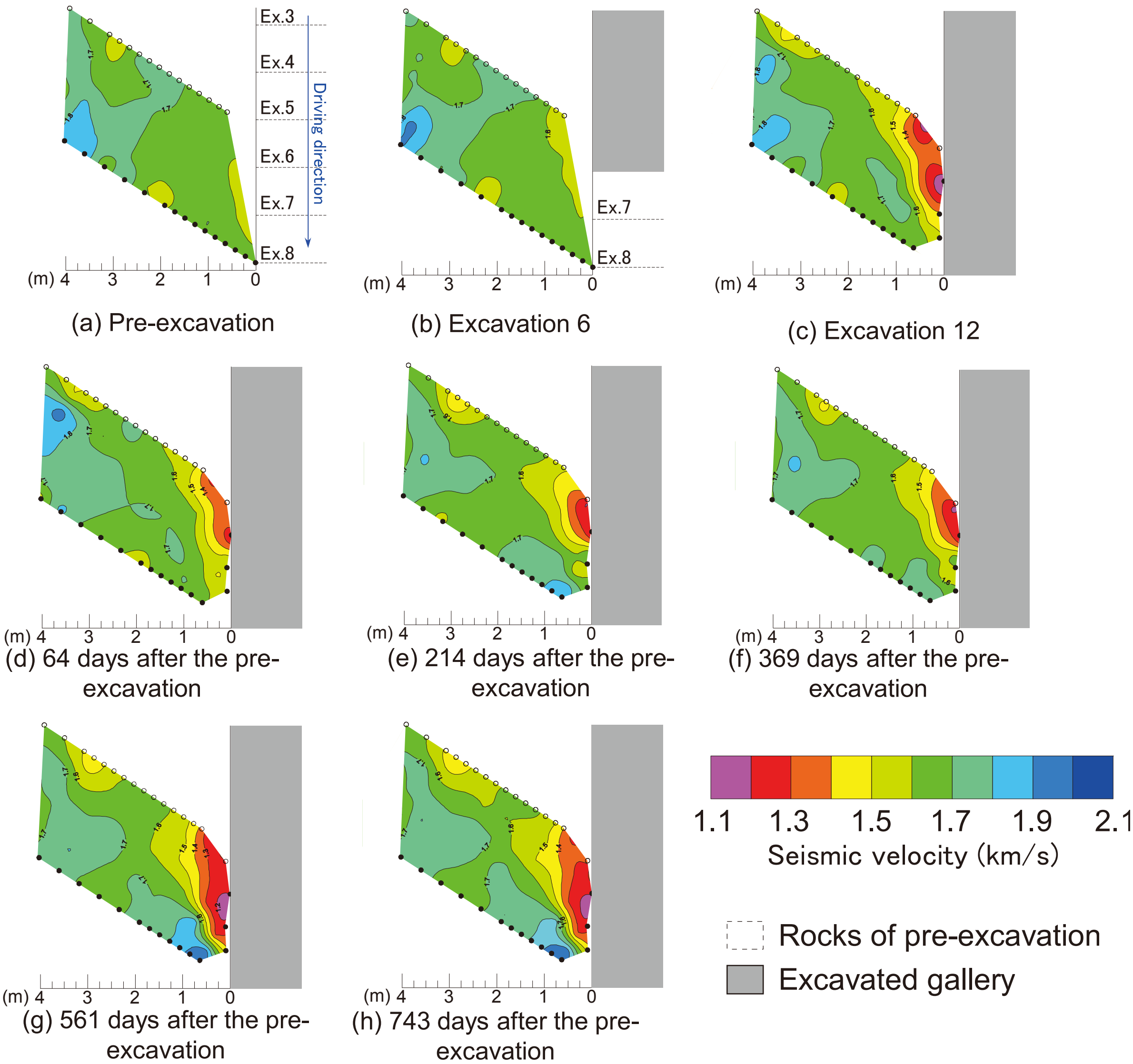

Fig. 3.4.3-7 Representative results of seismic tomography surveys conducted in the G.L. −250 m gallery

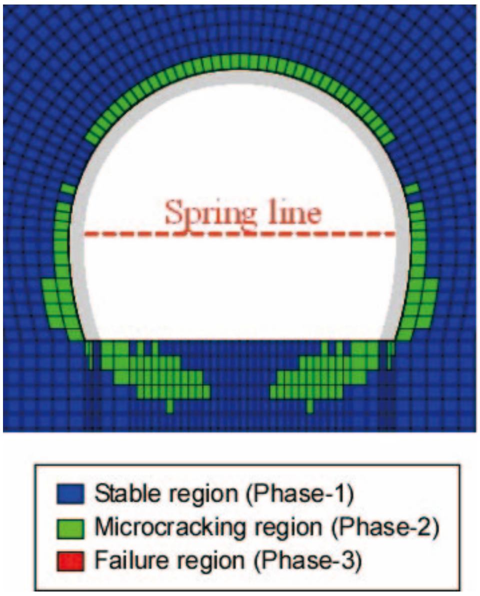

Fig. 3.4.3-8 Microcracking region around the gallery from the results of FEM analysis[10)]

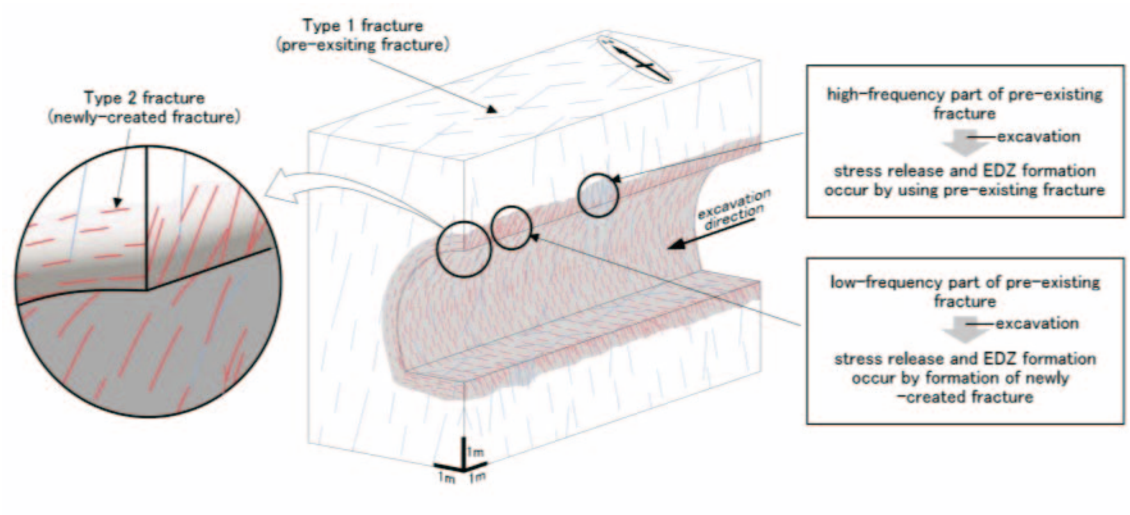

Fig. 3.4.3-9 Conceptual model of the fracture distribution around the gallery[14)]

3) Generic results

There are differences between the rock mechanical model, the elasto-plastic model for porous media, and the crack tensor model for fractured media, and the rock strength of soft rocks and hard rocks. Almost all investigation techniques and numerical analysis techniques are applicable to both rock types.

3.4.4 Summary

Rock mass displacement and strain measurements were performed to understand the width of the EDZ in Mizunami. The modeling methodology for the rock mass using the equivalent continuum model was discussed. Water pressure monitoring, tomography measurements, and hydraulic test were performed to understand the EDZ, and an instrument for use in conditions with flammable gas was developed in Horonobe. An EDZ model considering induced fractures caused by excavation was also developed.

The data concerning EDZ have been obtained, and the mechanism of EDZ development has also been determined. Future plans are as follows:

- Understanding of coupled behavior in the EDZ
- Failure mechanism because of thermal effect, and measurement examples
- Understanding the behavior of the EDZ during gallery closure and development of a prediction methodology

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3.5 Mass transport

3.5.1 Introduction

As part of the study of mass transport, we have been working on themes (1) through (3) below for the purpose of understanding the retardation effects on mass transport in rock masses and groundwater[1)] (Fig. 3.5.1-1), as well as theme (4) from the perspective of the establishment and systematization of techniques for investigation and evaluation of mass transport to support safety assessment[2),3)].

(1) Understanding the sorption and diffusion properties of rock mass

From the perspective of the safety assessment of geological disposal, it is important to understand the sorption and diffusion properties of rock masses. It is also necessary to establish techniques for acquisition of highly reliable data on these properties and for analysis and evaluation.

(2) Understanding mass transport fields

From the perspective of safety assessment of geological disposal, it is necessary to understand the initial conditions concerning geological structures, groundwater pressure, permeability of rocks, and groundwater chemistry. In addition, it is also necessary to establish techniques for acquisition of the highly reliable data needed for this purpose and for analysis and evaluation.

(3) Understanding the effects of colloids, organics, and microbes

As the presence of colloids, organics, and microbes in the geological environment affects the mass transport properties of a rock mass in various ways, it is necessary to develop individual elemental techniques for the characterization of the factors in a specific given geological environment, as well as to systematize investigation, analysis, and evaluation techniques, as essential means for understanding the initial conditions of the geological environment.

(4) Establishment of techniques for analysis and evaluation of mass transport properties

From the perspective of conducting safety assessment for geological disposal, it is important to establish analysis and evaluation techniques for appropriate understanding of the mass transport phenomena occurring in the geological environment based on the acquired data on the characteristics of mass transport.

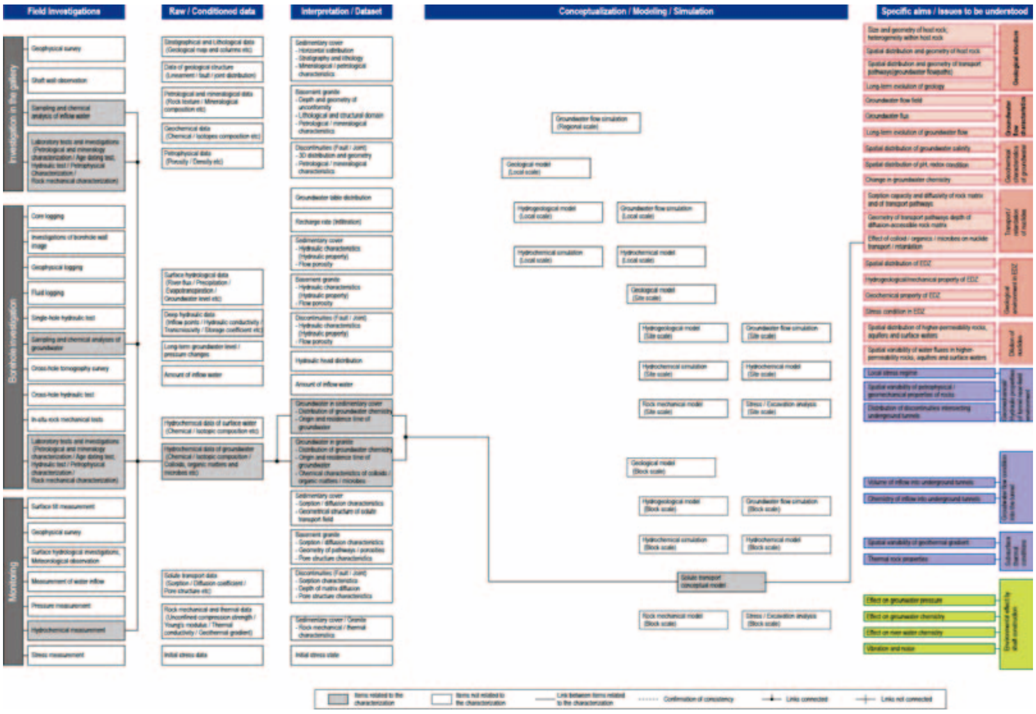

Fig. 3.5.1-1 Geosynthesis data flow diagram (mass transport study)[1)]

3.5.2 Objectives in the second mid-term research phase

The study at underground facilities needs to produce outcomes and scientific knowledge that can be reflected in the decision-making concerning site selection, construction of facilities, commencement of disposal, completion of placement of waste packages, and final sealing in the actual disposal operation. From this perspective, the level of technical development we aim to achieve for use in decision-making concerning the construction of facilities and the commencement of disposal, in the context of understanding the short-term changes and recovery behavior in the geological environment, is the establishment of survey and evaluation techniques that can indicate the favorable underground facility layout and disposal hole layout in terms of mass transport and the confirmation of the in situ applicability of such techniques, as well as the systematization of the series of techniques from survey to analysis/evaluation enabling us to obtain the mass transport properties and their heterogeneity in the geological environment during facility construction and operation (Table 3.5.2-1).

During the second mid-term research phase, we conducted investigation and study addressing themes (1) to (4) described above in vertical shafts and horizontal galleries reaching depths of 500 m at Mizunami and 350 m at Horonobe. We conducted laboratory tests, in situ tests, and modeling and analysis concerning mass transport and started the accumulation of in situ data and knowledge.

Table 3.5.2-1 Performance target of R&D in the mass transport study

Focus	Performance target of R&D	Tasks
Decision to construct, to begin disposal, to end emplacing waste and on final closure	To identify the domain that is favorable for the mass transport study.	Sorption capacity and diffusivity of rock matrix and of transport pathways • Methodology development to understand sorption/diffusion property by in-situ experiment
		Geometry of transport pathways; depth of diffusion-accessible rock mass • Methodology development to understand transport pathway by in-situ experiment
		Effect of colloid/organics/microbe on nuclide transport/retardation • Methodology development to understand the effect on mass transport
	To evaluate the safety of geological disposal system.	Evaluation technology for the characterization of mass transport property • Methodology development to evaluate mass transport property (investigation, modeling, analysis)

3.5.3 Project details and outcomes

(1) Understanding the sorption and diffusion properties of rock mass

For the purpose of understanding the mass transport properties of a rock mass, we developed techniques for acquiring relevant parameters from in situ tests using non-sorbing and sorbing tracers. In the Mizunami and Horonobe URLs, we developed in situ mass transport test apparatuses and test methods that can be applied to various underground environments, such as those with high groundwater pressure and groundwater containing dissolved gases and geological environments containing rock masses with different properties, and confirmed the applicability of such techniques. As mass transport in the underground environment is a complex phenomenon involving sorption and diffusion in a rock mass, advection accompanying the flow of groundwater, and other factors, this part of the study also included development of techniques for understanding the properties of mass transport caused by advection.

1) Mizunami

We started in situ mass transport tests focusing on fractures in crystalline rocks. Specifically, we aimed to examine the applicability to an actual underground environment using the test apparatuses developed by the Central Research Institute of Electric Power Industry (CRIEPI), and started in situ tests at the −300 m stage. We drilled multiple boreholes and conducted geological and hydrogeological investigations to obtain basic data for the evaluation and selection of test sections, where we plan to perform in situ mass transport tests using tracers.

In addition, we conducted laboratory through-diffusion tests using drillcore samples for the purpose of detailed examination of the relationship between fracture characteristics and mass transport parameters[4),5)].

2) Horonobe

By adding tracer injection and recovery functions to existing cross-hole hydraulic test apparatus, we developed a test apparatus that can perform in situ tests using tracers[6)] (Fig. 3.5.3-1). In the in situ tests using this apparatus, we conducted borehole drilling, core logging, various physical logging, fluid logging, single-hole, cross-hole hydraulic tests, and tracer tests at the 250 m Niche off Ventilation Shaft No. 1 focusing on fractures in rock masses. During this in situ testing, we conducted duplicate tests under varying conditions, including tracer injection flow rate, pumping flow rate, and injected tracer concentration, for the purpose of establishing the test apparatus and test methods and confirming their applicability (Fig. 3.5.3-2). For the purpose of application to tests under gaseous conditions, we established a function that can remove gases from the test section in the borehole and a procedure for test apparatus installation that minimizes the generation of free gases in the test section (Fig. 3.5.3-3). This made it possible to perform tests in the presence of dissolved gases and obtain reliable data. Our method also improved the reliability of test results obtained in the presence of dissolved gases, as it became possible to confirm the effective exclusion of the influence of dissolved gases based on the fluid compressibility in the test interval. The results demonstrated the validity of permeability tests based on injection and tracer tests using low injection and pumping rates and a dipole ratio (the ratio of injection flow rate to pumping rate) of 1 in the underground environment near the test site.

Regarding the development of techniques for in situ analysis of tracers, we constructed a system consisting of flow cells for online fluorescence analysis, which were installed in the test intervals in both the injection and pumping boreholes and connected via optical fibers (Fig. 3.5.3-1), and confirmed the applicability of the in situ analysis techniques to the sedimentary rock environment through duplicated tests using uranine. Although the analytical value from the flow cell on the recovery side differed from the values for samples of pumped water, suggesting the possibility of fluorescent scattering caused by microbubbles in the flow cell, it was confirmed that reliable data can be obtained by correcting the in situ data with the analytical value of pumped water. We also examined the application of deuterium as a non-sorbing tracer for in situ tests (Fig. 3.5.3-4). With an eye to the application of a flow cell online analysis technique, we performed absorption spectrophotometric analysis of deuterium concentrations: the results supported the prospect of using deuterium as a tracer in in situ tests. On the other hand, it became clear that online analysis would require further improvement of analytical accuracy through an increase in optical length and integration of scattered light.

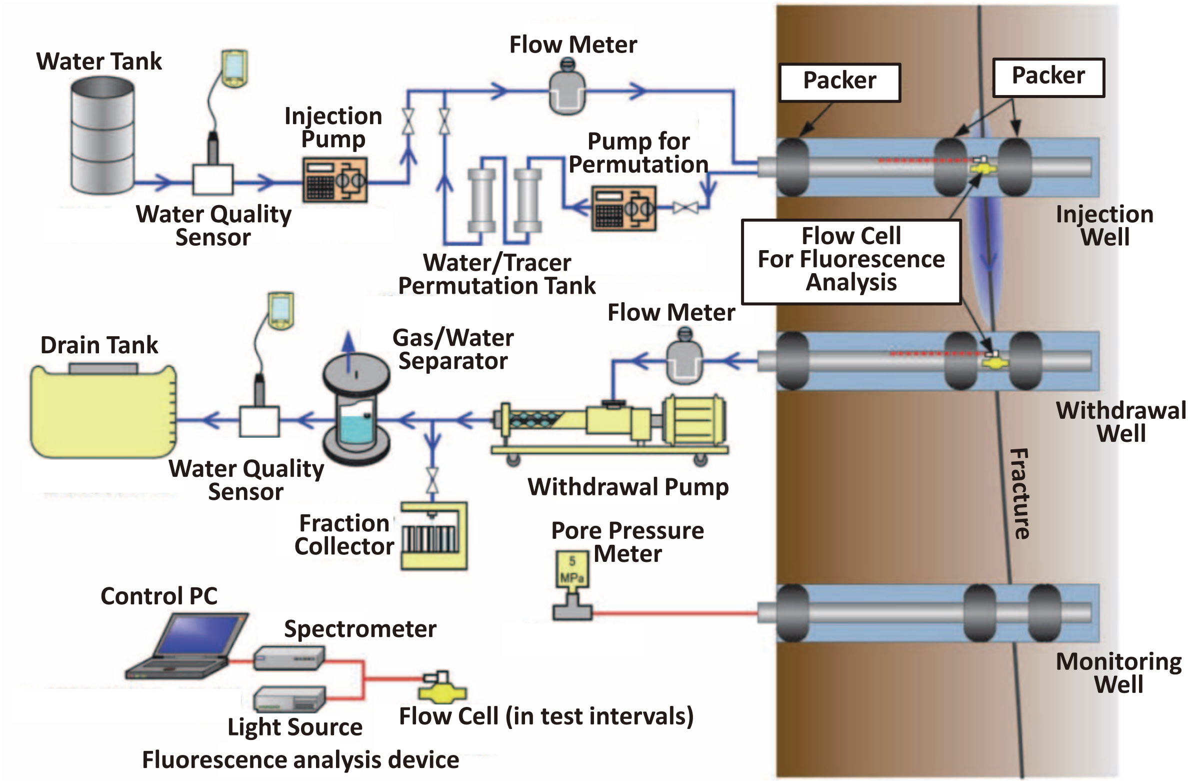

Fig. 3.5.3-1 Overview of the test equipment used in the in situ tracer test[6)]

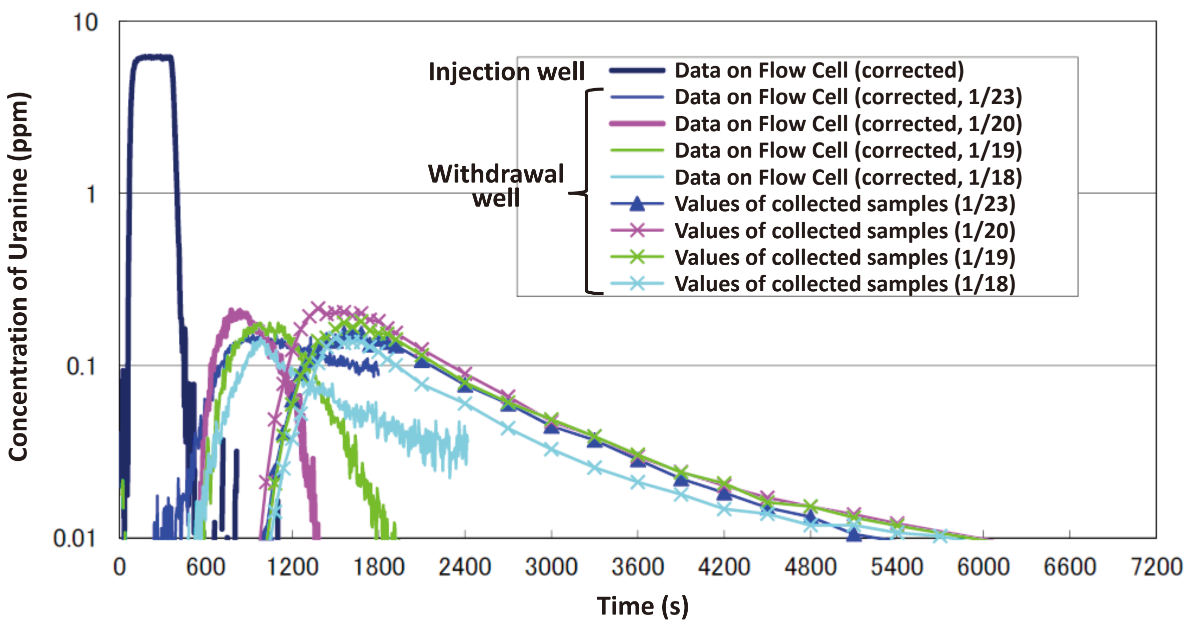

Fig. 3.5.3-2 Reproducibility verified by duplicated tracer migration tests

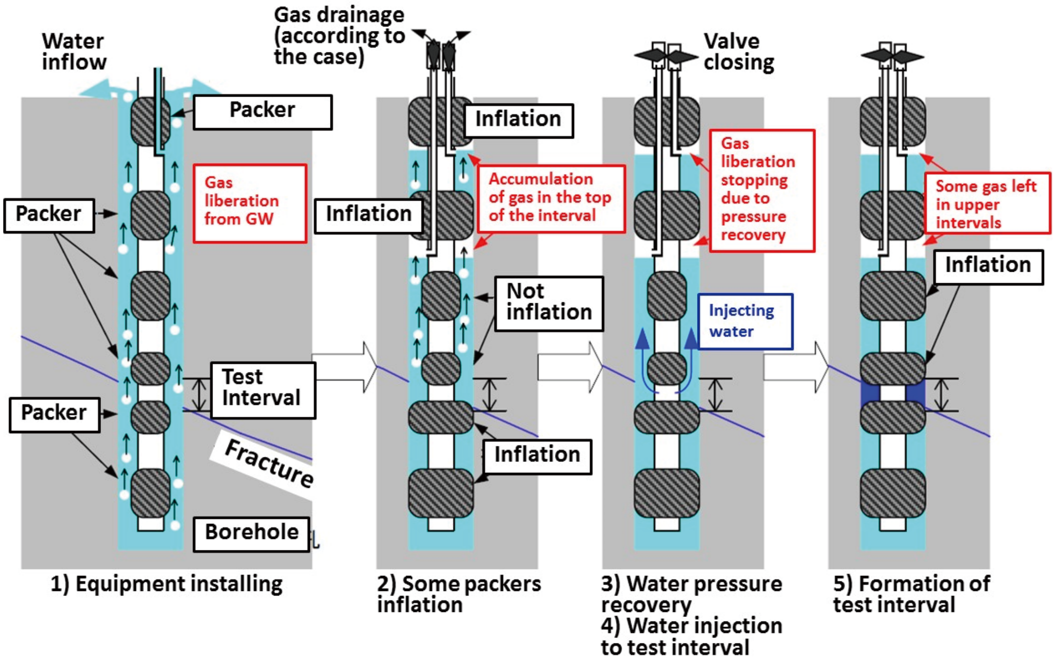

Fig. 3.5.3-3 Packer inflation/deflation procedure under gaseous conditions

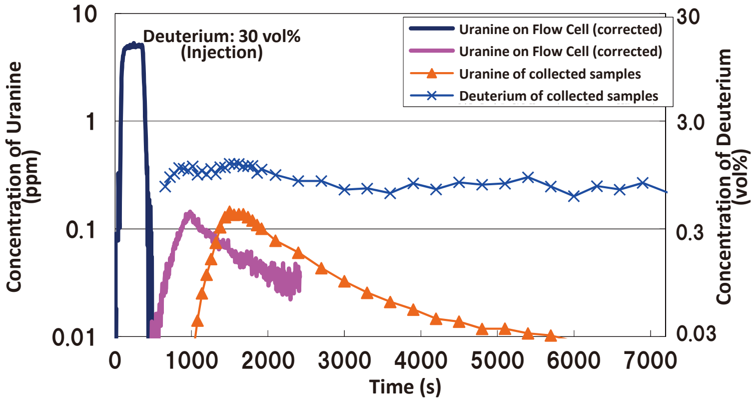

Fig. 3.5.3-4 Results of tracer migration tests using uranine and deuterium

(2) Understanding mass transport fields

We developed investigation techniques to understand the mass transport pathways. The mass transport pathways in a rock mass are formed by interconnected spaces (cavities), such as pores between mineral particles and clastic particles occurring in the rock matrix and fractures and discontinuous structures present in the rock mass. Of these types of spaces, we focused on fractures and discontinuous structures, where relatively rapid mass transport is likely to be caused by advection, and classified these structures as a means of clarifying the targets of our efforts to understand the characteristics of mass transport.

1) Mizunami

Faults and fractures that could form mass transport pathways were identified based on the results of surface-based borehole investigations, investigations during shaft excavation, and investigations in the underground facilities. These faults and fractures were classified into five types according to the type and presence/absence of fracture-filling minerals, the degree of alteration and color of host rock near the fracture, permeability, and the ages of the faults and fractures [5] (Table 3.5.3-1, Fig. 3.5.3-5). We plan to proceed with in situ tests, laboratory tests, and modeling focusing on discontinuous structures such as fractures and faults.

Table 3.5.3-1 Classification of types of discontinuous structures in the Toki Granite

Type	Fracture fillings	Wall rock alteration around fracture	Hydraulic conductivity	Age and temperature
I : Fractures	Chlorite	Not altered	Low	69-43Ma 300-200℃
II : Fault	-	Strongly altered	Very low	64-43Ma 400-300℃
III : Fractures	Chlorite	Altered (wall rocks show greenish or white-tinged color)	Low	64-43Ma 300-200℃
IV : Fractures	Calcite, Chlorite or not	Altered (wall rocks show grayish or orange color)	High	69-24Ma <200℃
V : Low-angle Fractures	Calcite or not	Not altered	High	43-22Ma <100℃

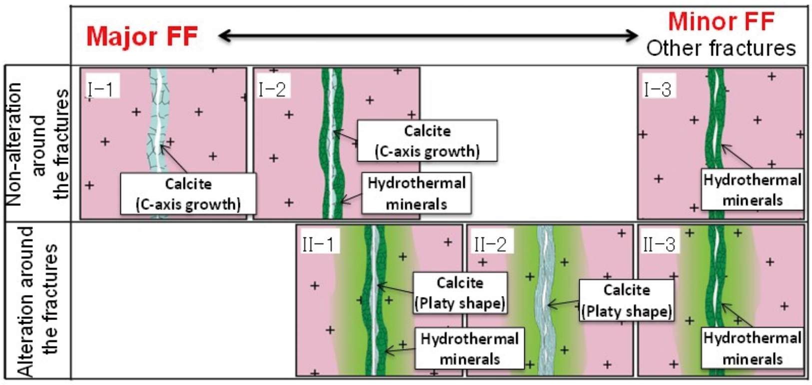

Fig. 3.5.3-5 Conceptual model of the relationship between petrography and flow-path fractures (Fracture type I and type II in the Table 3.5.3-1)

2) Horonobe

Discontinuous structures that can form the mass transport pathways were identified based on the results of surface-based borehole investigations, investigations during shaft excavation, and investigations in the underground facilities. These structures were classified into four types according to the mechanism of fracture formation (tensile and shear), the presence/absence of fault rock accompanying shear fractures[7], and the presence/absence of shear band formation[8] (Fig. 3.5.3-6).

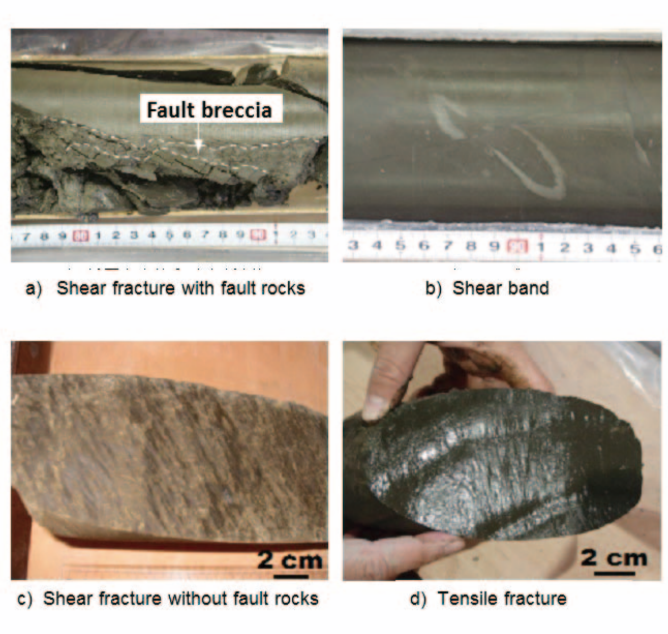

Fig. 3.5.3-6 Discontinuous geological structures around the Horonobe URL
(a, c, d[7] ; b[8])

(3) Understanding the effects of colloids, organics, and microbes

We developed investigation techniques to understand the effects of colloids, organics, and microbes as phenomena contributing to mass transport in the geological environment. Because the medium for material transport in a rock mass is groundwater, we conducted investigations to understand the phenomena occurring in the underground environment and established investigation and analysis techniques for this purpose, focusing on groundwater–rock–colloid/organics/microbe interactions and the characteristics of mass transport. This clarified that the effects of colloids in groundwater on mass transport phenomena vary depending on the chemical elements involved and the environment of colloid formation, and enabled us to develop mathematical models of sorption and diffusion phenomena in a diffusion system featuring organic matter in groundwater. In addition, we developed investigation and analysis methods to evaluate the effects of microbial activities in groundwater on mass transport phenomena and understand the effects of biofilms on diffusion and sorption phenomena.

1) Mizunami

For the development of in situ investigation techniques to understand the effects of colloids in groundwater on mass transport, we constructed a system for collecting colloids in groundwater using ultrafiltration under in situ groundwater pressure in a borehole drilled from the gallery, and confirmed its applicability to in situ investigations[9]. In this system, the parts that come in contact with groundwater are protected by passivation treatment, which minimizes the elution of iron from materials. To address the effects of organic matter in groundwater, we conducted investigations of rare earth elements that work effectively as analog elements for radionuclides. After size fractionation using ultrafiltration was conducted on the colloids in groundwater, the concentrations of rare earth elements in each size fraction were analyzed. The results showed, based on thermodynamic calculations, that rare earth elements form complexes with organic matter (humic acid) and occur in groundwater in a colloidal state[5),10)] (Fig. 3.5.3-7). With respect to the effects of microbes in groundwater, we constructed a system in which the water for drilling is used after sterilization with ultraviolet light to avoid contamination that would affect the results (Fig. 3.5.3-8), and applied this system in the investigations. The use of this system reduced the viable cell count in drilling water to 1/4–1/5 of the level prior to application of the system. In addition, we performed genetic analysis of microbial populations after the addition of various electron donors to groundwater to evaluate the activity of microbes in groundwater. The results demonstrated that the dominant microbial species changes in response to the addition of different electron donors[5),11)] (Fig. 3.5.3-9).

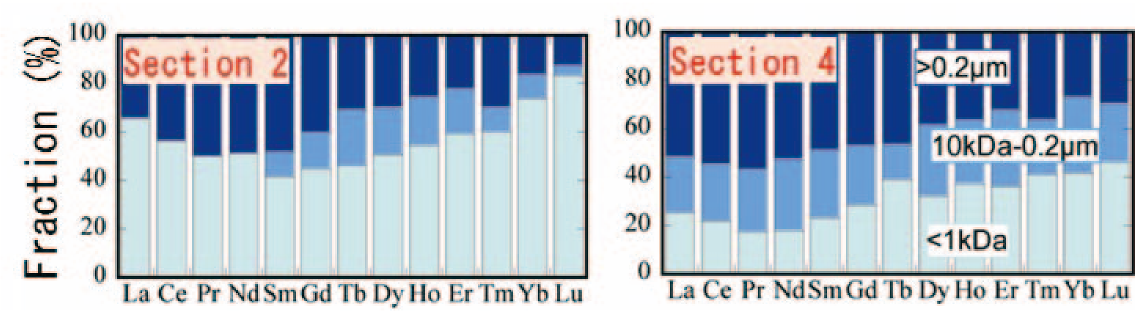

Fig. 3.5.3-7 Size distribution of rare earth elements in groundwater in the Toki Granite

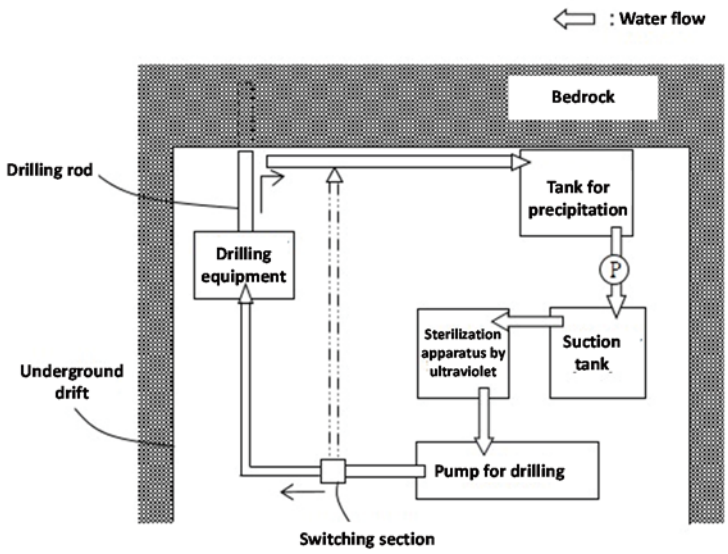

Fig. 3.5.3-8 Drilling fluid sterilization system

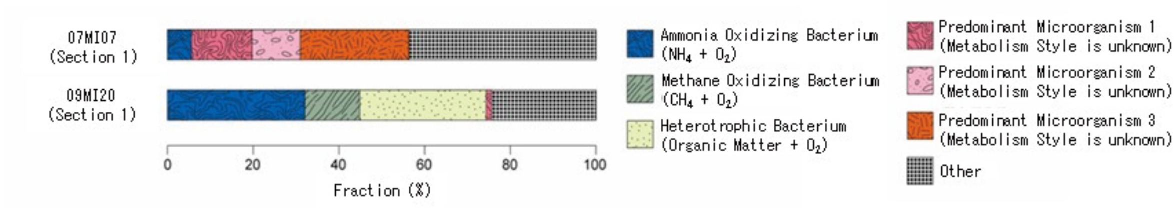

Fig. 3.5.3-9 Results of microbial genetic analysis of the groundwater

2) Horonobe

To understand the forms and mass transport behavior of elements in groundwater, we examined the interactions between natural colloids and substances such as rare earth elements that are effective analogs for minor actinide (MA) elements. The results showed that colloid particles in groundwater mainly consist of silicate minerals, phosphate minerals, carbonate minerals, and sulfate minerals and that lighter rare earth elements were distributed more readily in colloids than heavier rare earth elements. In addition, we established a method for pre-treatment of groundwater with high salinity and a method for quantitative determination using mass spectroscopy to evaluate the state of polyvalent metal ions (uranium, thorium, and rare earth elements) (Fig. 3.5.3-10). The results of tests using these methods indicated that tetravalent ions of uranium and thorium may increase the apparent solubility as a result of colloid formation and interactions with natural organic acids in groundwater, and hence we need to examine in greater detail their states in solution. In addition, the results of experiments taking organic matter into consideration suggested the possibility that MAs in the groundwater environment around the tunnel may exhibit limited solubility because of formation of phosphate precipitates and may be transported in groundwater as pseudo-colloidal particles with MA-humic substance complexes[12]. To clarify the mass transport behavior of radionuclides in the underground environment, we conducted qualitative analysis using an SEC-ICP-MS chromatogram technique, which consisted of size-exclusion chromatography coupled on-line to ultraviolet–visible detection and inductively coupled plasma mass spectrometry (Fig. 3.5.3-11). The results showed that uranium is bound to low-molecular-weight silica that does not contain metallic elements such as alkaline metals and aluminum, and that organic colloids completely lack radioactive waste-relevant elements such as selenium, strontium, iodine, cesium, thorium, and uranium[13]. This study provided the first evidence for the fact that the carrier associated with transport of uranium is not colloids but low-molecular-weight silica.

With respect to the effects of organic matter in groundwater, we aimed to develop investigation and evaluation methods for quantitative evaluation of whether these effects constitute a scenario relevant to performance assessment of a geological disposal system. We examined dissolved humic substances that had been separated and purified from the groundwater from Horonobe (Fig. 3.5.3-12) and investigated sedimentary rocks for characterization and evaluation, and studied realistic models based on these investigations (Fig. 3.5.3-13). A comparison was made between the humic substances separated and purified from groundwater sampled at Horonobe URL and the results of simulation using the data for

Eu^{3+} complexation and existing model parameters[14], as well as laboratory diffusion tests to investigate the possibility of matrix diffusion of element–humic substance complexes in sedimentary rock[15] (Fig. 3.5.3-14). The results showed that sorption of europium in the ternary system (element–organic matter–host rock) can be modeled using the additive law approach, which combines a model for complexation equilibrium with organic matter and a model for sorption to the rock mass, and that the matrix diffusion of humic substance complexes into sedimentary rock is negligible, suggesting that the matrix diffusion of trivalent elements in the ternary system can be described by a model for complexation of organic matter and a model for rock sorption and diffusion. On the other hand, these findings obtained from the groundwater samples from Horonobe URL cannot be applied to generic groundwater–organic matter systems, indicating the need for further study to be able to form generalizations.

With respect to the effects of microbes in groundwater, we developed and improved research and analysis methods for the purpose of understanding the changes in groundwater chemistry caused by microbes and the impact of biofilm formation on mass transport and the safety performance of geological disposal systems. We investigated sedimentary rock and groundwater samples obtained in the gallery under different redox conditions, and assessed the results in comparison with the model analysis for evaluation of microbial effects (Fig. 3.5.3-15). The involvement of microbial activities depending on redox condition changes in the underground environment has been confirmed by laboratory tests and analysis[16]. However, because of the importance of in situ evaluation of groundwater–rock–microbe reactions, we performed in situ tests using an analysis apparatus. The system was designed to monitor water chemistry in a circulatory line connecting the parts in the borehole and in the gallery, and the test result demonstrated its applicability to in situ study. The inclusion of a pressure filtration tank in the analysis system provided an addition to the volume of circulating test water, reducing the influence of periodical water sampling on monitoring results and ensuring a sufficient supply of samples (Fig. 3.5.3-16). The results showed that air exposure in the underground environment caused oxidation of porewater and a pH rise, while in the presence of sufficient electron donors, the microbial activities were likely to induce rapid recovery to a reduced state.

Observation of biofilm morphology showed that the channel structure arising from cell density differences in biofilms affected the mass transport (Fig. 3.5.3-17). According to diffusion tests and sorption tests (Fig. 3.5.3-18), the presence of biofilm coverage on rock surfaces causes slow diffusion of elements into biofilms, and after reaching very high concentrations, elements are transferred into the rock through matrix diffusion.

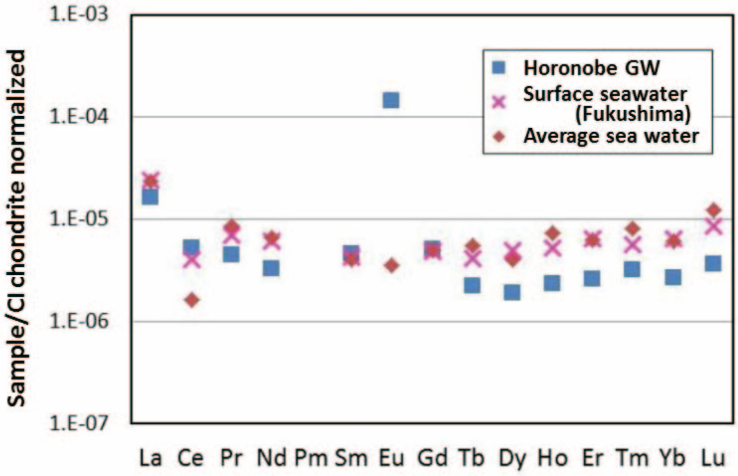

Fig. 3.5.3-10 Normalized concentrations of rare earth elements in groundwater

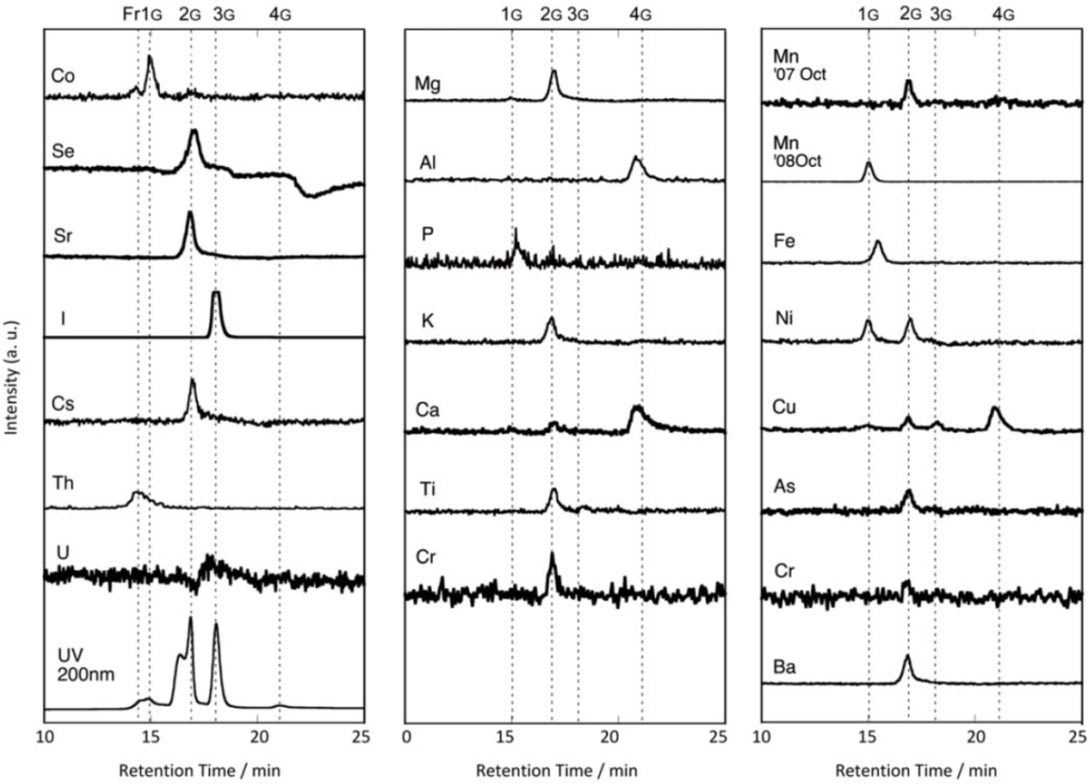

Fig. 3.5.3-11 Groundwater analysis using a size-exclusion chromatography coupled plasma mass spectrometry technique[13)]

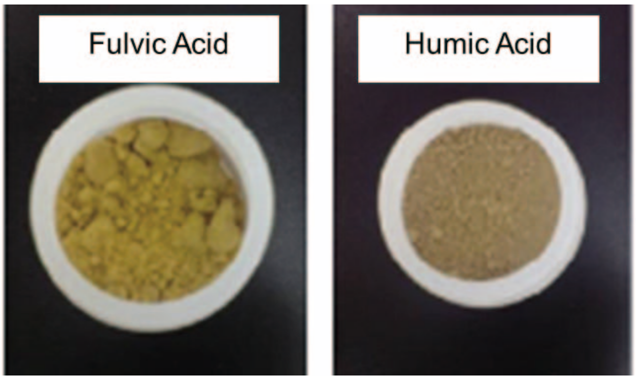

Fig. 3.5.3-12 Humic substances in groundwater at the Horonobe URL

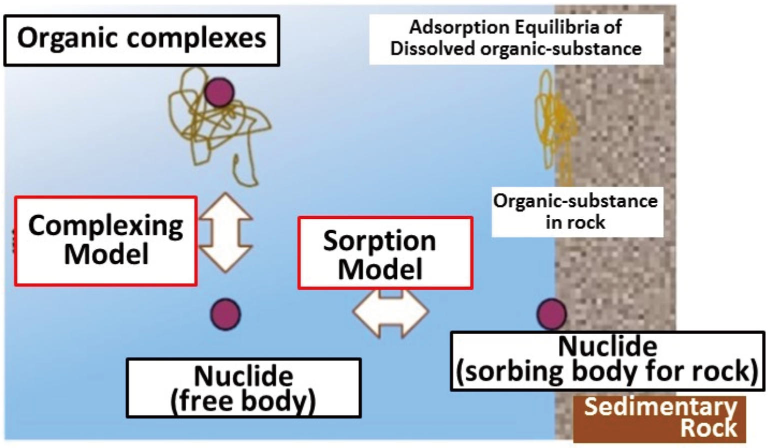

Fig. 3.5.3-13 Sorption in the element/organic substance/sedimentary rock ternary system

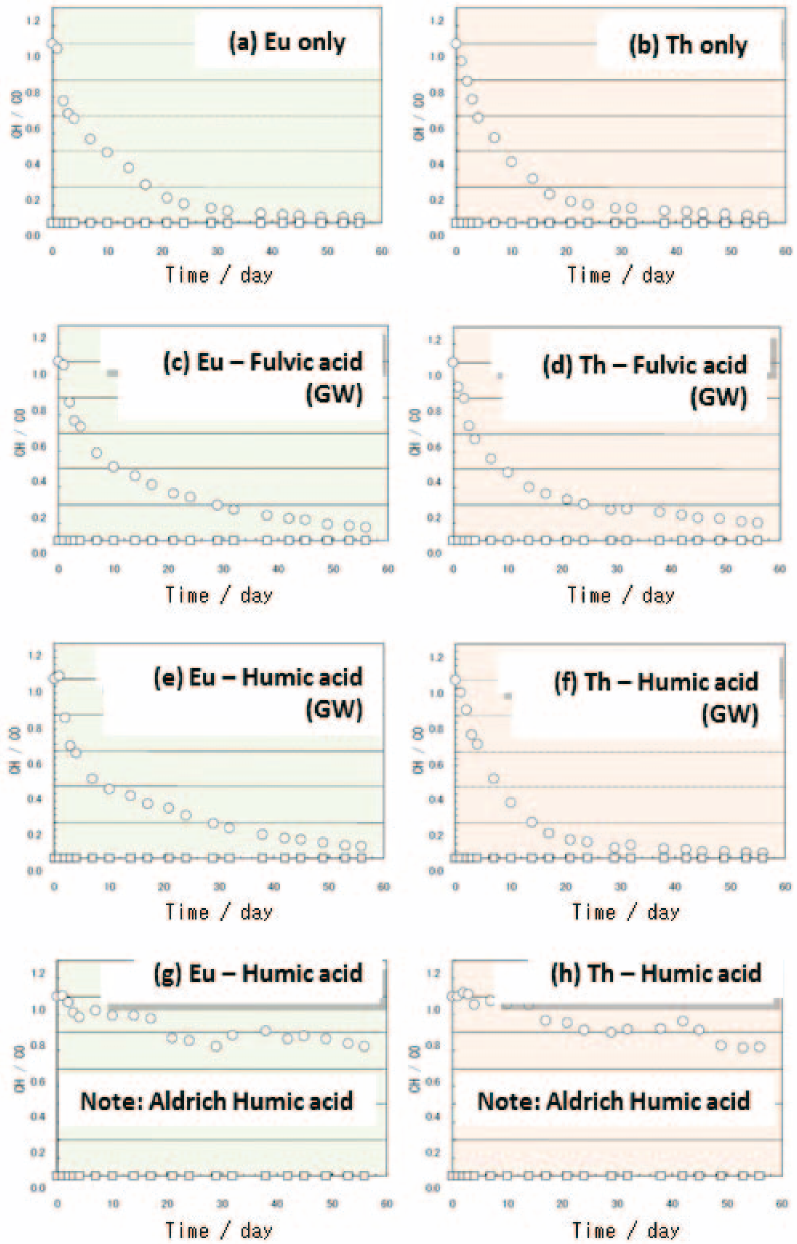

Fig. 3.5.3-14 Reservoir-depletion curves (circles) and breakthrough curves (squares) with coexisting humic substances (laboratory diffusion experiments for Eu and Th)

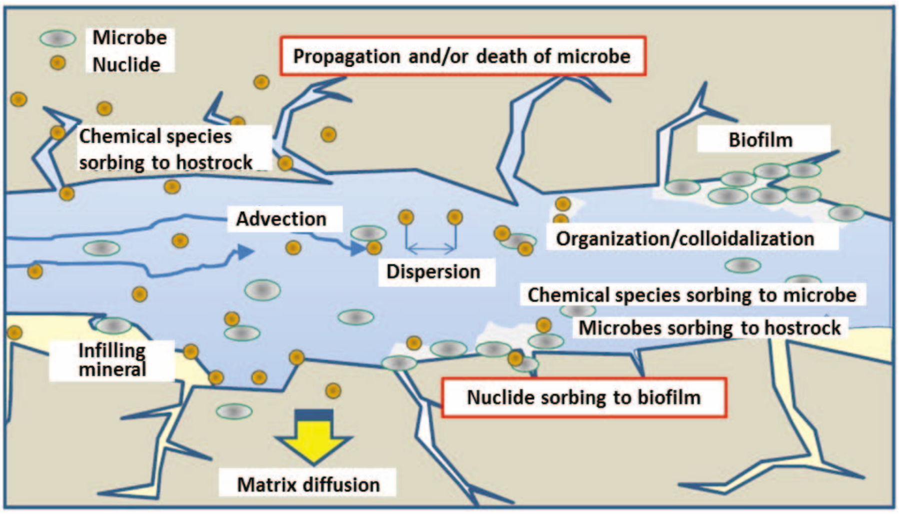

Fig. 3.5.3-15 Overview of microbial effects on mass transport in the geological environment

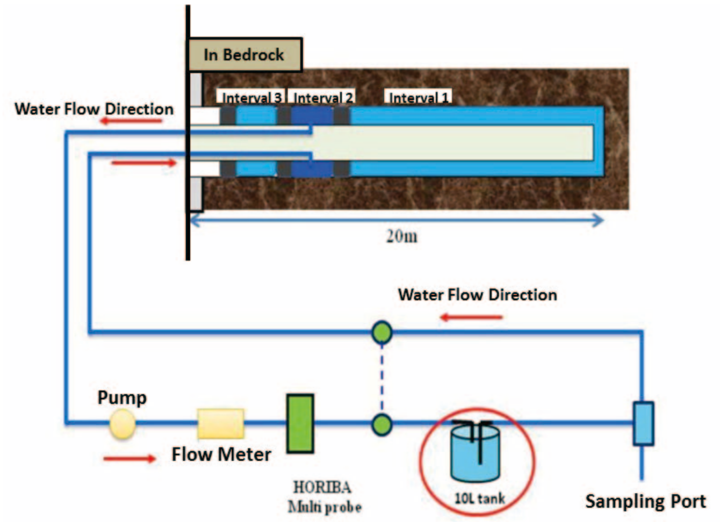

Fig. 3.5.3-16 The hydrochemical monitoring system on the circulation line

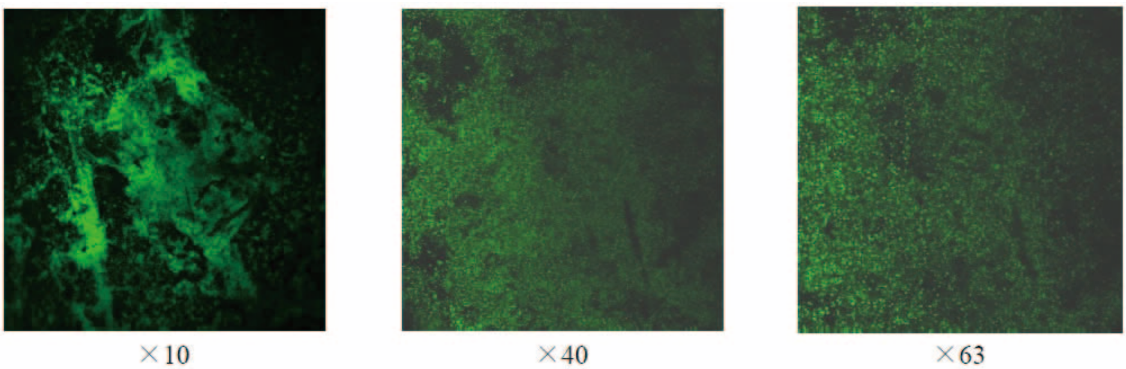

Fig. 3.5.3-17 Biofilms collected at the Horonobe URL and imaged using a confocal laser scanning microscope

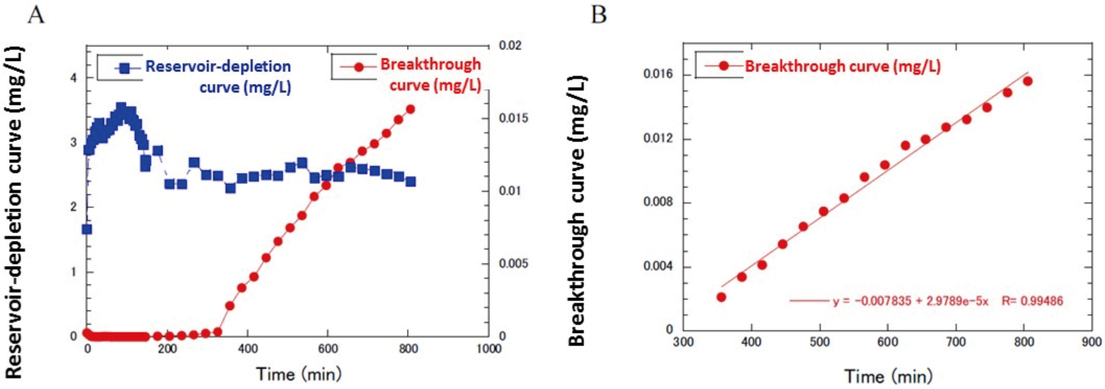

Fig. 3.5.3-18 Biofilm diffusion experiment using Cu^{2+} (A: reservoir-depletion and breakthrough curves, B: breakthrough curve and calculated approximate curve)

(4) Establishment of techniques for analysis and evaluation of mass transport properties

Regarding the techniques for analysis and evaluation of mass transport characterizations, we conducted the following studies with an eye to direct and indirect use in safety assessment studies: development and construction of procedures and methodologies for investigation and measurement, modeling, parameter setting, and evaluation; study of the methods for planning in situ tests through modeling of heterogeneous mass transport behavior on fracture planes based on analysis of the mass transport heterogeneity of permeability depending on fracture structure and in situ data; and development of detailed test protocols.

1) Horonobe

We conducted dipole tracer migration test simulation using models considering the control of fracture structure on the heterogeneity of permeability and examined the effects of the heterogeneous distribution of permeability on fractures, the test scale, and background flow of groundwater (Fig. 3.5.3-19). The results revealed that the dispersion length identified in the one-dimensional model was larger than that identified in the two-dimensional model irrespective of the heterogeneity of permeability in fracture planes, and when the background flow of ground water was perpendicular to the direction between boreholes, this tendency is more likely to increase than when increasing the dipole ratio (the ratio of injection flow rate to withdrawal flow rate) and the hydraulic gradient. In addition, in a field with a small background flow of groundwater, the uncertainty of the results in analysis using the one-dimensional parallel plane model was observed to decrease when the dipole ratio was small and the direction between boreholes was parallel to the background flow of groundwater[17),18)]. Furthermore, based on the results of in situ mass transport tests conducted in the −250 m gallery, we conducted a preliminary analysis using the one-dimensional analytical solution[19)] (Fig. 3.5.3-20) and examined the heterogeneity of mass transport characterization in fracture planes considering asymmetrical permeability and the relationship between the tracer migration test conditions and the recovery rate. These results suggested the presence of two or more mass transport pathways in fracture planes. Based on these study results and considering the geological environment in the Horonobe area, we developed detailed plans for in situ diffusion tests in intact rock focusing on diffusion systems, in situ dipole tests in fracture zones focusing on advection/dispersion systems, and in situ tracer migration tests in single fractures focusing on the evaluation of heterogeneity in the fracture plane and sorption/matrix diffusion, and commenced in situ tests in the −350 m gallery.

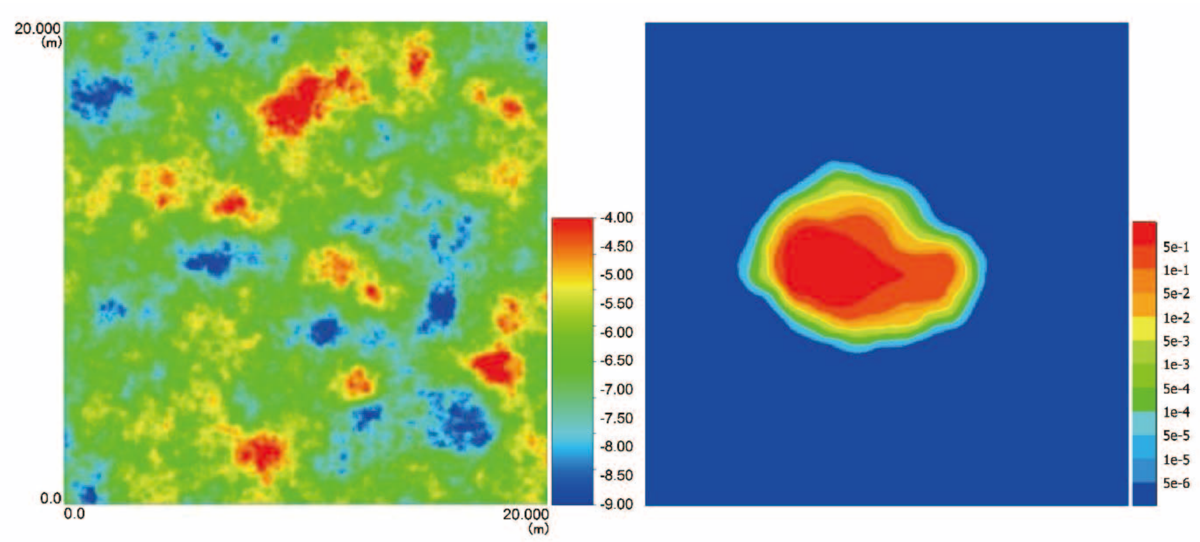

Fig. 3.5.3-19 Results of dipole test simulation
(The left-hand figure shows transmissivities distributed heterogeneously in a two-dimensional parallel plate fracture model. The right-hand figure shows the simulated tracer distribution in the model. 【 Dipole ratio: 0.2, background groundwater flow direction: injected borehole to withdrawn one, hydraulic gradient: 0.1】)

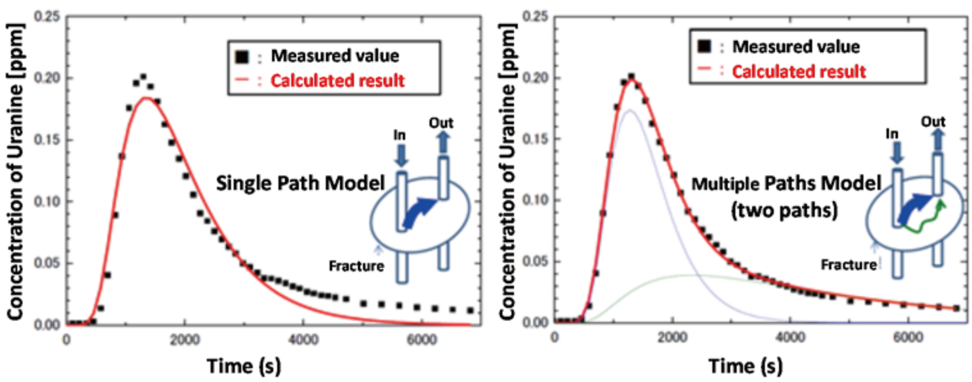

Fig. 3.5.3-20 Best-fit calculation for the one-dimensional solute transport model[19)]

3.5.4 Summary

This section summarizes the technical findings concerning the understanding of short-term changes and recovery behavior in the geological environment obtained from the surface-based investigations, investigations during shaft excavation, and investigations in the underground facilities concerning mass transport.

(1) Understanding the sorption and diffusion properties of rock mass

- We commenced in situ mass transport tests focusing on fractures in crystalline rock in the underground facility, obtained the basic in situ data for evaluation and selection of test areas, and commenced laboratory through-diffusion tests to evaluate the relationship between fracture characteristics and mass transport parameters (Mizunami).
- We conducted in situ mass transport tests focusing on fractures in sedimentary rocks in the underground facility, established test apparatuses and test methods, and confirmed their applicability to in situ tests (Horonobe).
- We established a test apparatus that can perform in situ mass transport tests based on an existing hydraulic test apparatus (Horonobe).
- We employed flow cell online fluorescence analysis in test intervals and confirmed the applicability of the in situ analysis techniques to the sedimentary rock environment (Horonobe).
- We confirmed that the absorption spectrophotometric analysis of the concentration of deuterium can be applied to the in situ tracer migration tests (Horonobe).
- We developed apparatuses and test methods that can limit the influence of dissolved gases on in situ mass transport tests: these methods enabled acquisition of highly reliable data (Horonobe).

(2) Understanding material transport fields

- We categorized the discontinuous structures that can be the mass transport pathways into five types at Mizunami and four types at Horonobe to clarify the targets of study on characteristics of mass transport (both sites).

(3) Understanding the effects of colloids, organics, and microbes

- We established a system for collecting colloids in groundwater based on ultrafiltration under artesian conditions (Mizunami).
- We established the methods for pre-analysis treatment of groundwater containing high salinity and quantitative determination for the purpose of evaluating the state of multivalent metal ions in groundwater, and confirmed their applicability to in situ study (Horonobe).
- We demonstrated that rare earth elements in groundwater form complexes with organic matter and occur in the form of colloids (Mizunami).
- We showed that the colloid particles in groundwater mainly consist of silicate minerals, phosphate minerals, carbonate minerals, and sulfate minerals, and more readily contain lighter rare earth elements than heavier rare earth elements. (Horonobe).
- We provided the first proof of the fact that the carrier for uranium in the underground environment is not colloids but low-molecular-weight silica in groundwater (Horonobe).
- We demonstrated that the sorption of a trivalent element in the ternary system (element–organic matter–host rock) can be modeled using the additive law approach and that the matrix diffusion of trivalent elements can be described by a model for complexation with organic matter and a model for rock sorption and diffusion into rock mass (Horonobe).
- The humic substances in groundwater at Horonobe had similar properties to humic

substances in groundwater from other areas in Japan (Horonobe).

- The investigation system with ultraviolet sterilization, which was applied to in situ borehole investigations, can reduce contamination of microbes from drilling fluid (Mizunami).
- We confirmed a monitoring system with a circulation line from in the gallery to in the borehole can be used to obtain sufficient samples without an influence of volume change in the system (Horonobe).
- We demonstrated that different microbial species become dominant after the addition of different electron donors and that microbes enable rapid recovery of groundwater containing sufficient electron donors from an oxidizing to a reducing state (both sites).
- We showed that cell density differences in biofilms affect mass transport and that the biofilm covering on rock surfaces buffers the matrix diffusion of elements into rock (Horonobe).

(4) Establishment of techniques for analysis and evaluation of mass transport characterizations

- Based on the tracer migration test simulation considering the heterogeneity of permeability depending on fracture structure, we proposed test conditions that can reduce the uncertainty produced in analysis using the one-dimensional parallel plate model (Horonobe).
- We showed that there are two or more mass transport pathways in the fracture plain in sedimentary rock mass using the results from in situ mass transport tests (Horonobe).
- Considering the above results and the geological environment in the Horonobe area, we developed detailed plans for in situ mass transport tests and commenced these tests (Horonobe).

An important requirement for future studies of mass transport is to continue research on and development of investigation and analysis/evaluation techniques, which are needed for appropriate understanding of the phenomena and characteristics involved in mass transport in rock beds. The future themes are summarized in Table 3.5.4-1.

With respect to understanding the sorption and diffusion properties of rock mass, concrete themes are to clarify the possibility and limitations of application of various tracers to groundwater and rock, to develop in situ test and analysis methods for geological environments, and to accumulate data from such tests.

With respect to understanding mass transport fields, concrete themes are to understand the distribution of discontinuous structures such as fractures that contribute to mass transport in rock masses, and to understand the mass transport phenomena that occur therein. In addition, it is necessary to develop investigation techniques for identifying and understanding the structures that contain mass transport pathways.

With respect to understanding the effects of colloids, organic matter, and microbes, concrete themes are to accumulate in situ and laboratory test data concerning the effects of colloids, organic matter, and microbes as a whole, to develop investigation techniques to obtain in situ data with little uncertainty, to investigate the state of dissolved elements in detail, and to confirm the applicability of constructed techniques concerning colloids/organic matter/microbes and mass transport for other geological environments.

With respect to the establishment and systematization of techniques for analysis/evaluation of mass transport properties supporting safety assessment, concrete themes are to confirm the applicability of the evaluation technique of mass transport characterizations and safety assessment methodologies to actual geological environments.

Study of mass transport is placed as an important theme in Phase III (investigations in the underground facilities) both in the Mizunami[20] and Horonobe URLs. Construction of horizontal galleries for in situ tests and other works are making good progress at Mizunami and Horonobe URLs. In the timeframe of the second mid-term research phase, we have just commenced the in situ study on mass transport. In the future, we plan to conduct mass transport tests and other in situ tests and proceed with modeling of fracture networks and mass transport analysis. Building on the outcomes of such study, we will evaluate the effects of disturbance of the geological environment resulting from the construction of tunnels on mass transport characterizations and also evaluate the alteration of material transport properties caused by long-term changes in the geological environment.

Table 3.5.4-1 Future themes in the next research phase

Focus	R&D performance target	Tasks	Issues
Decision to construct, to begin disposal, to end emplacing waste and on final closure	Favorable URL layout and disposal pit can be designed from the viewpoint of solute transport property.	Characterization methodology	• Methodology for the characterization of mass transport pathway • Methodology for the characterization of important factor affecting mass transport property • Generalization of characterization methodology
		Example proposal	• Show example through the execution of URL project

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3.6 Engineering technology for deep underground applications

3.6.1 Introduction

The underground research laboratory projects will provide the opportunity to demonstrate the feasibility of safe and reliable construction, maintenance, and management of an underground research facility by applying conventional and state-of-the-art engineering technology in a deep geological environment. Engineering technologies, such as design, construction planning, construction, countermeasures, and safety management, have been applied to Mizunami and Horonobe.

3.6.2 Objectives in the second mid-term research phase

The objectives of engineering technology for deep underground applications in the second mid-term research phase is to test the applicability of construction and countermeasure technologies and maintenance technology during extension of shafts and galleries at depths of 500 m (Mizunami) and 350 m (Horonobe). Design and construction planning technologies have been also estimated in this phase. Table 3.6.2-1 shows the performance target level of technical development for engineering technology.

Table 3.6.2-1 Performance target of R&D for engineering technology

Focus	Performance target of R&D	Tasks
Decision-making for start of construction	Application of construction technology and countermeasures.	• Construction technology for underground facilities • Countermeasures during construction of underground facilities ◆Water inflow, inflammable gas ◆Spalling, rock burst
Decision-making for start of operation	Security of underground facility. Maintenance of underground facilities.	• Technology for security and maintenance of underground facility

3.6.3 Project details and outcomes

(1) Construction technologies

1) Mizunami

Two consecutive drill, blast, and mucking steps (1.3 m + 1.3 m) and one shaft-lining step (2.6 m) per cycle to optimize cycle time for shaft excavations were adopted in Mizunami. The designed cycle time was compared to the actual cycle time: the applicability of the short-step shaft sinking method is valid. This results in reduction of cycle time for preparation of the concrete lining and the geological survey at the shaft wall. The applicability of the revised shaft-sinking method is evaluated by comparison of the designed and actual cycle times. The conclusions are as follows[1),2),3),4),5)]:

- The cycle times for drilling, explosive insertion, and blasting are short due to the distribution of fractured rock at the Main Shaft. In contrast, the cycle time for the concrete lining and other operations increased. Other operations consisted of trouble and repair of facilities, auxiliary methods, and moving scaffolding (Fig. 3.6.3-1).

- The cycle time for all works did not increase with depth. Some works decreased with depth as the skill of the work increased (Fig. 3.6.3-2).
- The cycle times for the Ventilation Shaft also increased. The cycle times for drilling, explosive insertion, and blasting were shorter due to the distribution of fractured rock at the Main Shaft.
- The short-step shaft-sinking method was applied in different conditions in the Main Shaft and the Ventilation Shaft. Thus, the applicability of this method was evaluated for a wide range of geological environments.

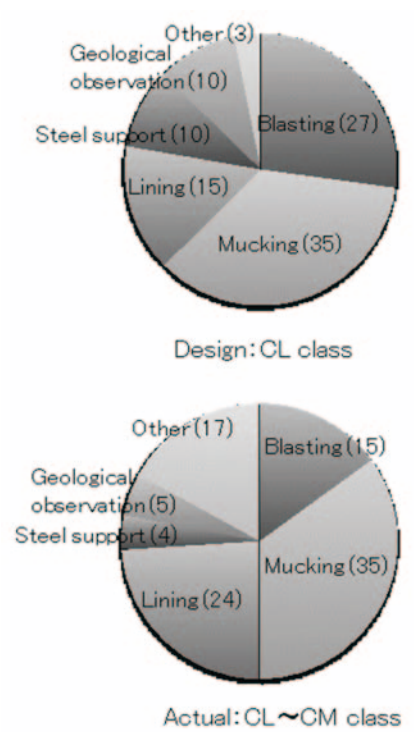


Fig. 3.6.3-1 Actual excavation cycle time of the Main Shaft

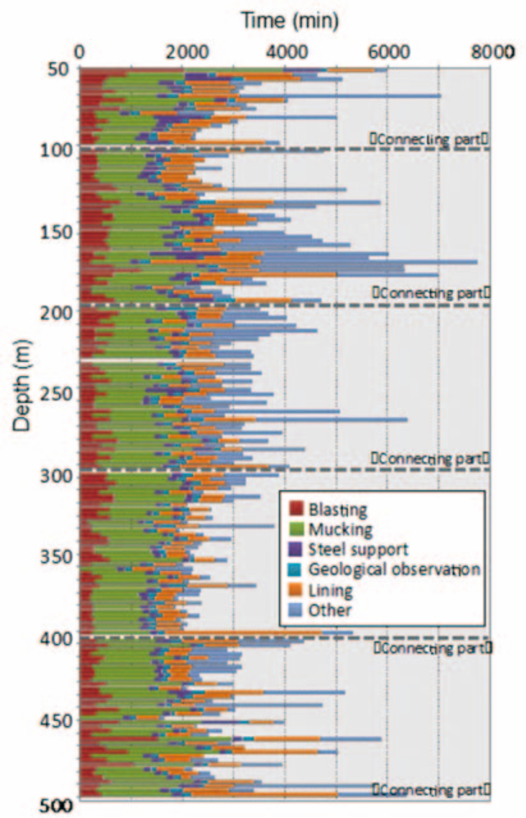


Fig. 3.6.3-2 Designed and actual excavation cycle times of the Main Shaft

2) Horonobe

In Horonobe, by June 2014, excavation of the G.L. −140 m, −250 m, and −350 m galleries had been accomplished. The Ventilation and East Access Shafts had been excavated to 380 m depth; the West Access Shaft had been excavated to 365 m depth. During shaft sinking at depths greater than 250 m, severe breakout and spalling in the shaft wall was induced in response to shaft sinking in a region with a fault zone and a low competence factor zone. The three-dimensional shape of the shaft wall was detected using a three-dimensional laser scanner together with geological surveys of the shaft wall. At some depths, measurement of stress in the lining and displacement of rock mass around the wall of the shaft were conducted. The results are as follows:

- In shaft sinking, there is a high possibility of severe breakout and spalling in the direction of minimum principal stress owing to stress concentration. In the fractured zone, the possibility of spalling becomes high at the top and bottom of the faults with size greater than the shaft diameter. Overlapping of these two effects leads to an increase in the depth of spalling[6),7)].
- In the Ventilation Shaft, vertical tensile stress developed in the concrete lining installed above the location where spalling developed. This tensile stress was greater than the tensile strength of the concrete lining when the spalling had developed more than 100 cm into the wall of the shaft. This tensile stress induced a circumferential crack in the concrete lining (Fig. 3.6.3-3)[8)].
- Spalling affects the stability of the concrete lining; subsequently, the spalling depth of the rock mass around the shaft wall was considered to be a practical guideline for the selection of support pattern to prevent the occurrence of severe open cracks (Fig. 3.6.3-4). The applicability of this guideline has been being verified during the construction of the East and West Access Shafts[9),10)].
- In the fault zone, the spalling depth was decreased with shortening the installation span of concrete lining and additional rock bolts[9),10)].

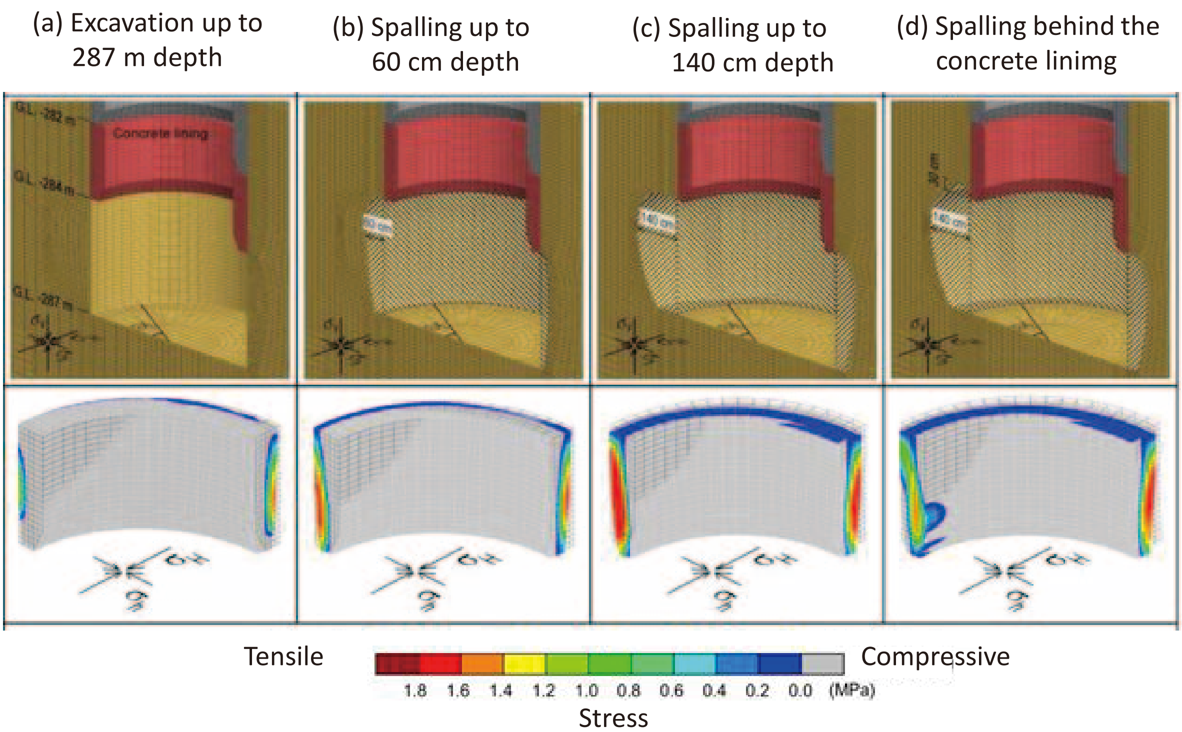


Fig. 3.6.3-3 Calculated results of changes in vertical stress with development of spalling of the rock mass around the shaft wall in the concrete lining

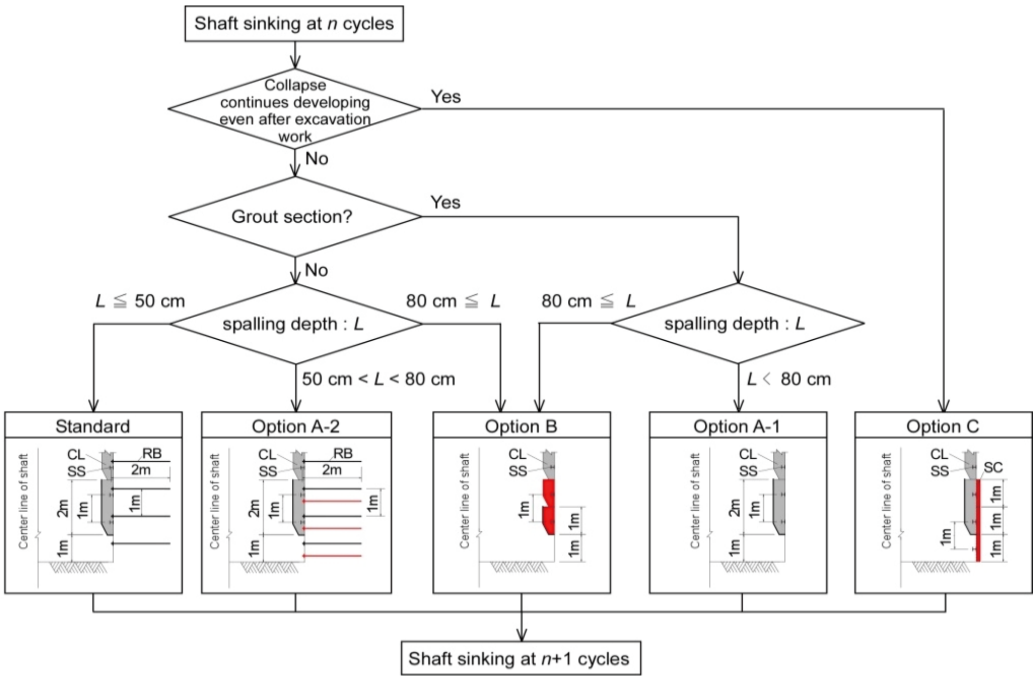


Fig. 3.6.3-4 Flowchart for selecting the optimum support pattern in the Ventilation Shaft[10)]

3) Generic results

The matters that should be treated carefully are not greatly different between Mizunami and Horonobe. Excavation technologies applied to both sites are based on engineering technology for road and railway tunnel excavation and mining technology, so the technologies can apply to many rock types.

(2) Countermeasure technology

1) Mizunami

Pre-excavation grouting as a countermeasure against groundwater inflow to shafts and gallery using normal Portland cement, super-fine Portland cement, and liquid-type colloidal silica were performed corresponding to geological conditions at depths of 200, 300, 400, and 500 m. Post-excavation grouting testing was performed at the depth of 145 m in the Ventilation Shaft[11),12),13),14),15),16)]. Numerical analysis to understand the effect of grouting was also performed[17),18),19),20),21)]. The conclusions are as follows:

- Fig. 3.6.3-5 and Fig. 3.6.3-6 show the results of parametric groundwater flow analysis for post-excavation grouting at the Ventilation Shaft. A 50% reduction of inflow to the shaft was predicted under conditions of a one-order decrease of hydraulic conductivity in a 6 m grouting area with a length of 80 m[16)]. The results of post-excavation grouting were that injection rate decreased with the amount of grouting, and inflow to the injection holes also decreased (Fig. 3.6.3-7, Fig. 3.6.3-8).
- Pre-excavation grouting using normal Portland cement was performed at the G.L. −300 m access/research gallery. The total amount of inflow to this gallery was several 10 to 100

L/min after excavation with pregrouting, in spite of the large amount of inflow (over 1,000 L/min) in a pilot borehole investigation before excavation of the gallery[12].

- Pre-excavation grouting using super-fine Portland cement was performed at a depth deeper than 400 m in the Ventilation Shaft. This cement can improve low-permeability rock with an initial value of approximately 1 Lugeon, which normal Portland cement could not improve. The rate of decline for total head of groundwater decreased with shaft excavation progress in the area where pre-excavation grouting had been performed[13] (Fig. 3.6.3-9, Fig. 3.6.3-10).

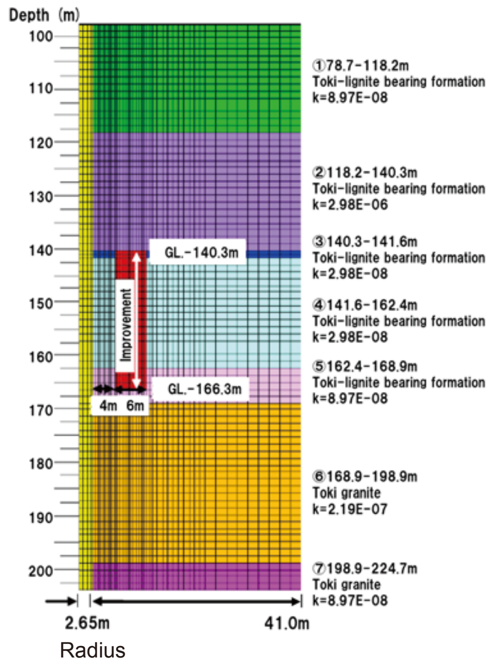


Fig. 3.6.3-5 Model for groundwater flow analysis

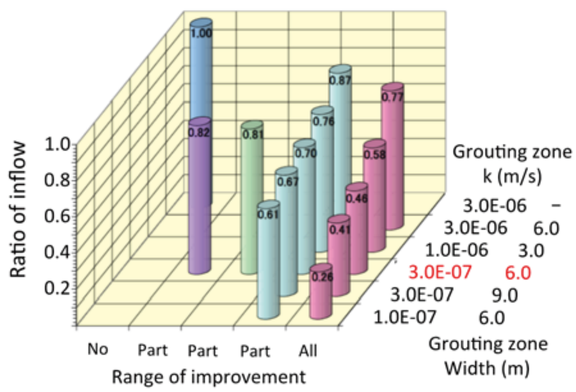


Fig. 3.6.3-6 Results of groundwater flow analysis for post-excavation grouting

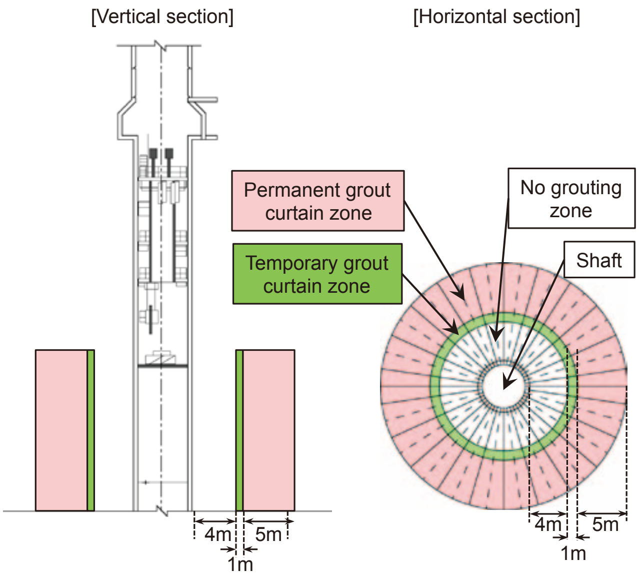


Fig. 3.6.3-7 Post-excavation grouting test

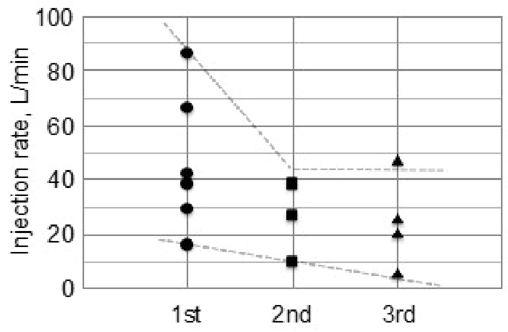
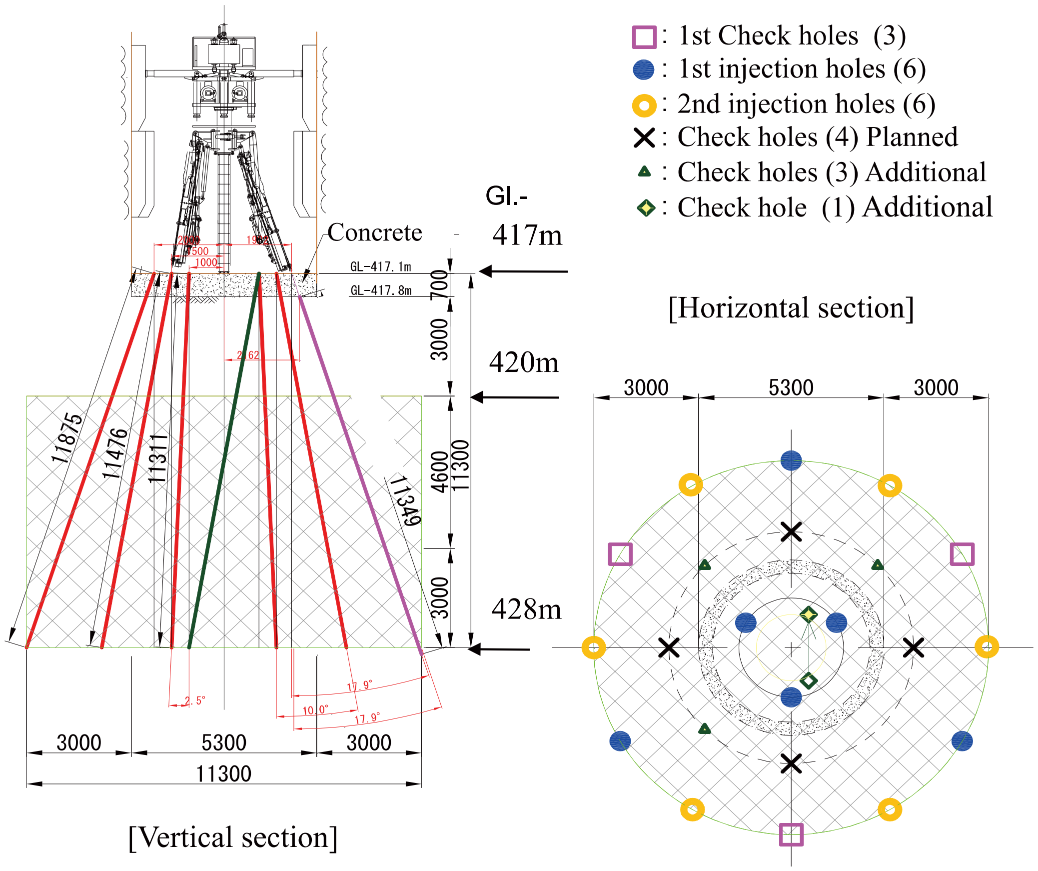


Fig. 3.6.3-8 Results of post-excavation grouting test



The unit in numbers is a millimeter.

Fig. 3.6.3-9 Pre-excavation grouting plan for shaft sinking

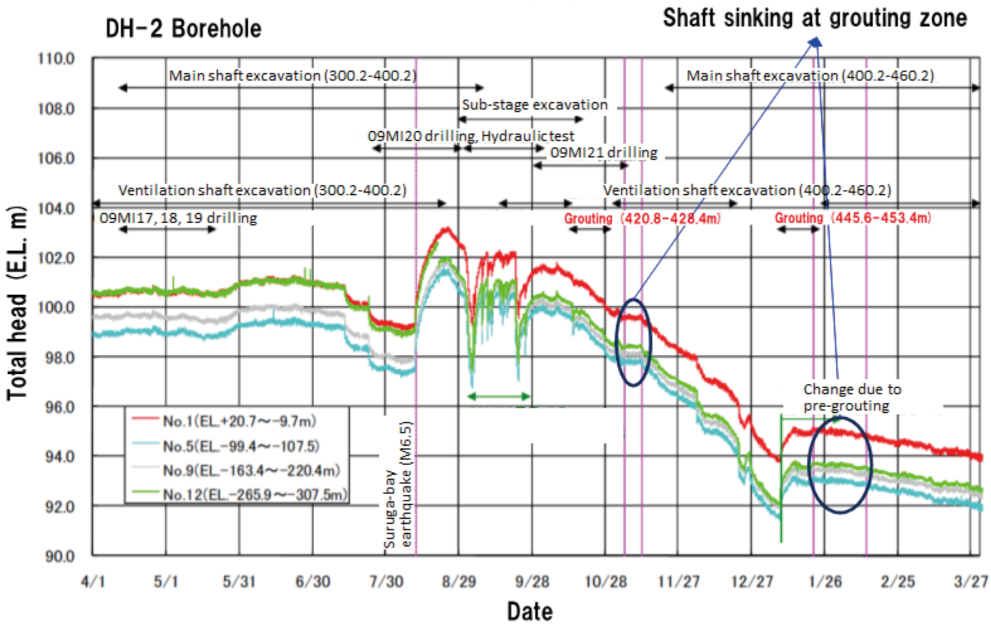


Fig. 3.6.3-10 Confirmation of effectiveness of grouting (groundwater pressure monitoring in the borehole)

A vertical fault with gauge is present at the location of the Main Shaft. One of the mechanisms of spalling is "Takanuke"[22], so countermeasures for spalling at the shaft wall were designed. Rock bolts with silica resin were used as reinforcement and the forepoling method of shaft sinking at the depth of 150 m. The effectiveness of the countermeasures was valid based on the volume of concrete liner (Fig. 3.6.3-11)[3),12)].

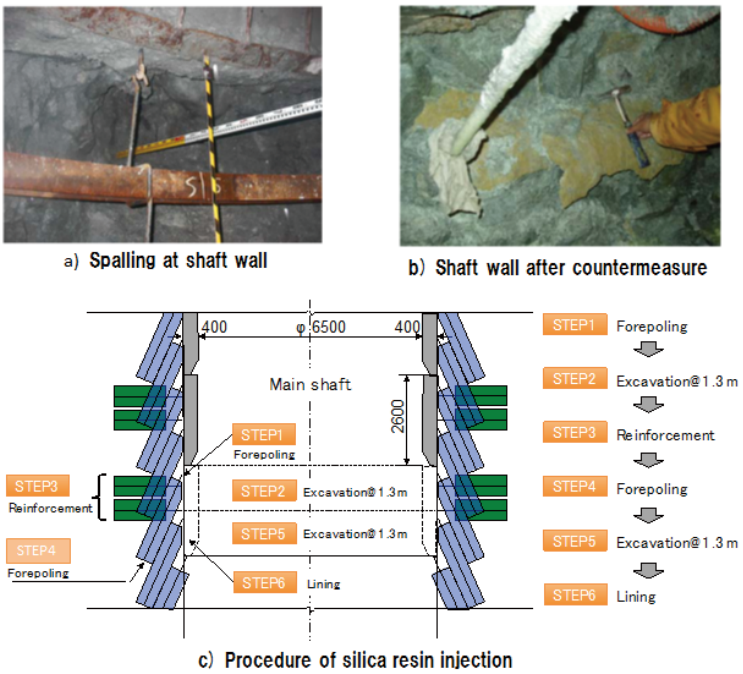


Fig. 3.6.3-11 Countermeasures against spalling at the Main Shaft wall

2) Horonobe

From borehole surveys, it was found that a fracture zone with high permeability existed below the depth of 250 m. To properly control the groundwater inflows to the shafts and drifts, pre-excavation grouting operations were conducted for the permeable zone detected from borehole surveys prior to shaft sinking below 250 m depth. The operation was planned to reduce permeability in rock to less than 0.1 Lugeon value within 3.0 m of the wall of the Ventilation Shaft and 4.0 m of the wall of the East Access Shaft. Ultra-fine-grained cement was mainly used as the grout material. The results can be summarized as follows:

- From the information on the three-dimensional distribution of the injected volume of grouting material, additional faults were detected and integrated into the 3D visualization system. The revised distribution of faults was applied to select the optimal support patterns for the Ventilation and East Access Shafts (Fig. 3.6.3-12)[7].
- From fracture mapping on the shaft wall, grouting material was mainly observed on the branching part from the fault rather than the fault itself (fault core); nevertheless, the fault has high continuity. Fig. 3.6.3-13 shows a conceptual image of grout injection to the fault[23]. This result will lead to construction of an effective plan for grouting and the location of injection holes.

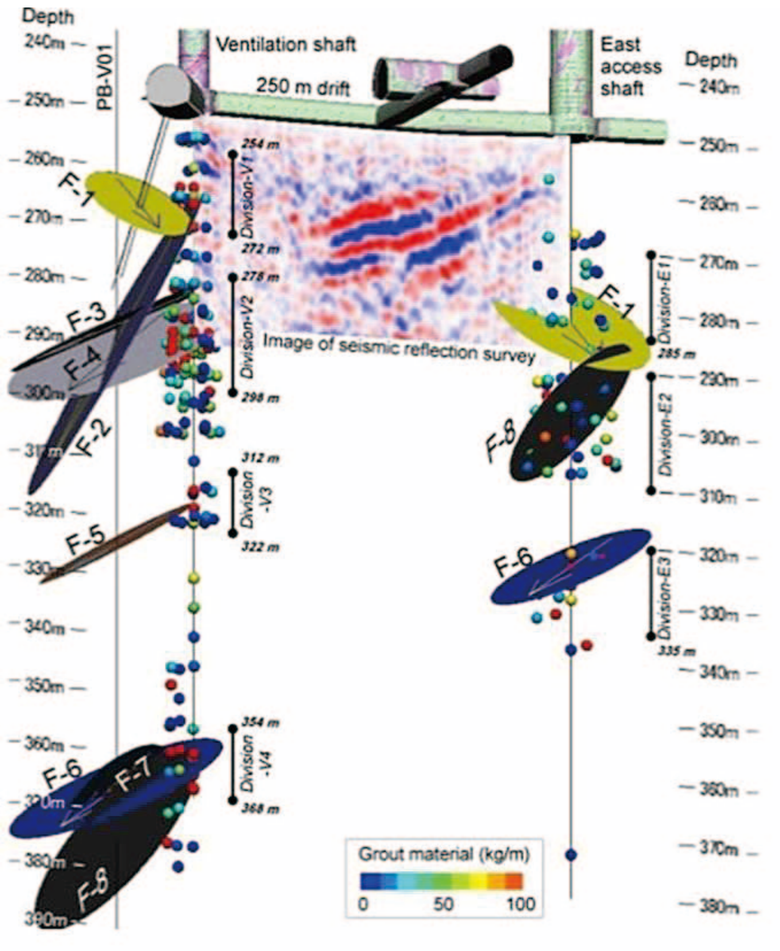


Fig. 3.6.3-12 Distribution of faults and volume of grout material injected in two shafts[7]

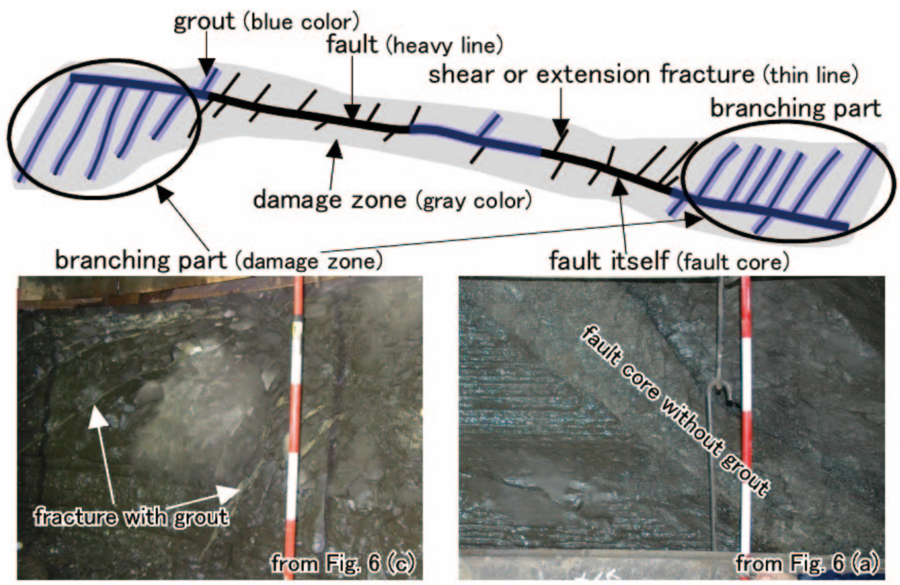


Fig. 3.6.3-13 Conceptual image of fractures with grout material on the shaft wall[23)]

3) Generic results

The matters which should be treated carefully are little different between Mizunami and Horonobe. The countermeasure technologies applied to both sites are based on engineering technology for road and railway tunnel excavation and mining technology, so the technologies can apply to many rock types.

(3) Technology for security and maintenance of underground facility

1) Mizunami

Based on the results of ventilation network analysis, the required air volume versus velocity limits, gas inflow, and dust generated by shotcreting were calculated, and capacity and optimum location of the ventilation equipment were determined. The results of non-steady state airflow analysis and the state of the airways (smoke-filled, smoke-free) in the event of a fire in the URL during each construction step were evaluated and an evacuation and a refuge plan were confirmed[24)] (Fig. 3.6.3-14, Fig. 3.6.3-15).

The effectiveness of the safety and maintenance technology for the concrete liner has been validated from photographs taken using a video camera and a crack detection sensor using optical fiber (Fig. 3.6.3-16, Fig. 3.6.3-17).

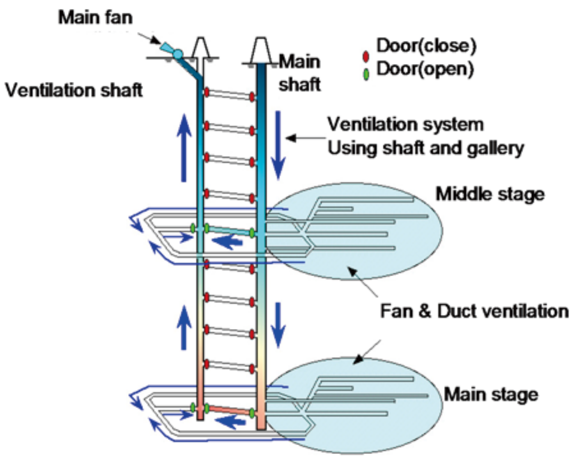


Fig. 3.6.3-14 Ventilation system for Mizunami

- Design of ventilation system
  - ・Shaft: fan & duct ventilation
    → shaft & gallery ventilation
    (at G.L. −500 m)
  - ・Gallery: Extension of fan & duct
- Ventilation analysis
  - ・Specification of ventilation system
    (fan & duct)
- Fire gas analysis
  - ・Fire detection
  - ・Refuge concept
  - ・Specification of refuge

Fig. 3.6.3-15 Examination items for ventilation network analysis

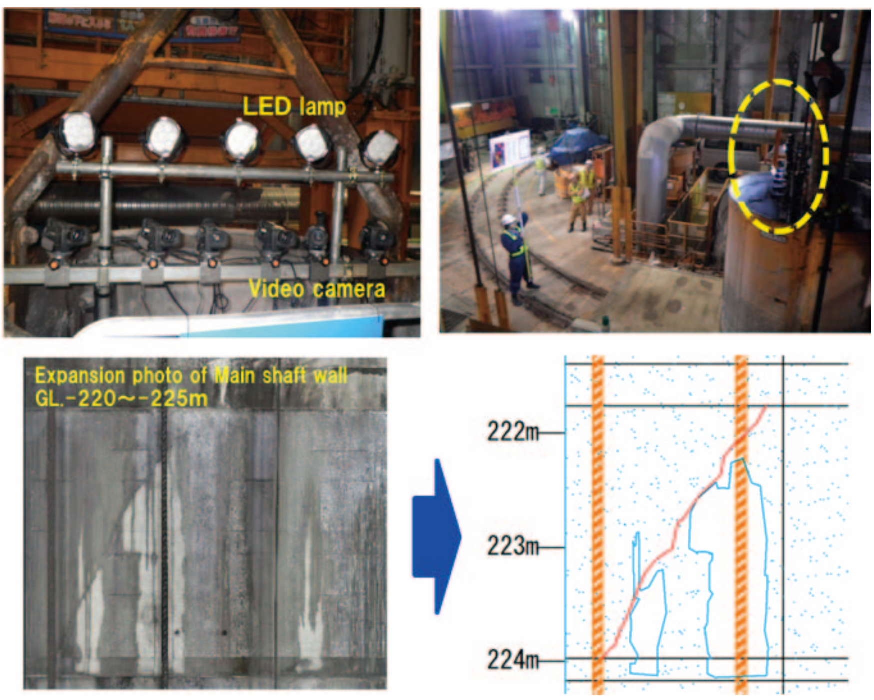


Fig. 3.6.3-16 Observation of the concrete liner of the shaft using a video camera

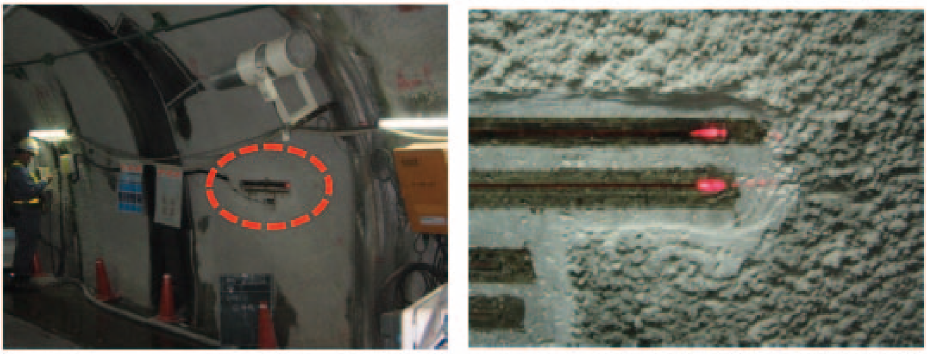


Fig. 3.6.3-17 Durability test of the crack detection sensor using optical fiber

2) Horonobe

In excavation of shafts and galleries in the presence of flammable gas such as methane, it is important to predict the behavior of fire gases as part of emergency planning. The behavior of ventilation air was investigated experimentally using a model of underground galleries. On the basis of the results of these experiments, a system for ventilation network analysis that can simulate various types of aerial behavior was developed[25].

The results of the ventilation network analysis were applied to the ventilation plan. A tool for estimation of the behavior of fire gases was prepared to improve the reliability of disaster prevention in the galleries. Considering the behavior of fire gases obtained from the analysis, an evacuation route was secured by controlling the gate (Fig. 3.6.3-18).

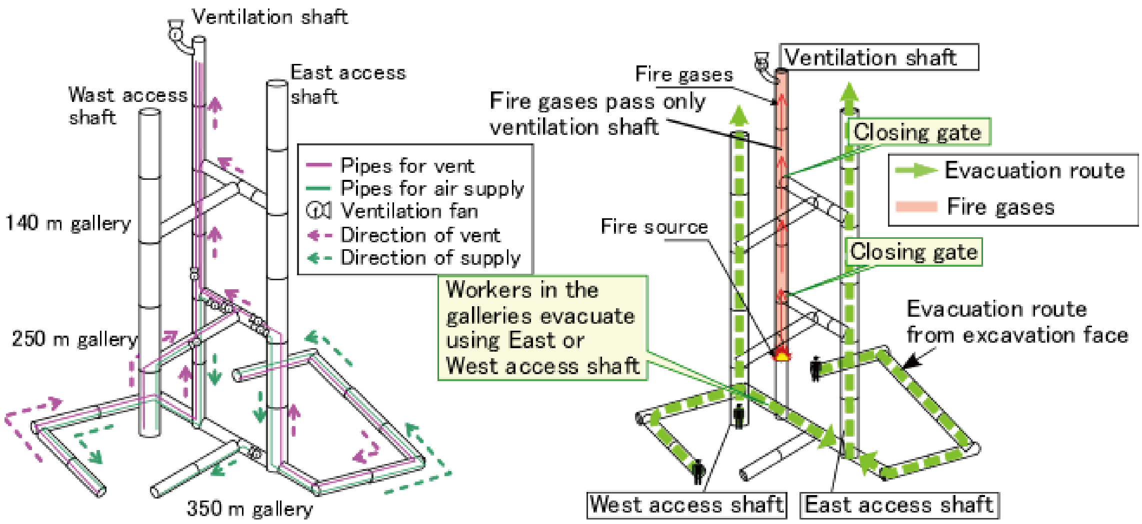


Fig. 3.6.3-18 Results of the ventilation network analysis in the excavations of the G.L. −350m galleries

3) Generic results

The technologies for security and maintenance of the underground facility applied to both sites are based on engineering technology for road and railway tunnel excavation and mining technology, so the technologies can apply to many rock types.

3.6.4 Summary

The effectiveness of construction technology and countermeasures for inflow and spalling have been confirmed. The safety management technology has also been confirmed. Additional studies are necessary in the future:

- Post-excavation grouting
- Estimation of the influence of countermeasures on the geological environment
- Development of safety management technology and closure technology
- Estimation of the safety of the underground facility against large earthquakes

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3.7 Performance and setting condition of the engineering barrier

3.7.1 Introduction

R&D for contribution to the selection of the detailed investigation areas and the conceptual design of the repository based on the results of the preliminary investigation by NUMO (Nuclear Waste Management Organization of Japan), and the formulation of the safety review basic guideline by safety regulation authority has been performed in phase II of the basic technology program on geological disposal in Japan (FY2007–2012) based on the master plan[1]. Thus, in the basic technology program regarding repository design and engineering technology in Japan, it is important to improve the design and engineering technology of a deep geological repository and the evaluation technology of the integrity of the engineered barrier system (EBS) as a technical basis. Especially, it is essential to demonstrate some technologies used in the construction and operation phase of geological repository prior to the implementation and safety regulation of geological disposal.

3.7.2 Objectives in the second mid-term research phase

In R&D on geological disposal technology at the Horonobe Underground Research Laboratory (URL) project during the second mid-term research phase, "development of an evaluation technology applicable to actual geological environment and presentation of its engineering implementability" was set as the whole target. Table 3.7.2-1 shows the performance targets of R&D for geological disposal technology at the Horonobe URL project.

Table 3.7.2-1 Performance target of R&D for geological disposal technology

Focus	Performance target of R&D	Task
Construction decision	Underground facilities of repository can be designed and constructed.	• Development of usable construction material for underground facilities of a repository with a low long-term influence on the geological environment • Development of design & construction technology of underground facilities of a repository
Operation decision	EBS can be designed, constructed, and evaluated.	• Development of design & construction technology of EBS
	Tunnel sealing can be designed, constructed and, evaluated.	• Development of design & construction technology of tunnel sealing (backfill & plug)
	Disposal pit can be designed, constructed and, evaluated.	• Development of design & construction technology of a disposal pit

3.7.3 Project details and outcomes

The research results on geological disposal technology at Horonobe URL project are divided into two sections, as follows:

(1) Design and engineering technology of a deep geological repository

- Low-alkaline cement, which has been developed for the long-term stability of the barrier systems and is named high fly-ash silica-fume cement (HFSC), was used in construction of the underground facility as shotcrete and lining and in grouting at the Horonobe URL (Table 3.7.3-1, 3.7.3-2, Fig. 3.7.3-1). As a result, it was confirmed that the initial strength, workability, and hydraulic conductivity of support and grout made of HFSC were equivalent to those of conventional material. Then, it was confirmed that support and grout made of HFSC was able to be applied in the construction of an underground facility in a repository[2),3),4),5),6)].
- Demonstration of the auger machine with casing as an excavation technology for a disposal pit was performed (Fig. 3.7.3-2)[6)].
- The buffer and overpack which were presented in H12 report were manufactured. The surface temperature of the overpack can be controlled with electric heaters. Demonstration of the vacuum hoisting method as an emplacement technology for an engineered barrier system (EBS) was performed (Table 3.7.3-3, Fig. 3.7.3-3)[6)].
- In consideration of the geological environment at the Horonobe URL, backfill material that uses the debris (rock fragments) generated in tunnel excavation and bentonite was designed and constructed. Specifically, the specification of the backfill material was determined on the design requirements relating to water permeability and swelling ability and the results of laboratory and in situ tests (Table 3.7.3-4, Fig. 3.7.3-4)[6)].
- The HFSC plug was designed and constructed taking into account the geological environment at the Horonobe URL.

(2) Evaluation technology of the integrity of the EBS

- The experiment on EBS focusing on overpack corrosion, re-saturation phenomena in the near-field, displacement of buffer into backfill, interactions between bentonite, cement, and carbon steel, and intrusion of buffer into the host rock was started (Fig. 3.7.3-5, Fig. 3.7.3-6).

Table 3.7.3-1 Mixing proportions of HFSC shotcrete used in the G.L. −250 m gallery

Type of cement	Water to Binder Ratio (%)	Sand Ratio (%)	Unit weight (kg/m³)						
			Water	Binder			Fine Aggregate	Coarse Aggregate	Super Plasticizer
				OPC	SF	FA			
HFSC	35.0	60.2	175	200	100	200	945	638	5.25
BB	40.0	55.7	170	400	-	25	990	802	2.40

HFSC: High Fly-ash Silica-fume Cement, OPC: Ordinary Portland Cement, BB: Blast-furnace slag cement type B, SF: Silica-fume, FA: Fly ash

Table 3.7.3-2 Compressive strength at the material age of 28 days used in the G.L. −250 m gallery

	Result at the surface (N/mm²)	Result at the underground (N/mm²)	Design strength (N/mm²)
HFSC shotcrete core	45.9	41.2	36.0
BB shotcrete core	51.1	-	

The results show the average of three test replicates.

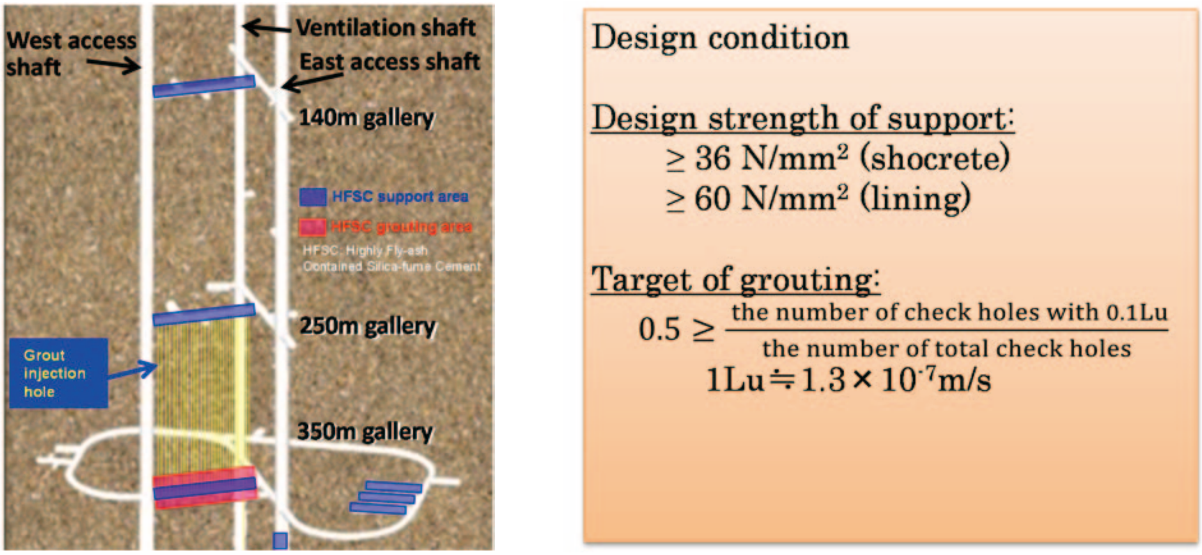
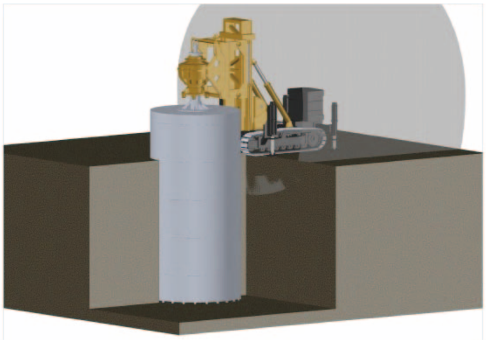
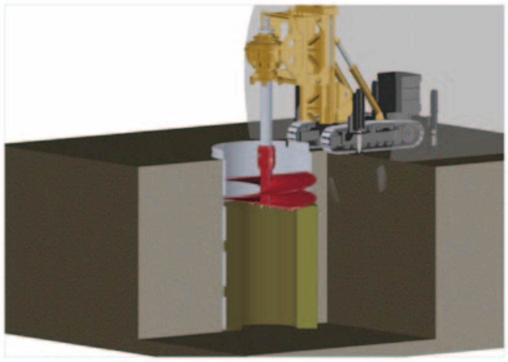


Fig. 3.7.3-1 The areas where HFSC was applied for support and grouting at the Horonobe URL

(a) Edge cutting - Circumference casing (b) Excavation by augering inside casing

Fig. 3.7.3-2 Test pit excavation method

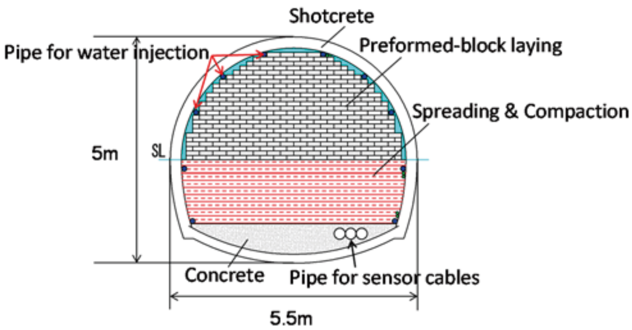
Table 3.7.3-3 Specifications of the buffer and electric heater

(1)Buffer (H12 reference)	
·Material	Sodium Bentonite Blocks (70% bentonite and 30% quartz sand)
·Shape	Two shapes, 82 cm diameter columns and a fan-shaped type with 45°central angles, an outside radius of 113 cm, and a thickness of 70 cm.
·Design dry density	1.87 g/cm^3 (ω = 10.5%) (the average dry density may be 1.6 g/cm^3 when the gap between blocks is filled.)
·Emplacement method	a vacuum hoisting method (Fig. 3.7.3-3)
(2)Electric heater (Simulated overpack)	
·Material	Carbon steel to simulate the overpack
·Dimensions	82 cm in diameter, 173 cm in height, and 5.8 ton in weight.

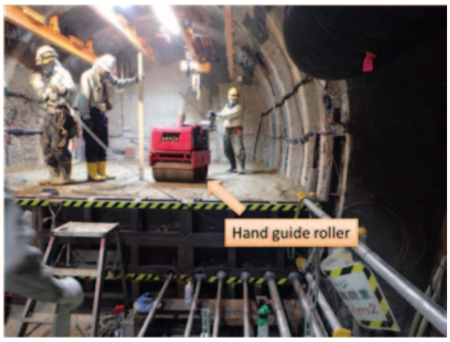
Fig. 3.7.3-3 Emplacement method of the buffer (vacuum hoisting method)

Table 3.7.3-4 Design requirements and specification of backfill

(1)Design requirements	
･Hydraulic conductivity $<10^{-9}$ m/s	To prevent tunnels from becoming preferential flow-paths, they must be backfilled with materials that have a hydraulic conductivity as low or lower than the surrounding rock.
･Swelling pressure >0.1 MPa	Backfill materials need to have swelling properties to ensure close contact with the walls of a tunnel, thus sealing boundaries and voids between the rock and the backfill.
(2)Specification	
･Material	60/40 mixture of debris (rock fragments) and sodium bentonite
･Design dry density	≥1.2 g/cm^3
･Construction method	spreading and compaction (lower part), preformed-block laying (upper part)

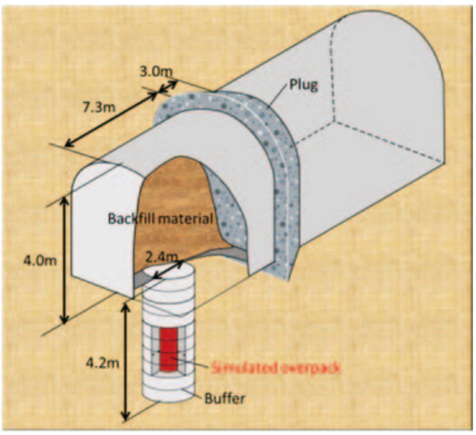


(a) Image view

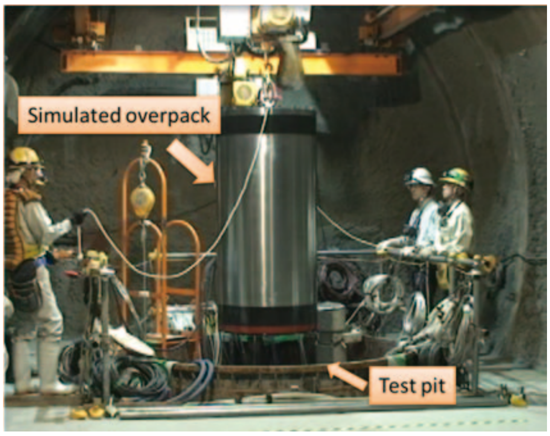


(b) Spreading & compaction method

Fig. 3.7.3-4 Tunnel sealing technology

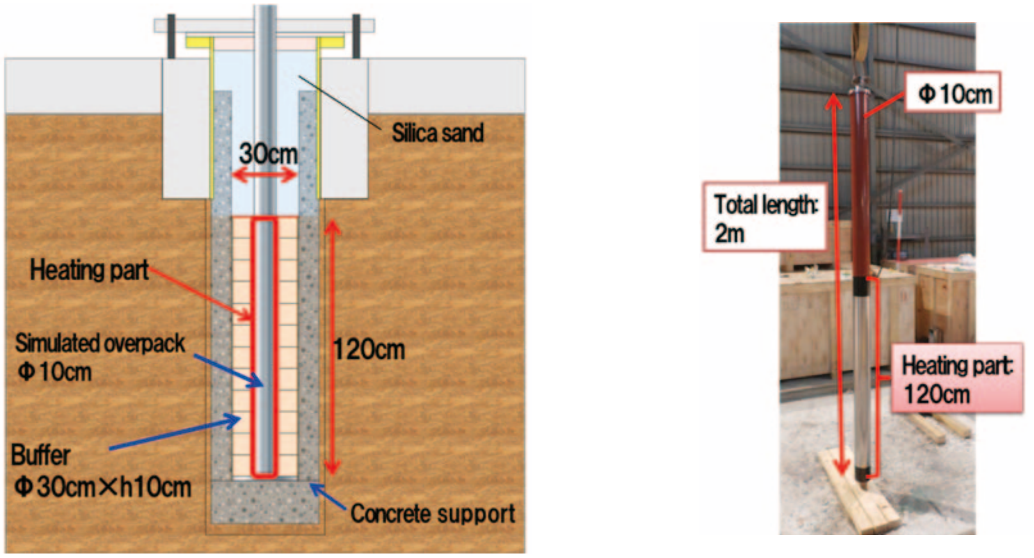


(a) Image view



(b) Emplacement of simulated overpack

Fig. 3.7.3-5 Engineered barrier system experiment at the Horonobe URL



(a) Image view (b) Simulated overpack for corrosion test

Fig. 3.7.3-6 Image view of the overpack corrosion test

3.7.4 Summary

The following results were obtained from R&D on geological disposal technology at the Horonobe URL project during the second mid-term research phase:

(1) Design and engineering technology of a deep geological repository

- Confirmation of applicability of the design method for buffer, backfill, plug, support, and grout to the geological environment of the Horonobe URL.
- The demonstration of an excavation technology of a disposal pit, an emplacement technology of EBS, a tunnel sealing technology, and a countermeasure against groundwater inflow.

(2) Evaluation technology of the integrity of the EBS

- The embarking upon the experiment on EBS focusing on overpack corrosion, re-saturation phenomena in the near-field, displacement of buffer into backfill, interactions between bentonite, cement, and carbon steel, gas migration in buffer, and intrusion of buffer into host rock.

The issues in the future R&D on geological disposal technology at the Horonobe URL project are as follows:

- Data acquisition focusing on modeling to evaluate the long-term performance of low-alkaline cement in the geological environment.
- Improvement of the evaluation model for the long-term behavior of EBS and sealing materials of drift.
- Demonstration of technologies necessary for operation of the repository including procedures relating to retrievability from the actual geological environment.
- Demonstration of options for the repository components in the real geological environment.

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4. Understanding long-term changing/recovering behavior of geo-environmental conditions

4.1 Geology

4.1.1 Introduction

Prediction analysis of the long-term evolution of geological environments, such as hydrogeological, geochemical, and geomechanical conditions, and thermal rock properties, is essential for the safety assessment of a site to be used as a repository.

In terms of this issue, we considered the transition of geological phenomena from the past to the present, based on an approach to estimate the future evolution by extrapolating highly probable processes to the future that takes into account a sufficient understanding of major geological processes and their long-term evolution from the past to the present.

4.1.2 Objectives in the second mid-term research phase

The existing data obtained in the Mizunami and Horonobe areas have been reviewed to reach the performance target of R&D, as shown in Table 4.1.2-1.

Table 4.1.2-1 Performance target of R&D for perceiving topographical/geological long-term evolution

Focus	Performance target of R&D	Tasks
Decision to begin disposal	Enable to estimate long-term evolution of host rock.	• Demonstration of technique of investigation and interpretation to estimate long-term evolution of topography and geological structure

4.1.3 Project details and outcomes

The R&D has been carried out for estimating the transition of geological phenomena that could affect the long-term evolution of the geological environment, such as uplift, subsidence, erosion, topographical changes, folding, as well as discontinuities such as paleo-stress fields, faults, and fractures. Through these activities, data and technical knowledge regarding the long-term evolution of the topography and geological structures from the past to the present have been accumulated.

1) Mizunami

Discontinuities such as fractures are considered to be the major groundwater flow paths in crystalline rocks. Therefore, the histories of uplift, subsidence, and related topographical changes and stress field changes that are considered to affect the development process of fractures were studied in and around the Mizunami area. Results of these studies are summarized as follows.

In regards to the uplift and subsidence processes, histories after sedimentation of the Mizunami Group have been considered around the Mizunami URL site[1]. The thickness of each formation in the Mizunami Group was measured from the borehole investigation data obtained from the Tono mine located to the west of the site, and the changes in elevation of the unconformity between the Toki Granite and the Mizunami Group at the time period of the sedimentation of each formation and the unconformity of each formation were estimated, respectively (Fig. 4.1.3-1). The sea-level change in this estimation was based on results from Haq et al. (1987)[2], while the consolidation and erosion of the stratum at the unconformity period were not considered. The paleo-topography at the unconformity period was also set to EL-0 m.

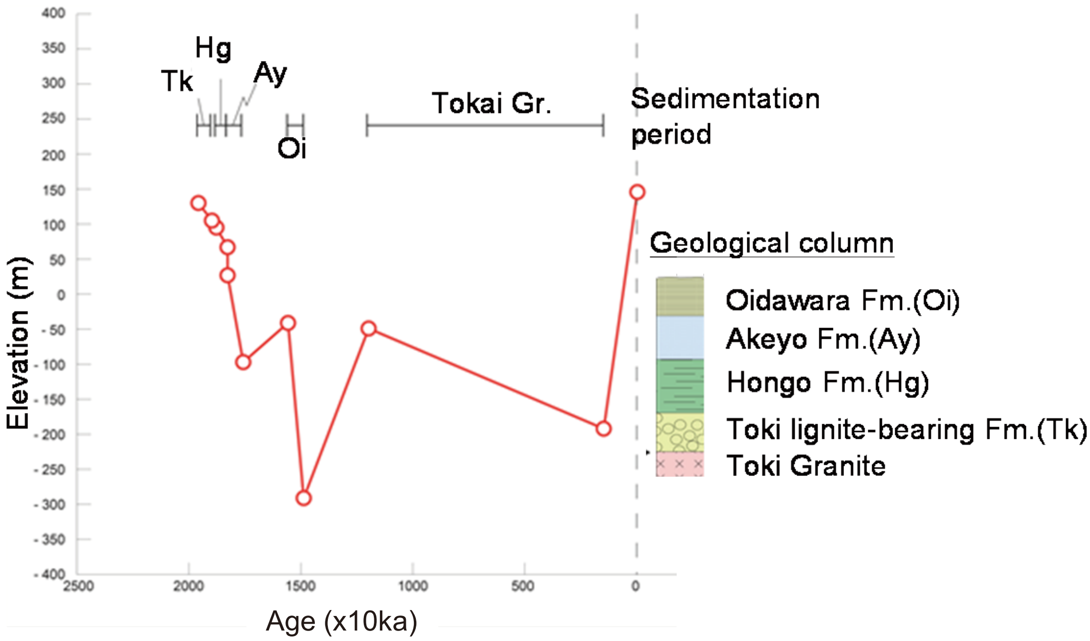

Fig. 4.1.3-1 Uplift and subsidence rates estimated from the change in thickness of different strata[1)]

In addition, Amano et al. (2003)[3)] estimated the uplift rate using plural methods that focused on the uplift after sedimentation of the Tokai Group.

Four methods were applied to estimate the average uplift rate from the sedimentation period of the Tokai Group (estimated to be ca. 1.5 Ma) to the present as a target:

i. Estimation using the dating of the Toki Granite and cooling rate.
ii. Estimation using the altitude of the low relief surface by erosion observed in the Tokai Group.
iii. Estimation using the height and age of the terrace surfaces.
iv. Estimation using vertical crustal movement during the past 100 years measured by the leveling.

From the results of these estimations, the uplift from 1 Ma to the present in this area was considered to be approximately 250 m to 300 m, and the estimated uplift rates obtained by the four methods listed above were as follows: i. 0.10–0.14 mm y^{-1} (assuming that the cooling rate reflected the uplift rate under the condition of a constant geothermal gradient), ii. 0.25–0.30

mm y^{-1}, iii. 0.10–0.24 mm y^{-1}, and iv. 0.15–0.30 mm y^{-1}.

Though there were differences in the assumption conditions and investigation accuracies between the different methods, the results showed approximately the same rate. Thus, uplift with a constant rate was assumed to have occurred from 1 Ma to the present in this area, and the average uplift rate was considered to be within 0.10–0.30 mm y^{-1} [3].

According to the latest research result, the age of the top part of the Tokai Group (Toki sandy gravel layer) was estimated to be 1.5 Ma[4]. Based on this result, the uplift rate of method ii was estimated to be 0.16–0.2 mm y^{-1}.

The uplift rate (0.11–0.16 mm y^{-1})[5] of the Toki River basin, estimated from the height and age of the terrace surfaces based on the detailed classification of the terrace surfaces of the Toki River, was within the above estimated rate.

To evaluate the influence of topographical changes on groundwater flow, a restoration of the paleo-geography was carried out in the area from the Kiso Mountains to the Nobi Plains[6]. In this study, five time section models (ca. 1.5 Ma, 1.1 Ma, 0.6 Ma, 0.2 Ma and present) were constructed considering the uplift starting time of major mountains and the transition of each fault displacement (Fig. 4.1.3-2). However, since the uplift and erosion rates were assumed to be constant in the study, the actual uplift and erosion rates might not have been properly reflected.

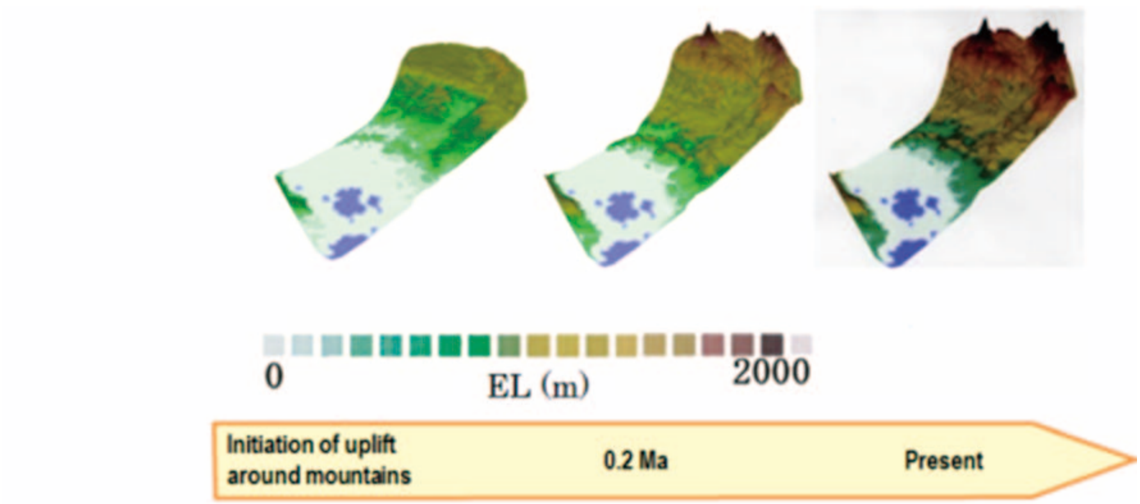

Fig. 4.1.3-2 Estimated paleo-geography from the Kiso Mountains (upper right) to the Nobi Plains (lower left)[6]

In regard to the stress field changes, the direction of the fault displacement and paleo-stress fields at the age of fault activity was estimated by the multiple inverse method based on the direction of striations and shear senses of the fault identified by borehole cores drilled at the underground facility and around the Mizunami URL site[7].

The results showed that the maximum principal stress in the target fault in this study was in a N-S direction with a low angle, the minimum stress was in an E-W direction with a low angle, the stress ratio was approximately 0.3, and the paleo-stress fields of the lateral fault were universally obtained. These paleo-stress fields indicated the paleo-stress states at 60 Ma[7], as suggested by a previous study using the micro-cracks around the Mizunami URL site[8]. The paleo-stress fields estimated to reflect the lifting deformation during the extension of the Sea of Japan were also confirmed. The paleo-stress changes based on the results of these study and the evolution histories of geological structures around the Mizunami area are summarized in Fig. 4.1.3-3[7].

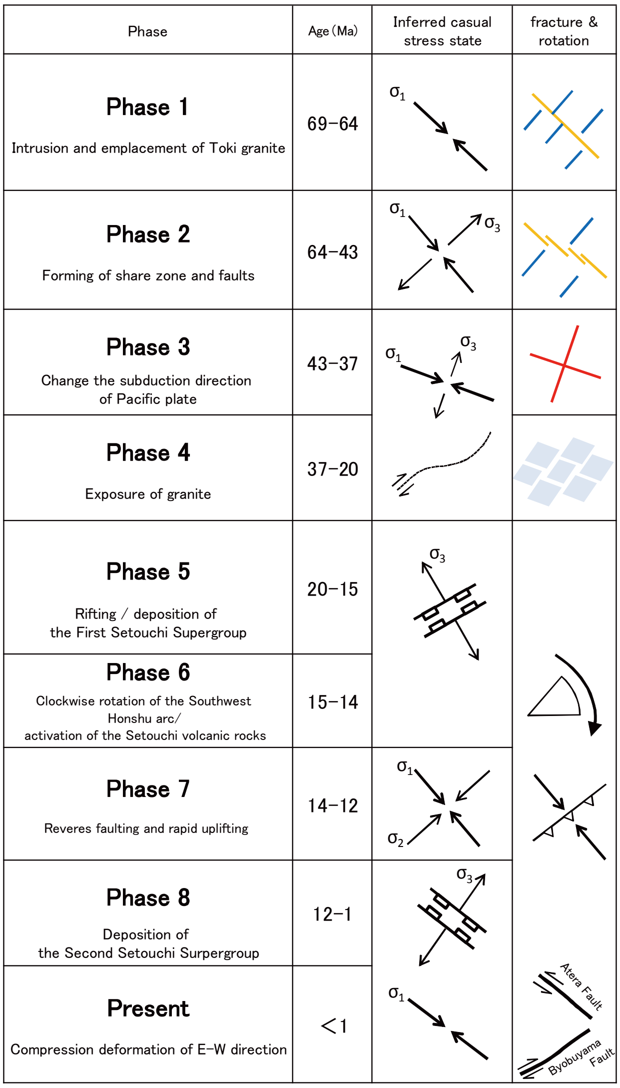

Fig. 4.1.3-3 Evolution histories of geological structures and paleo-stress fields in the Mizunami area[7]

From the above results and the geological history in the Mizunami area (Fig. 4.1.3-4), the formation period of fractures observed by geological mapping at the underground facilities can be classified as follows: i. the cooling period of the granite, ii. the exposure period of the granite before sedimentation of the Mizunami Group, and iii. the fault activity period[9]. Low-angle fractures in the upper part of the granite were assumed to have been formed by the unloading of the vertical load induced by erosion during period ii, and high-angle fractures distributed in the lower part of the granite were assumed to have been formed during periods i and iii. The fractures observed by geological mapping at the underground facilities were assumed to have been formed from the time of granitic intrusion to before sedimentation of the Mizunami Group, because period iii likely occurred before the sedimentation of the Mizunami Group[9].

The evolution of geological events in the Mizunami area is summarized in Fig. 4.1.3-4.

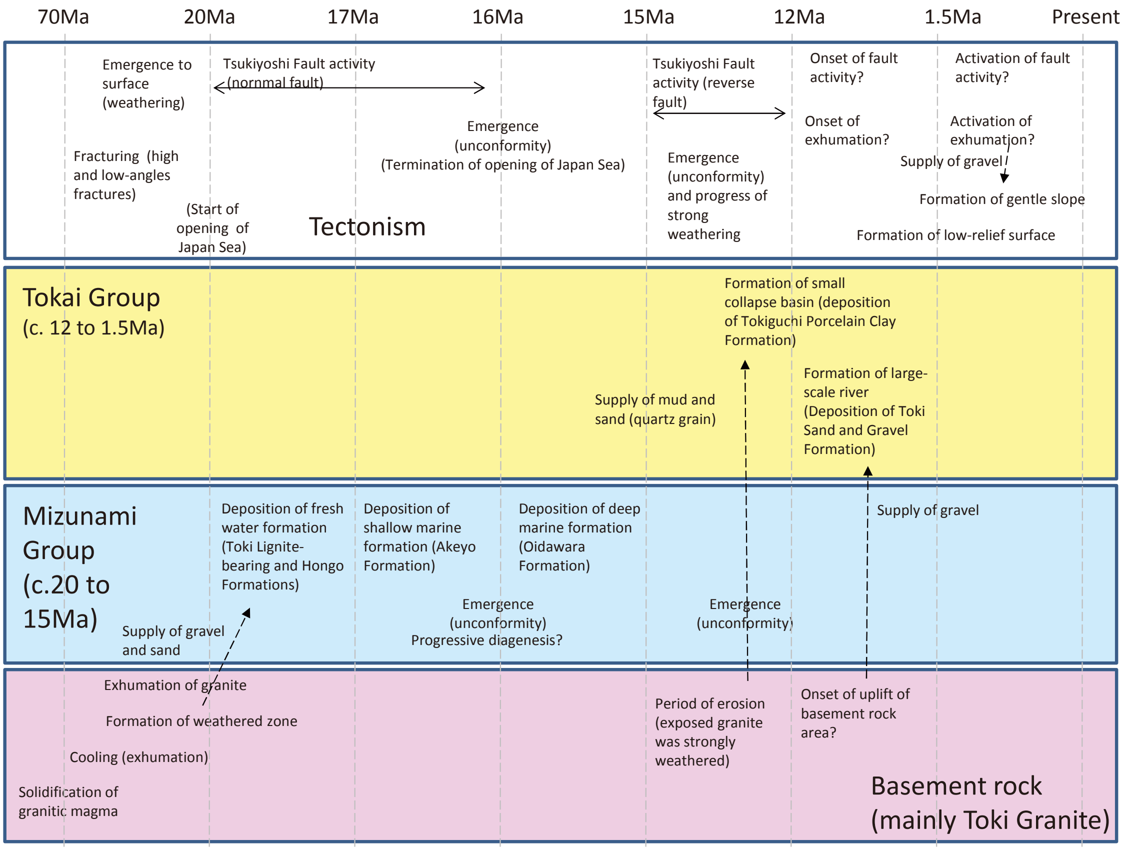

Fig. 4.1.3-4 Evolution of the geological events in the Mizunami area

2) Horonobe

Sedimentary rocks are generally treated as porous media. However, groundwater is considered to flow through not only the pores of the particles in sedimentary rocks but also through faults and fractures formed in solid sedimentary rocks due to the progression of burial diagenesis.

The histories of uplift, subsidence, erosion from the past to the present and related topographical changes, and burial diagenesis and changes in stress fields from the past to the present were studied, as these phenomena were expected to influence the evolution of sedimentary structures. The results of these studies are summarized as follows.

In regard to the uplift and subsidence, the uplift rate was estimated from marine terrace surfaces and the crustal horizontal strain rate was estimated from a geodetic method using GPS observation data and triangular survey data, as well as a geological method based on active tectonics[10),11)].

The uplift rate was calculated by subtracting the eustatic change in sea level from the former shore line level of the marine terrace according to Koike and Machida (2001)[12] and Koaze et al. (2003)[13]. The rates estimated from the marine terraces in the western part of the Horonobe area are shown in Fig. 4.1.3-5[10),11)]. A maximum difference of approximately a factor of two was observed in the uplift rate estimations, which was attributed to the differences in the MIS (Marine oxygen Isotope Stage) correlation of the marine terraces reported in Koike and Machida (2001)[12] and Koaze et al. (2003)[13]. Koike and Machida (2001)[12] based their uplift rate estimation on MIS 7 and obtained a value of 0.29–0.34 m ky^{-1}, whereas Koaze et al. (2003)[13] reported an estimated value of 0.16–0.26 m ky^{-1}. The uplift rate near the Sarobetsu Anticline, which is an active fold, was estimated to be larger than that for the surrounding area based on the MIS correlation reported by Koike and Machida (2001)[12]. Taking MIS 5e as an example, the rate is approximately 0.60 m ky^{-1} at the anticlinal axis and 0.48 m ky^{-1} at the fold limb, indicating the presence of local uplift at the anticlinal axis owing to the activity of the Sarobetsu Anticline[14].

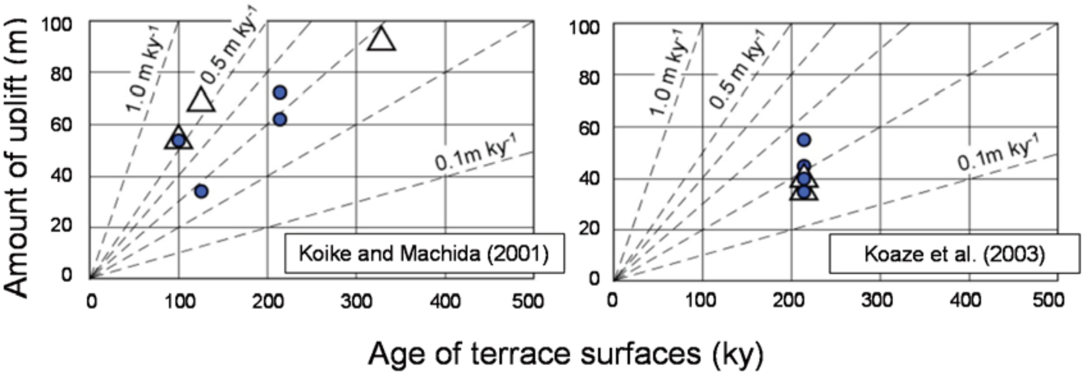

Fig . 4.1.3-5 Plot of uplift versus time for a sequence of marine-terrace surfaces[10]
(Modified from Niizato and Yasue, (2005)[14]).
The solid circles for estimation by Koike and Machida (2001)[12] and Koaze et al., (2003)[13].
The open triangles indicate marine-terrace surfaces at the Sarobetsu Anticline in this study.

The uplift/subsidence history for the Horonobe area is summarized in Fig. 4.1.3-6[11], based on the present depth, thickness, depositional age[15], and depositional environment of each formation and paleogeography in the area. The thickness and depositional age of each formation in the Sarobetsu Lowland were taken from existing information[16,17]. The palaeowater depth during the time of sedimentation of each formation was estimated from the sedimentary facies of each formation[18] on the basis of the relationship between the sedimentary facies and water depth[19,20]. Altitudes relative to the current sea level were obtained from sea levels during the period of sedimentation of each formation using the eustatic change curve of sea-level[2,21] and palaeowater depth. Fig. 4.1.3-6 represents the overall trend of uplift/subsidence in the Horonobe area, although it is based on some assumptions such as the exclusion of a potential decrease in the thickness of the formation due to compaction, isostatic uplift, and subsidence.

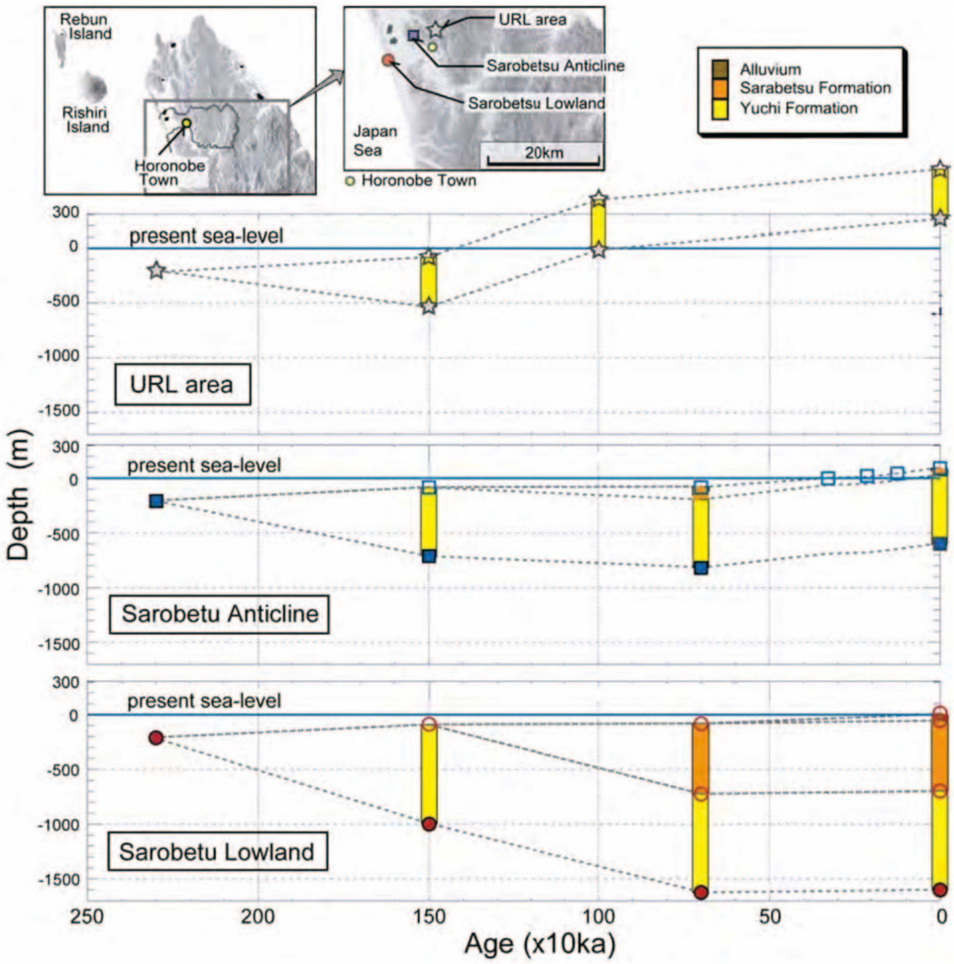

Fig. 4.1.3-6 Uplift and subsidence history in the Horonobe area[11)]

The amount and rate of erosion were estimated on the basis of the ambient air temperature, paleogeothermal gradients, and the transformation of the silica minerals[11)]. Palaeogeothermal gradients in and around the Horonobe area have been obtained in the north (MITI Tenpoku borehole) and the southeast (Kitakawaguchi SK-1 borehole) of Horonobe Town[22)]. From these data, the palaeogeothermal gradient in the Horonobe area was estimated to be 3.5 °C per 100 m. For the ground surface temperature of the Horonobe area, the average temperature at the mouth of 13 boreholes (including MITI Tenpoku borehole11) and the average ambient air temperature observed at the JMA Teshio Weather Station from 1979 to 2000 were 15 °C and 6.2 °C, respectively. The amount of erosion (denudation) was estimated by taking these temperatures as the ground surface temperature at the time when the palaeogeothermal gradients were obtained[11)]. The transformations of the silica minerals were attributed to burial diagenesis and were not influenced by igneous and hydrothermal activity after diagenesis, based on results from the surface geological surveys and borehole investigations in and around the Horonobe area. Given the above conditions, the depth where amorphous silica (opal A) became low-temperature cristobalite (opal CT) in the past was assumed to occur at approximately 860–1,250 m. The amount of erosion could be estimated from the differences between these depths and the depth of the current boundary between opal A and opal CT. As a result, the amount of erosion at the locations of the borehole investigation was estimated to be at least 435–820 m[11]. The boundary between the Wakkanai Formation and the Koetoi Formation exposed at the ground surface was consistent with the boundary between opal A and opal CT. Thus, the boundary could be used as the reference surface for estimating the amount of erosion (denudation). A contour map was drawn for the amount of erosion in the Hokushin district of Horonobe Town based on the boundary between opal A and opal CT at each borehole location and between the Wakkanai Formation and Koetoi Formation on the ground surface (Fig. 4.1.3-7).

In the case where the temperature for opal A to become opal CT is 45 °C and the ground surface temperature is taken as 15 °C, the amount of erosion was presumed to be in excess of 860 m at the anticlinal axis and approximately 275 m around borehole HDB-7 at the limb of the anticline. For the areas in and around the Hokushin district, distances of approximately 860 m and 1,250 m above the boundary between opal A and opal CT corresponded to locations at the base of the Sarabetsu Formation and within the Sarabetsu Formation, respectively. Therefore, the Hokushin district could be considered to not have been a subsidence area since 0.7–1.3 Ma, which is the depositional age of the Sarabetsu Formation[23]. The values of the erosion amount were converted to erosion rates (per 1,000 years), resulting in estimated values of approximately 0.66–1.79 m ky^{-1} at the anticlinal axis, where the uplift was the largest, and approximately 0.21–0.86 m ky^{-1} at the limb of the anticline, where the uplift was smaller[11].

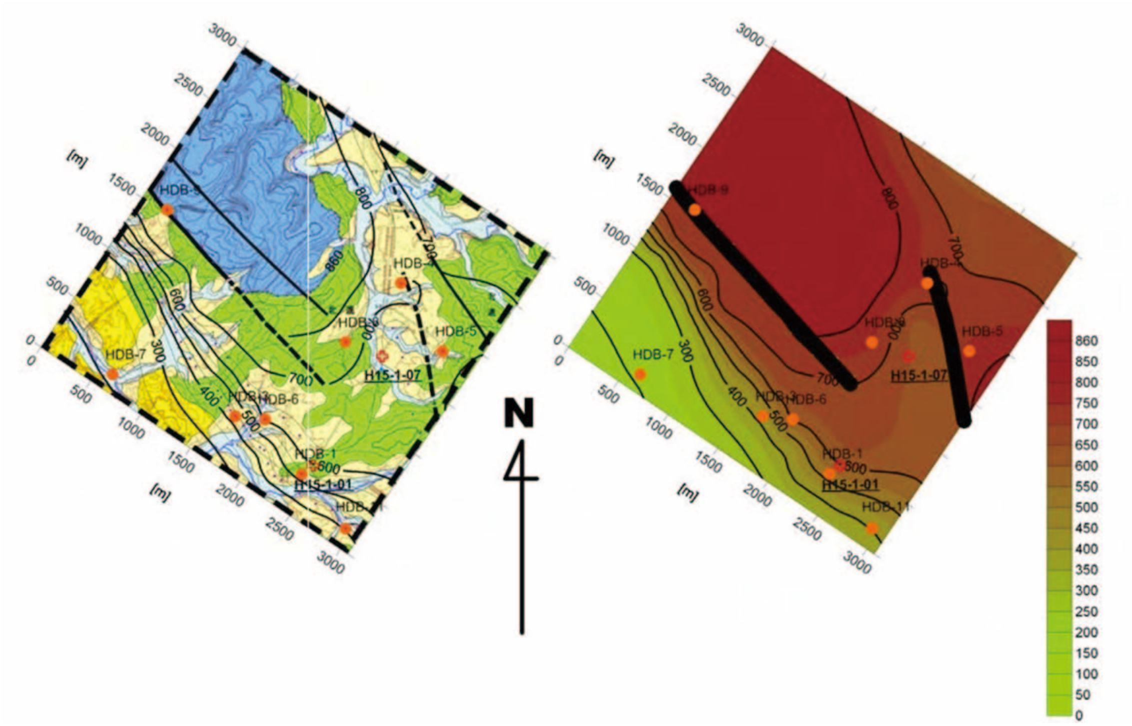

Fig. 4.1.3-7 Amount of erosion in the URL area[11)]
The orange circles indicate the location of the boreholes used for estimating the amount of erosion.

The Koetoi and Wakkanai formations, which are composed of biogenic fine-grained siliceous rocks, are distributed in the Horonobe area. Silica minerals contained in siliceous sediments were transformed from opal A to opal CT and then to low-temperature quartz[24)] owing to burial processes and temperature increases. The transformation of silica minerals, along with zeolite and feldspar with an abundance of Na and Ca, is known as the mineral index of burial diagenesis. The transformation of silica minerals, in particular, is strongly controlled by changes in temperature owing to the burial of sediments[25)].

Based on the results of visible and electron microscopic observations and X-ray diffraction analysis[26)], the typical minerals that constitute the Koetoi and Wakkanai formations were identified as silica minerals (opal CT/opal A) with minor amounts of quartz, feldspar, clay minerals (kaolinite, smectite, illite, chlorite), pyrite, and carbonate minerals (siderite, magnesite). However, there was a large difference in the silica mineral phase between the Wakkanai Formation and the Koetoi Formation, where the Wakkanai Formation was constituted mainly of opal CT formed by the burial and diagenesis of diatom remains (opal A), while the Koetoi Formation did not contain opal CT.

In regard to the horizontal strain rate, the amount of horizontal shortening and the horizontal strain rate around the Horonobe area were estimated by a geodetic method using GPS observation data and triangular survey data, and by a geological method using active tectonics data and geological cross-sections. The estimate for the strain rate in the Horonobe area was 10^{-8}–10^{-7} y^{-1} with the geodetic method and 10^{-9}–10^{-8} y^{-1} with the geological method.

The values obtained using the two methods were similar, and the strain rate obtained from the geological method was smaller than that obtained from the geodetic method by less than a factor of 10. It is generally the case that estimates using the geological method based on data on active faults and historical earthquakes tend to be smaller than those obtained by the geodetic method by a factor of around 10.

From the viewpoint of long-term stability of the geological environment, the trend of the crustal movement and the horizontal crustal strain rate should be obtained using the geological method that covers a duration of more than several tens of thousands of years[11)].

In regard to the change in stress states, analysis using GPS observation data and the direction of striations and shear planes of minor faults were carried out to understand the paleo-stress fields around the northern part of Hokkaido. From the results, horizontal displacement vectors based on GPS observations displayed E-W compressive stress. This result coincided with the direction of maximum principal stress obtained by hydraulic fracturing tests carried out using boreholes. Therefore, the present stress field in the Horonobe area appeared to be in an E-W compressive stress state[27)]. The direction of the maximum principal stress obtained by analysis using minor faults was several tens of degrees of rotation counterclockwise from the E-W direction[27)]. The difference of these stress fields could be corrected by taking the folding process into account during the deposition state[28),29)]. This result suggested that the E-W compressive stress field had not changed since the time of formation of these minor faults in the Horonobe area. Although the present stress state and paleo-stress state had been discussed individually, the results enabled the estimation of the transition of stress states from the past to the present by considering the evolution of the geological structures.

An analog model experiment using a sandbox device was carried out to develop the techniques for understanding the evolution process of geological structures (such as a fault and a fold) and estimating the quantitative uplift and subsidence rates induced by the evolution. From the experiment, the trend of the geological displacement associated with the evolution process of faults could be observed quantitatively[30)].

Based on the R&D to date, natural events and processes in the Horonobe area could be summarized[31)]. Furthermore, the techniques for modeling and analysis enabled three-dimensional geological modeling and groundwater flow analysis to consider the evolution of the geological environment including folds, faults, uplift/subsidence, erosion, decreases in the thickness of the formation owing to compaction, and changes in the groundwater recharge and shoreline (Fig. 4.1.3-8 and Fig. 4.1.3-9)[32),33)]. In addition, technical knowledge for estimating topographical and geological long-term evolution could be accumulated, and an approach and procedure for constructing the topographical and geological evolution model could be developed.

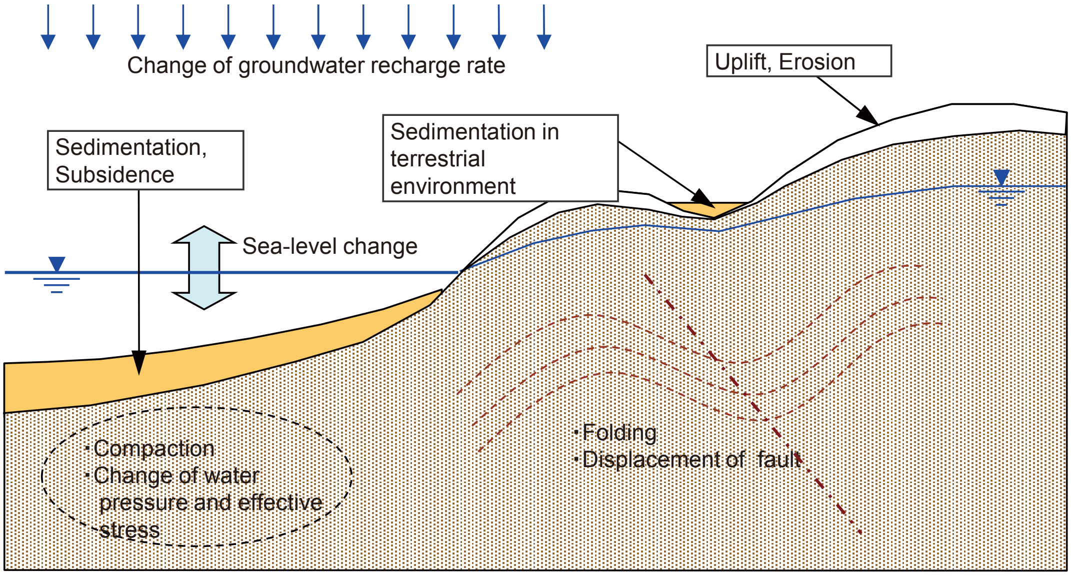

Fig. 4.1.3-8 Diagram of the considered geological events

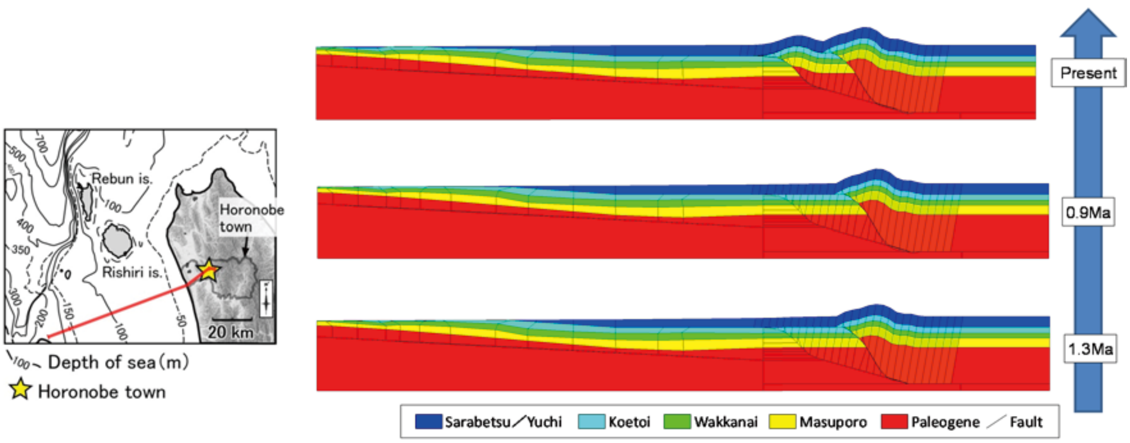

Fig. 4.1.3-9 Topographical and geological evolution model constructed by the sequential modeling system (SMS) of the impact of geological evolution on groundwater flow[32)]

4.1.4 Summary

Techniques and accumulated technical knowledge regarding the investigation, analysis, and assessment for estimating the long-term evolution of the topography and geological structure from the past to the present are as stated below:

- In regard to the transition of stress states from the past to the present, the present stress state and paleo-stress state were discussed individually. The results enabled the development of a technique to estimate the stress states by considering the formation and evolution of geological structures.
- Technical knowledge for estimating topographical/geological long-term evolution has been accumulated, and an approach and procedure for constructing the topographical/geological evolution model have been developed.
- Techniques for modeling and analysis enabled three-dimensional geological modeling and

groundwater flow analyses to consider the evolution of the geological environment including folding, fault activity, uplift/subsidence, erosion, decreases in the thickness of the formation owing to compaction, and the change in groundwater recharge and shoreline.

In future studies, improvement in the accuracy of the constructed model based on the accumulation of knowledge of long-term geological phenomena is required. Furthermore, the development of techniques for evaluating uncertainties in modeling and analyzing and the range of influence of natural events such as faults and fractures is needed.

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4.2 Hydrogeology

4.2.1 Introduction

The objective of the study is to establish the following techniques of investigation, analysis, and assessment for estimation of long-term evolutionary ranges of groundwater flow conditions over geological time scales.

It is assumed that the groundwater flow field, which contains the following, and the spatial variability of groundwater flux will evolved as a result of natural events and processes such as landform and climatic changes over geological time scales.

- Groundwater flow system from recharge area to discharge area
- Type of groundwater flow condition (advective field and diffusive field)
- Type of driving force of groundwater flow (hydraulic gradient, density flow, and thermal convection)

From these hydrogeological points of view, the features to be focused on and processes to be characterized and the resulting data requirements relevant to safety assessment, design, and construction were identified[1),2)]

(1) Long-term evolution of the groundwater flow field

(2) Long-term evolution of the spatial variability of groundwater flux

4.2.2 Objectives in the second mid-term research phase

The following studies have been performed to achieve the performance target of R&D for perceiving long-term evolution and recovery behavior of groundwater flow conditions (Table 4.2.2-1):

- Enable estimation of the long-term stabilities of hydraulic characteristics and groundwater flow conditions

Table 4.2.2-1 Performance target of R&D for perceiving the long-term evolution and recovery behavior of groundwater flow conditions

Focus	Performance target of R&D	Tasks
Decision to begin disposal	Enable estimation of long-term stabilities of hydraulic characteristics and groundwater flow condition.	• Techniques of investigation, analysis, and assessment for estimation of long-term evolutionary ranges of groundwater slow conditions over geological time scales

4.2.3 Project details and outcomes

Features and processes that mainly affect the long-term evolution of groundwater flow condition are specified and the hypothesized long-term evolution of groundwater flow conditions is listed in Table 4.2.3-1.

Table 4.2.3-1 Hypothesized long-term evolution of groundwater flow conditions

Feature & process	Hypothesized long-term evolution of groundwater flow conditions
Landform	• Evolution of topography such as mountain making affects groundwater flow system (recharge and discharge area, and flow path) and hydraulic gradient
Hydraulic property	• Evolution of hydraulic property of rock affects groundwater flow velocity • Evolution of hydraulic property of large-scale discontinuous structures such as fault affects groundwater flow system and hydraulic gradient (Evolution of hydraulic property is occurred by changes of porosity of rock, and density, orientation, trace length and mineral filling of fracture, which may be caused by evolution of overburden pressure due to geological processes such as subsidence and sedimentation.)
Thermal gradient	• Evolution of thermal gradient may cause additional driving force of groundwater flow, such as thermal convection
Salinity concentration	• Evolution of salinity concentration may cause additional driving force of groundwater flow, such as density flow
Fault motion (Earthquake activity)	• Fault motion may cause volumetric strain of rock and change hydraulic property, which then affect spatial variability of groundwater pressure
Recharge rate	• Evolution of recharge rate, which occurs as a result of climatic and topographic evolution, affects groundwater level distribution, and then it affect groundwater flow system, hydraulic gradient and dilution effect
Sea level change	• See level change affects groundwater flow system (location of discharge area)

1) Mizunami

In the case of the Tono region, it is supposed that thermal convection because of hydrothermal activity had occurred and the hydraulic properties had evolved for several million years. Therefore, influential factors have been identified based on the following groundwater flow analyses taking into account landform and climatic changes[3]. Climatic change has been modeled as changes of recharge rate.

- Regional groundwater flow analysis taking into account paleo-topography and climatic change[4] (Fig. 4.2.3-1, Fig. 4.2.3-2)
- Local groundwater flow analysis based on restored paleo-topography using river terraces[5),6] (Fig. 4.2.3-3)
- Local groundwater flow analysis based on topography estimated by the landform development simulation[7] (Fig. 4.2.3-4)
- Local groundwater flow analysis taking into account landform changes and change of fault distributions such as hydrogeological continuity in the depth direction and connectivity in the lateral direction[8] (Fig. 4.2.3-5)

The results of these groundwater flow analyses demonstrate that landform and climatic changes have the potential to affect hydraulic gradient. On the other hand, these results show that some groundwater flow systems are not affected by the landform and climatic changes. Based on the results, the areas of groundwater flow analyses in Fig. 4.2.3-3 and Fig. 4.2.3-4 have been assigned. Additionally, it was inferred that the influence of changes in fault distribution is smaller than those of landform and climatic changes.

Groundwater pressure changes have been measured in several boreholes in Mizunami (Fig. 4.2.3-6). An overview of the changes caused by the 2011 off the Pacific coast of Tohoku Earthquake can be summarized as follows[9]:

- Groundwater pressure changes shortly after the earthquake were caused by volumetric strain induced by the earthquake.
- Groundwater pressure recovery took at most two years after the earthquake.
- Changes in the vertical and horizontal hydraulic gradient after the earthquake were negligibly small.
- Different trends of changes in groundwater pressure indicate that faults are likely boundaries of groundwater flow zones.

Based on the results of groundwater flow analyses and measurements of groundwater pressure changes, the geological synthesized scenario for modeling long-term evolution of groundwater flow conditions is summarized in Fig. 4.2.3-7.

For the groundwater flow analysis, development of a method for estimation of the recharge rate during glacial stages is important. Therefore, existing information on climate, which is the important parameter of surface hydrological conditions, was reviewed. The relationships between mean annual temperature and evapotranspiration and between latitude and evapotranspiration display an approximately positive correlation (Fig. 4.2.3-8)[6]. The correlation suggests that approximate evapotranspiration rates can be estimated using the mean annual temperature value and latitude.

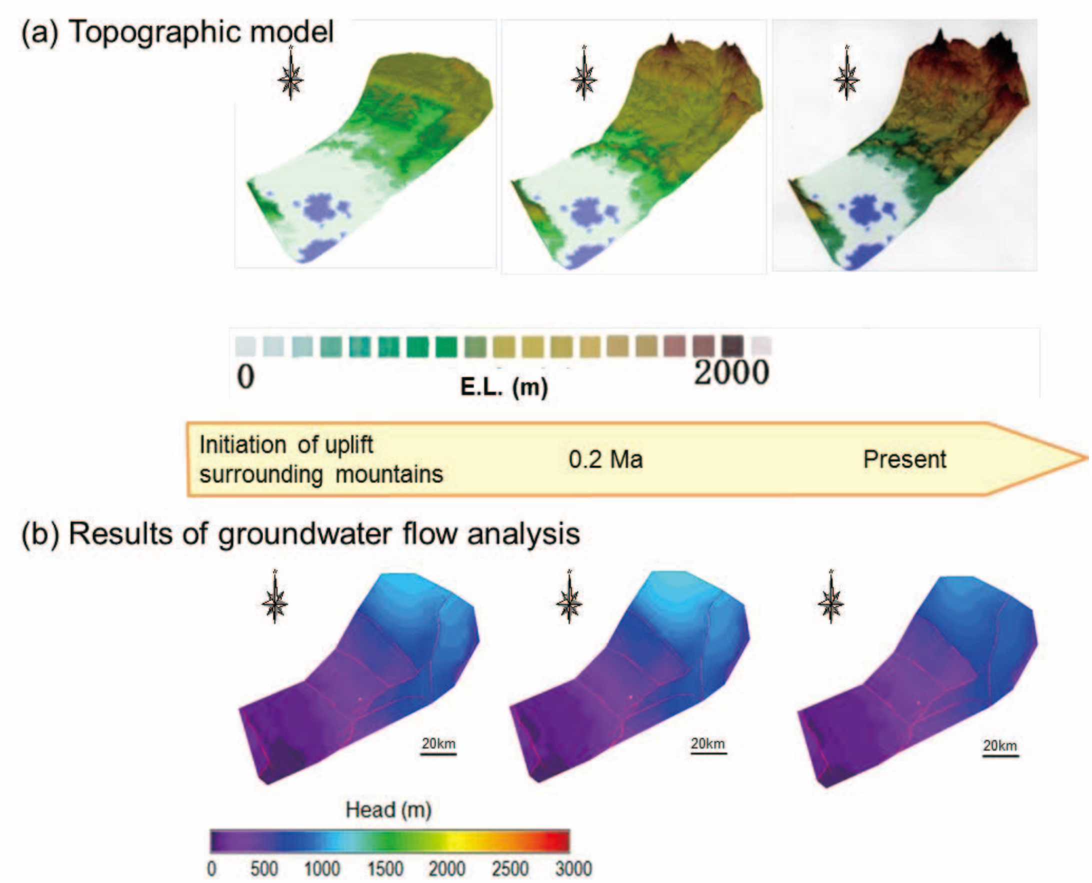

Fig. 4.2.3-1 Results of restoration of paleo-topography and groundwater flow analysis based on the paleo-topography in the region from the Kiso Mountains to Ise Bay (Tono region)

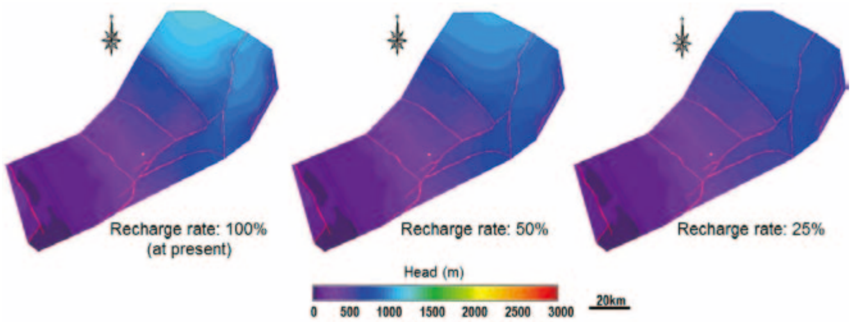

Fig. 4.2.3-2 Modeled hydraulic head distributions from groundwater flow analyses focusing on the impact of recharge rate (Tono region)

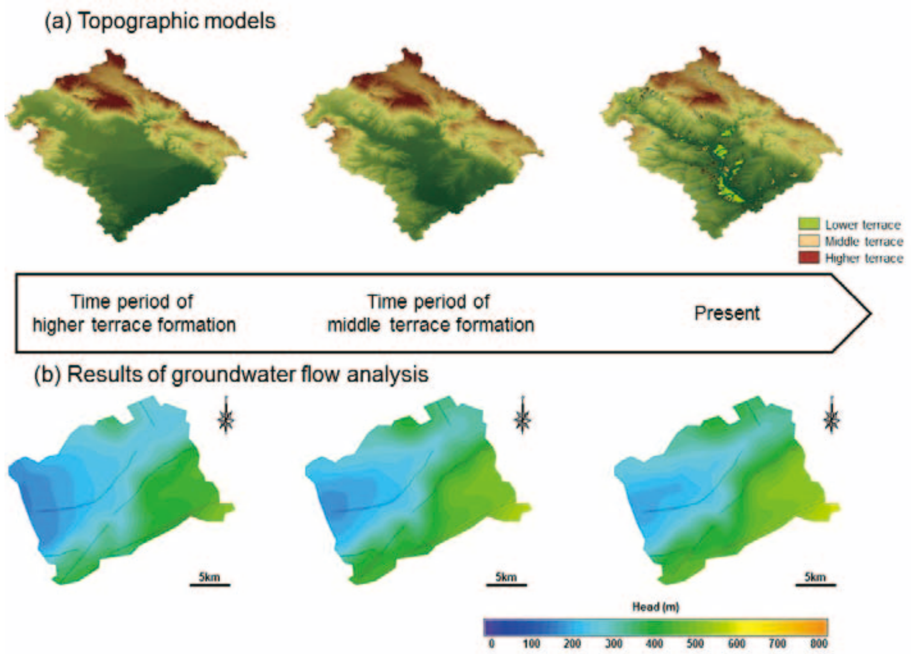

Fig. 4.2.3-3 Paleo-topography restored based on river terraces and groundwater flow analysis based on the paleo-topography (Tono region)

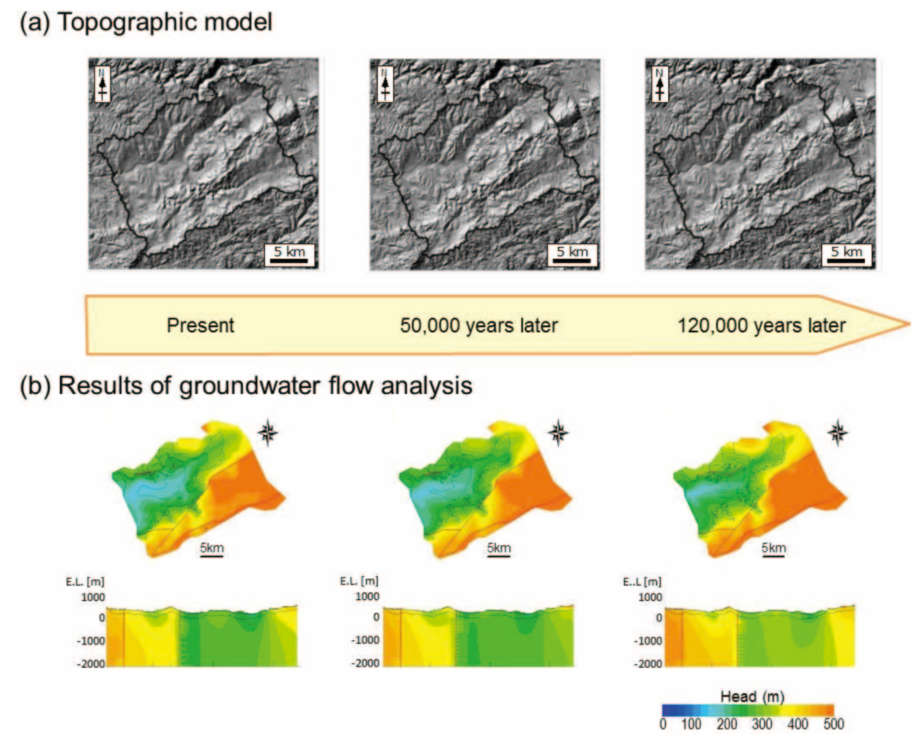

Fig. 4.2.3-4 Results of landform development simulation and groundwater flow analysis based on topography estimated by the simulation (Tono region)

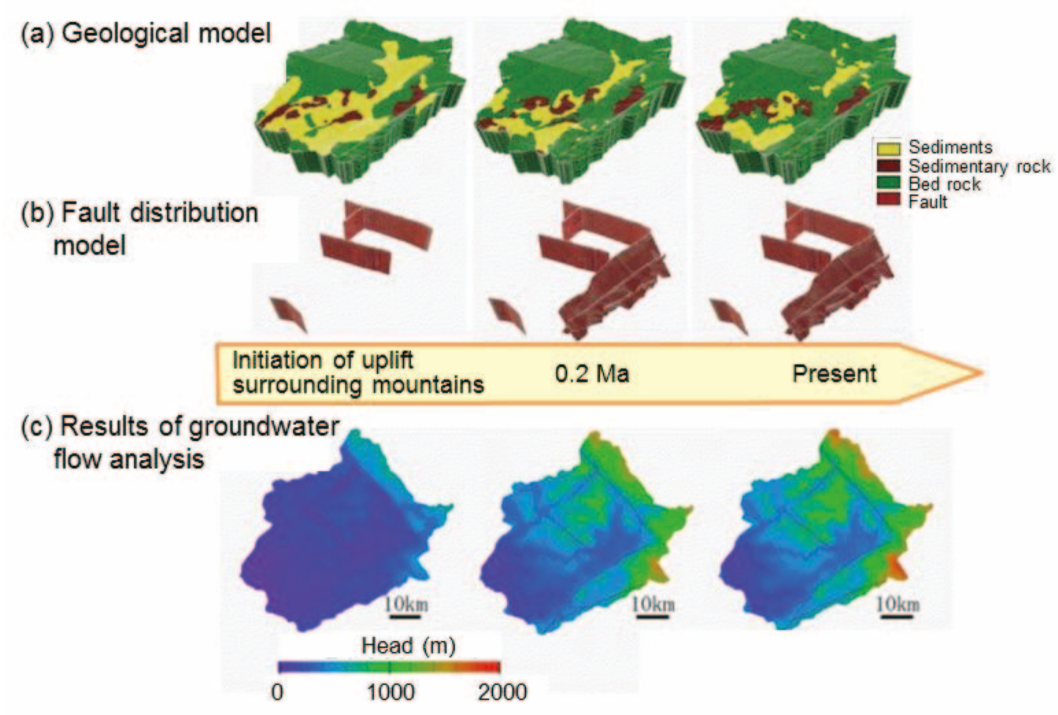

Fig. 4.2.3-5 Results of groundwater flow analysis taking into account topographic changes and fault distributions (Tono region)

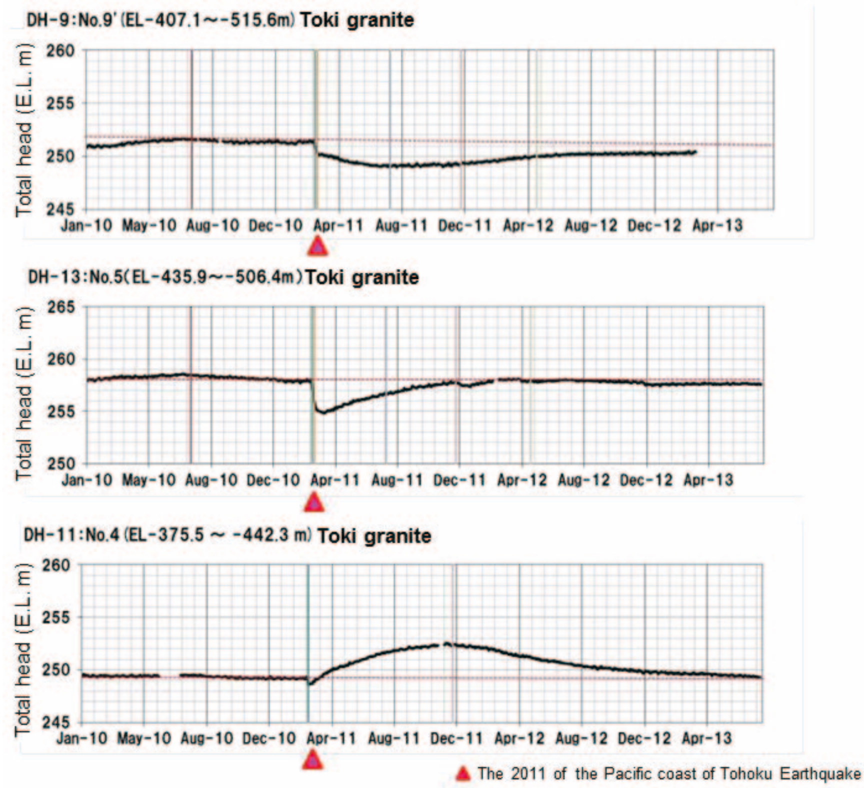

Fig. 4.2.3-6 Groundwater pressure changes caused by the 2011 off the Pacific coast of Tohoku Earthquake (Tono region)

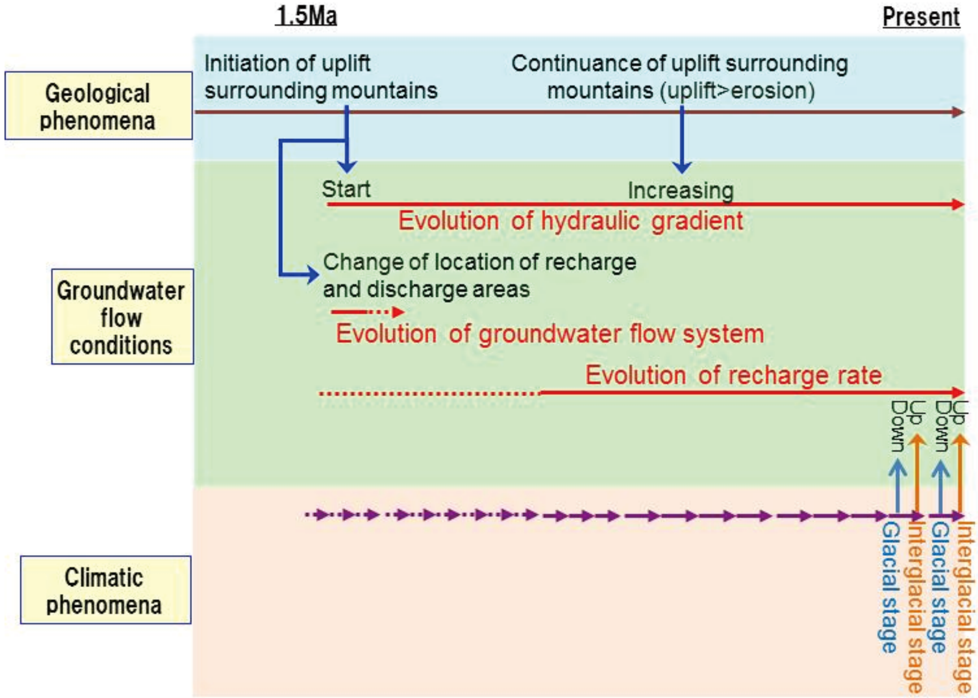

Fig. 4.2.3-7 Geological synthesized scenario for modeling the long-term evolution of groundwater flow conditions (Tono region)

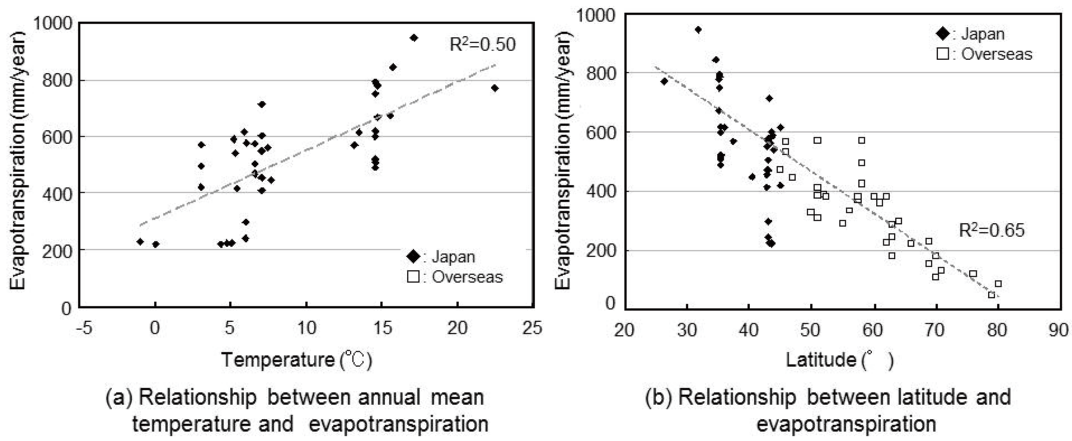

Fig. 4.2.3-8 Relationship between mean annual temperature and evapotranspiration (left), and between latitude and evapotranspiration (right)

2) Horonobe

In Horonobe, regional groundwater flow analysis has been performed taking into account landform changes including sea level change, change of recharge rate because of climatic change, and evolution of hydraulic properties because of burial and compaction[10),11),12)].

An unsteady state groundwater flow simulation system named SMS (Sequential Modeling System for evolution of groundwater flow), which can take into account natural events and processes such as topographical, geological, and hydrogeological changes because of uplift and denudation and temporal changes in recharge rate caused by climate change, has been developed and applied[13] (Fig. 4.2.3-9, Fig. 4.2.3-10). The results of groundwater flow analysis using SMS show that landform and climatic changes including sea level change and evolution of hydraulic properties resulting from burial and compaction have the potential to affect the hydraulic gradient.

Groundwater level changes were also measured in several boreholes in Horonobe[14),15)] (Fig. 4.2.3-11). An overview of the changes caused by the 2011 off the Pacific coast of Tohoku Earthquake can be summarized as follows:

- Groundwater level changed as a result of the earthquake in the zone with relatively high hydraulic conductivity ($\geqq 10^{-6}$ m/sec: C, D, E in Fig. 4.2.3-11).
- Groundwater level recovery took several months after the earthquake.
- There is no clear relationship between the recovery period and the hydraulic conductivity.

Based on the results of groundwater flow analysis and measurements of groundwater pressure changes, the geological synthesized scenario for modeling the long-term evolution of groundwater flow condition is summarized in Fig. 4.2.3-12.

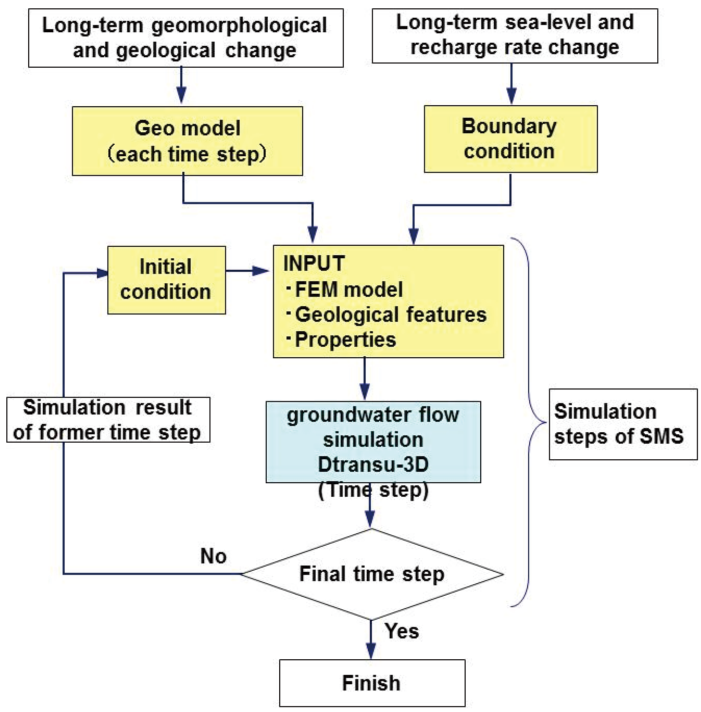

Fig. 4.2.3-9 Overall procedure used in SMS

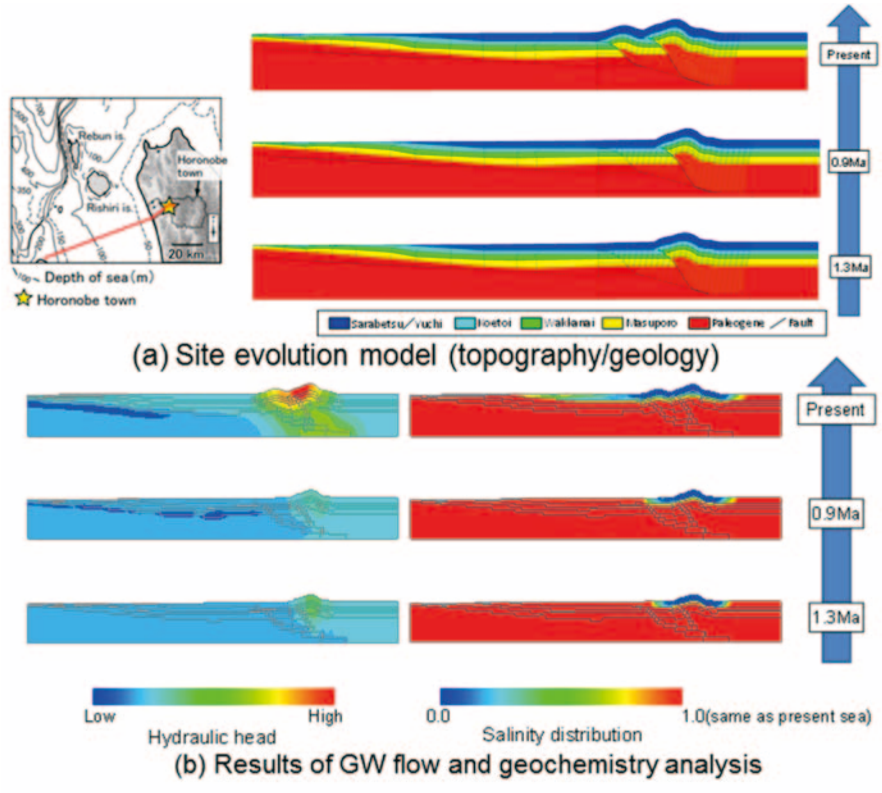

Fig. 4.2.3-10 Geological evolution model and results of groundwater flow analysis (Horonobe region)

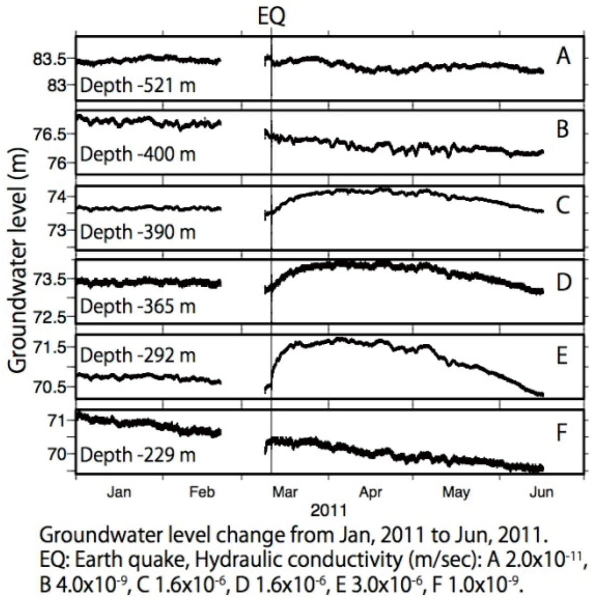

Fig. 4.2.3-11 Groundwater pressure changes caused by the 2011 off the Pacific coast of Tohoku Earthquake (Horonobe region)

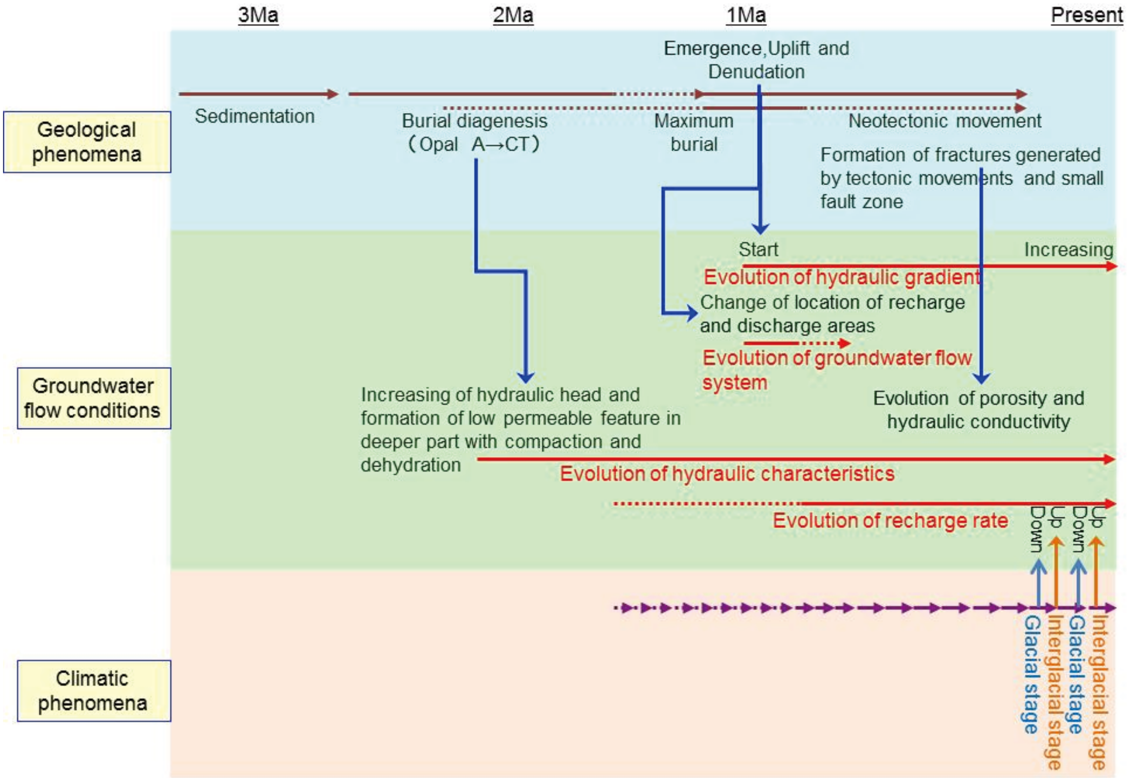

Fig. 4.2.3-12 Geological synthesized scenario for modeling the long-term evolution of groundwater flow conditions (Horonobe region)

4.2.4 Summary

Techniques and accumulated technical knowledge regarding individual techniques of investigation and analysis for estimation of the long-term evolutionary ranges of groundwater flow conditions over geological time scales are as stated below:

- To understand the effects of long-term geological phenomena on groundwater flow conditions, groundwater flow modeling taking into account topographic and climatic changes is useful.
- Groundwater pressure changed shortly after the 2011 off the Pacific coast of Tohoku Earthquake, and groundwater pressure recovery took at most two years after the earthquake.
- Changes in the vertical and horizontal hydraulic gradient after the earthquake were negligibly small.

In further, studies will be done to solve the open issues described below:

- Development of techniques of investigation, analysis, and assessment for identification of long-term geological phenomena affecting groundwater flow conditions and estimation of the long-term evolutionary ranges of groundwater flow condition.
- Understanding of the mechanisms generating groundwater pressure changes and their influences on hydraulic characteristics and groundwater flow conditions.

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4.3 Hydrogeochemistry

4.3.1 Introduction

For the issues surrounding geological isolation of HLW, estimation of the long-term hydrogeological and hydrochemical conditions of the groundwater system is required for the safety assessments. To satisfy this requirement, paleo-hydrogeological analysis was performed with construction of a scenario conception on past groundwater compositions, groundwater flow rates, and flow directions, using a combination of geological evidence, chemical and isotopic compositions of groundwater, mineralogical data, and hydraulic measurements. The following approaches were applied:

i. Documentation of past geological events and their impact on geological features

ii. Highlight the most important geological phenomena and their relationships, and scenario documentation

iii. Inference of future scenarios and their impact on geological features

Scenario documentation was performed based on the international FEP (Feature, Event, Process) list and paleo-hydrogeological study[1),2),3)]. FEP analysis is an efficient method for construction of a scenario on the long-term relations between various geological events and variation of features.

4.3.2 Objectives in the second mid-term research phase

In the second mid-term research phase, the R&D shown in Table 4.3.2-1 has been conducted using the results from the previous phase (surface-based investigation). The main aims of R&D are to provide and demonstrate methodology to show a long-term hydrochemical variation for making a decision on the implementation of disposal.

Table 4.3.2-1 Performance target of R&D on long-term variation of hydrochemical conditions

Focus	Performance target of R&D	Tasks
Siting Facility construction	To identify the long-term chemical conditions.	• Estimate long-term variations in hydrochemistry

4.3.3 Project details and outcomes

(1) Methodology for estimation of past hydrochemical conditions

pH conditions

As described in section 2.3, the dominant processes controlling the pH and redox conditions of the present groundwater are buffering reactions by carbonate minerals and microbial catalytic reactions including iron and sulfur minerals both in Mizunami and Horonobe. The spatial distribution and occurrence of these minerals probably reflects the chemical conditions. For instance, because carbonate minerals are unstable in acidic pH conditions, the presence of carbonates implies neutral to alkaline conditions. Similarly, sulfide minerals imply reducing conditions[4)] (Fig. 4.3.3-1). Such minerals form over the long-term in terms of the geological time scale. By identifying the precipitation age of these minerals, it is possible to estimate the long-term stability of the chemical conditions.

Observations of the spatial distribution of these minerals at Mizunami showed that carbonates precipitate in fractures within granite at depths below approximately 200 m. The depths from the surface to 200 m possibly correspond to the zone in which pH is buffered by carbonate–water interactions.

In contrast, a signature of past dissolution of fossil shells has been observed at depths from 50 to 300 m in the Horonobe area. It should be taken into account, however, that the dissolution of fossil shells can also occur under the partially acidic conditions resulting from organic degradation by microbiological processes. Therefore, it is necessary to consider carefully what might be the dominant phenomenon in the interpretation of dissolution of fossil shells. In the Mizunami and Horonobe areas, iron oxide, which could be an indicator for intrusion of shallow oxygenated water, has been observed within a depth of 30 m. A zone of several tens of meters below the surface would correspond to the pH buffering zone. The pH of groundwater deeper than the buffering zone might be maintained in neutral to alkaline conditions over the long term[5] (Fig. 4.3.3-2). The results obtained in both the Tono and Horonobe areas show that the pH of groundwater is within the range 6–10 where carbonate minerals have been identified.

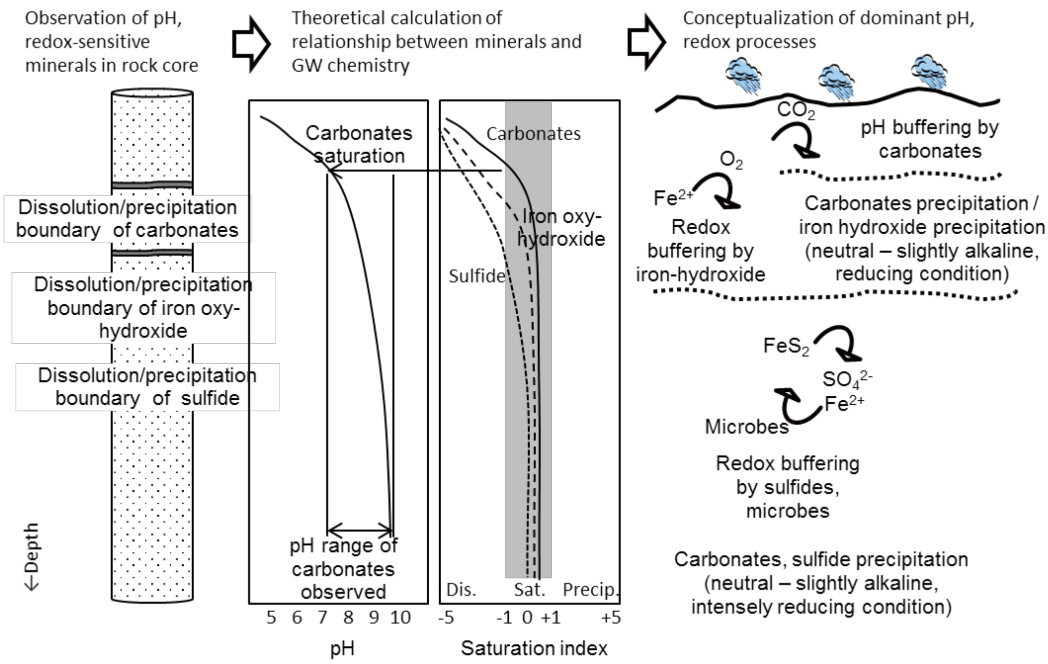

Fig. 4.3.3-1 Overview for modeling hydrochemical characteristics based on mineralogical investigation

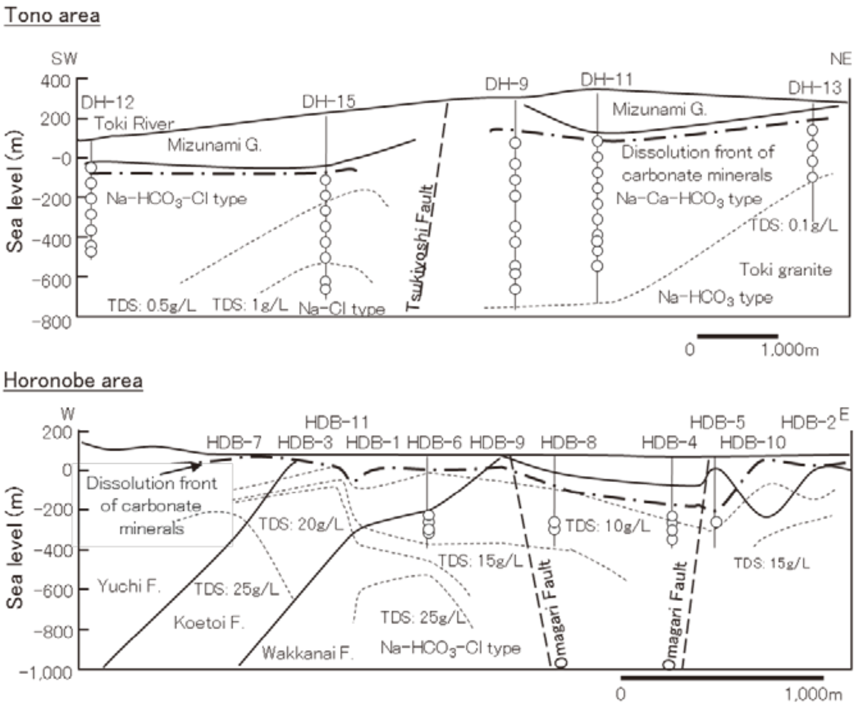

Fig. 4.3.3-2 Spatial distribution of fracture-filling calcite

The precipitation age of carbonates can be estimated on the basis of isotopes ($\delta^{13}C$, $\delta^{18}O$, and ^{14}C), morphology, and geohistory[6),7),8),9)]. These methods can be applied to areas in which groundwaters with a distinct isotopic and chemical signature has been replaced in the past. The methods may not be suitable for areas where the groundwater has been isolated in the geological formation since the time of deposition. In the Mizunami, the carbonate origins identified by these methods are the past hydrothermal water, seawater, and fresh water. The carbonates deeper than 200 m have been preserved for more than a few millions of years[10)]. On the other hand, it is difficult to estimate the precipitation age of secondary carbonate minerals because the evolutionary processes of heavy $\delta^{13}C_{PDB}$ values of DIC in groundwater in the Horonobe area are poorly understood. Isotopically heavy carbonate minerals such as calcite would be formed from biochemical processes during organic maturation. Regarding the pH condition of groundwater, neutral to alkaline conditions would be estimated at the depth of fossil shell occurrence.

Redox conditions

The occurrence of iron oxy-hydroxide and sulfide minerals can be used as a guide to infer past long-term changes (Fig. 4.3.3-1). Iron oxides, which imply oxidizing conditions, precipitate to the depths of 30 m and sulfide minerals, indicating reducing conditions, occur deeper than 60 m in the sedimentary rocks overlying granite in the Tono area (including the MIU). In the basement granite, iron oxides occur on fracture surfaces at depths shallower than 200 m; sulfide minerals also occur on fracture surfaces without iron oxides in the depths[11)]. Oxidized shallow water heterogeneously inflows into the deep controlled by the continuity and connectivity of fractures in the granite. The present groundwater shows reducing conditions at depths deeper than 200 m.

In the Horonobe area, the presence of iron oxide has been observed in the lower limit of depth at approximately 30 m. In the parts deeper than 30 mbgl, pyrite (which is believed to form during early diagenetic processes in marine sediment) has been identified ubiquitously in the rock matrix.

The present redox boundary in terms of depth can be evaluated based on the distribution of iron and iron sulfide minerals in the rocks. However, a method to evaluate the long-term stability of redox conditions has not yet been well established, although a method to evaluate the long-term stability of pH of groundwater has been developed by estimating the origin and precipitation age of carbonate minerals[12)]. Recently, several methods (e.g., interpretation of the concentration patterns of metal elements such as uranium and iron in carbonate minerals and interpretation of the degree of metal-element substitution for the cations Mg and Ca in carbonate minerals depending on their concentrations and speciation in groundwater) that take into account the results for precipitation age of carbonate minerals have been tested to evaluate the redox condition over the long term[13),14)]; however, the applicability of these methods has not been fully confirmed.

Salinity of past groundwater

The salinity of past groundwater can possibly be inferred by analysis of fluid inclusions in secondary minerals such as calcite. The freezing temperature of an inclusion relates to its salinity. Observations of inclusions under cooling conditions enable estimation of the groundwater salinity at which the carbonates precipitated[13)]. The result of this research at the MIU suggests that some carbonates precipitated from groundwater with a salinity of 0.47–4.53 wt% (1 wt% NaCl Eq. corresponds to approx. 10,000 ppm NaCl) during the period of lacustrine to marine sedimentation (Fig. 4.3.3-3).

If fluid inclusion samples are not available, the variation of past salinity cannot be directly estimated. Other approaches such as methods based on FEP and scenario analysis (see next section) are required.

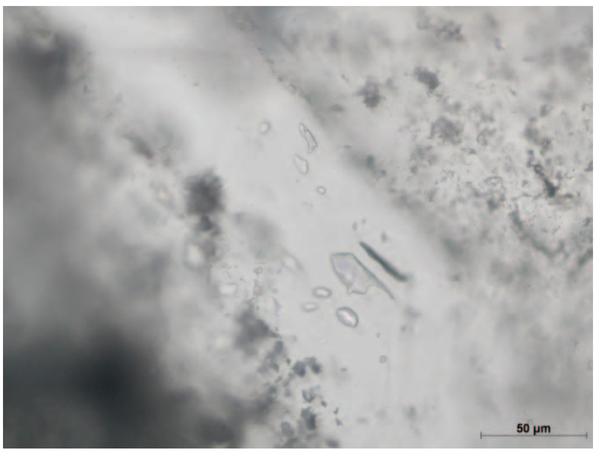

Fig. 4.3.3-3 Fluid inclusions in fracture-filling calcite in the Toki Granite

In addition, the impact of past earthquake (e.g. 2011 off the Pacific coast of Tohoku Earthquake) on the groundwater pressure and chemistry were observed in the research gallery of Mizunami (Fig. 4.3.3-4). Groundwater chemistry varies from changes in the mixing proportion between chemically distinct waters according to the change of groundwater flow. The variation of groundwater chemistry would fall within the range of end-member waters in the area.

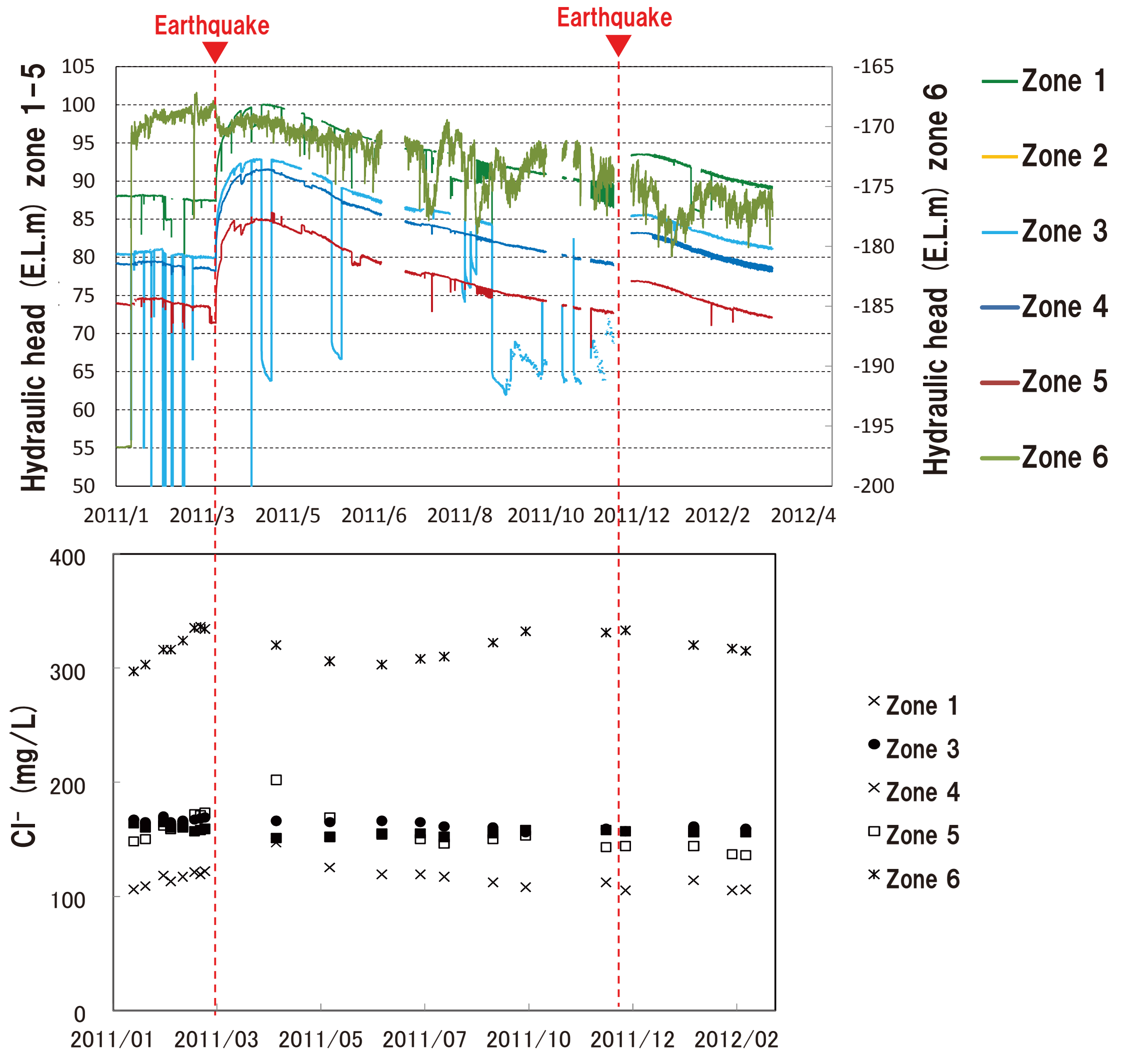

Fig. 4.3.3-4 Changes in groundwater pressure and hydrochemistry related to earthquakes

The groundwater pressure was raised immediately after the earthquakes, and afterward decreased to the initial conditions. Cl concentrations were altered in several monitoring zones, and subsequently also showed recovery. The groundwater chemistry will change as a result of mixing of salinity-distinct waters because of hydraulic changes. The changes in groundwater chemistry are probably within the range of the mixing end-member waters.

(2) Methodology of scenario analysis for long-term variation

Understanding of the impact of geological events on chemical conditions is indispensable when using long-term variation of chemical conditions in the past estimated based on mineralogical evidence for safety analysis[1)]. It is important to infer future variation by focusing on the geological events that would have a heavy impact if they took place. In other words, understanding of past geological events in the chemically long-term stability area detected using mineralogical evidence provides an insight into the influence of each geological event in future.

In the second mid-term research phase, FEPs around the Mizunami and Horonobe URLs in the past and their relations to chemical conditions were analyzed. We summarized long-term changes in groundwater recharge, uplift/erosion, and faulting activity in the past and their relation with the geology, geological structure, hydrology, and groundwater chemistry. Moreover, we considered long-term scenarios based on probable processes to estimate the variations of chemical conditions.

In the Mizunami, Miocene lacustrine and marine sediments overlies Cretaceous basement granite. Saline, brackish, and fresh waters probably inundated the formations. Fresh water and slightly saline water occur in the upstream and downstream, respectively, in the present. Long-term hypothetical scenarios of groundwater replacement are illustrated in Fig. 4.3.3-5.

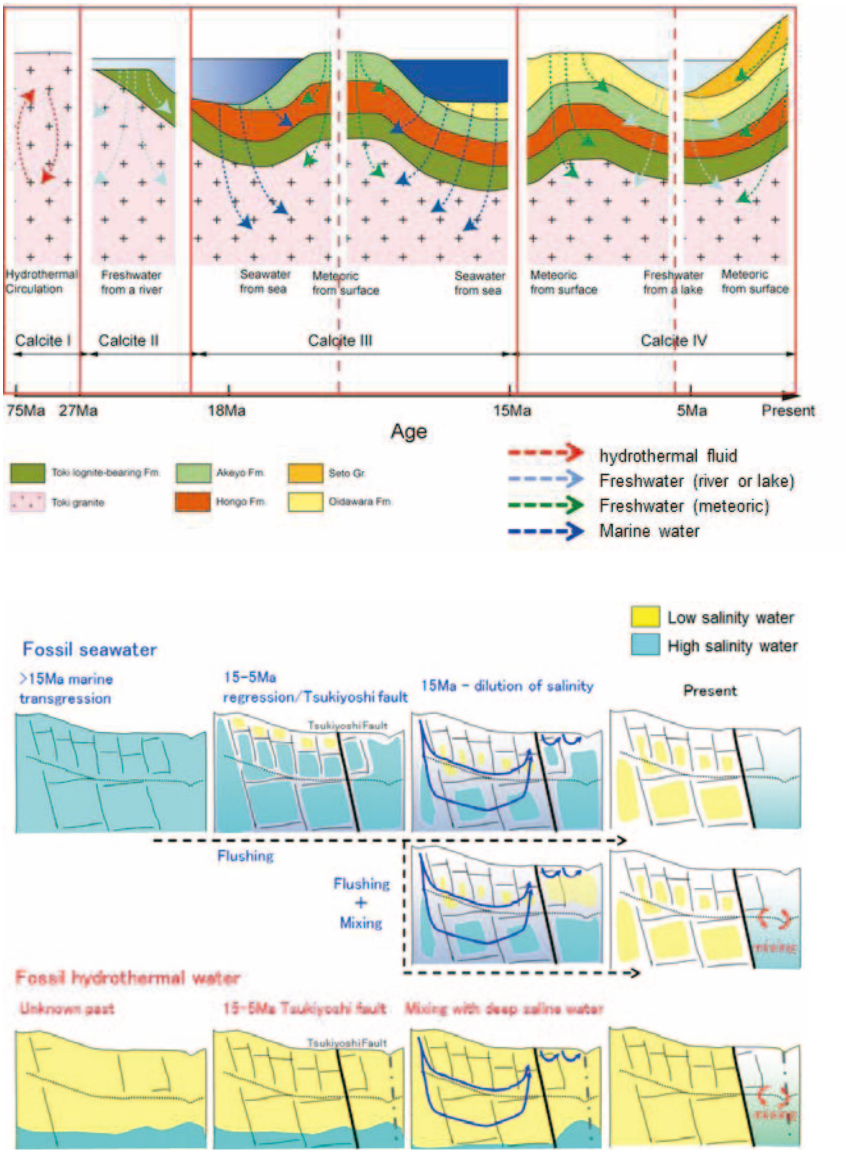

Fig. 4.3.3-5 Schematic illustration of the long-term hydrochemical evolution in the Tono area

FEPs regarding hydrochemistry in the Tono area are shown in Fig. 4.3.3-6. The dominant groundwater in deep granite had experienced replacement from the initial hydrothermal water to seawater and to fresh water during sedimentation of rock, marine transgression, and regression. Carbonate minerals had precipitated from groundwater during each period.

It is not known exactly when the sulfide minerals (the presence of which indicates reducing conditions) were precipitated, but groundwater rich in sulfate ions is required for formation of these minerals. The sulfide minerals possibly originated from hydrothermal water or seawater. Carbonate and sulfide minerals generally occur in fractures deeper than 200 m.

Geological events such as climate change and groundwater replacement since the marine regression that took place a few million years ago have possibly influenced chemical conditions down to a depth of 200 m, and neutral to alkaline pH and reducing conditions would have been preserved for a long time period. Calculating from the uplift rate in this area (0.1 to 0.3

m/1,000 yrs)[15], uplift of 200–300 m occurs over hundreds of thousand years. It is supposed that new fractures occur and the rock permeability increases during reduction of rock pressure by uplift/erosion. This process facilitates intrusion of shallow water at depth, and the salinity of the groundwater will be diluted. The pH and redox conditions of groundwater at depth may be preserved by buffer reactions with carbonate and sulfide minerals; however, these minerals in the current depths down to 400–500 m would possibly been dissolved and eliminated by shallow water infiltration.

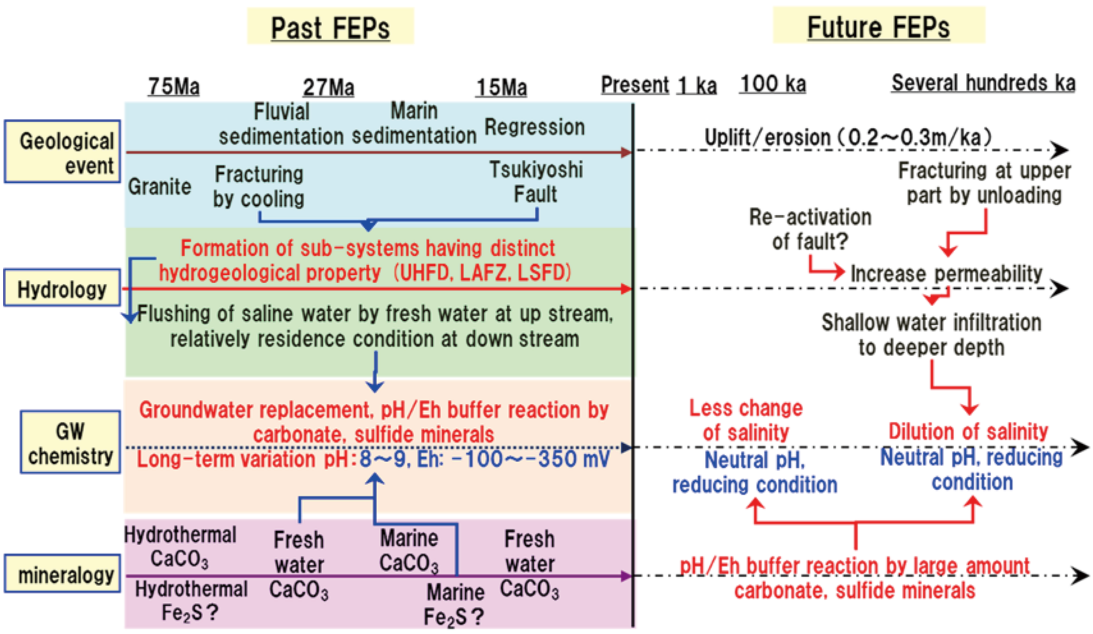

Fig. 4.3.3-6 Scenario of long-term hydrochemical evolution in the Tono area

In the case of Horonobe, a long-term hydrologically and hydrochemically stagnant area would be present in the deeper part because of the closed system formed during the burial diagenesis stage (Fig. 4.3.3-7). An FEP (Feature, Event, and Process) scenario focused on geochemical evolution from the past to the present is shown in Fig. 4.3.3-8. Because of the mineral–water interactions and organic maturation catalyzed by biochemical reactions, the deep groundwater at Horonobe might have a neutral pH and reducing conditions. Based on the assumption of the average uplift/erosion rate being 0.3 m/ky[16], the geological and geochemical conditions after a hundred thousand years would still be similar to the present-day conditions in the part deeper than 700 m. However, in the part shallower than 700 m, it is suggested that several significant changes may occur (e.g. decrease in salinity from saline to fresh, increase in pH by cation exchange reactions, and increase in permeability in the fault zone [17,18]).

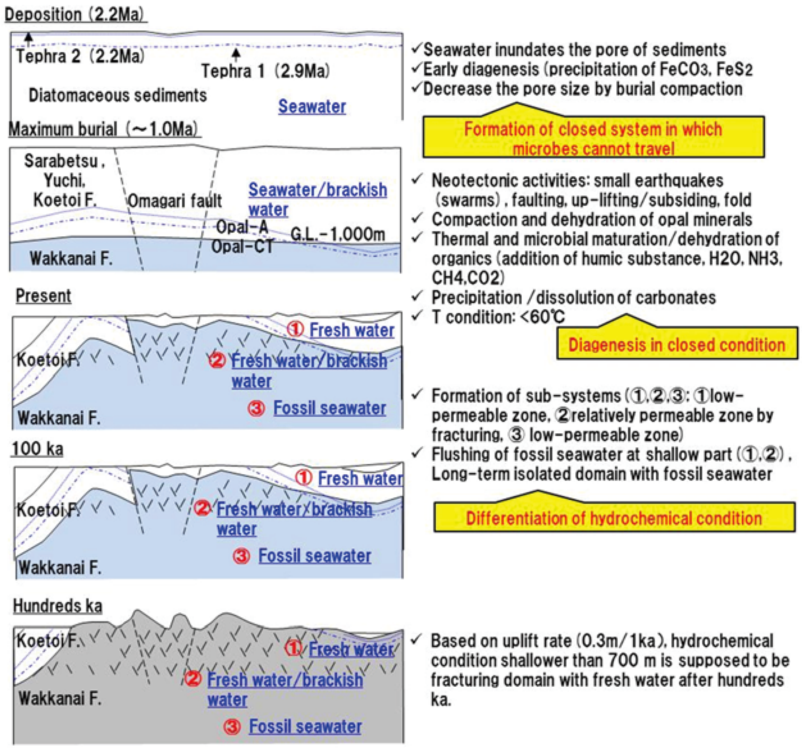

Fig. 4.3.3-7 Schematic illustration showing long-term hydrochemical evolution in the Horonobe area

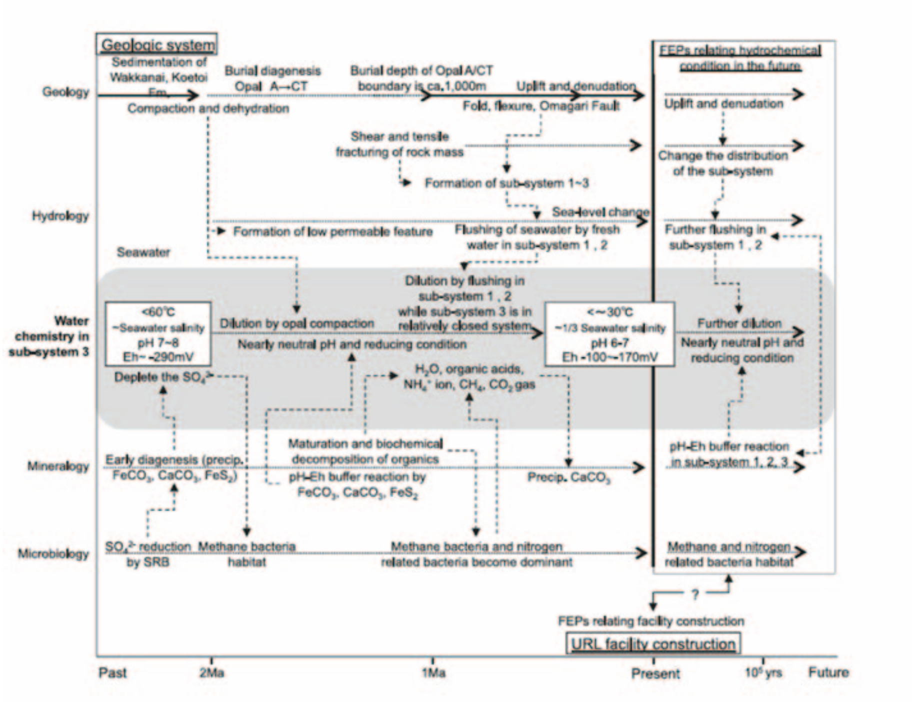

Fig. 4.3.3-8 Long-term scenario related to hydrochemical evolution in the Horonobe area

It is supposed that the pH of groundwater may be buffered by interactions with carbonate minerals over the long term. Regarding the redox conditions of groundwater, the dissolution/precipitation reactions of iron oxide or iron hydroxide and of pyrite would control the conditions in the shallower and deeper parts, respectively. These redox buffering reactions will continue in the future; however, they may gradually become weakened or exhausted if shallow oxygenated groundwater intrudes because of the permeability increase following uplift/erosion. A geochemically stable area is suggested by considering the averaged uplift/erosion rate. For example, the area that maintains neutral to weakly alkaline pH and strongly reducing conditions (e.g., −300 mV vs. standard hydrogen electrode (SHE), suitable for pyrite occurrence) after the forthcoming several hundred thousand years, might be the present depth deeper than 700 to 800 m in Tono and deeper than approximately 700 m in Horonobe.

Regarding the area in which both carbonate and sulfide minerals may not be exhausted in the future, it is possible to calculate the long-term variations of the redox conditions by assuming equilibrium with redox-controlling minerals. In the calculations, both estimation of past groundwater composition and prediction of future potential groundwater composition will be considered. When considering the groundwater composition, expected scenarios and/or conditions will be assumed broadly; e.g., groundwater compositions in the upstream or downstream of the groundwater flow regime, and the ancient sea water composition that was recharged in the past.

As described in section 3.3, shallow water infiltrates into the depths around the shaft in Mizunami. This is likely to accelerate experiments on long-term shallow water infiltration to depth. Long-term monitoring of pH and redox conditions around the shaft is essential research .

In the Horonobe area, it is considered that reactions related to sulfide minerals such as pyrite might control the redox conditions of the groundwater. According to this finding, the range of redox potential of groundwater from the past to the present can be estimated using the pH–Eh diagram shown in Fig. 4.3.3-9. Salinity change (dilution) will occur by infiltration of shallow fresh water because of the uplift/erosion event; however, the pH and Eh of groundwater could be buffered against such perturbations in the future. This is because of the presence of large amounts of pH/Eh buffering minerals (e.g., carbonate and sulfide minerals) in the sedimentary rock. With regard to pH/Eh buffering phenomena, the occurrence of fossil shells and pyrite in the formation deeper than dozens of meters indicates long-term buffering evidence, in contrast to shallow oxygenated water intrusion by the uplift/erosion event during the most recent 1 to 2 million years.

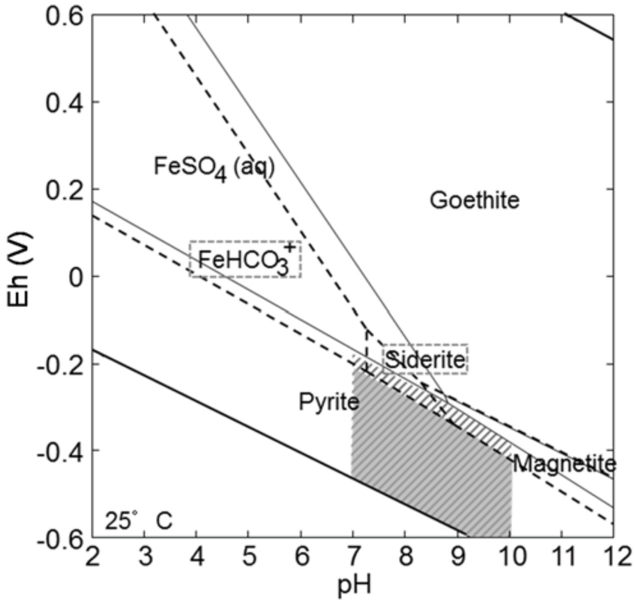

Fig. 4.3.3-9 Long-term variations of redox potential and pH based on mineralogical equilibrium conditions

The chemical compositions of present groundwater and seawater as a past end-member groundwater are included. Solid line and hatched part: present groundwater; dotted line and shadowed part: seawater.

4.3.4 Summary

The procedure for estimation of long-term hydrogeochemical variation using mineralogical methods and scenario analysis is shown in Fig. 4.3.4-1. We propose that the following generic know-how and point should be considered.

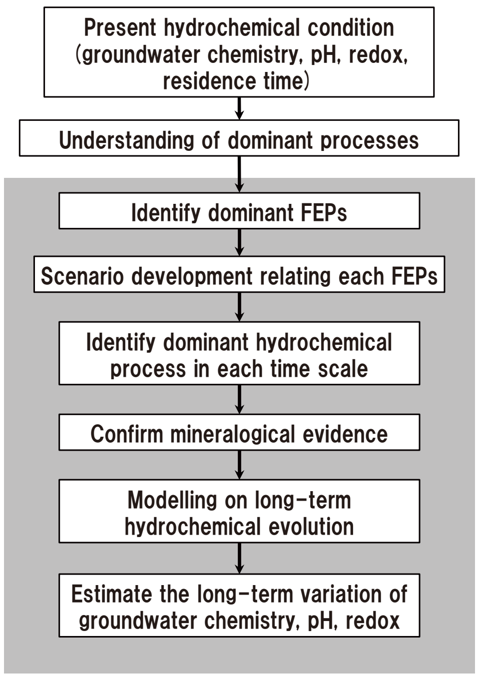

Fig. 4.3.4-1 Generic procedure for estimation of long-term hydrochemical evolution

(1) Estimation methods of past hydrogeochemical variation using minerals

- The past pH, redox state, and salinity of groundwater can be inferred by using mineralogical signatures such as chemical and isotopic composition and morphology.
- Carbonate minerals can be applied to estimate the long-term pH conditions for the area where chemically distinct groundwaters have been replaced[10),13),19)]. However, the method may not be applicable to the area in which the groundwater has been isolated without replacement. In addition, the carbon isotopic ratio of carbonate minerals in rock containing abundant organic matter, such as sedimentary rocks, might be significantly affected by microbial processes.
- Redox conditions can be estimated based on the occurrence of iron oxy-hydroxide and sulfide minerals regardless of rock type. However, the long-term redox conditions cannot be identified because we do not possess a method to estimate the precipitation age of these minerals.
- The observational results of hydrochemical changes in groundwater caused by earthquake suggest that the chemical variation occurs by mixing of end-member groundwaters. The changes in groundwater chemistry probably lie in the range of end-member groundwaters.

(2) Inference of future hydrochemical variation by scenario analysis

- Classify the investigation area into sub-systems based on hydrogeological features. Summarize the various past geological events and hydrochemical changes (FEPs)[1)] in the sub-system where construction of an underground facility is planned.
- Illustrate the FEPs and hydrochemical response as a history table, paying attention to cycles or irreversible phenomena.
- Identify the interactions with a high probability for each time period, e.g., microbial sulfate reduction causes pyrite precipitation, which decreases the sulfate ion concentration. The pore size is reduced by compaction, which lowers the hydraulic conductivity and suppresses the material supply for chemical reactions.
- Consider the responsiveness of geochemical conditions and the robustness for a past geological event. Then, extrapolate past inter relations to the future and infer the long-term range of hydrogeochemical variation. Groundwater residence time is a key feature in this process. For instance, groundwater with a residence time of ten thousand years would be influenced by climate (recharge rate) change over tens of thousands of years, whereas groundwater with a residence time of millions of years would not be affected by short-term climate change.
- Estimate the long-term stability area and depths based on this scenario analysis.

The development of dating methods for minerals, such as sulfides, that are related to redox conditions is a future subject to demonstrate long-term redox stability. Additionally, integration of FEPs on facility construction and on long-term natural environmental change is required to clarify the important issues during facility construction (Fig. 4.3.4-2).

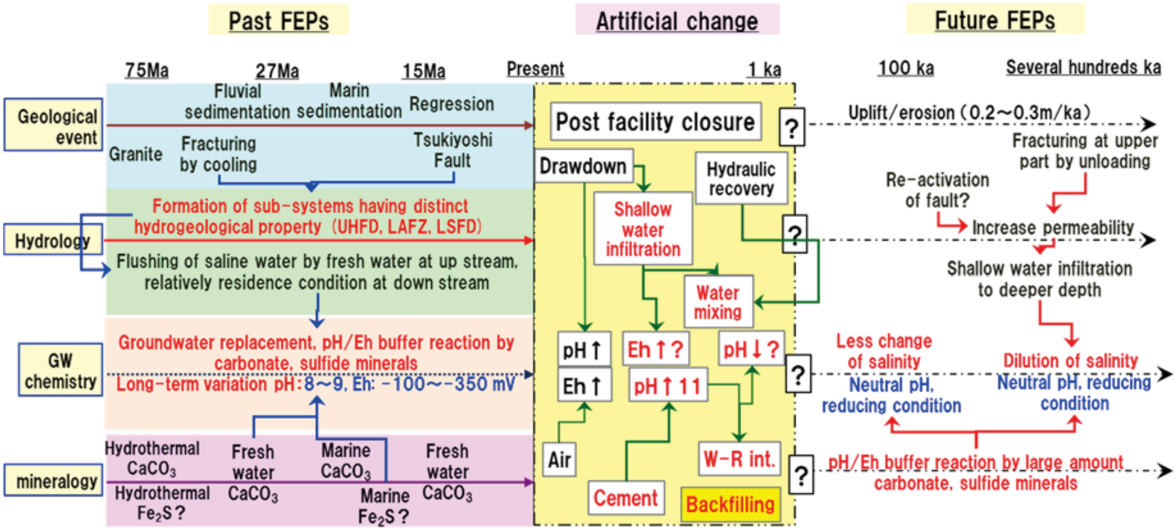

Fig. 4.3.4-2 Synthesized scenario for analysis of medium- and long-term hydrochemical evolution (MIU)

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4.4 Rock mechanics

4.4.1 Introduction

The in situ stress and rock properties are important in the design and construction of large and deep underground structures. In fact, in situ stress is recognized as the primary factor in the development of an excavation damaged zone (EDZ). An EDZ is likely to be less stable than the undisturbed rock mass and to provide higher-permeability pathways for groundwater flow in the vicinity of excavations. Thus, development of an EDZ is recognized as a key issue in the design and construction of disposal facilities and in safety assessment. During surface-based investigation (Phase I), it is necessary to understand initial state of rock condition by borehole investigations and laboratory tests using core samples. In the construction phase (Phase II) and operation phase (Phase III), it is necessary to obtain detailed information by investigations from shafts and galleries and to compare the results with those obtained during Phase I, and also to obtain data on EDZ.

On the other hand, rock and rock masses show time-dependent behavior such as termed creep, stress relaxation. In this section, we discuss our knowledge of the long-term mechanical behavior of rock mass.

4.4.2 Objectives in the second mid-term research phase

The objectives of rock mechanics investigations in the second mid-term research phase is to understand the detailed in situ stress condition and rock mechanical properties by borehole investigations from shafts and galleries, and laboratory tests during shaft and gallery extension at depths of 500 m (Mizunami) and 350 m (Horonobe). Also, it is necessary to confirm the validity of the conceptual model and analysis technique applied in Phase I. An additional objective is to understand the changes in the geological environment caused by the excavation. Table 4.4.2-1 shows the performance target of R&D and tasks in this session. These are not set as goals of the second mid-term research phase.

Table 4.4.2-1 Performance target of R&D for rock mechanical characterization

Focus	Performance target of R&D	Tasks
Decision-making for start of operaion	Decision-making for excavation of disposal pit and emplacement of waste.	• Technology of prediction of EDZ and long-term rock mass behavior

4.4.3 Project details and outcomes

(1) Long-term behavior of rock

1) Mizunami

Long-term creep testing and stress relaxation testing have been performed to understand the time-dependent behavior of rock[1),2),3),4),5),6),7),8),9),10),11),12),13),14),15),16),17)]. Observation of the microstructure of rock has been performed, and important factors that influence the long-term behavior have been discussed[18),19),20),21),22),23),24),25),26)]. The main conclusions are as follows:

- Long-term creep testing, over 10 years, of the Tage tuff has been performed to obtain data to estimate the long-term behavior of rock and openings[27),28)] (Fig. 4.4.3-1).

- Unconfined compressive testing under microscopic observation was performed to understand the mechanism of micro-fracturing and dissolution of quartz (Fig. 4.4.3-2).
- The creep phenomenon of Toki Granite around the shaft caused by excavation was predicted by numerical simulation using a compliance variable equation.

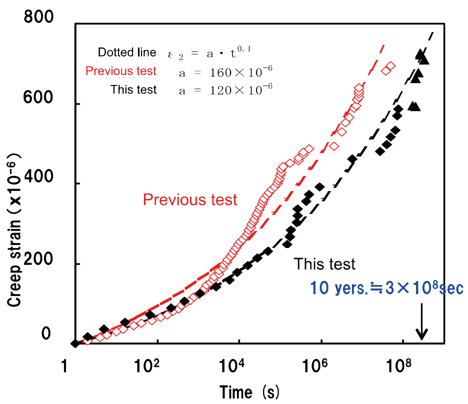

Fig. 4.4.3-1 Results of long-term creep testing (Tage tuff)

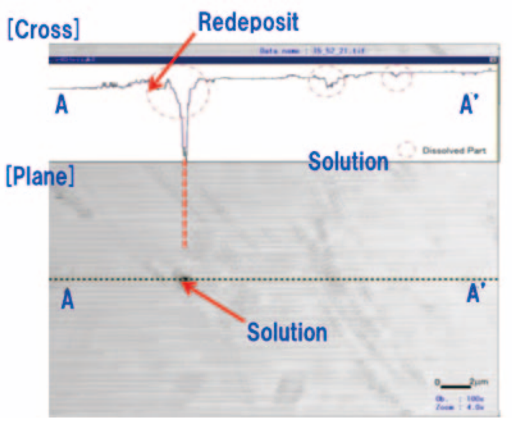

Fig. 4.4.3-2 Pressure-solution testing of quartz

2) Horonobe

Strength recovery, generalized stress relaxation, tensile strength tests (Brazilian and uniaxial tensile tests), and drying-induced deformation tests were performed using siliceous mudstone sampled from the Wakkanai Formation. The results are summarized as follows:

- From the results of compaction tests (strength recovery tests) on fractured rock, the uniaxial compressive strength of the specimens after failure was increased with increasing axial strain induced by compaction after failure of the specimen (Fig. 4.4.3-3)[29)]. The uniaxial compressive strength increases with an increase in the time of compaction. Also, as illustrated in Fig. 4.4.3-4, the permeability of the specimen after failure was decreased with an increase in the axial strain induced by compaction[29)]. These results are useful for investigation of the mechanism of self-sealing of fractures induced around the gallery.
- A constitutive equation focusing on time-dependent strength recovery and the effect of bedding planes was modified[30)].
- From the results of generalized stress relaxation tests, changes in the creep strain and relaxation stress are small when the strain rate during loading is small. Also, under dry conditions, the changes in the creep strain and relaxation stress are smaller than those in saturated conditions[31)].
- From Brazilian tests and the uniaxial tensile strength tests under saturated condition, the tensile strengths of specimens that were loaded perpendicular to bedding were two times larger than those that were loaded parallel to the bedding[31)].
- The dependence of the deformation behavior (elastic modulus and strength) of siliceous

mudstone on water content was investigated. From the results, the relationship between elastic modulus and water content and the relationship between the strength of rock and water content can be explained as exponential functions[30] (Fig. 4.4.3-5 and Fig. 4.4.3-6). The constitutive equation considering the effect of drying-saturated-induced deformation will be improved in future.

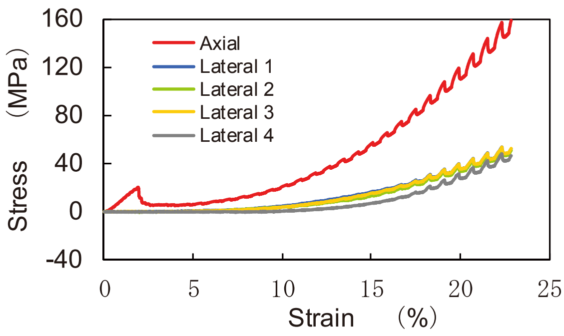

Fig. 4.4.3-3 The relationship between axial strain and stress in strength recovery tests[30]

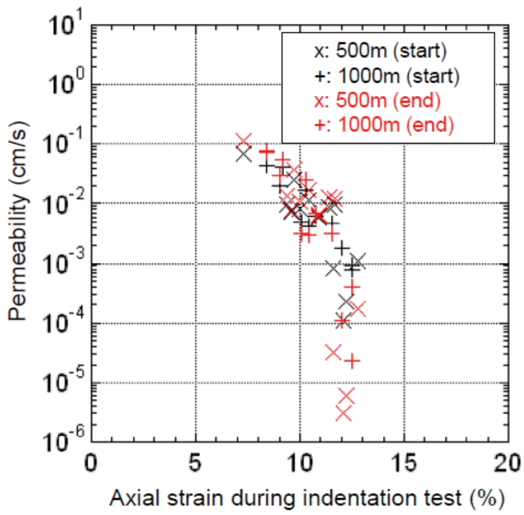

Fig. 4.4.3-4 The result of hydraulic tests in strength recovery tests[29]

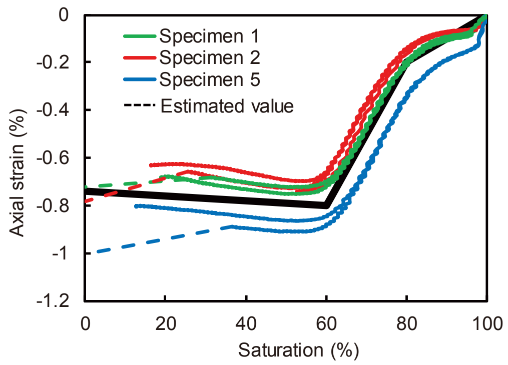

Fig. 4.4.3-5 The relationship between saturation and axial strain in measurement of drying-induced deformation[30]

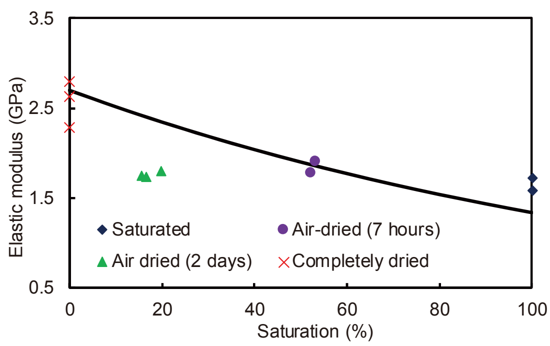

Fig. 4.4.3-6 The relationship between saturation and elastic modulus[30]

3) General knowledge

Understanding of creep and relaxation phenomena is important to estimate the long-term behavior of rock. In the case of soft rock, understanding of the controlling factors is also important, as strength recovery is expected in association with loading. Accumulation of data is important, as there is no information about the long-term behavior of EDZ.

4.4.4 Conclusions and future plan

The available information about the long-term behavior of rock and its controlling factors has been increased from laboratory tests and observations. Future plans are as follows:

- Understanding the behavior of EDZ caused by earthquakes
- Understanding the range of variation of EDZ before closure of the facility
- Understanding the self-sealing mechanism of EDZ and its model

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4.5 Mass transport

4.5.1 Introduction

As part of the study of mass transport, which involves understanding retardation effects in rock masses and groundwater, we have been working on themes (1) and (2) (listed below) to establish techniques of investigation/analysis/evaluation focusing on the long-term changes and processes in geological environments.

(1) Understanding long-term changes in the sorption and diffusion properties of rock mass

From the perspective of safety assessment of geological disposal, it is important to understand long-term changes in the sorption and diffusion properties of rock masses. It is also necessary to establish techniques for analysis and evaluation of these long-term changes.

(2) Understanding long-term changes in mass transport fields

From the perspective of safety assessment of geological disposal, it is necessary to understand long-term changes in groundwater pressure, rock-mass permeability, and distribution of groundwater chemistry. It is also necessary to establish the techniques for acquisition of highly reliable data on these changes and for analysis and evaluation.

4.5.2 Objectives in the second mid-term research phase

Studies at underground facilities must produce outcomes and scientific knowledge that can be reflected in the decision-making concerning site selection, construction of facilities, commencement of disposal, completion of placement of waste packages, and final sealing in the actual disposal operation.

From this perspective, the level of technical development we aim to achieve for use in decision- making concerning the commencement of disposal, completion of placement of waste packages, and final sealing, in the context of understanding long-term changes and recovery behavior in geological environments, is the establishment of investigation and evaluation techniques that can predict the changes in mass transport characteristics on a geological time scale and indicate the long-term changes in environmental conditions concerning material transport, as well as the systematization of a series of techniques from investigation to analysis/evaluation (Table 4.5.2-1).

During the second mid-term research phase, we conducted investigations in the boreholes drilled from the surface, laboratory tests using core and groundwater samples, and investigations in the vertical shafts and horizontal galleries reaching depths of 500 m at Mizunami and 350 m at Horonobe. We established investigation, analysis, and evaluation techniques to estimate mass transport phenomena on a geological time scale and the range of the long-term changes in mass transport characteristics.

Table 4.5.2-1 Performance target of R&D in the mass transport study

Focus	Performance target of R&D	Tasks
Decision to construct, to end emplacing waste and on final closure	Long-term evolution of geological environment can be evaluated from the viewpoint of solute transport property.	Long-term evolution of sorption capacity and diffusivity of rock matrix and of transport pathways • Methodology development for the characterization
		Long-term evolution of geometry of transport pathways; depth of diffusion-accessible rock mass • Methodology development for the characterization

4.5.3 Project details and outcomes

(1) Understanding long-term changes in the sorption and diffusion properties of rock mass

Sorption and diffusion in the geological environment are important phenomena that control the retardation of mass transport. The sorption and diffusion of nuclides vary greatly depending on the solid-phase mineral composition and interstice structure, the groundwater and porewater chemistry, the state of dissolved nuclides in water (chemical species), and other physicochemical conditions. However, it is difficult to understand directly the long-term changes in these properties on a geological time scale from laboratory and in situ tests. It is, therefore, important to establish investigation techniques for the evaluation of the changes in sorption and diffusion properties using natural analogs and to obtain data using such techniques. From this perspective, we conducted several investigations for the purpose of obtaining basic data, such as the chemical composition and mineral composition of the rock masses and the distribution of elements.

1) Mizunami

Mainly using cores from boreholes drilled from the surface, we estimated the depth of matrix diffusion from the distribution profiles of uranium-series nuclides (^{238}U, ^{234}U, and ^{230}Th) occurring near permeable fractures in the Toki Granite. The results showed that matrix diffusion near permeable fractures can extend as much as more than several tens of millimeters. This use of natural analogs is considered capable of evaluating long-term mass transport characteristics.

2) Horonobe

Using cores from the boreholes drilled from the surface, we conducted mineral and chemical analyses of the Koetoi Formation and the Wakkanai Formation around the gallery to examine the heterogeneity in the concentration distribution of analog elements and the relationships linking geological structures, groundwater flow, and geochemical environment to the concentration of analog elements. The results of analysis and examination showed that no significant movement of elements occurred in intact rock, and some faults that show accumulation of elements were important as mass transport pathways[1] (Fig. 4.5.3-1).

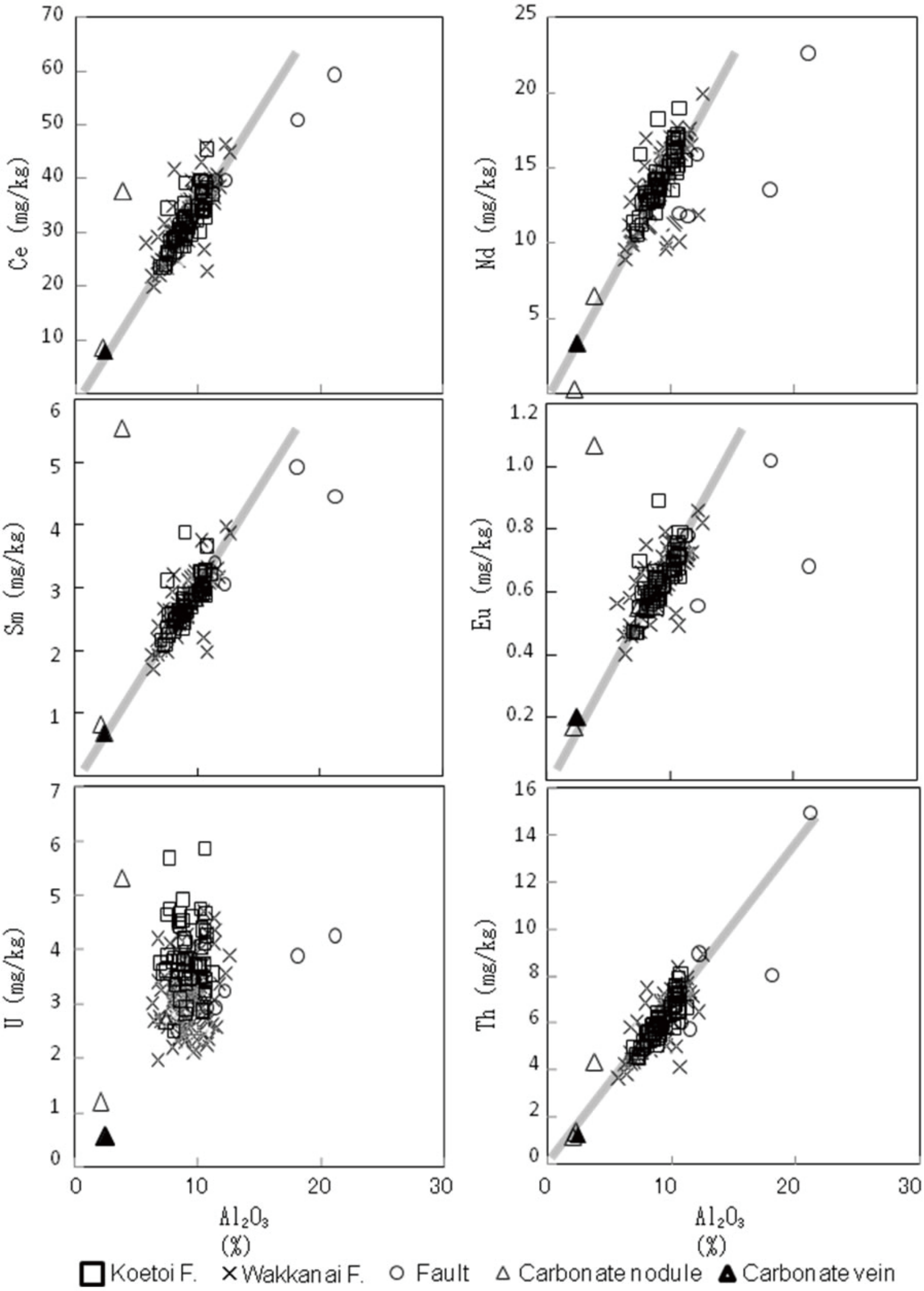

Fig. 4.5.3-1 Correlation of minor elements with Al in the rock samples[1]

(2) Understanding long-term changes in mass transport fields

We started a review of information that might assist with prediction of long-term changes in mass transport fields, focusing on geological structures that affect mass transport and the processes of their formation, and also the geologic history such as uplift and subsidence. As a result, it was found possible to estimate the long-term transitions of mass transport fields based on understanding of geologic history and the process of permeable fracture formation.

1) Mizunami

For the purpose of understanding long-term changes in mass transport fields, we extracted the faults and fractures that could act as mass transport pathways from the results of surface-based borehole investigations, investigations during tunnel excavation, and investigations in the underground facilities. These faults and fractures were classified into five types mainly from a geological standpoint according to the type and presence/absence of fracture-filling minerals, the degree of alteration and color of host rock near the fracture, and the age of the fault or fracture[2] (Table 4.5.3-1). We plan to proceed with the investigation into the origins and development processes of these fractures, faults, and other discontinuous structures, and accumulate knowledge that will contribute to the evaluation of long-term mass transport.

Table 4.5.3-1 Classification of types of discontinuous structures in the Toki Granite

Type	Fracture fillings	Wall rock alteration around fracture	Hydraulic conductivity	Age and temperature
I : Fractures	Chlorite	Not altered	Low	69-43Ma 300-200℃
II : Fault	-	Strongly altered	Very low	64-43Ma 400-300℃
III : Fractures	Chlorite	Altered (wall rocks show greenish or white-tinged color)	Low	64-43Ma 300-200℃
IV : Fractures	Calcite, Chlorite or not	Altered (wall rocks show grayish or orange color)	High	69-24Ma <200℃
V : Low-angle Fractures	Calcite or not	Not altered	High	43-22Ma <100℃

2) Horonobe

For the purpose of understanding the long-term changes in mass transport fields, we extracted the discontinuous structures that could act as mass transport pathways from the results of surface-based borehole investigations, investigations during tunnel excavation, and investigations in the underground facilities. We classified the extracted discontinuous structures into four types on the basis of the mechanism of fracture formation (tensile and shear), the presence/absence of fault rock accompanying shear cracks[3], and the presence/absence of shear bands[4] (Fig. 4.5.3-2).

We constructed models for the transition of geology and geological structures based on the geologic history in the Horonobe area.[5] (Fig. 4.5.3-3). In addition, the processes of the formation of permeable fractures and lateral faults were clarified based on the relationships linking uplift, subsidence, and other phenomena that affect the diagenesis of the strength and brittleness of rock[6] (Fig. 4.5.3-4). Based on understanding of these processes of geological structure development and fracture formation, it is considered possible to estimate the long-term transition of mass transport fields on a geological time scale.

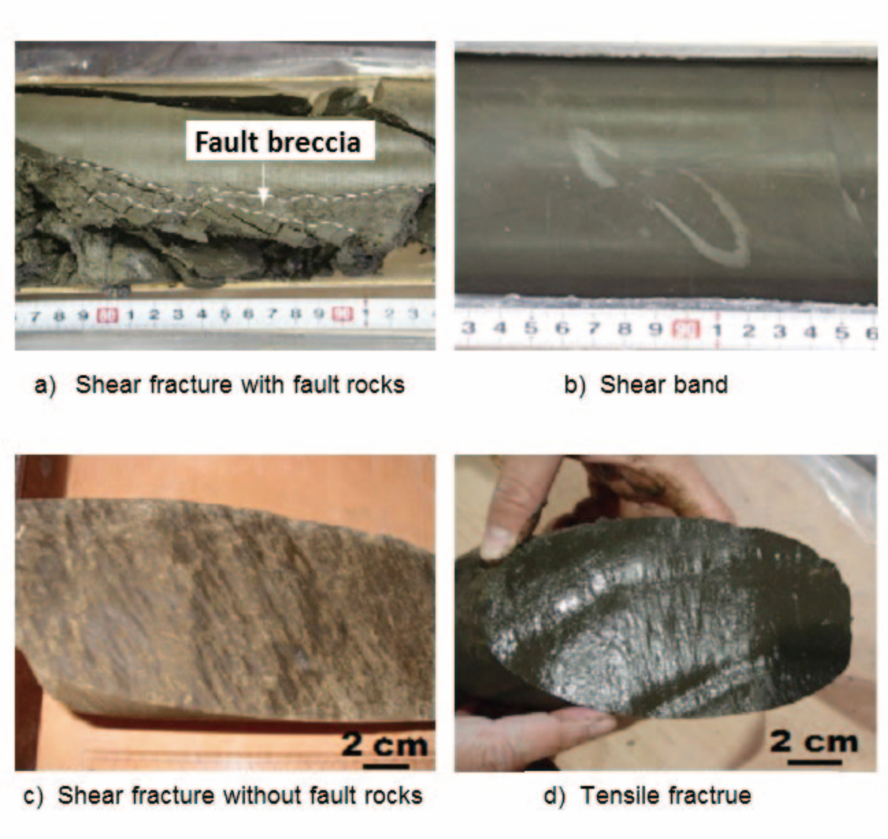

Fig. 4.5.3-2 Discontinuous geological structures around the Horonobe URL (a, c, d [3] ; b [4])

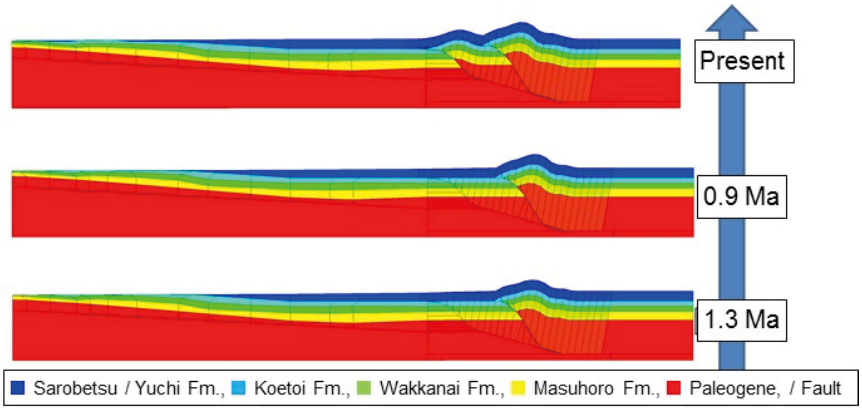

Fig. 4.5.3-3 Topographic and geological evolution model constructed by SMS (Sequential Modeling System of geological evolution impact on groundwater flow)[5)]

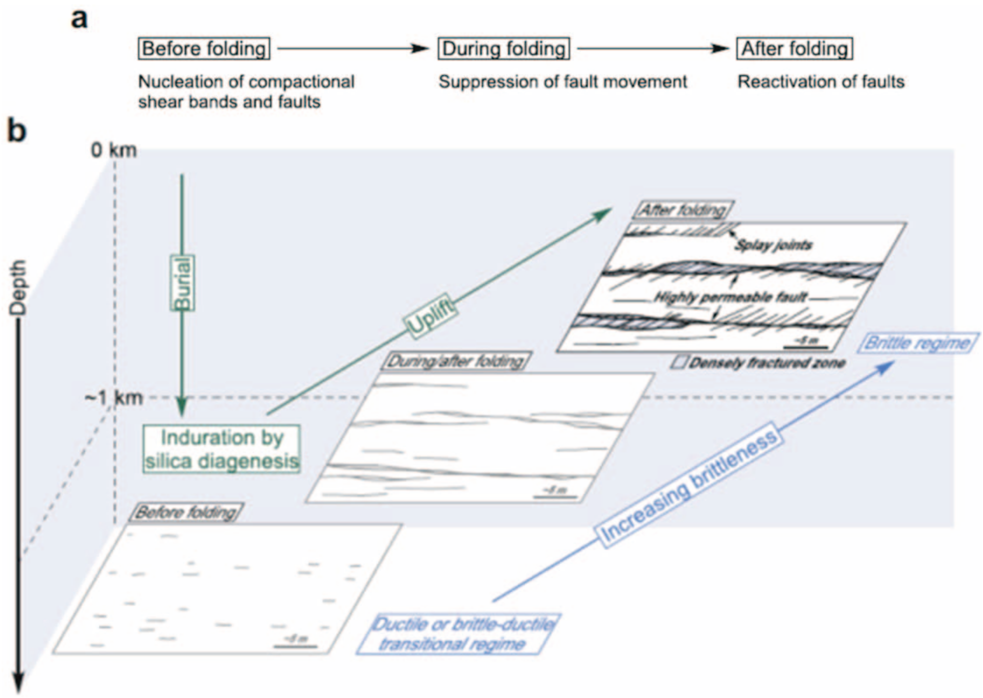

Fig. 4.5.3-4 Processing the formation of the lateral fault[6)]

4.5.4 Summary

This section summarizes the technical findings concerning understanding of long-term changes and recovery behavior in the geological environment obtained from surface-based investigations, investigations during tunnel excavation, and investigations in the underground facilities.

(1) Understanding long-term changes in the sorption and diffusion properties of rock mass

- The distribution profiles of uranium-series nuclides occurring near permeable fractures in the Toki Granite showed that matrix diffusion can extend as much as more than several tens of millimeters. Analyses of the mineral and chemical composition of sedimentary rocks around the tunnel showed that no significant movement of elements occurred in intact rock, and some faults were important as mass transport pathways. It was demonstrated that long-term mass transport characteristics can be evaluated by methods that use natural analogs (both sites).

(2) Understanding the long-term changes in mass transport fields

- We classified the discontinuous structures that can act as mass transport pathways into five types at Mizunami and four types at Horonobe for the prediction of long-term changes in material transport fields. This result shows that it is possible to estimate the long-term transitions of material transport fields by considering the origins and development processes of these discontinuous structures (both sites).
- The modeling of the long-term transition of geology and geological structures, which was constructed based on the geologic history of the Horonobe area and understanding of the processes of formation of permeable fractures and lateral faults, enables estimation of the long-term transitions in mass transport fields. (Horonobe).

With respect to understanding of the long-term changes and recovery behavior in the geological environment related to mass transport, we commenced development of investigation, analysis, and evaluation techniques for estimating material transport phenomena in the geological environment on a geological time scale and the long-term range of changes in these characteristics.

In study of mass transport from the perspective of long-term changes and recovery behavior in the geological environment, it is important to develop investigation, analysis, and evaluation techniques to understand the long-term changes in mass transport characteristics that occur both near to and far from the underground facilities, and also to understand the changes in mass transport fields accompanying the long-term changes in the geological environment.

An additional important theme is to provide examples of investigation, analysis, and evaluation techniques at the Mizunami and Horonobe underground facilities.

The study of mass transport is placed as an important theme in the Phase III (construction phase) in the underground research project[7]. Construction of horizontal tunnels for in situ tests and field investigations have been making progress at the Mizunami and Horonobe. In the second mid-term research phase, we have just commenced the study of mass transport. In the future, while continuing organization of information for prediction of long-term changes in mass transport phenomena, we plan to proceed with the development of investigation and evaluation techniques that can estimate the long-term range of changes in mass transport characteristics in and around the underground facilities. We also plan to establish techniques for modeling of changes in mass transport characteristics on a geological time scale.

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4.6 Geosphere stability for long-term isolation

4.6.1 Introduction

The framework of research on geosphere stability for long-term isolation of high-level radioactive waste is structured into three categories to contribute to the site selection and the national safety regulation of the final disposal. These three categories are: development and systematization of investigation techniques; development of models for long-term estimation and effective assessment; and development of dating techniques. Development of models for long-term estimation and effective assessment aims at technical preparation to show the occurrence possibility of a scenario relating to the influence of natural phenomena on the geological environment, and the variation range of the geological environment including the uncertainty in forecast As an important study and technical preparation for estimation and evaluation relating to the safety assessments based on less likely scenarios, we performed the work described below. This report documents the main results of the research and development.

4.6.2 Objectives in the second mid-term research phase

The scientific program for fiscal years 2010–2014 was set taking into account the importance and urgency of the needs of the implementing bodies and the regulatory agencies[1),2),3),4),5)] with attention to acts and reports after having investigated the trend of basic research in universities as well as related research institutes (Table 4.6.2-1).

Table 4.6.2-1 Performance target of R&D on geosphere stability for long-term isolation

Focus	Performance target of R&D	Tasks
Decision on the beginning of disposal and repository closure	Enable understanding the variation range of the geological environment affected by a Rare Natural Event.	Estimation techniques for hydrological changes with faulting • Development of estimation techniques for hydrological change using analysis of volumetric strain with subduction-zone earthquakes • Technique validation based on the observation on the 2011 off the Pacific coast of Tohoku Earthquake
	Enable simulation of landform changes for approximately 100,000 years.	Simulation techniques for landform changes • Validation of simulation techniques using the previously developed physical model
	Enable understanding of the uncertainty in long-term estimation over a period of a hundred thousand years in general.	Estimation and evaluation techniques for very-long-term natural phenomena • Development of estimation and evaluation techniques for very-long-term natural phenomena • Development of quantitative methodology on the uncertainty of the estimation and evaluation

4.6.3 Project details and outcomes

(1) Estimation techniques for hydrological change with faulting

The 2011 off the Pacific coast of Tohoku Earthquake (M9.0) triggered earthquakes and earthquake-induced changes in water level and the quality of groundwater and hot spring water[6),7)]. These are considered to be phenomena caused by changes in crustal stress resulting from trench-type megathrust earthquake. Understanding these phenomena is important for assessment of the long-term stability of the geological environment because these events can affect the regularity and continuity of regional tectonics. In our study, the relationship between the calculated stress changes induced by trench-type earthquakes and the results of groundwater observation was examined.

We focused on changes in groundwater pressure in and around MIU (Mizunami Underground Research Laboratory) induced by the Tohoku Earthquake. For the calculation of volumetric strain changes because of the earthquake, we used the program Coulomb3.1[8),9)] and input fault slip models reconstructed from previously reported rupture processes. The calculation outputs dilation in most of the Eastern Japan (Fig. 4.6.3-1). Next, strain response sensitivity for water pressure changes of artesian groundwater was estimated based on calculation from earth tide variations. Finally, theoretical groundwater level changes were determined by multiplying the estimated dilation around MIU because of the Tohoku Earthquake; these theoretical values were compared to the observed data. The theoretical groundwater level changes indicate a range of several tens centimeters, consistent with single-day drawdowns for the earthquake observed in boreholes more than 1 km distant from the MIU (Table 4.6.3-1)[10].

This study obtained a typical relationship between changes in crustal stress and groundwater pressure caused by the trench-type earthquake. This can contribute to a safety assessment considering geologic events with a recurrence interval of more than 1,000 years.

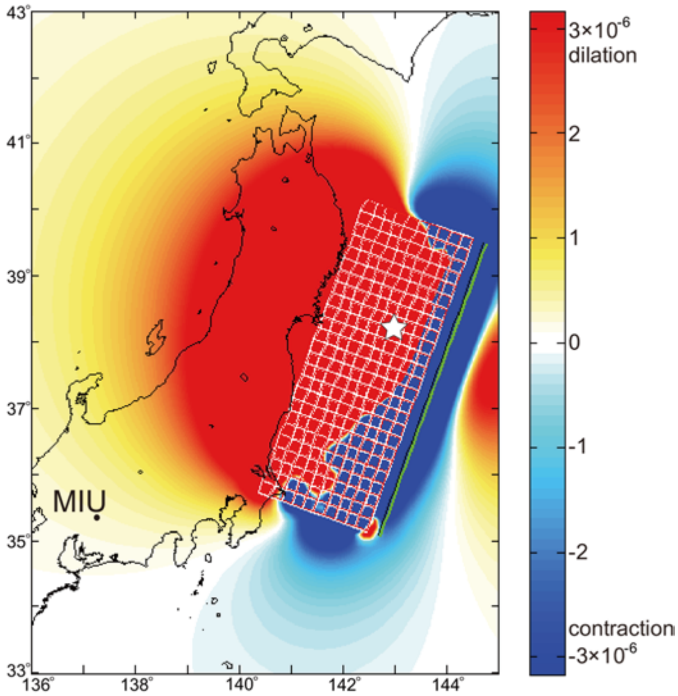

Fig. 4.6.3-1 Volumetric strain changes in Eastern Japan after the Tohoku Earthquake described by Coulomb 3.1[10]. The fault model is from Yagi and Fukahata (2011)[11]. The star means the epicenter of the Tohoku Earthquake.

Table 4.6.3-1 Comparison of the theoretical coseismic groundwater level changes with the observed ones at boreholes more than 1 km distant from the MIU[10)]

borehole	interval	groundwater level change (cm)	
		theoretical	observed*
DH-7	No.1	44	62
DH-7	No.2	33	46
DH-7	No.3	54	88
DH-7	No.5	65	35
DH-11	No.1	68	19
DH-11	No.3	65	33
DH-11	No.4	84	35
DH-11	No.5	78	39
DH-13	No.1	77	80
DH-13	No.4	48	77
DH-13	No.5	50	75
DH-13	No.7	68	6
AN-1	No.1	37	72
AN-1	No.6	61	49
AN-1	No.10	58	35
AN-1	No.12	64	45
AN-3	No.1	49	72
AN-3	No.3	42	69
AN-3	No.4	60	74
AN-3	No.5	34	69
MIU-2	No.2	49	18
MIU-2	No.5	51	19
MIU-2	No.9	64	26
MIU-2	No.12	96	54
MIU-3	No.1	81	15
MIU-3	No.4	50	46
MIU-3	No.6	73	46
MIU-3	No.8	73	57
MIU-4	No.6	57	36
MIU-4	No.8	64	29
MIU-4	No.9	68	25
MIU-4	No.10	77	37

*Single-day groundwater level change calculated from the data between 14:30 local time on 11 and 12 March 2011.

(2) Simulation techniques for landform changes

It is assumed that landform changes cause changes in geological environments such as movement and quality of groundwater[12)]. The landform changes over the next hundred thousand years are basically extrapolated or analogized from the uplift, erosion, and climate cycle for the past hundreds of thousands of years. We developed a program that included a simulation method for river depositional processes based on changes in particle sizes to understand the wider topographic changes on a scale of more than 10 km of one cycle of a glacial-interglacial cycle (Patent No. 5422833)[13)]. However, it is difficult to prove the validity of future prospects of irreversible phenomena such as landform development. Thus, methods to simulate the current topography starting from restorations of the past topography based on topographical and geological data are effective (Fig. 4.6.3-2). This study compared the current landforms with the result of the numerical simulation that started from the restored topography for approximately 100,000 years ago.

A case study was conducted around the middle and upper stream on the Toki River, which flows through the neighborhood of the border between the Mikawa Highlands and the Mino

Highlands. The old landforms of approximately 140,000 years ago were estimated based on the river terrace formed in Marine Isotope Stage 6 and the longitudinal current river profiles. The results of the simulation that started from the old landforms were similar to the current landforms in broad altitude and distribution and relative height of the river terraces (Fig. 4.6.3-3, Fig. 4.6.3-4). This finding supports the validity of the landform change simulation for approximately 100,000 years in the future[14]. In addition, the old landforms were restored at the conceivable present-day maximum and minimum erosion rates. These simulation results showed the elevation difference that reflected difference in initial state (Fig. 4.6.3-4)[14]. This difference is interpreted as the width of uncertainly in the estimate of erosion rate in the mountain slope. This result demonstrates that the landform change simulation technique over approximately 100,000 years using the physical model is valid.

Improvement of the reliability of the forecast by comparison between the numerical simulation results and the results of extrapolation or analogy will be a theme in future work.

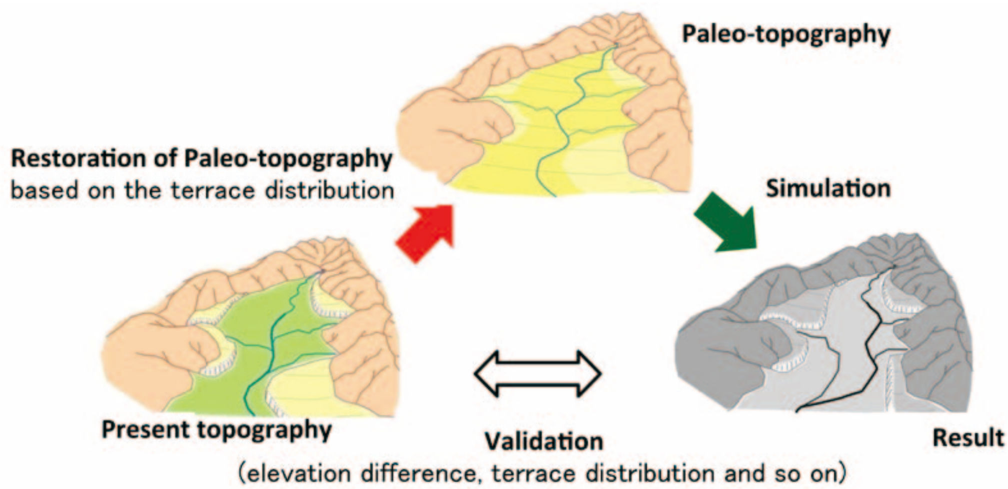

Fig. 4.6.3-2 Evaluation of landform changes using the old topography restored to the original (conceptual diagram)[14]

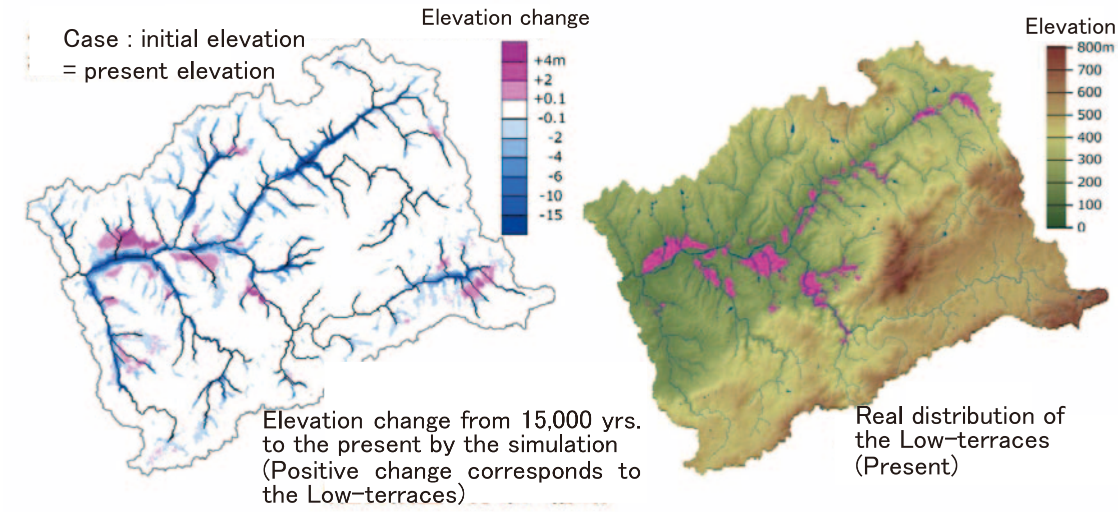

Fig. 4.6.3-3 Comparison between the results of a landform development simulation and the spatial distribution of real low terraces[14)]

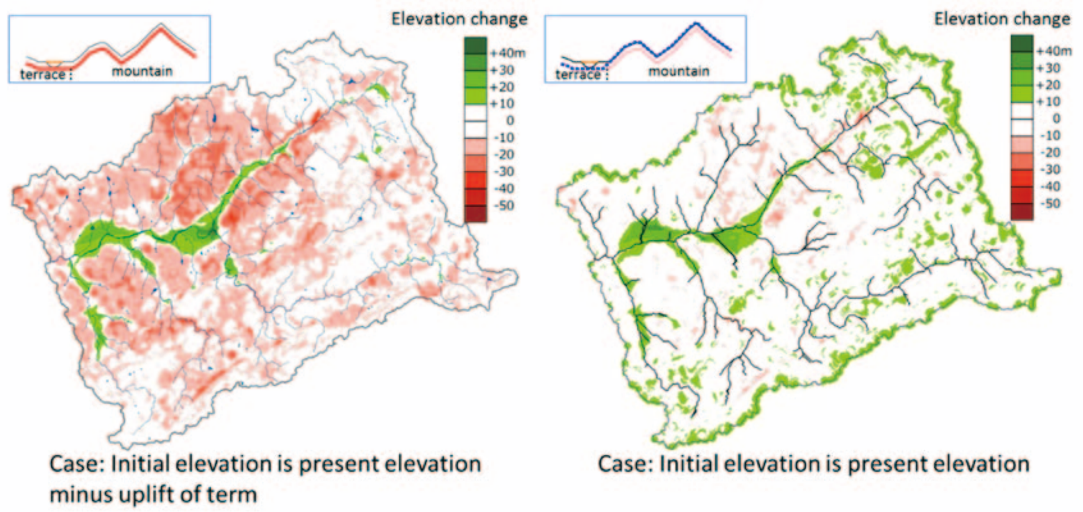

Fig. 4.6.3-4 Differences in terms of summit plane between the simulation landforms and the real landforms[14)]

(3) Estimation and evaluation techniques for very-long-term natural phenomena

The estimation and evaluation of natural phenomena such as upheaval, subsidence, erosion, and sedimentation are important in safety assessment based on less likely scenarios. However, estimation using extrapolation is important because these phenomena take place over the long term in a framework of slow plate motion over a wide area[15)]. According to Tanaka (2011)[16)], estimation by extrapolation is performed using the following procedure: (1) statement and extraction of the natural law related to a phenomenon from the past to the present; (2) cause of the occurrence of the phenomenon and clarification of the mechanism; (3) obtaining of information on the duration of a factor controlling the natural phenomenon; and (4) extrapolation to the future using the tendency for past change based on (1) to (3). Therefore the duration of a factor (e.g., crustal movement in the broad sense, including plate motion) controlling a geologic phenomenon is important in assuring the reliability of estimation by extrapolation. Kasahara and Sugimura (1978)[17)] and Matsuda (1988)[18)] determined the uniformity of the displacement direction and velocity in the crustal movement in the Quaternary concerning the causation and continuity of a past geological phenomenon, and called these the uniform mode and rate. Subsequently, the Japan Association for Quaternary Research (1987)[19)] suggested that extrapolation to the future of the same period is possible based on a variable trend and speed from the past to the present when a uniform mode and rate are in operation. It is necessary to clarify the area and period of the uniform mode and rate from the available topographical and geological information to confirm the validity of estimation of the future by extrapolation.

Fig. 4.6.3-5 shows the distribution of sedimentary rock from the late Miocene (about 7 million years ago) to the Late Pleistocene (about 125,000 years ago). The distribution shown for each age does not facilitate exact discussion, because the distribution does not distinguish between marine and non-marine deposits. However, it is thought that marine deposits are distributed widely in the shore area. For example, for the Lower Pleistocene, the sediment of the seabed after approximately 2.6 Ma is included in sediment distributed over the land after approximately 0.78 Ma. In other words, the part of the area where this sediment was distributed became an area of uplift rather than subsidence after approximately 0.78 Ma. This demonstrates that ongoing crustal movement began in the area along the shore after hundreds of thousands of years ago. Fig. 4.6.3-6 shows the frequency histogram and cumulative distribution of onset times for active fault movements every 100,000 years for a 6-million-year period from Doke et al. (2012)[20)]. The onset times of many active faults are after approximately 2.5 Ma. In addition, more than half of the onset times of faulting are after 1 Ma. This distribution of onset times suggests that the uniform mode and rate of crustal deformation were present after 1 Ma. Furthermore, Umeda et al. (2013)[21)] estimated the onset time of the constant uplift rate of representative mountainous based on the model of mountain development by concurrent tectonics and denudation of Ohmori (1978)[22)] (Fig. 4.6.3-7). According to this deductive estimate, the onset times of the uniform mode and rate of crustal deformation vary by area. However, the onset times are at least after from hundreds of thousands of years ago to 1 million years ago. This result does not contradict the inductive estimate obtained from geomorphological and geological data.

Concerning the possibility that new faults and volcanoes may occur, estimation of the future occurrence probability can be obtained from the frequency, scale, and range of past occurrence[23)]. Previous studies have modeled the long-term spatio-temporal characteristics of volcanism using probabilistic approach with geological information such as the location, occurrence time, and magnitude[24),25)]. We developed a multiple-inference model that included geophysical and geochemical data using a Bayesian method to improve the reliability of estimation in the second mid-term research phase(Fig. 4.6.3-8)[26),27)].

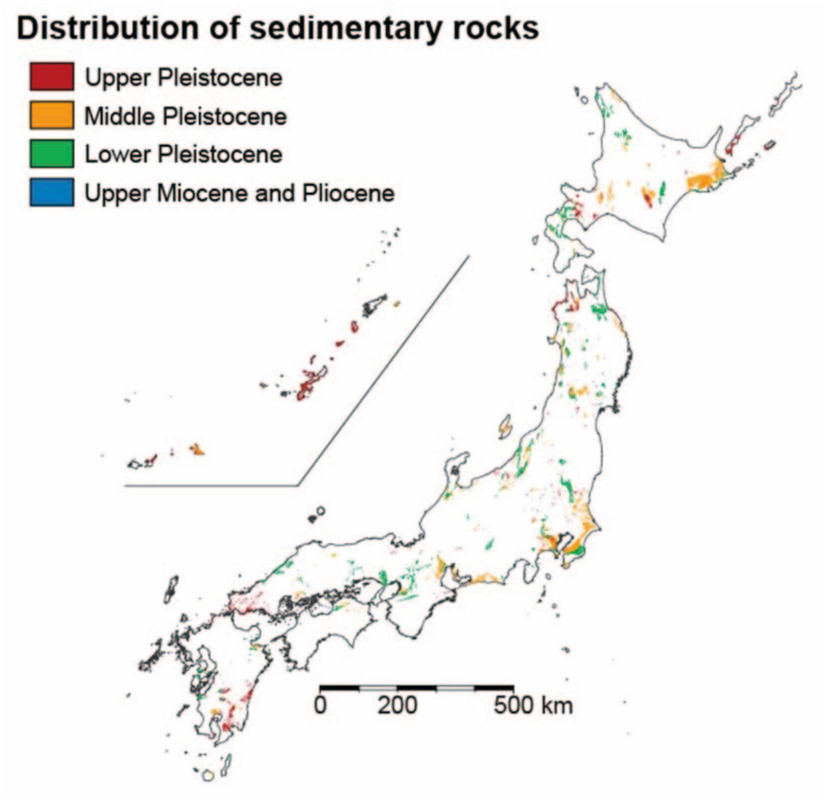

Fig. 4.6.3-5 Distribution of late Miocene to late Pleistocene sedimentary rocks in Japan[21)]

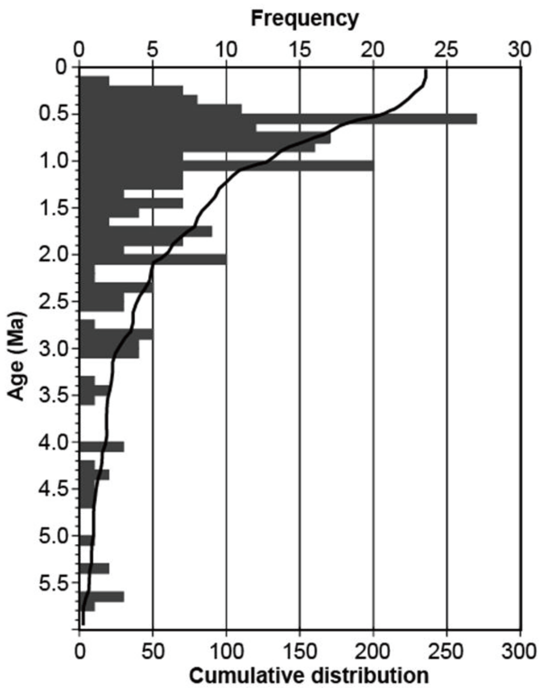

Fig. 4.6.3-6 Frequency histogram and cumulative distribution of onset times for active fault movements[21)]

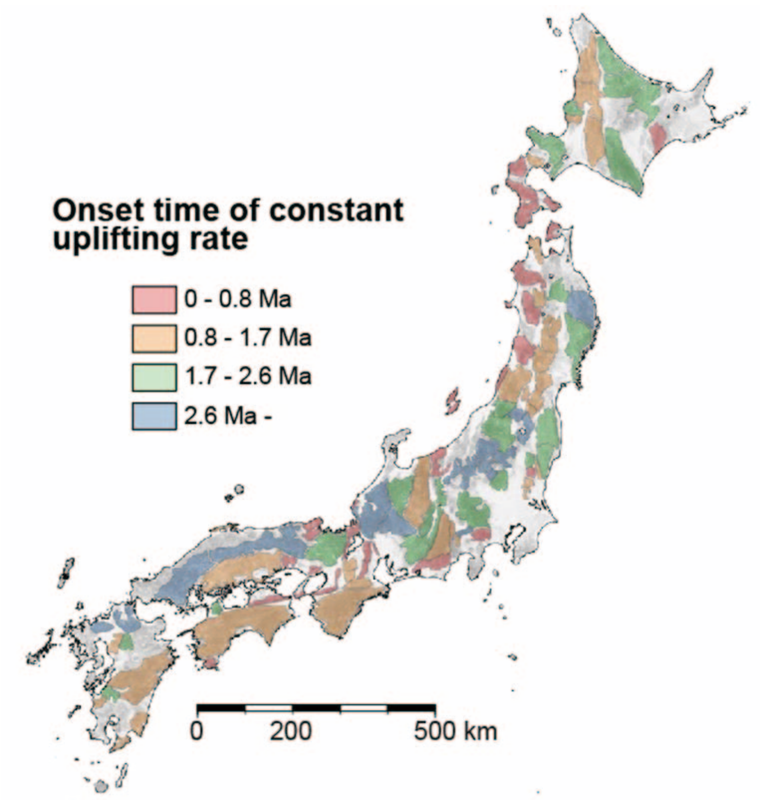

Fig. 4.6.3-7 Onset times of consistent mode and rate of crustal deformation in Japan based on simulations of temporal changes in mean altitude developed under concurrent tectonics and denudation processes[21)]

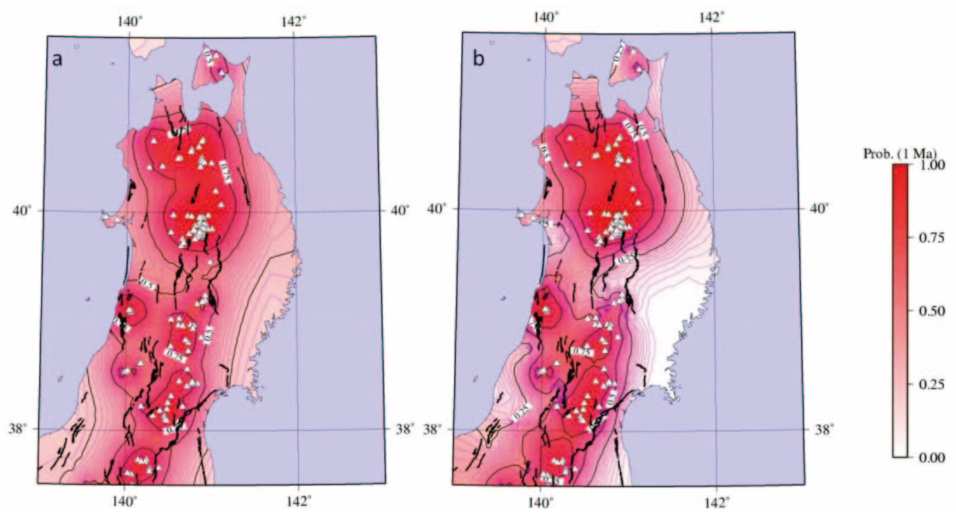

Fig. 4.6.3-8 Probability of the occurrence of a new volcanic event over the next 1 Myr[27)]
The probabilities were calculated using a multiple-inference model that included geophysical data and geochemical data using the Bayesian approach.
(a) Calculation using the distribution of volcanoes, age, and seismic velocity structure
(b) Calculation including the helium isotope ratio distribution in (a)

4.6.4 Summary

As an important study and technical preparation for estimation and evaluation relating to the safety assessment based on the less likely scenarios, we performed the following:

- Validation of simulation techniques for landform changes over approximately 100,000 years.
- Development of estimation techniques for hydrological changes using analysis of volumetric strain with subduction-zone earthquakes.
- Development of estimation and evaluation techniques for very-long-term natural phenomena.
- Development of quantitative methodology for the uncertainty of the estimation and evaluation.

The future theme is technical upgrading and quantification of the uncertainty.

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5. Tool development for integration of knowledge from each research result

5.1 Introduction

A specific feature of the geological disposal of radioactive waste is to ensure extremely long-term safety, extending several tens of thousands years in the future. Such extreme long-term safety of geological disposal is difficult to demonstrate in actuality. It is being widely recognized that there is a need to gain the understanding of the public for the safety by explaining the safety case that is an integration of the arguments and evidence for the safety and reliability of the geological disposal system.

The arguments to demonstrate the safety of geological disposal involve a great deal of knowledge in a variety of disciplines. The related knowledge will be increased over the several decades of the disposal project period. Compilation of such knowledge of geological disposal in the framework of explanation of the safety and sharing of this knowledge among relevant persons will be important. JAEA has developed the JAEA KMS (Knowledge Management System) and CoolRep as frameworks for that purpose[1),2)].

The knowledge obtained at the URLs will become important information for the design and safety evaluation of the repository. In developing a safety case, integration of information in three R&D areas (site characterization, repository design, and performance assessment) will be required, rather than use of each of these areas individually, which will require communication.

A geological environment model is used to communicate the knowledge obtained at the URLs to the people in charge of design and performance assessment of a repository (Fig. 5.1-1). However, direct use of the geological environment model in the communication will result in unclear understanding of the validity of the model and the data used for the persons in charge of design and performance assessment.

JAEA developed the Information Synthesis and Interpretation System (ISIS) as part of the "Development of advanced integration system of the geological environment" (2007–2012) supported by the Agency for the Natural Resources and Energy, METI[2),3),4),5),6),7),8),9),10),11),12)].

In chapter 5, traceability from the geological environment model to the data used for the model and communication strategy will be shown, focusing on ISIS.

It should be noted that descriptions, including both overviews and detailed ones, can be structured in the CoolRep because it is a report on a web site. The CoolRep can ensure traceability of the knowledge, because access to detailed descriptions, technical reports or KMS could be possible as appropriate.

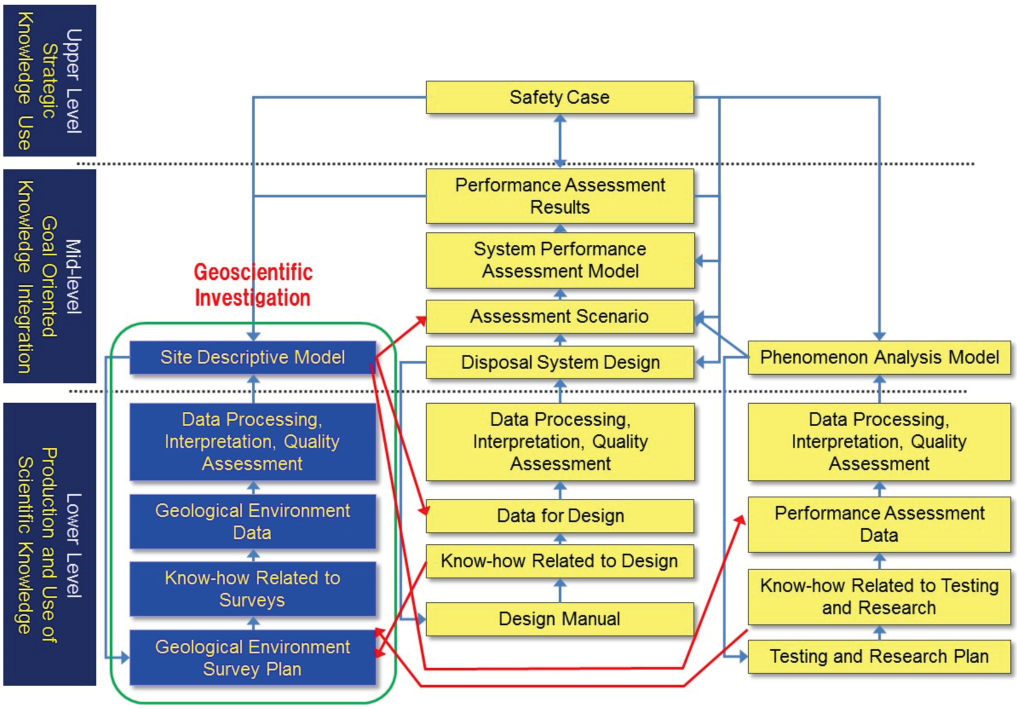

Fig. 5.1-1 Relationship between each field of knowledge in construction of a safety case

5.2 Concept of ISIS

The ISIS consists of an expert system that supports construction of geological environment models and planning and implementation of a research program, a visualization tool for the constructed geological environment model, an expert system development tool, an investigation process management and geological environment electric document system, and a management cockpit that integrates these tools[8),9)] (Fig. 5.2-1). The management cockpit is a tool to integrate the other tools and knowledge under four tabs (Fig. 5.2-2) together with different management tools and search tools such as a document management tool to manage relevant documents and users.

The four tabs contain various tools, as described below[8),9)]:

- "Research program management tab": To manage work plans such as investigation, analysis, and evaluation; with tools to register different types of work (tasks) related to the site characterization and to display them as a Gantt chart.
- "GEM" viewer tab: to display constructed 3D geological environment models or plans (views); possible to manage discussion or history of discussions on the view.
- "My page tab": A groupware with tools to register tasks relevant to each person or request tasks to other workers.
- "KMS tool group tab": Arranged buttons to initiate tools or tools developed as part of the ISIS such as a tool to elicit experts' knowledge (expert system developing interface).

Utilizing the tools described above, ISIS can promptly and effectively support the decision-making by managers taken in various situations in the site characterization through the management cockpit. The system also allows knowledge to be shared among relevant persons and ensure traceability of that knowledge.

In developing ISIS, potential major users were assumed to be those involved in the site characterization (managers, persons in charge of in situ tests, design and performance assessors) in the implementation body of the geological disposal (NUMO), and regulators in the regulatory body on safety. With the aim of supporting different works related to the preliminary investigation or the preceding stage of the site characterization stages, ISIS was developed to allow information considered to be useful for conducting site characterization at potential sites for geological disposal, the results of R&D conducted at the URLs in JAEA, the results of R&D on the geological environment conducted in and outside of Japan, and the experiences, knowledge, and skills obtained by applying these results to be used effectively, by utilizing knowledge engineering methodology and IT as much as possible[8),9)].

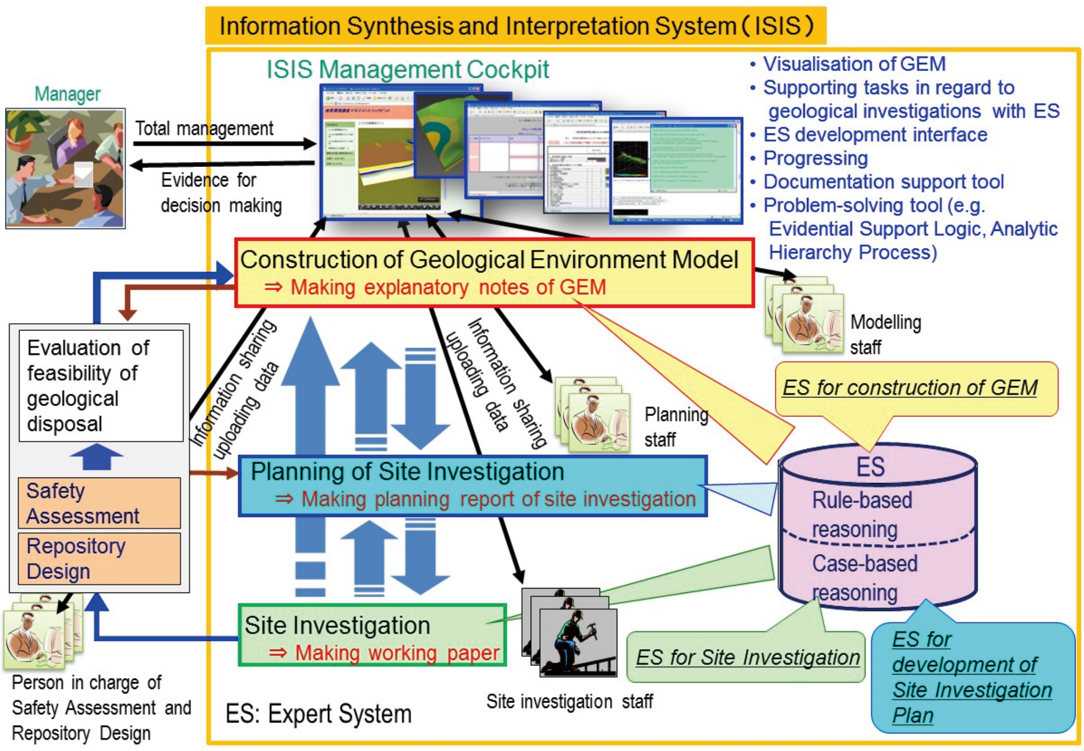

Fig. 5.2-1 Concept of ISIS

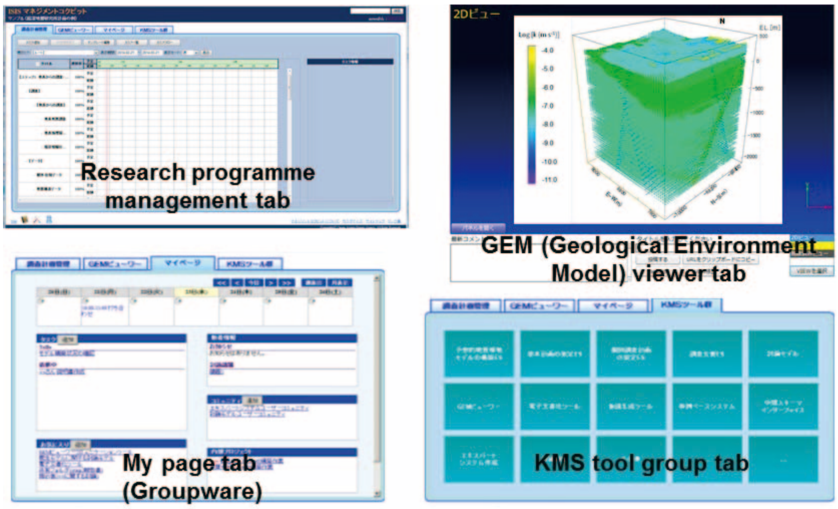

Fig. 5.2-2 Four tabs in the management cockpit

5.3 Results

As described in section 5.1, geological environment models are used for communicating knowledge of the site characterization with the persons in charge of the design and performance assessment of a repository. In providing knowledge of the site characterization to the persons in charge of the design and performance assessment of a repository, the following points are important:

1) Method to ensure traceability of knowledge, such as the validity of the geological environment model, the data used for the modeling, and the methods used to obtain the data;
2) Communication method – a method to reflect knowledge of persons in charge of design and performance assessment;
3) Knowledge-eliciting method – a method to elicit arguments for the judgment by experts;
4) Knowledge-sharing method – a method to elicit the knowledge described in 1) to 3) above.

These methods for utilizing ISIS are described in detail below.

5.3.1 Method to ensure traceability of knowledge

This section describes the method of ensuring traceability of knowledge for the geological environment model.

In constructing a geological model, several options generated because of uncertainties in the geological structure or several versions produced associated with the progress of the investigation will be studied. To manage these options or versions, the "geological environment model history management tool" is equipped[8),9)].

The tool will be run from the KMS tool group tab. The geological environment models that were studied can be displayed in a tree-like structure to identify the relationships between those options or versions of the studied geological environment models (Fig. 5.3.1-1).

A general description of each geological environment model can be displayed and linked to the related knowledge as in a) through e) listed below. In addition, the system allows features of the concerned geological environment model and data used for developing the model to be checked. This tool will allow knowledge related to the geological environment model to be traceable (Fig. 5.3.1-2).

a) Rule-base: Decision points, procedures, and concepts for developing a concerned geological environment model

b) Case-base: Note to be reminded in developing a geological environment model

c) Relevant documents: Technical reports, academic literatures, used data books, and related web sites that describe the characteristics of the geological environment model

d) Related images: Figures of geological environment models, etc.

e) Related tasks: Information related to the task of "development of concerned geological environment model" (including objective, responsible persons, duration, and used information or results)

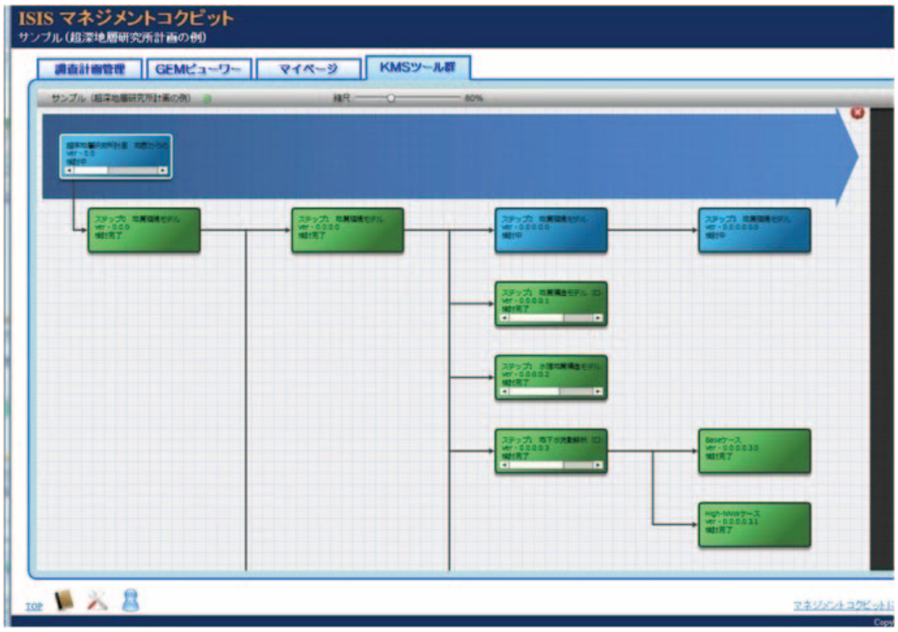

Fig. 5.3.1-1 The GEM historical management tool

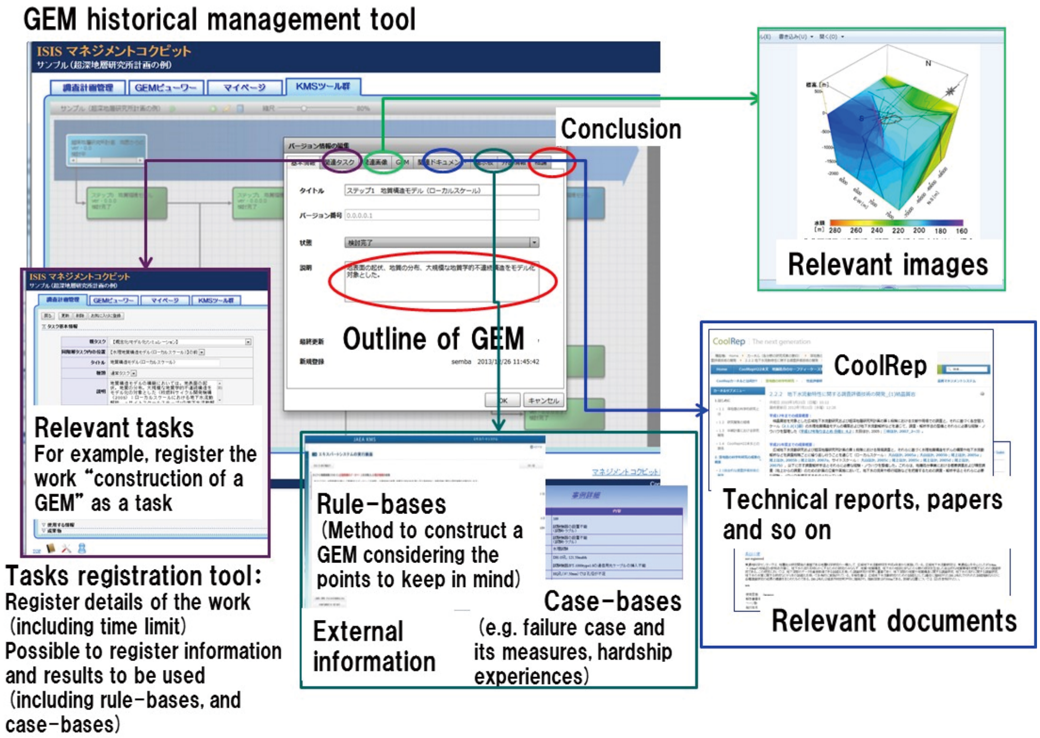

Fig. 5.3.1-2 Knowledge linkable to the GEM historical management tool

Item e) described above is the one registered to the research programme management tab in ISIS.

By registering the task to the tab, the processes for developing a geological environment model and the data-obtaining process used in developing a concerned geological environment model can be displayed on this tab (Fig. 5.3.1-3).

The information listed below could be registered and linked to each task:

f) General description of task: Description of concerned tasks (objective, specific task, discrepancy between plan and record, and responsible persons)

g) Information used to implement the task: Link to existing rule-base or case-base, link to related task and external web site, registration of documents in the management cockpit, and other information (note to be reminded in implementing the task)

h) Output obtained by implementing the task: Description of overviews, registration of documents additionally compiled and registered in the management cockpit.

The system has a tool to make a task flow using tasks registered in the research program management tab. The tool will allow correlation of the geological environment model and the investigation in which data used for developing the model was obtained, which will help to ensure traceability (Fig. 5.3.1-4).

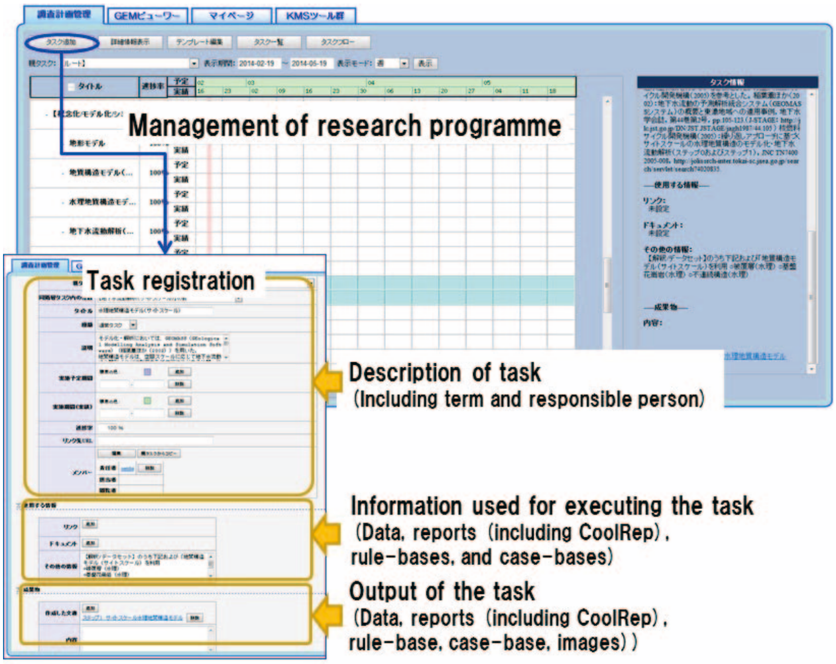

Fig. 5.3.1-3 Registration of tasks to the research programme management tab

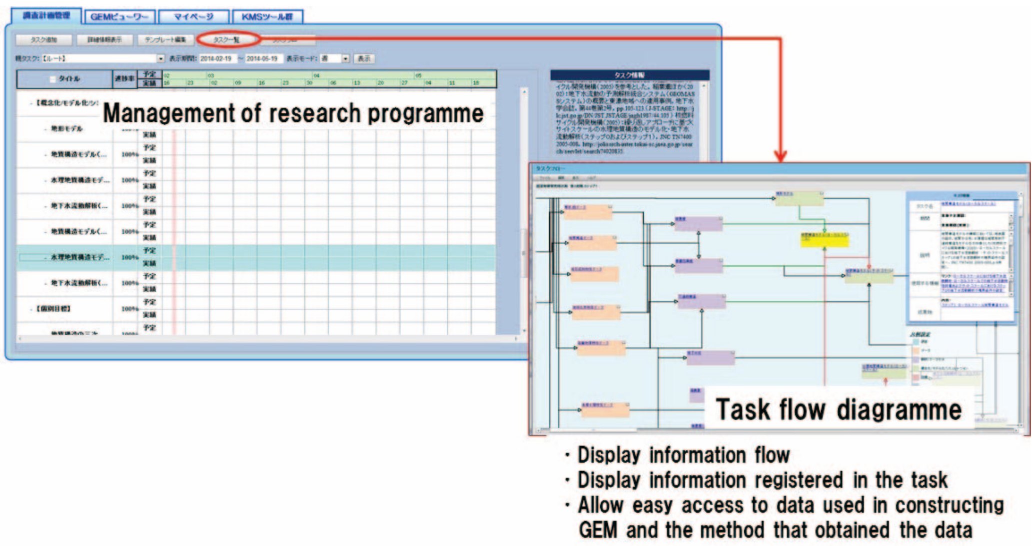

Fig. 5.3.1-4 Task flow diagram constructed using the registered tasks

5.3.2 Communication method

The information used for developing a geological environment model can be obtained by using the tools shown in section 5.3.1. However, communication between related persons will be required for developing a geological environment model in practice or checking conformity with other geological environment models with respect to characteristics of the geological environment, or providing a geological environment model to persons in charge of the design and performance assessment. In addition, people involved in different disciplines may require cooperation in preparing a research program for the subsequent phases.

The methods for supporting communication and cooperative work will be described in this section.

The “GEM viewer” tab can be utilized for communication[8),9)] (Fig. 5.2-2).

In the “GEM viewer” tab, geological environment models and figures among related persons can be registered as a view, which can be displayed Fig. 5.3.2-1. By writing on the marker set on the view, discussions can be developed on the web site (Fig. 5.3.2-1), which will facilitate communication. As the conclusion of the discussion can be recorded, this can be checked as information related to the geological environment model by correlating to the task that was made using the geological environment model history management tool or research program management tab, as described in section 5.3.1.

The discussion on the web site will allow cooperation in planning subsequent phases.

A “story board” tool is also equipped as a tool to support cooperative work. As an example, evolution of the geological environment at a certain location or T-H-M-C evolution around the engineered barriers can be defined by cooperative work[8),9)] (Fig. 5.3.2-2). The story board will be run from the KMS tool group tab.

Fig. 5.3.2-1 Discussion using a view

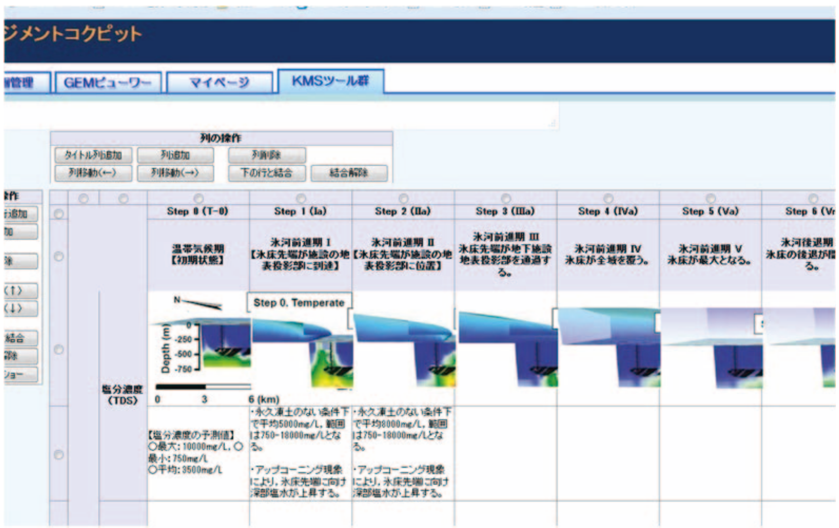

Fig. 5.3.2-2 An example of a story board

5.3.3 Knowledge-eliciting method

Site characterization will be conducted using different knowledge and skills that are owned by experts. Such knowledge and skills are unlikely to be described in reports, and experts often possess their own knowledge and skills. It will be important to obtain this type of knowledge as much as possible in passing information on to future generations, developing human resources, and transferring technologies. The knowledge-eliciting method will be described in this section.

In order to elicit the knowledge possessed by experts and facilitating utilization of this knowledge by other persons, repeated communications between knowledge engineers and site-characterization experts are required in general. However, eliciting knowledge using this method is time-consuming. The time available for site-characterization experts to share for interview were limited, and this process was thus a bottle-neck in gaining knowledge. In addition, although the site-characterization experts do not necessarily have knowledge of the program language; knowledge of program language is essential for storing the extracted knowledge. Therefore, in order to enable the experts to elicit knowledge by themselves as much as possible, a knowledge-eliciting method was constructed by developing a task flow and decision-making flow diagram[4),5),6),7),8),9),13)]. In addition, based on the decision-making flow diagram, an interface to develop an expert system was developed to allow extraction of knowledge and storage of the extracted knowledge by inputting knowledge that the experts have using natural language through a web site[8),9),14)].

The expert system for the ISIS consists of a rule-base and a case-base.

The knowledge that is expressed as a rule such as an "if…then format" can be elicited by using a rule-base development interface (Fig. 5.3.3-1). Information such as those referred to in implementing similar events in the future including failure or successful experiences could be elicited by using a case-base development interface, though these cases can not be defined by rules (Fig. 5.3.3-2).

Experts in site characterization can prepare a rule-base or case-base by themselves using these interfaces. As these bases can be corrected, existing rule-bases or case-bases will be updated or newly prepared as appropriate when new knowledge is obtained.

Researchers in JAEA and other institutes have compiled knowledge by developing a task flow and decision-making flow diagram to date. Based on the decision-making flow diagram, the rule-bases have been developed and case-bases based on experiences obtained through investigations and analyses have also been constructed[13),15),16),17),18),19),20),21),22),23),24),25),26),27),28),29),30),31),32),33),34),35),36),37),38),39)].

Interfaces for the rule-base and case-base will be run from the KMS tool group tab.

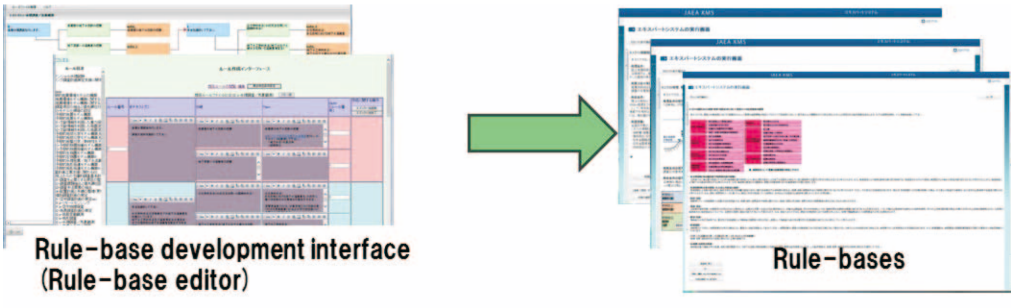

Fig. 5.3.3-1 Development of rule-bases using the rule-base development interface

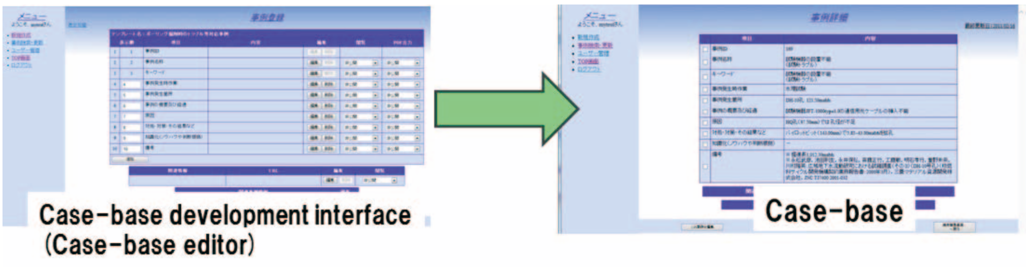

Fig. 5.3.3-2 Development of case-bases using the case-base development interface

5.3.4 Knowledge sharing method

As described in section 5.2, the ISIS management cockpit has tools to manage documents to be shared in addition to knowledge in the rule-base and case-base. The system can manage them while correlating with tasks and other ISIS tools, which can assist with sharing knowledge among related persons during the progress of the project. After completing the project, the system can provide information correlated to each other, by which it can support sharing knowledge between different generations[8),9)].

5.4 Summary

In developing a safety case, the results of site characterization and design of a repository and performance assessment need to be integrated. The geological environment model will be used for communicating between those persons in charge of these three areas. However, the use of the geological environment model directly will result in unclearness regarding the model validity and data used for the persons in charge of the design and performance assessment. Assuming that knowledge of the site characterization be provided to the persons in charge of design and performance assessment of a repository, traceability of knowledge must be ensured and communication between these persons will be required. Knowledge about the project including the validity of the method to obtain the provided knowledge is also required to be shared between the related persons. Eliciting experts' knowledge will be important for fostering human resources and communicating knowledge.

The chapter 5 demonstrated that a tool to support ensuring traceability of knowledge about site characterization, communication, eliciting of knowledge, and knowledge sharing could be successfully developed using ISIS for use in JAEA KMS, i.e., a system related to the site characterization.

This system will allow communication and sharing of information with traceability in constructing a safety case. Such knowledge will be further improved and increased by utilizing ISIS in the future.

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^{2}
体積	立方メートル	m^{3}
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^{2}
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^{3}
面積密度	キログラム毎平方メートル	kg/m^{2}
比体積	立方メートル毎キログラム	m^{3}/kg
電流密度	アンペア毎平方メートル	A/m^{2}
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^{3}
質量濃度	キログラム毎立方メートル	kg/m^{3}
輝度	カンデラ毎平方メートル	cd/m^{2}
屈折率(b)	（数字の）　1	1
比透磁率(b)	（数字の）　1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^{2}/m^{2}
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		m kg s^{-2}
圧力，応力	パスカル	Pa	N/m^{2}	m^{-1} kg s^{-2}
エネルギー，仕事，熱量	ジュール	J	N m	m^{2} kg s^{-2}
仕事率，工率，放射束	ワット	W	J/s	m^{2} kg s^{-3}
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	m^{2} kg s^{-3} A^{-1}
静電容量	ファラド	F	C/V	m^{-2} kg^{-1} s^{4} A^{2}
電気抵抗	オーム	Ω	V/A	m^{2} kg s^{-3} A^{-2}
コンダクタンス	ジーメンス	S	A/V	m^{-2} kg^{-1} s^{3} A^{2}
磁束	ウエーバ	Wb	Vs	m^{2} kg s^{-2} A^{-1}
磁束密度	テスラ	T	Wb/m^{2}	kg s^{-2} A^{-1}
インダクタンス	ヘンリー	H	Wb/A	m^{2} kg s^{-2} A^{-2}
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^{2}	m^{-2} cd
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	m^{2} s^{-2}
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	m^{2} s^{-2}
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	m^{-1} kg s^{-1}
力のモーメント	ニュートンメートル	N m	m^{2} kg s^{-2}
表面張力	ニュートン毎メートル	N/m	kg s^{-2}
角速度	ラジアン毎秒	rad/s	m m^{-1} s^{-1}=s^{-1}
角加速度	ラジアン毎秒毎秒	rad/s^{2}	m m^{-1} s^{-2}=s^{-2}
熱流密度，放射照度	ワット毎平方メートル	W/m^{2}	kg s^{-3}
熱容量，エントロピー	ジュール毎ケルビン	J/K	m^{2} kg s^{-2} K^{-1}
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	m^{2} s^{-2} K^{-1}
比エネルギー	ジュール毎キログラム	J/kg	m^{2} s^{-2}
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	m kg s^{-3} K^{-1}
体積エネルギー	ジュール毎立方メートル	J/m^{3}	m^{-1} kg s^{-2}
電界の強さ	ボルト毎メートル	V/m	m kg s^{-3} A^{-1}
電荷密度	クーロン毎立方メートル	C/m^{3}	m^{-3} s A
表面電荷	クーロン毎平方メートル	C/m^{2}	m^{-2} s A
電束密度，電気変位	クーロン毎平方メートル	C/m^{2}	m^{-2} s A
誘電率	ファラド毎メートル	F/m	m^{-3} kg^{-1} s^{4} A^{2}
透磁率	ヘンリー毎メートル	H/m	m kg s^{-2} A^{-2}
モルエネルギー	ジュール毎モル	J/mol	m^{2} kg s^{-2} mol^{-1}
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	m^{2} kg s^{-2} K^{-1} mol^{-1}
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} s A
吸収線量率	グレイ毎秒	Gy/s	m^{2} s^{-3}
放射強度	ワット毎ステラジアン	W/sr	m^{4} m^{-2} kg s^{-3}=m^{2} kg s^{-3}
放射輝度	ワット毎平方メートル毎ステラジアン	W/(m^{2} sr)	m^{2} m^{-2} kg s^{-3}=kg s^{-3}
酵素活性濃度	カタール毎立方メートル	kat/m^{3}	m^{-3} s^{-1} mol

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	1 ha=1 hm^{2}=10^{4}m^{2}
リットル	L，l	1 L=1 l=1 dm^{3}=10^{3}cm^{3}=10^{-3}m^{3}
トン	t	1 t=10^{3} kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1 eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1 Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1 u=1 Da
天文単位	ua	1 ua=1.495 978 706 91(6)×10^{11}m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100 kPa=10^{5}Pa
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100fm^{2}=(10^{-12}cm)^{2}=10^{-28}m^{2}
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1cm^{2} s^{-1}=10^{-4}m^{2} s^{-1}
スチルブ	sb	1 sb =1cd cm^{-2}=10^{4}cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} =10^{4}lx
ガル	Gal	1 Gal =1cm s^{-2}=10^{-2}ms^{-2}
マクスウエル	Mx	1 Mx = 1G cm^{2}=10^{-8}Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド(a)	Oe	1 Oe ≙ (10^{3}/4π)A m^{-1}

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ=1 nT=10^{-9}T
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2×10^{-4}kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	1 µ =1µm=10^{-6}m

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