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(Eds.) Hiromitsu SAEGUSA and Toshiyuki MATSUOKA

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Geological Isolation Research and Development Directorate

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The Mizunami Underground Research Laboratory (MIU) Project is a comprehensive research project investigating the deep underground environment within crystalline rock being conducted by Japan Atomic Energy Agency at Mizunami City in Gifu Prefecture, central Japan and its role is defined in “Framework for Nuclear Energy Policy” by Japan Atomic Energy Commission. The MIU Project has three overlapping phases: Surface-based Investigation phase (Phase I), Construction phase (Phase II), and Operation phase (Phase III), with a total duration of 20 years. The overall project goals of the MIU Project from Phase I through to Phase III are: 1) to establish techniques for investigation, analysis and assessment of the deep geological environment, and 2) to develop a range of engineering for deep underground application. During Phase I, the overall project goals were supported by Phase I goals. For the overall project goals 1), the Phase I goals were set to construct models of the geological environment from all surface-based investigation results that describe the geological environment prior to excavation and predict excavation response. For the overall project goals 2), the Phase I goals were set to formulate detailed design concepts and a construction plan for the underground facilities. This report summarizes the Phase I investigation which was completed in March 2005. The authors believe this report will make an important milestone, since this report clarifies how the Phase I goals are achieved and evaluate the future issues thereby direct the research which will be conducted during Phase II.

With regard to the overall project goals 1), “To establish techniques for investigation, analysis and assessment of the deep geological environment,” a step-wise investigation was conducted by iterating investigation, interpretation, and assessment, thereby understanding of geologic environment was progressively and effectively improved with progress of investigation. An optimal procedure from investigation to assessment was compiled as a set of geosynthesis data flow diagram for each investigation step. With regard to the overall project goals 2), “To formulate detailed design concepts and a construction plan for the underground facilities,” an optimal design of MIU was completed with the aim to provide a foundation for engineering technologies in deep underground to safely construct and operate an underground facility which will be built for the purpose of acquiring data and demonstrating disposal technologies.

Thus, this report summarizes geosynthesis procedures to investigate and assess the crystalline rock, and development of individual investigation and assessment methods. At the same time, technical findings and know-how which can serve as foundation to implementation of the disposal project were compiled. Also, this report clarified the necessity for the Phase II and Phase III investigation by compiling unresolved issues during the Phase I investigation.

The results described in this report will be utilized as technical knowledge of disposal technology and effectively used to enhance technical foundation which will support both the implementation and formulation of safety regulations.

Keywords: Mizunami Underground Research Laboratory (MIU) Project, Crystalline Rock, Surface-based Investigation (Phase I), Deep Geological Environment

超深地層研究所計画における地表からの調査予測研究段階（第 1 段階）
研究成果報告書

日本原子力研究開発機構　地層処分研究開発部門　東濃地科学研究ユニット
（編）三枝 博光、松岡 稔幸

（2010 年 12 月 20 日受理）

超深地層研究所計画は、原子力政策大綱に示された深地層の研究施設計画の一つであり、結晶質岩を対象として、独立行政法人日本原子力研究開発機構が岐阜県瑞浪市で進めているプロジェクトである。この超深地層研究所計画では、「第 1 段階：地表からの調査予測研究段階」、「第 2 段階：研究坑道の掘削を伴う研究段階」、「第 3 段階：研究坑道を利用した研究段階」の三つの段階に区分し、約 20 年をかけて進める計画である。超深地層研究所計画は、「深部地質環境の調査・解析・評価技術の基盤の整備」および「深地層における工学技術の基盤の整備」を第 1 段階から第 3 段階までを通した全体目標として定め、そのうち第 1 段階では、全体目標の前者については「地表からの調査研究による地質環境モデルの構築および研究坑道掘削前の深部地質環境状態の把握」、後者については「研究坑道の詳細設計および施工計画の策定」を段階目標として調査研究を進めた。本報告書は、2005 年 3 月で終了した第 1 段階の調査研究成果を取りまとめたものである。この取りまとめは、これらの段階目標に対して、その達成度と今後の課題を明らかにするとともに、第 2 段階以降における調査研究の方向性を具体化するうえで重要な意味を持っている。

第 1 段階における「深部地質環境の調査・解析・評価技術の基盤の整備」に関する調査研究では、調査からモデル化・解析、評価に至る一連のプロセスを繰り返し行うことによって段階的な調査研究を実施した。その結果、調査研究の進展に伴い、地層処分にとって重要な地質環境特性を効率的に理解することができた。また、調査から評価までの合理的な道すじを統合化データフローとして整理した。「深地層における工学技術の基盤の整備」に関する調査研究では、実際に取得された地質環境情報に基づき、情報の取得や技術の実証を目的とした地下施設を安全に建設・維持するための工学技術の基盤の整備を目標として研究坑道を合理的に設計することができた。

このように、第 1 段階の調査研究をとおして、結晶質岩（硬岩）を対象とした調査・評価のための方法論を示すとともに、重要な調査技術や解析技術を整備した。また、処分事業の基盤技術となる技術的知見やノウハウなどを整理した。さらに、第 1 段階において残された課題を整理し、第 2 段階以降の調査研究の必要性を明確化することができた。

ここで取りまとめる成果は、地層処分技術の知識基盤として整備されるばかりでなく、処分事業ならびに安全規制の両面を支える技術基盤の強化を図っていくうえで、有効に活用されるものである。

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1. Introduction

The Mizunami Underground Laboratory project (MIU project) is a comprehensive research and development (R&D) project aimed at studying the crystalline rock formations at Mizunami City in Gifu Prefecture, central Japan. The MIU project was initiated in 1996 by the Power Reactor and Nuclear Fuel Development Corporation (PNC), which subsequently became the Japan Nuclear Cycle Development Institute (JNC) and is now the Japan Atomic Energy Agency (JAEA). Together with the Horonobe Underground Research Laboratory project, which is focusing on sedimentary rock formations, the MIU project is one of the two deep underground research laboratory (URL) projects prescribed in "Long-term Program on Research, Development and Utilization of Nuclear Energy" (Long-Term Program)[1)] and "Framework for Nuclear Energy Policy" (Framework)[2)] , both of which were issued by the Atomic Energy Commission of Japan (AEC).

This report describes the results of investigations carried out during the surface-based investigation phase (Phase I) of the MIU project. Section 1.1 provides an overview of the URL projects within the context of the Japanese geological disposal program; Section 1.2 describes the R&D program of the MIU project and Section 1.3 discusses the aims and outline of this report.

1.1 General background

1.1.1 URL projects

Building on the technical basis provided by JNC's report "H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan" (H12 report)[3)], the geological disposal program for high-level radioactive waste (HLW) in Japan has moved from the stage where only R&D is performed to the implementation stage, in which a geological disposal project and safety regulations will be implemented. Necessary R&D activities will be continued in parallel. In June 2000, the Specified Radioactive Waste Final Disposal Act (the Act) was promulgated and, based on this legislation, the Nuclear Waste Management Organization of Japan (NUMO) was established as the implementation body for the geological disposal of HLW in October of the same year. The Nuclear Safety Commission of Japan (NSC) issued the "Basic Concept of Safety Regulation on HLW Disposal" First Report[4)]. Thus, the preliminary framework for the geological disposal project and the associated safety regulations has been established.

AEC then specified a new national program framework in its Long-Term Program[1)], which outlined the activities leading up to final disposal of HLW and who would be responsible for performing these. NUMO *"...should take charge of developing those consistent with the safe implementation of the final disposal project and with the improvement of its economic performance and efficiently"*. The government and related organizations *"...should actively push forward with research and development projects necessary for safety regulation and safety assessment of the final disposal, with fundamental research and development activities, including scientific studies of the deep geological environment, and with development of technologies to enhance the reliability of geological disposal technology"*. In particular, JNC was assigned responsibility to *"...steadily carry on research and development activities to verify the reliability of geological disposal technologies and to establish a safety assessment method, using research facilities for deep geological environments and the Quantitative Assessment Radionuclide Migration Experiment Facility in Tokai village"*.

In accordance with those responsibilities assigned to it in the Long-Term Program[1], JNC formulated an R&D program for the stages following submission of the H12 report. This was published as the "Generic Program for R&D on Geological Disposal of HLW" (Generic Program)[5]. In the Generic Program and within the context of improving 'the technical reliability of geological disposal in Japan', demonstrated in H12 report, and enhancing the technical basis supporting the disposal project and the associated safety regulations, two goals were set for the R&D program: 'confirmation of the applicability of disposal technologies to specific geological environment' and 'understanding of the long-term behavior of the geological disposal system' (Figure 1.1.1-1). The aim of the former was to confirm the reliability and practicability of technologies developed to date by applying them to specific geological environments; the latter was intended to improve the reliability of the evaluation by increasing the understanding of various phenomena that affect the disposal system and to improve the associated models and databases. The URLs were focal points for achieving the first goal. In the Generic Program, the R&D program was divided into two areas: 'R&D on geological disposal technology' and 'geoscientific research'. The former involves improving the reliability of the disposal technologies and developing advanced safety assessment methodologies, while the latter forms the necessary basis for the former. Specific R&D items were set for each area. Since JNC was merged with the Japan Atomic Energy Research Institute (JAERI) to form JAEA, R&D has continued in line with the above two R&D goals. A new fundamental policy report of JAEA entitled "Plan for Meeting the Midterm Goal – Midterm Plan (October 1, 2005 to March 31, 2010)" (Midterm Plan)[6] states that JAEA will pursue R&D in the fields of geoscientific research and geological disposal technologies. The URL projects at Mizunami in Gifu, central Japan and Horonobe in Hokkaido, northern Japan are mentioned specifically in the Midterm Plan.

The R&D activities summarized in the H12 report were carried out to demonstrate the basic technical feasibility of geological disposal in Japan, without specifying any particular geological environment. In order to improve the technical reliability of geological disposal and enhance the technical basis for the disposal project, it was important that the practicability and reliability of the technologies used in the H12 report should be demonstrated by applying them to specific geological environments; URLs can be used for this purpose.

It was proposed that *"two or more URLs should be constructed, considering the range of characteristics and distribution of the geology of Japan"*[7]. JNC therefore set up the Mizunami URL project[8] for investigating crystalline rock with fresh groundwater and the Horonobe URL project[9] for sedimentary rock with saline groundwater (Figure 1.1.1-2). Both projects consist of three phases that will extend over a period of around 20 years[10]: surface-based investigations (Phase I), investigations during tunnel excavation (Phase II) and investigations in the underground facilities (Phase III). For the MIU project, these are called the surface-based investigation phase (Phase I), the construction phase (Phase II) and the operation phase (Phase III) (Table 1.1.1-1). It should be noted that the investigations for repository site selection, which will be carried out by NUMO, will also proceed stepwise, with literature surveys, preliminary investigations and detailed investigations (surface-based investigations in the early stages and those in underground facilities in the later stages) over a period of around 20 years, as specified in the Act. Phase I of the URL projects corresponds to the preliminary investigations and the first half of the detailed investigations in the NUMO program and Phases II and III to the detailed investigations using underground facilities. The technical basis for the preliminary investigations has been developed by synthesizing the results in the H12 report and investigations carried out during Phase I of the URL projects. It is of importance that the reliability of surface-based investigations and associated modeling techniques should be improved during Phase II investigations; for instance, geological environment models developed during Phase I should be tested using geological data obtained during Phase II. This is defined also in the national "R&D Program for the Geological Disposal of HLW"[11]; the goal of the fundamental R&D in Phase 2 (2006–2010) will be to establish the technical basis for surface-based investigations and that in Phase 3 (after 2011) to establish the technical basis for investigations using underground facilities.

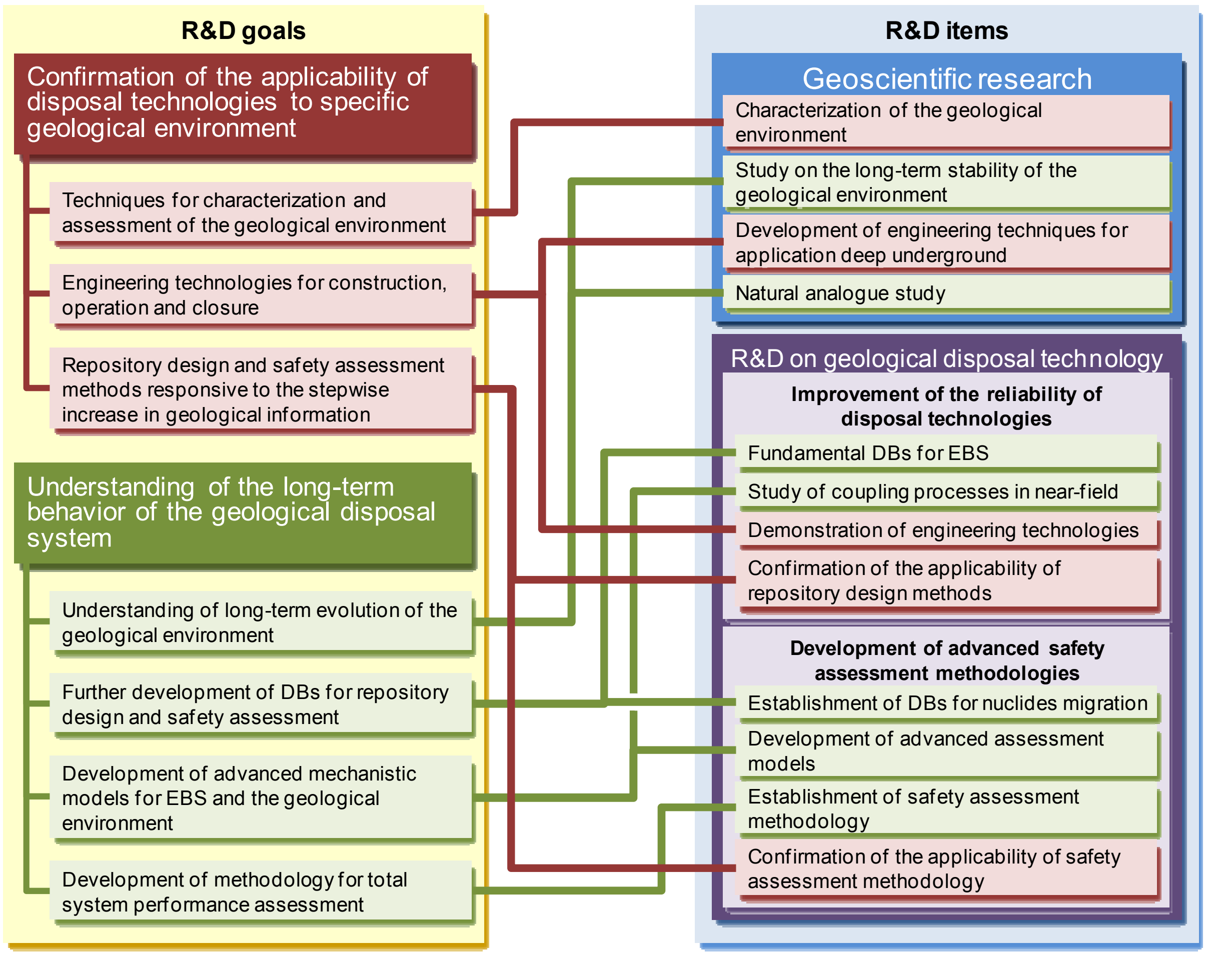


Figure 1.1.1-1 Goals of the R&D plan (2001–2005) mapped onto specific work areas

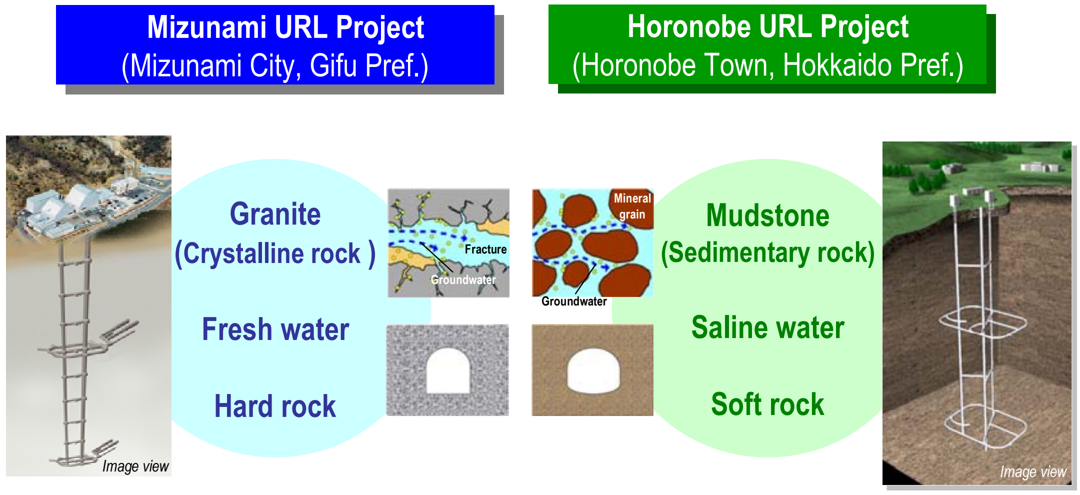
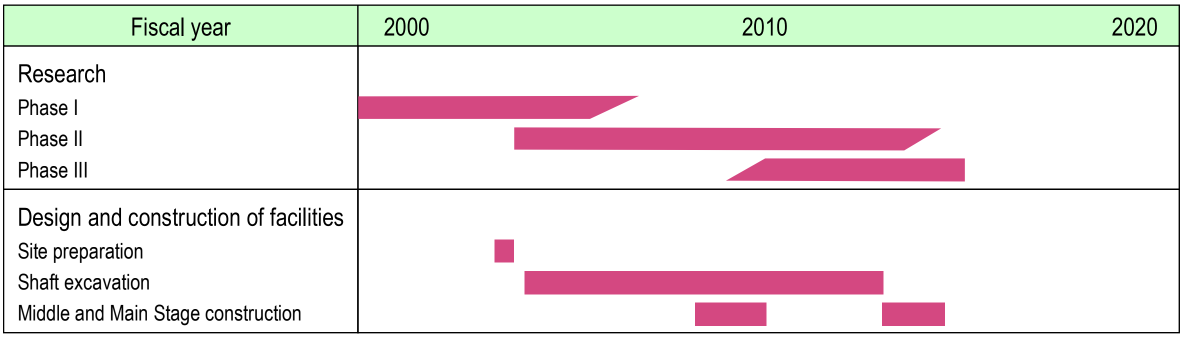


Fig. 1.1.1-2 Two generic URL projects in Japan

Table 1.1.1-1 Schedule of the MIU project



1.1.2 R&D goals of the URL projects

The primary goal of the R&D in the URL project is to improve the reliability of geological disposal technologies by applying them to specific geological environments. In the H12 report, techniques and methods for characterizing the geological environment were developed based on studies carried out in existing tunnels in the Tono mine (sedimentary rock) and the Kamaishi mine (granitic rock), as well as joint research projects in overseas URLs. After comparing and reviewing the information acquired in these studies and from key literature, it was demonstrated that a safe repository could be designed and constructed economically based on current engineering technologies or if necessary future developments thereof and that the long-term safety of geological disposal could be assessed by current modeling and simulation techniques. It can be concluded that the H12 report successfully demonstrated the feasibility of geological disposal in principle combining information from various fields.

The reliability of geological disposal technologies will be evaluated based on information on the geological environment accumulated with the progress of the URL project, with investigations advancing stepwise starting from undisturbed conditions. A stepwise approach helps in enhancing and ensuring the depth of understanding of the deep geological environment and eventually developing a sound technical basis for systematically characterizing the deep geological environment. Design and construction of URLs based on the geological information acquired will result in developing engineering technologies relevant to geological disposal programs. A key technical challenge for the geoscientific research in the URL project will thus be to establish the basis for techniques for characterizing the geological environment and engineering technologies for use in the deep underground.

The information and knowledge acquired through geoscientific research will be used as key input for R&D aimed at improving the reliability of repository engineering technologies and developing advanced safety assessment methodologies. In addition, rock and groundwater samples obtained in the geoscientific research will be utilized in the R&D. In this way, the applicability of geological disposal technologies can be confirmed. Consequently the relationship between the degree of understanding of the geological environment and the sensitivity of the characteristics of the geological environment in a safety assessment or the required volume of investigations can be reviewed by feeding the confirmed results back into geoscientific research. Key issues for the planning and/or evaluation of repository design and construction can be identified and compiled as a knowledge base, depending on the progress of the stepwise investigations and the depth of understanding of the geological environment. Laboratory and engineering-scale experiments under controlled conditions or experiments using radionuclides also provide an understanding of various phenomena relevant to the geological disposal system. In the Horonobe URL project, R&D on geological disposal technology is conducted in parallel with geoscientific research, which, particularly in the phases subsequent to Phase II of the project, will involve using drifts for experiments to confirm EBS construction technologies and their performance in sedimentary rock and in situ experiments for improving the reliability of safety assessment models[12)].

1.1.3 Role of the URL projects in Japan

The role of the URL projects in Japan is to develop and confirm the relevant technologies that will be applied in a real geological environment. This is achieved by maintaining an awareness of the overall goal – accurate understanding of the geological environment – while setting tasks such as data acquisition and evaluation of the applicability of the technologies. This will lead to optimization and improvement of the technologies, as well as an understanding of the adequacy and limitation of technologies. Understanding the limitations of the technologies will form a basis for the detailed planning of repository implementation and the formulation of realistic safety regulations. Since the waste disposal project will proceed stepwise, as specified in the Act, and safety regulations will be developed in accordance with the progress of the waste disposal project, these activities should be preceded by R&D that will provide a sound technical basis for them. It is of particular importance that the results from each URL investigation phase should be synthesized and reported with an appropriate lead-time for the site selection process. This is also essential for reviewing the design and safety assessment methodologies for the geological disposal system using information on the specific geological environments, which will be acquired through the URL program. This will thus ensure adequate techniques for characterizing the geological environment efficiently and an efficient approach to reviewing the design and safety assessment methodologies for the geological disposal system based on limited stepwise information on the geological environment.

When designing a disposal system and evaluating its safety based on the results of characterization of the geological environment, major challenges include understanding the spatial heterogeneities of the actual geological environment and addressing the uncertainties associated with these heterogeneities. This involves frequent trial and error and repeated feedback. In general, the depth of understanding will increase in proportion to the extent of investigations. However, the further the investigations progress, the less the increase in understanding and cost effectiveness of the efforts become. Detailed investigations of the geological environment generally involve high costs and no investigations, however detailed, will result in complete understanding. The geological disposal system is inherently associated with various degrees of uncertainty and the degree of conservativeness to be taken into consideration in the repository design will vary depending on the level of uncertainty associated with the understanding of the geological environment. For the actual disposal project, this will be reflected in the degree of conservativeness in the repository design and, subsequently, in the construction costs. Understanding the geological environment and reflecting the remaining uncertainties in the margins included in the design and safety assessment is thus a complex issue and the investigations have to reduce the uncertainties to an acceptable level. Hence, in each investigation in the stepwise site selection process, it will be important to examine the objectives and content of the investigations by assessing the level of understanding to be achieved and the requirements to be considered, as well as identifying issues and uncertainties to be carried over to the next stage. Even for investigations of a similar scale, the accuracy of the results and the depth of understanding obtained will vary depending on the geological and geomorphic conditions and the social environment at the site. In order to reflect such realistic conditions, it is important not only to prepare catalogues of investigation techniques and equipment, but also to accumulate experience at the site and to learn from actual case studies. The experience and knowledge gained in the URL projects should support methodologies for investigations for repository site selection and be used to establish safety regulations. For the URL projects, efforts should be made to build a knowledge base and to systematize multidisciplinary results and technological successes as well as experience with failures, recognizing that the latter are also important aspects of the ongoing R&D. The approach to the investigations in the URL projects is thus not linear, but involves a process in which planning, execution and evaluation are iterated in each phase. Recognizing the relationship between the progress of investigations and the depth of understanding and reduction of uncertainties will result in optimization of the investigation program as a whole, with the findings of preceding phases being reflected in subsequent phases.

It is stated in the Long-Term Program[1)] that *"The research facility for deep geological environment will serve not only as a place for scientific investigation, but also as a place for deepening public understanding of research and development activities related to the geological disposal of waste. Accordingly, this research facility project should be clearly distinguished from the disposal facility".* It is worth noting in this respect that an agreement between JAEA and the local government restricts JAEA's activities in the sense that *"JAEA will never bring or use HLW in the URLs and JAEA will never lend or transfer the URL facilities to the implementing entity"*. Collaborative research with domestic and overseas organizations and experts will also be pursued intensively in the URL projects. The public will have the opportunity, in the URLs, to experience the deep geological environment first-hand and to increase their awareness of geological disposal and the associated R&D activities. The investigation program and results of the URL projects will be open to the local and national public. An agreement between JNC (now JAEA) and the local government defines two boundary conditions for JAEA's activities in the MIU project: i) JAEA may never bring or use HLW in the area used for the project and, ii) JAEA may never lease or transfer the URL facilities to the implementing organization.

1.2 The Mizunami URL project

1.2.1 Background

Fig. 1.2.1-1 shows geological map and geological section of the Tono area. Around the MIU Construction Site, Tertiary sedimentary rocks widely and unconformably overlay the Cretaceous Toki Granite, which was emplaced ca. 60-70 Ma ago[13]. The Tertiary sedimentary rocks are lithologically divided into the Mizunami Group (age ca. 15-20 Ma) and the Seto Group (1.5-12 Ma). The Mizunami Group is further sub-divided into the Toki Lignite-bearing Formation, the Akeyo/Hongo Formation and the Oidawara Formation, in ascending order. The lower part of the Mizunami Group is mainly composed of tuff, silt/sandstone and conglomerate. The middle and upper parts of the Mizunami Group are mainly composed of mudstone and silt/sandstone alternating with shallow marine facies. The Seto Group consists of unconsolidated clay, sand and gravel. The Toki Granite is typically felsic and is sub-classified by biotite content. The most significant structure in the area is the Tsukiyoshi fault, which has an E-W trend and a dip of 70-80° to the south. The Toki Granite and Mizunami Group are both cut by the fault, with approximately 30 meters of vertical displacement[14]. The underground facilities of the MIU project will be constructed mainly in the Toki Granite basement (Fig. 1.2.1-2). Topographically, the Tono area, where the MIU Construction Site is located, is hilly and bounded by the Mino-Hida Highland to the north-west and the Mikawa Highland to the south-east. In the highlands area to the north, the antecedent Kiso River forms a deep valley. In the central part of the area, the Toki River flows from north-east to south-west. Terraces developed along the Toki River and its tributaries form platforms and alluvial deposits extend into the lowlands along the river.

The MIU project was initiated in 1996 at the JAEA-owned Shobasama Site in Mizunami, Gifu Prefecture under an agreement between the local governments of Gifu Prefecture, Mizunami City, Toki City and PNC (now JAEA), with the approval of the Science and Technology Agency (now the Ministry of Education, Culture, Sports, Science and Technology) signed in December 1995, entitled “Agreement on Geoscientific Research at the Tono Geoscience Center.” In January 2002, JNC and Mizunami City concluded a lease contract for city-owned land at Akeyo in Mizunami, finalizing the decision to construct the underground facilities and related installations of the MIU project at this location[8]. Preparation of the land for the project began in July 2002, with excavation of the shaft basement in July 2003, followed by initiating full excavation work for the shaft in 2004. The Phase I investigations at the MIU Construction Site extended over three years from 2002 to 2004.

The Tono Geoscience Center program preceded the MIU project, with studies being carried out in sedimentary rocks in the Tono mine between 1986 and 2003. A Regional Hydrological Study (RHS) was initiated covering an area of 10 km x 10 km encompassing the Tono mine in 1992. With the exception of long-term hydraulic monitoring, the field work of the RHS was completed in March 2006 and the results were compiled in detailed reports[15),16]. Since the area covered by the RHS included the MIU Construction Site, long-term monitoring of changes in groundwater chemistry and pressure associated with the construction of the MIU underground facilities continued around the MIU Construction Site, using existing monitoring systems and boreholes. The program at the MIU Construction Site has incorporated the results of investigations at the Shobasama site as well as those from the RHS.

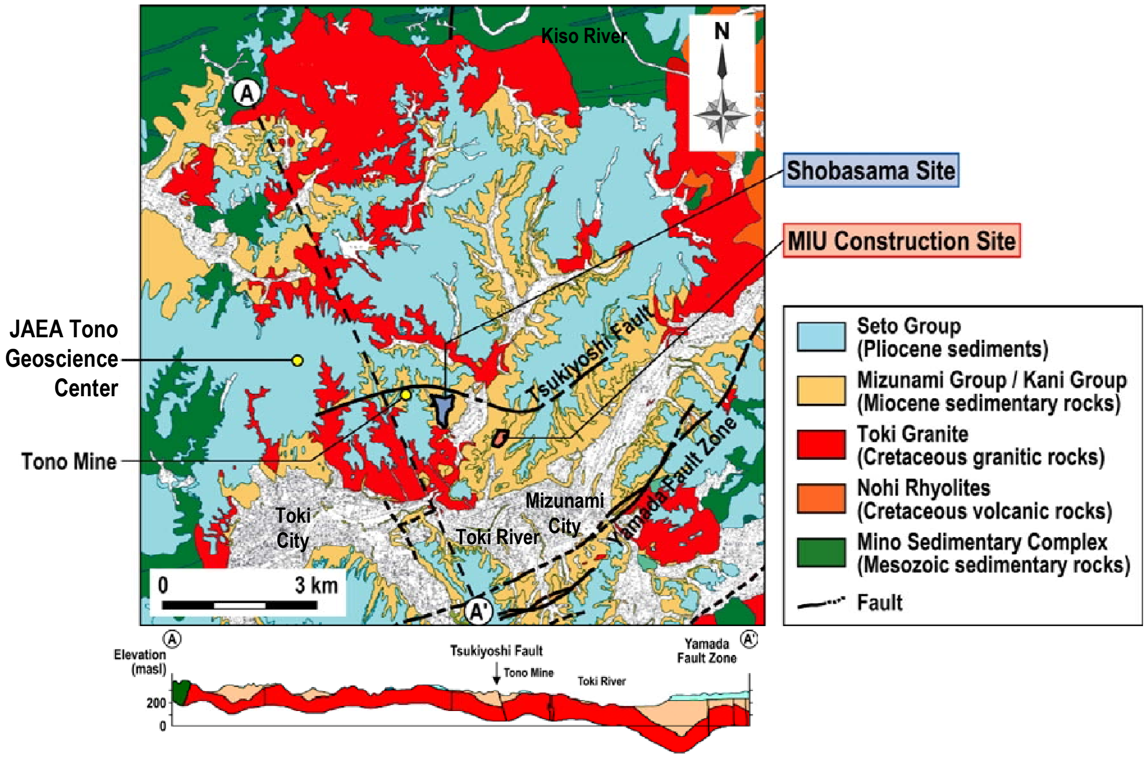


Fig. 1.2.1-1 Geological map and geological section of the Tono area
(Simplified from Itoigawa (1980)[13])

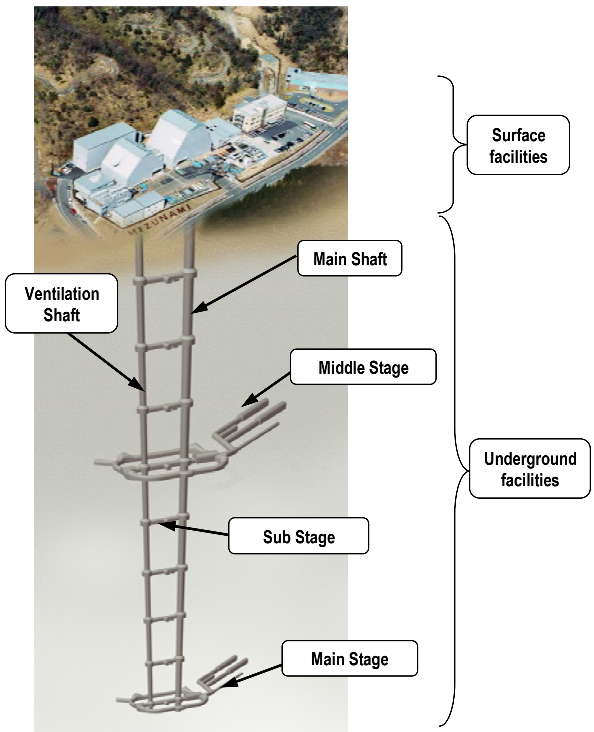


Fig. 1.2.1-2 Layout of the MIU facilities

1.2.2 Goals and approach of the MIU project

The overall goals of the MIU project defined in the basic program for geoscientific research at the MIU[8)] include:

1) To establish techniques for investigation, analysis and assessment of the deep geological environment
2) To develop a range of engineering for deep underground application

These goals correspond to the investigation of the geological environment and establishment of the basis for engineering technologies for deep geological applications relevant to geoscientific research as defined in the Generic Program[5)] mentioned in section 1.1.2.

A description of these goals is given below.

(1) Establishing techniques for investigation, analysis and assessment of the deep geological environment

This goal involves clarification of the geology, flow and chemistry of groundwater, thermal and mechanical rock properties, solute transport in the rock and the effects of tunnel excavation on the surrounding rock. Through implementation of the MIU project, the understanding of the deep geological environment will be improved and the technical basis for systematic investigation, analysis and assessment techniques will be established.

More specifically, during the stepwise investigations in the MIU project, the reliability and applicability of investigation techniques and assessment methods developed to date will be checked by applying them to actual geological environments. As part of this process, the understanding of the geological environment will become more detailed and the acquired geological information will be refined. Geological environment models will also be tested and investigation techniques and assessment methods will be improved. These will then be integrated into a system applicable to relevant geological environments in each step. The emphasis will be on demonstrating a range of methodologies for understanding the geological environment, including data acquisition, modeling and analyses. In addition, as shown in the Midterm Plan[6)], in order to establish a knowledge base for geological disposal technologies that support both the disposal project and formulation of safety regulations, experience including examples of inherent partial successes will also be compiled. Key issues in this respect include how to determine the spatial heterogeneity associated with the properties of the geological environment and how to deal with the uncertainties resulting from this heterogeneity. The knowledge and know-how built up in this process will form the technical basis that supports the disposal project and safety regulations more profoundly.

(2) Developing a range of engineering for deep underground application

This goal involves establishing the basis for developing the engineering technologies required to construct the underground facilities, with the objective of acquiring data and demonstrating technologies that are unique to geological disposal in terms of their design, construction and maintenance. The goal is to construct and provide maintenance for the underground facilities as an investigation tool for understanding the deep geological environment and to establish a research field for the deep underground environment. The technologies developed and experience accumulated through the design, construction and maintenance of the underground facilities will serve as the technical basis for the detailed investigations carried out for the selection of a final repository site in the actual disposal project.

Specifically, in the MIU project, based on the information on the geological environment obtained in Phase I, the deep underground facilities, where investigations and examinations will be conducted, will be designed based on conventional civil (tunnel) engineering and mining engineering technologies. The facilities will then be constructed safely and economically in Phase II. At this stage, information obtained through these activities (including measured data) will be fed back into the design and construction projects in order to check their applicability. Major challenges include the development of methods for evaluating the effects on the geological environment associated with the excavation of the underground facilities and the development of technologies for avoiding, remediating or minimizing these effects[8)]. The design and construction of the underground facilities will also enhance the understanding of the deep underground environment for the general public.

1.3 Aims and outline of the report on the surface-based investigation

1.3.1 Aims of the report

Synthesis of the results from the Phase I investigations involved systematically compiling the results and knowledge from surface-based investigations up to the end of March 2005. This synthesis is important for evaluating the Phase I goals for which the investigations have been carried and for identifying issues to be addressed in the future, as well as providing guidelines for the investigations in Phase II and subsequent phases. The results of the synthesis should be used as a knowledge base that supports both NUMO's repository implementation (e.g. preliminary investigations and detailed surface-based investigations for site selection) and the formulation of safety regulations by national agencies (e.g. establishing siting factors for the selection of detailed investigation areas and guidelines for the safety review). The results of the Phase I investigations were incorporated into the supporting reports 1 of the project "H17: Development and Management of the Technical Knowledge Base for the Geological Disposal of HLW" (H17 report)[15)] published in September 2005.

The strategy for the synthesis of Phase I was specified as compiling the results of the investigations and associated knowledge in accordance with the goals of Phase I and defining the investigation needs in Phase II and subsequent phases. More specifically, all the results obtained during Phase I, including those obtained after publication of the H17 report, will be compiled and synthesized and, based on future issues identified in the H17 report and comments provided on the H17 report, the techniques for characterizing the geological environment and engineering technologies for deep underground application, developed during Phase I, will be reviewed. Also, from the viewpoint of establishing a knowledge base for geological disposal technologies, it is important to document the full spectrum of experience, including both successes and failures.

Details of the formulation of a program for the Construction Phase which is one of the goals identified for Phase I, are presented in a separate report.

1.3.2 Outline of the report

This report consists of five chapters. Chapter 2 provides an overview of the Phase I geoscientific research, including the goals of the research in Phase I and how the investigations were conducted. Chapter 3 describes the results of the investigation, analysis and assessment techniques for the deep geological environment, summarizes the technical know-how and findings regarding these techniques for crystalline rocks from Phase I and the predictions made regarding the deep geological environment and its change as input for the investigations in Phase II. Chapter 4 compiles the technologies and techniques for the geoscientific investigations, which were developed through the investigations in Phase I. Chapter 5 deals with the establishment of the basis for engineering technologies for application in the deep geological environment and describes design and construction techniques and safety measures for underground facilities constructed in hard rock. Chapter 6, the final chapter, summarizes the results of the geoscientific research in Phase I and discusses future perspectives.

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2. Overview of the surface-based investigation phase of the MIU Project

2.1 Goals of the surface-based investigation phase

The goals of Phase I of the MIU Project are: 1) to construct models of geological environment based on the results of surface-based investigations that describe the conditions of the deep geological environment prior to the excavation of the underground facilities and predict excavation response, 2) to formulate detailed design concepts and construction plan for the underground facilities, and 3) to establish detailed investigation plans for the construction phase[1)].

(1) Construct models of the geological environment from all surface-based investigation results that describe the geological environment prior to excavation and predict excavation response

Information on the deep geological environment was collected through surface-based investigations in order to characterize the undisturbed conditions of the geological environment in detail before excavating any underground facilities. Through synthesis and interpretation of the collected data, models of the geological environment were developed, including a geological model, a hydrogeological model, a hydrochemical model, a rock mechanical model and a solute transport conceptual model. Based on information accumulating sequentially during these investigations, the models of the geological environment were also continuously updated.

Using these models, the conditions in the deep geological environment (e.g. groundwater flow condition, groundwater chemistry and rock mechanical properties) before excavation of the underground facilities that are expected to change due to excavation could be estimated.

(2) Formulate detailed design concepts and a construction plan for the underground facilities

In accordance with the investigation program in Phases II and III as formulated in item (3) below, the detailed layout of the underground facilities should be determined based on information on the deep geological environment acquired in this phase and on predicted changes in the deep geological environment associated with the excavation of the underground facilities. Construction techniques and equipment should also be selected with a view to defining a detailed construction plan, designed to minimize disturbance of the deep geological environment due to the construction of the underground facilities.

(3) Establish detailed investigation plans for Phase II

A detailed investigation program for Phase II and an outline investigation program for Phase III should be formulated. These programs should be based on the aforementioned information on the deep geological environment and expected changes caused by the excavation of the underground facilities, considering the issues requiring R&D identified in the review of the H12 Report.

Taking into account number and resolution of the investigations in Phase I, limited reduction of the uncertainties associated with the evaluation models for the deep geological environment could be expected. Bearing in mind the requirements to be considered in the safety assessment of geological disposal and the design and construction of the underground facilities, the primary output from Phase I was to show, through case studies, the surfaced-based investigations required and the corresponding level of detail expected to be achieved. The level of understanding of the geological environment and the uncertainties based on the quality and quantity of the investigations as described above was evaluated through modeling of the results of integrated investigations on the geological environment. For the testing of the models of geological environment developed in Phase I, the performance measures were identified and included in the investigation program for Phase II and III.

2.2 Overview of the surface-based investigation phase

2.2.1 Specific aims for investigation

The functions of the geosphere in the repository concept are to provide physical isolation of the waste for long time periods from the bioshere and a suitable environment for the emplacement and subsequent performance of the engineered barriers[2),3)]. The requirements on the geological environment in terms of physically isolating waste for a long time period have been listed by NUMO as Siting Factors for the Selection of Preliminary Investigation Areas. In order to ensure the technical feasibility and safety of geological disposal (in addition to meeting environmental requirements), the geological environment studied has to fulfill the conditions and functions described below:

- Existence at a suitable depth and with sufficient spatial extent for the construction of a repository (ensuring the required rock volume for geological disposal)
- Virtually homogeneous stress conditions and low temperatures (e.g. lower than 40 degree Celsius) in the geological formations of interest, with a view to ensuring safe design and construction, as well as, maintaining the integrity of the engineered barriers and disposal facilities
- Small groundwater flux and velocity around the emplacement tunnels combined with moderate alkalinity and reducing groundwater chemistry, with a view to restricting erosion of the buffer material, overpack corrosion and glass dissolution
- Slow groundwater flow in the far field, long transport paths and sufficient retardation of radionuclide transport in order to restrict radionuclide migration
- Large dilution/dispersion of future groundwater fluxes from the repository, thus further reducing radionuclide concentrations.

To determine specific aims for R&D activities in the Phase I investigations, some important factors to be characterized and resulting data requirements relevant to safety assessment were identified as shown in Fig. 2.2.1-1. Reference was made in this context to the international generic FEP – Features, Events and Processes – lists[4)], as well as examples[2),5)] of investigation items for the preliminary investigations. An important difference here between the MIU construction site and NUMO’s preliminary investigation areas is that one proceeds with Phase II regardless of the results in Phase I, i.e., MIU is an R&D site and is not being evaluated as a future repository site. The information on the geological environment obtained for the MIU Project through the investigations in Phase I will be used in the design and construction of the underground facilities (see Chapter 4 for details). The important factors to be characterized and the resulting data requirements should therefore also be defined from the viewpoint of design and construction.

In recent years, increasing emphasis has been placed on the importance of evaluating not only the safety of the human environment but also the social and environmental impacts of geological disposal projects[6),7),8)]. Environmental impact assessments are therefore required, as is the case for other large-scale projects such as construction of tunnel and dams[9)]. In the MIU Project, the investigations will proceed in parallel with the actual construction of the underground facilities and the effects of constructing the underground facilities in the volume of rock extending from ground surface to deep underground on the surrounding environment (e.g. groundwater levels, groundwater chemistry, etc.) should be evaluated as a case study. In this context, and from the viewpoint of design and construction of underground facilities and the environmental impact assessment, the important factors to be characterized and the resulting data requirements were identified as shown in Fig. 2.2.1-1 and were set as specific aims to be addressed in the investigations.

The specific aims in the Phase I investigations were to clarify the characteristics of, and processes in, the geological environment as identified above, focusing mainly on safety assessment as well as the aspects mentioned above. It was also important, for each investigation discipline, to prepare investigation techniques for each aim and to integrate these into a systematic investigation and evaluation technology.

2.2.2 Spatial scales

Setting spatial scales is a key issue in effectively understanding the geological environment and its heterogeneity based on a limited number of investigations. This should be done bearing in mind the need to reflect the results of the investigations in the safety assessment and in the design and construction of the underground facilities. The RHS and the MIU Project adopt a stepwise approach to characterizing the geological environment based on surface-based investigations and evaluation of groundwater flow and solute transport behavior, focusing on a groundwater flow system extending from the recharge area to discharge area and including the MIU Construction Site and layout of the underground facilities. Therefore, four spatial scales were used for the investigations as shown in Fig. 2.2.2-1: regional, local, site and block scales[9)].

The idea of using different spatial scales for investigations has been applied in areas other than geological disposal. Guidelines for the review of geological and surface conditions for nuclear power plants, for example, require four scales of investigation: at least a 30 km radius from the proposed reactor site, around a 1 km radius, around a 200 m radius from the proposed reactor unit location and the base rock of the reactor building. For geological investigations of dam sites, an approach starting with investigations for acquiring regional information on overall trends, moving to investigation of smaller areas with specific objectives and investigation items is specified.

Spatial scales and their defined functions for the RHS and the MIU Project are shown in Table 2.2.2-1. For the RHS, studies were conducted on regional and local scales, while, for the MIU Project, studies were conducted on site and block scales. Study on the regional-scale was performed to define local-scale area. Investigations on a local scale address the groundwater flow system including from the groundwater recharge area to discharge area of groundwater flowing from the ground surface to 1,000 m depth at the MIU Construction Site. The site-scale area was defined as a rectangular area centered on the MIU Construction Site, as shown in Fig. 2.2.2-2, considering the distribution of major geological features including the Tsukiyoshi Fault. The boundary conditions for groundwater flow analyses for the site-scale area were determined based on output from the local-scale groundwater flow analyses. To determine the boundary conditions for the site-scale analyses, local-scale groundwater flow analyses considering the hydrogeological structures that could affect the boundary conditions for the site-scale analyses are required. Thus, when the locations or hydraulic properties of the hydrogeological structures were changed based on site-scale investigations, the local-scale hydrogeological model was also improved. Subsequently, the boundary conditions for the site-scale analyses were defined based on groundwater flow analyses using the improved local-scale hydrogeological model (Fig. 2.2.2-3). The block scale is the spatial scale that would be modeled in detail for determining the stress field around the underground facilities, excavation damage associated with the construction of the underground facilities and so on. The volume of the block scale is a part of the site-scale model of geological environment.

This report summarizes the site-scale (including the block-scale) investigations that have been conducted considering the specific aims as defined in Section 2.2.1.

2.2.3 Iterative approach

Various spatial and temporal as well as economic and socio-political constraints are likely to be encountered when characterizing the geological environment at specific sites. To allow effective investigations under these conditions, the relationship between the type and amount of information obtained during the investigations, the level of understanding and the results of the investigations should be evaluated at each stage. The results should then be reflected in the decisions made when proceeding to the next stage and planning of specific investigation programs in subsequent stages. The approach used for this is the iterative approach as shown in Fig. 2.2.3-1. The iterative approach consists of eight major steps:

(1) Developing and updating the concept of geological environment: Based on the information on characteristics of geological environment obtained from investigations and analyses in the preceding loop, structures and characteristics of geological environment relevant to geological disposal (e.g. discontinuities and hydrological heterogeneities in the rock that could affect groundwater flow and groundwater chemistry) are identified in order to conceptualize the geological environment in the area of interest.

(2) Planning of the investigations: The details of the investigation plan are formulated and revised appropriately based on the concept developed for the geological environment and the specific aims (taking into account boundary conditions).

(3) Execution of the investigations: According to the investigation plan.

(4) Interpretation of results: Referring to the specific aims, results of the investigations are interpreted. Then dataset for input to modeling/analyses is made taking into account the spatial distributions and uncertainties of the data.

(5) Modeling and analyses: Based on the results of data interpretation (e.g. datasets), the conceptual model developed in (1) is checked and revised, as necessary, and then geological, hydrogeological, geochemical, rock mechanical and solute transport models are developed. Since the specific aims of the investigations in question will differ depending on the investigation step, the objectives for modeling/analyses are determined for each investigation step. Using the developed models of geological environment, the groundwater flow, evolution of groundwater chemistry and stress condition are simulated.

(6) Assessment of consequences: Discussion of the results of modeling/analyses, in particular, examination of the consistency of the results among models utilizing different data. Through modeling and analysis, it can also be evaluated whether sufficient information on characteristics of geological environment has been obtained with respect to the specific aims of the investigations or in what detail

the geological environment of interest has been understood or described.

(7) Evaluation of uncertainties: Quantifying the results of the analysis and translating these into transparent information. In order to improve the adequacy and reliability of the results of modeling/analyses in terms of the specific aims for the investigations, it is necessary to quantify the uncertainties arising due to differing data quality, interpretations and modeling in order to demonstrate how far the uncertainties have been reduced.

(8) Specification of main and open issues: Based on the results of (1) through (7) above, key factors for achieving the specific aims are identified as issues to be addressed in the subsequent loop.

Based on the knowledge accumulated through a series of loops of iterative approach, applicability of comprehensive techniques for investigation, analysis and assessment of the geological environment, which is adopted on the MIU Project, are confirmed. Then, comprehensive techniques are optimized. The iterative approach described here is idealized and 'designed' for the MIU Project; in a different site the basic philosophy presented here should still be valid but the specific approach itself should be tailored to the given site. It should remain flexible enough to be able to consider the progress of investigations and adjust accordingly the steps in the iteration loop.

2.2.4 Strategy for the surface-based investigations

The investigations at the MIU Construction Site during Phase I followed the sequence of: preliminary characterization of the geological environment on wider area using techniques providing 2D information; identification of open issues requiring more detailed information; borehole investigations addressing the investigation items. Investigations were scheduled so that interactions among drilling or testing of borehole could be avoided (see Appendix 2). More specifically, investigations were categorized into five steps as shown in Fig. 2.2.4-1. In each investigation step, investigations were carried out according to the geosynthesis data flow diagram[10),11)] and following the iterative approach[9),12)]. The geosynthesis data flow diagram illustrates, for the specific aims, the types and combinations of investigations to be carried out, the types of data to be acquired, interpretation of data and synthesis of the information obtained in the different disciplines. In each step, models of geological environment were developed integrating the latest information and items to be addressed in the subsequent step were identified. Thus, by adopting the sequence described above, the relationship between type and quantity of the investigations, and the level of understanding regarding specific aims was made clear.

Specifically, based on compilation of acquired information (Step 0), the characteristics of geological environment related to specific aims, such as 3D distribution of geological structures, groundwater flow characteristics and groundwater geochemistry in the site scale area, were roughly understood. The acquired information included information obtained from literature surveys and RHS, and investigations carried out at the Shobasama Site before the Project on the MIU Construction Site started. The locations of lithological boundaries and discontinuities were then estimated two dimensionally by detailed surface geological mapping and reflection seismic surveys (Step 1), and borehole investigations were used to characterize all lithofacies and discontinuities (Steps 2 and 3). Ideally, the borehole investigations should have been conducted in series, i.e. investigations in existing borehole, new shallow borehole investigations and new deep borehole investigations. However, because the time for commencing shaft excavation had already been decided, investigations in existing borehole and new shallow borehole investigations (Step 2) were conducted in parallel, i.e. these two borehole investigations were combined to form one step. The locations and geometry of discontinuities, their hydrological characteristics and their continuity in the area between boreholes were determined by crosshole tomography and crosshole hydrological tests (Step 4).

Appendix 1 shows the locations of investigations conducted in Phase I and Appendix 2 contains the schedule for the investigations. Appendix 3 contains a summary table of borehole investigations.

The results of investigations conducted according to the flow described above were summarized for each investigation step using a geosynthesis flow diagram, which provides a logical sequence from investigation to specific aims (see Appendix 4).

2.2.5 Initial and boundary conditions for the surface-based investigations

In this section, the initial and boundary conditions for the investigations in Phase I are described.

(1) Boundary conditions

- Boreholes, underground facilities, surface facilities and other related installations should be constructed within the MIU Construction Site (an area of around 7.8 ha).
- In order to ensure an appropriate lead-time to allow results of the investigations to be reflected in the disposal project and the safety regulations, the investigations in Phase I should be completed within a period of three years from January 2002, when the land lease contract with the Mizunami City was concluded, to March 2005.
- Investigations should be conducted in parallel with the excavation of underground facilities (including land preparation at the MIU Construction Site and construction of surface facilities).
- Limited flat land is available at the MIU Construction Site, where rough terrain prevails. Land preparation needed to be carried out, deep borehole drilling rigs installed and surface infrastructure provided for the excavation of underground facilities. Since these construction activities were required to be conducted in parallel, only a limited number of locations were available for investigations.

(2) Initial conditions

- The results of the RHS and investigations at the Shobasama Site carried out before the investigations at the MIU Construction Site in Phase I could be used as existing information.
- Investigation technologies developed or confirmed as being applicable during the RHS and investigations at the Shobasama Site before the investigations at the MIU Construction Site could be used in the Phase I investigations.

	Important factors to be characterized	Data requirements
Safety assessment	Geological structure	Size and geometry of host rock; heterogeneity within host rock
		Size and extent of surrounding formations
		Spatial distribution and geometry of transport pathways (groundwater flowpaths)
	Groundwater flow characteristics	Spatial variability of magnitude of hydraulic gradient
		Spatial variability of hydraulic properties of rocks
	Geochemical characteristics of groundwater	Redox conditions
		Spatial variability of groundwater pH values
		Spatial distribution of different groundwaters; degree of groundwater mineralization
	Transport/retardation of nuclides	Sorption capacity and diffusivity of rock matrix and of transport pathways
		Geometry of transport pathways; depth of diffusion-accessible rock matrix
		Effect of colloid/organics/microbes on nuclide transport/retardation
	Dilution of nuclides	Spatial distribution of higher-permeability rocks, aquifers and surface waters
		Spatial variability of water fluxes in higher-permeability rocks, aquifers and surface waters
Designing & construction of underground facilities	Geomechanical/hydraulic properties of tunnel near-field environment	Local stress regime
		Spatial variability of petrophysical/geomechanical properties of rocks
		Volume of inflow into underground tunnels
		Size and structure of EDZ; petrophysical/geomechanical properties of EDZ
		Distribution of discontinuities intersecting underground tunnels
	Subsurface thermal conditions	Spatial variability of geothermal gradient
		Thermal rock properties
Environmental assessment	Environmental impact induced by construction of underground facilities	Impact on water table
		Impact on hydraulic pressure
		Impact on groundwater chemistry
		Effects of noise and vibration

（EDZ：Excavation Disturbed Zone）

Fig. 2.2.1-1 Important factors to be characterized and data requirements, relevant to safety assessment, designing/construction of underground facilities and environmental assessment

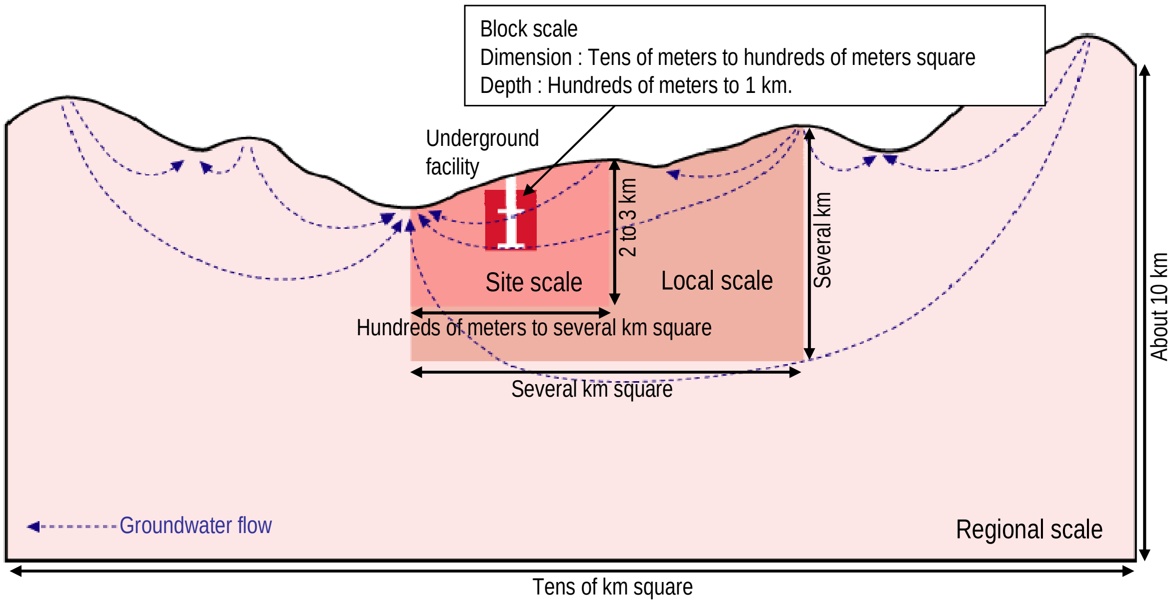

Fig. 2.2.2-1 Concept of scale[12)]

Table 2.2.2-1 Dimensions and objectives of each scale[12)]

Scale	Dimensions / Area and depth	Objectives
Regional	Hundreds of km^2 (Tens of km square) *Depth* : About 10 km.	✓ Set modeling area and boundary conditions of local scale
Local	Tens of km^2 (several km square) *Depth* : Several km.	✓ Evaluate the geological disposal system ✓ Collect fundamental information for design of underground facility ✓ Set modeling area and boundary conditions of site scale
Site	Several km^2 (hundreds of meters to several km square) *Depth* : 2 to 3 km.	✓ Evaluate the far-field and near-field around the engineered barrier ✓ Predict rock mechanical and hydrogeological conditions during construction of underground facility ✓ Set modeling area and boundary conditions of block scale
Block	Hundreds of m^2 (tens of meters to hundreds of meters square) *Depth* : hundreds of meters to 1 km.	✓ Evaluate near-field around the engineered barrier ✓ Predict rock mechanical and hydrogeological conditions during construction of underground facility

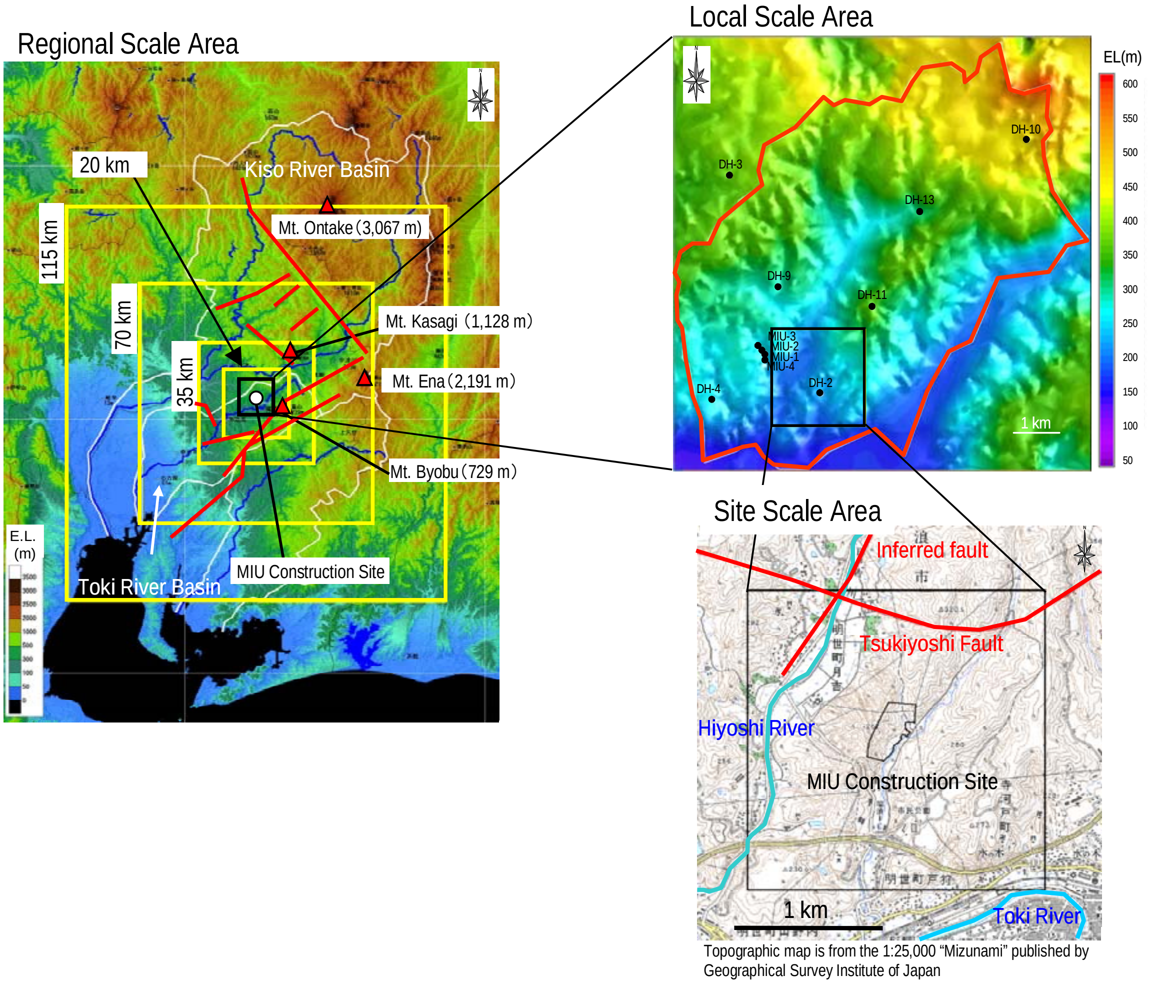

Fig. 2.2.2-2 Areas of each scale

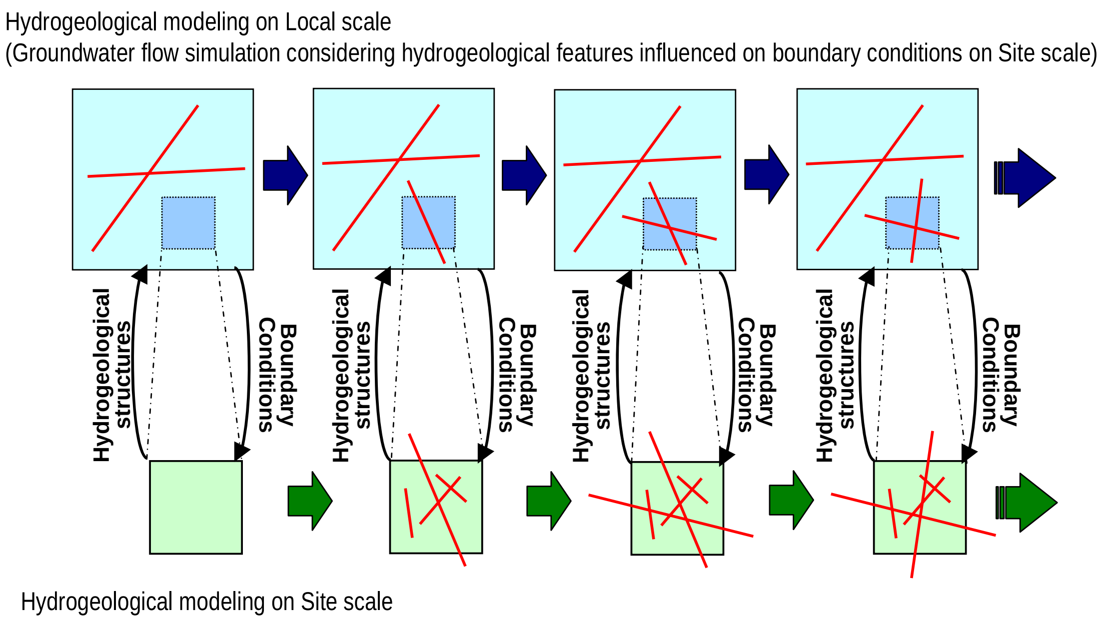

Fig. 2.2.2-3 Methodology for setting boundary conditions of groundwater flow simulation on Site scale

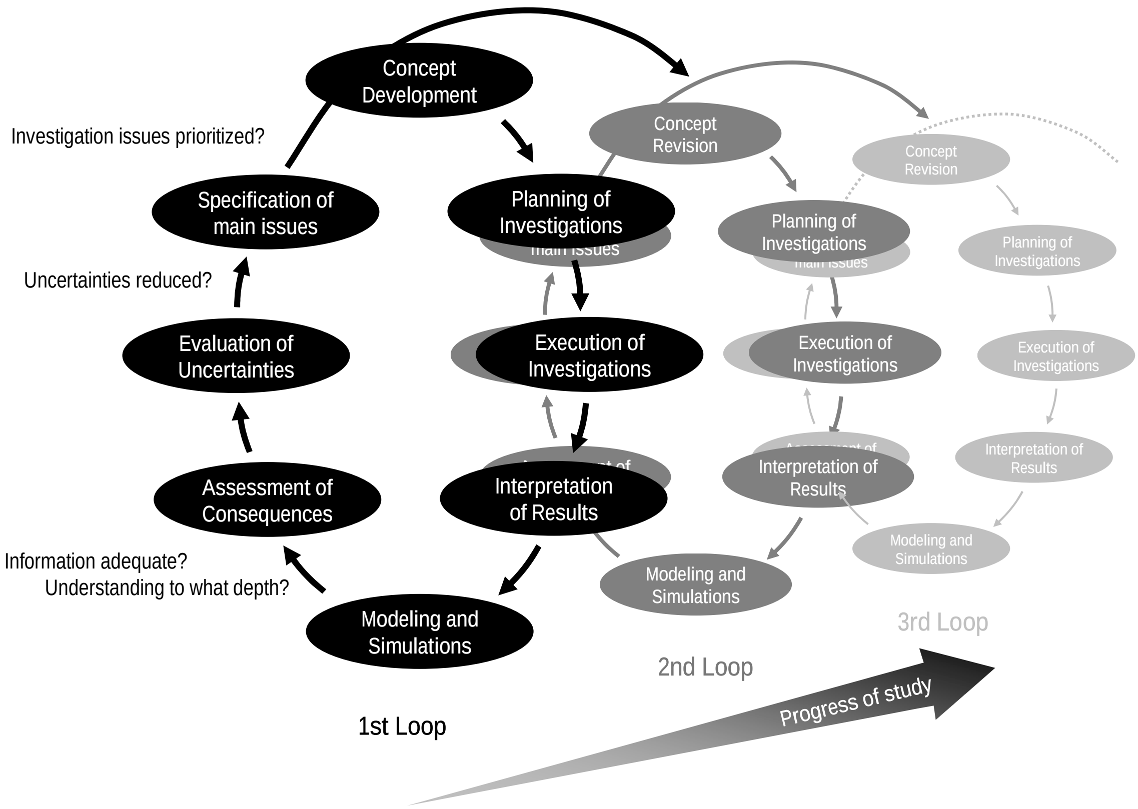

Fig. 2.2.3-1 Iterative approach for the characterization of geological environment[12)]

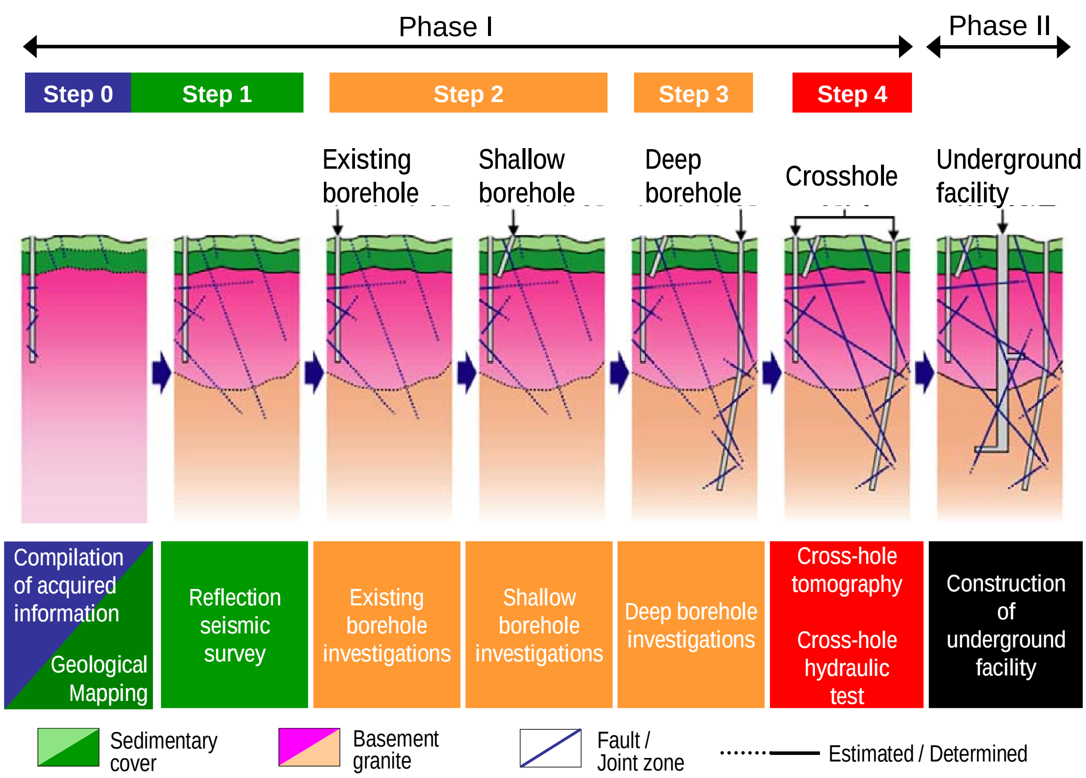

Fig. 2.2.4-1 Concept of Phase I investigations[12)]

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3. Geoscientific investigations: Stepwise approach

3.1 Overall strategy

In Phase I of the MIU Project, investigations with the specific aims as defined in Section 2.2.4 were conducted in five sequential steps.[1),2),3)]

In Sections 3.2 to 3.6, the results of the studies are compiled for each investigation step in terms of:

- Objectives of the investigations and analyses in each step
- A description of the investigations and an outline of the results/technical findings for each specific aim in each step
- A discussion of results and recommendations for further investigations from each step

A practical roadmap for the investigations and analyses addressing the specific aims in each step was prepared in the form of a geosynthesis data flow diagram based on experience obtained through the investigations in Phase I (see Appendix 4). The “existing information” in the geosynthesis data flow diagram indicates information obtained prior to the investigation step described.

The specific aims, for characterizing the important factors, vary according to the detail of the investigations. The relationship between the important factors to be characterized and the investigation step are shown in Table 3.1-1.

In Section 3.7, the conclusions of the stepwise investigation are described and the issues to be addressed in Phase II and III onwards are summarized.

The specific aims relating to the environmental impact assessment are summarized in Section 3.8. For the Phase II investigations, predictions of the deep geological environment and its changes near the shafts and galleries are summarized in Section 3.9.

The technologies and techniques for the geoscientific investigations, which were developed through the investigations in Phase I, are summarized in Chapter 4.

Table3.1-1 Important factors to be characterized in each investigation step

	Important factors to be characterized	Data requirements	Step 0	Step 1	Step 2	Step 3	Step 4
Safety assessment	Geological structure	Size and geometry of host rock; heterogeneity within host rock	x	x	x	x	x
		Size and extent of surrounding formations	x	x	x	x	x
		Spatial distribution and geometry of transport pathways (groundwater flowpaths)	x	x	x	x	x
	Groundwater flow characteristics	Spatial variability of magnitude of hydraulic gradient	x	x	x	x	x
		Spatial variability of hydraulic properties of rocks	x	x	x	x	x
	Geochemical characteristics of groundwater	Redox conditions	x	-	x	x	-
		Spatial variability of groundwater pH values	x	-	x	x	-
		Spatial distribution of different groundwaters; degree of groundwater mineralization	x	-	x	x	-
	Transport/retardation of nuclides	Sorption capacity and diffusivity of rock matrix and of transport pathways	x	-	-	x	-
		Geometry of transport pathways; depth of diffusion-accessible rock matrix	x	-	-	x	-
		Effect of colloid/organics/microbes on nuclide transport/retardation	x	-	-	-	-
	Dilution of nuclides	Spatial distribution of higher-permeability rocks, aquifers and surface waters	x	x	x	x	x
		Spatial variability of water fluxes in higher-permeability rocks, aquifers and surface waters	x	x	x	x	x
Designing & construction of underground facilities	Geomechanical/hydraulic properties of tunnel near-field environment	Local stress regime	x	-	x	x	-
		Spatial variability of petrophysical/geomechanical properties of rocks	x	-	x	x	-
		Volume of inflow into underground tunnels	x	-	x	x	x
		Size and structure of EDZ; petrophysical/geomechanical properties of EDZ	x	-	-	x	-
		Distribution of discontinuities intersecting underground tunnels	x	x	x	x	x
	Subsurface thermal conditions	Spatial variability of geothermal gradient	x	-	x	x	-
		Thermal rock properties	x	-	x	x	-

References

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3.2 Step 0 investigations

For studies using existing information, information from the literature, geological maps, RHS, geoscientific studies in the Tono mine and investigations at the Shobasama Site (as part of the MIU Project) were collected and reviewed with the aim of obtaining an overview of the specific aims as outlined in Table 3.1-1.

The main literature sources collected in this step are listed in Table 3.2-1.

RHS: Regional Hydrogeological Study

The aim of the RHS was to develop techniques for investigation, analysis and assessment of geological environment, such as geological structures, groundwater flow and groundwater chemistry in rock formations. The study extended from the surface to deep underground, over an area of several square kilometers covering the recharge area and discharge areas for deep groundwater flow.

The results of the RHS conducted prior to the commencement of Phase I of the MIU Project are summarized below[21),22)].

- On the regional-scale, groundwater flow analyses were conducted for several regions considering the characteristics of the hinterland topography. Based on this, the local-scale model domain was specified.[23),24)]
- In the local-scale domain, investigations were conducted as described below (see also Appendix 1).
- With the emphasis on acquiring data on the distribution of the geology and large-scale discontinuities at the surface and geological structures in the near-surface zone, remote sensing techniques (e.g. interpretation of aerial photographs), airborne geophysical surveys (e.g. electromagnetic, magnetic and radiometric surveys), ground geophysical surveys (reflection seismics, refraction seismics and high resolution electromagnetic surveys (Fig. 3.2-1)) and geological mapping were conducted[25),26),27),28),29),30),31)]. In particular, the geological structures in the near-surface zone, including the unconformity between the Mizunami Group and the Toki Granite, could be identified by ground geophysical surveys such as reflection seismics covering a wider area (Fig. 3.2-2).
- Surface hydrological investigations and meteorological observations were conducted[32),33),34)] and surface hydrological data for estimation of recharge rate were obtained. Sampling of precipitation and surface water were also conducted[37),38),39)] in order to obtain geochemical data of surface waters.[13)]
- Borehole investigations were conducted using several boreholes[28),40)]. The spatial distribution of large-scale discontinuities such as faults, a rough classification of rocks based on structural features (e.g. fracture zones), the distribution of hydraulic characteristics and groundwater chemistry were evaluated (see also Appendix 3, 5)[13),27),41),42),43)]. Long-term hydraulic monitoring was commenced following the completion of borehole investigations[26)].
- A 3-D local-scale geological model (10km x 10km; Fig. 3.2-3), a 3-D local-scale hydrogeological model (10km x 10km; Fig. 3.2-4) and a 2-D local scale hydrochemical model (10km; Fig. 3.2-5) were developed based on results of the investigations[44),45),46),47),48)].
- The distribution of the hydraulic gradient was estimated by groundwater flow analyses using the hydrogeological model, and the domain and the boundary conditions for the site-scale groundwater flow analyses were established (Fig. 3.2-6)[44),45)]. The adequacy of the results of the groundwater flow

analyses was evaluated by comparing them with data from long-term hydraulic monitoring and checking consistency with the hydrochemical model.

- Data on the initial stress and petrophysical/geomechanical/thermal characteristics of the rock were obtained and those were reflected in the concept and basic design of underground facilities[49].

Geoscientific studies in the Tono mine

Major results from the geoscientific studies in the Tono mine are summarized below[51,52,53,54]:

- Technical knowledge and information on the geological environment, including the geological, hydrogeological, geochemical, solute transport and rock mechanical characteristics, and excavation damage, from the geoscientific study in Tertiary sedimentary rocks that host uranium ore bodies.
- The uranium deposits made it possible to carry out natural analogue studies on geological processes and the associated changes in the geological environment occurring over long timescales.
- Studies of the mechanical stability of the rock allowed methods to be developed for evaluating long-term behavior and for performing and modeling long-term rock creep tests.
- Investigations of the geological environment around the tunnel allowed a method to be developed for measuring the long-term evolution of the hydrogeological/geochemical conditions in the sedimentary rock and for determining the mechanisms involved.

Shobasama Site investigations

Major results of the investigations at the Shobasama Site are summarized below:

- Reflection seismic surveys were conducted at the Shobasama Site to estimate the near-surface geological structure.
- The spatial distribution of Tsukiyoshi Fault was confirmed, and a rock classification based on the characteristics of the geological features and the distribution of hydraulic characteristics were determined based on data from several boreholes (see Appendix 3, 6)[27,55].
- The low hydraulic conductivity of the Tsukiyoshi Fault was confirmed and the hydraulic connectivity of fractured zones along the fault was confirmed by crosshole hydraulic tests using several boreholes[56,57,58].
- A 3-D geological model (Fig. 3.2-7) and a 3-D hydrogeological model were developed based on data from the investigations[59,60,61,62,63,64].
- Data on the initial stress and the petrophysical/geomechanical/thermal characteristics of the rock were obtained as input for the basic design of the underground facilities[65,66,67]. Using a rock mechanical model developed based this information, numerical analyses were conducted to estimate the degree of damage on the rock surrounding the research galleries associated with the excavation of the galleries[66,67].

In the Step 0, a geological conceptual model was developed (Fig. 3.2-8) based on available literature data and by interpreting the above investigation results. Geological, hydrogeological, hydrochemical and rock mechanical models were also developed for the site scale. Based on these models, analyses of groundwater flow and stress/excavation were conducted to estimate the groundwater flow condition at site scale and rock mechanical conditions around the underground facilities and to identify the key factors for the investigations and analyses in the next and subsequent steps.

The geosynthesis data flow diagram constructed based on the results of the investigations and analyses during this step is shown in Appendix 4 and the details of the approach used to address the specific aims are summarized in Sections 3.2.1 to 3.2.9. The key factors for investigations in the next and subsequent steps identified based on the investigations in this step are summarized in Section 3.2.10. The basic techniques for the disposal project and formulation of the safety regulations established through the investigations in this step are also summarized in Section 3.2.10.

Table 3.2-1 Principal literature used for the study

Discipline	Type of information	Literatures
Geology	Stratigraphical and Lithological data	Matsuzawa and Uemura, 1967[1)] Itoigawa, 1980[2)] Ishihara and Suzuki, 1969[3)] Todo collaborative research group, 1982[4)] Power reactor and nuclear fuel development corporation, 1994[5)] Yamanoi et al, 1996[6)]
	Structural data	Power Reactor and Nuclear Fuel Development Corporation, 1987[7)] Imanura and Kato, 1990[8)] Yamanoi et al, 1994[9)]
Hydrogeology	Hydraulic data	Umeda et al, 1997[10)] Ishibashi and Yamada, 1986[11)]
Hydrochemistry	Hydrochemical data	Mikai and Hayakawa, 1970[12)] Furue et al., 2003[13)]
Rock mechanics	Initial stress data	Kanagawa et al., 1986[14)] Saito et al, 1988[15)] Association for the Development of Earthquake Prediction, 1990[16)]
	Petrophysical data	Sato et al, 1992[17)] Sato et al, 1999[18)] Hoshino et al, 2001[19)]
	Thermal data	Geological Survey of Japan, 1991[20)]

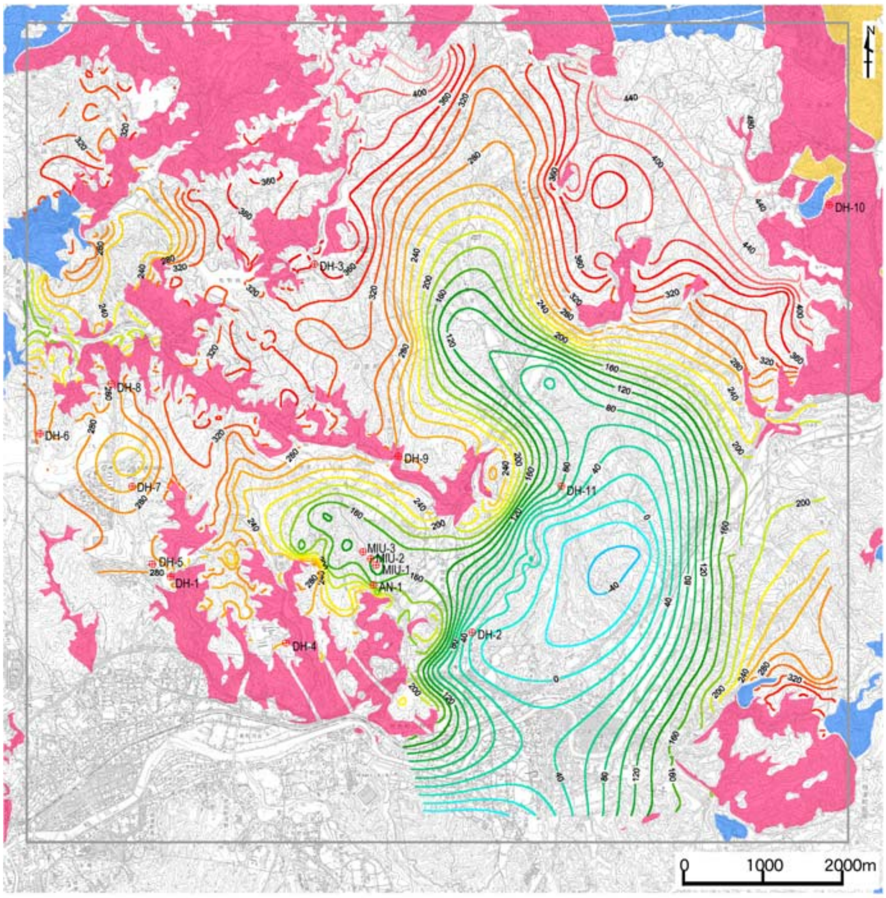


Fig. 3.2-1 Elevation of unconformity between Toki granite and Mizunami Group, determined by the electoromagnetic survey

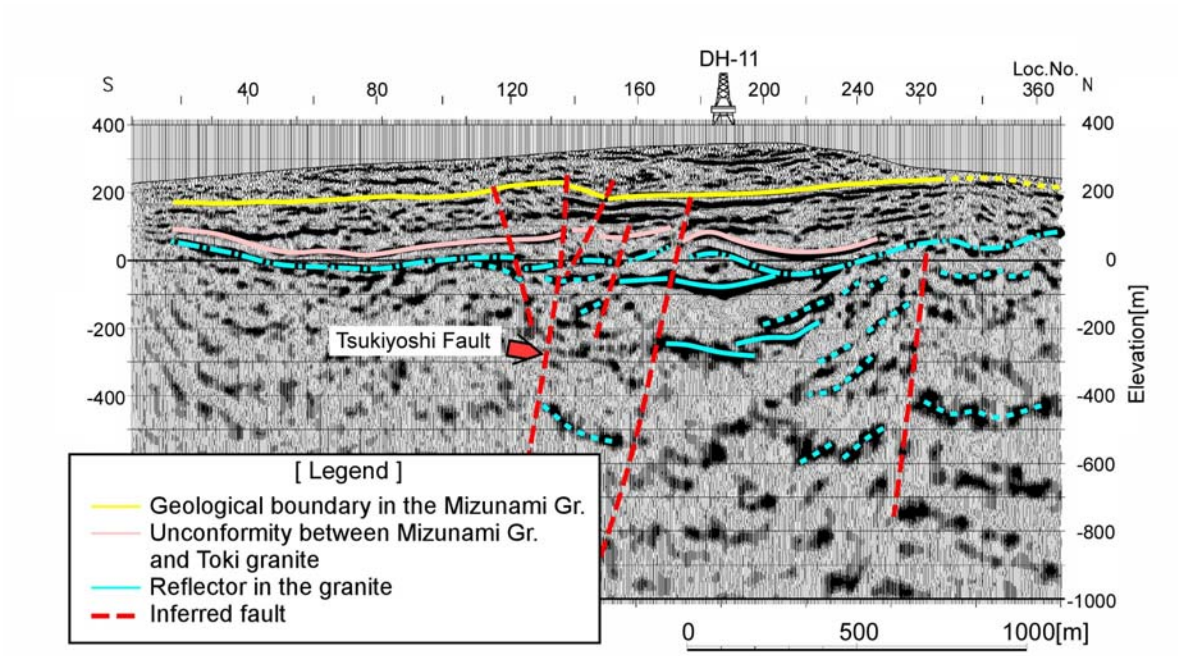


Fig. 3.2-2 Geological interpretation based on the results of reflection seismic survey in the RHS[21)]

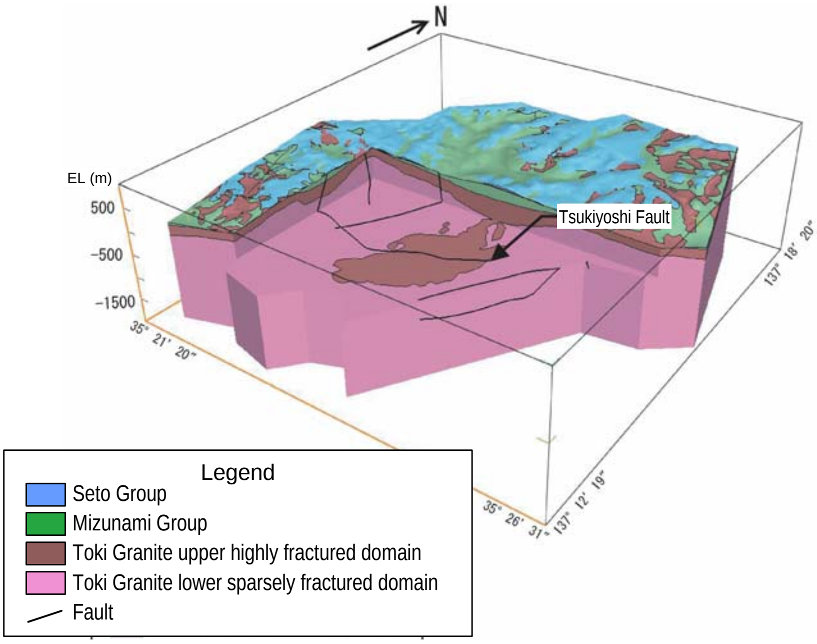


Fig. 3.2-3 Geological model on the Local scale[44)]

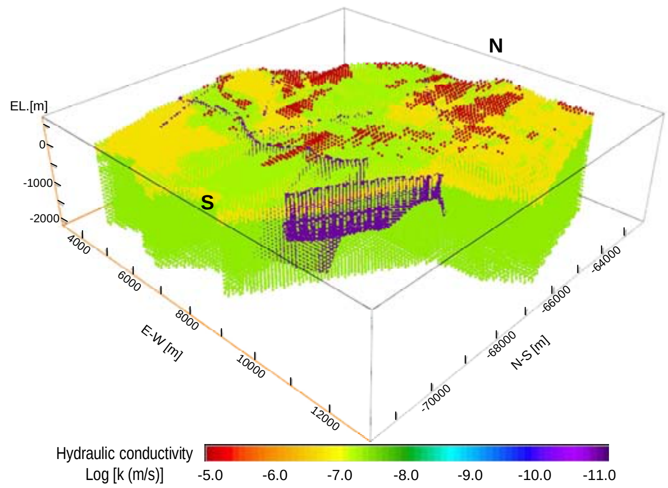


Fig. 3.2-4 Hydrogeological model on the Local scale[44)]

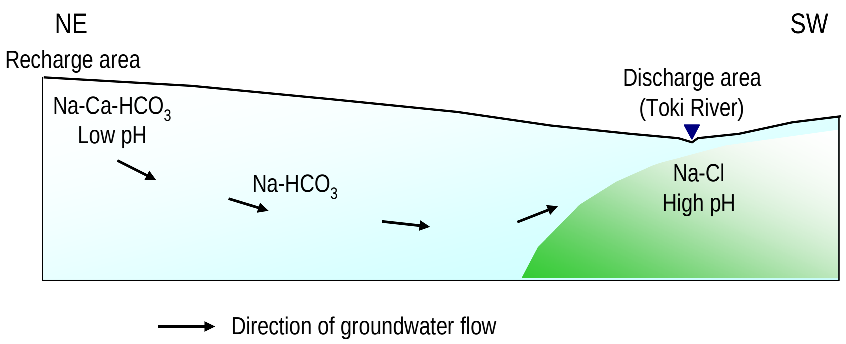


Fig. 3.2-5 Groundwater type on the Local scale[44)]

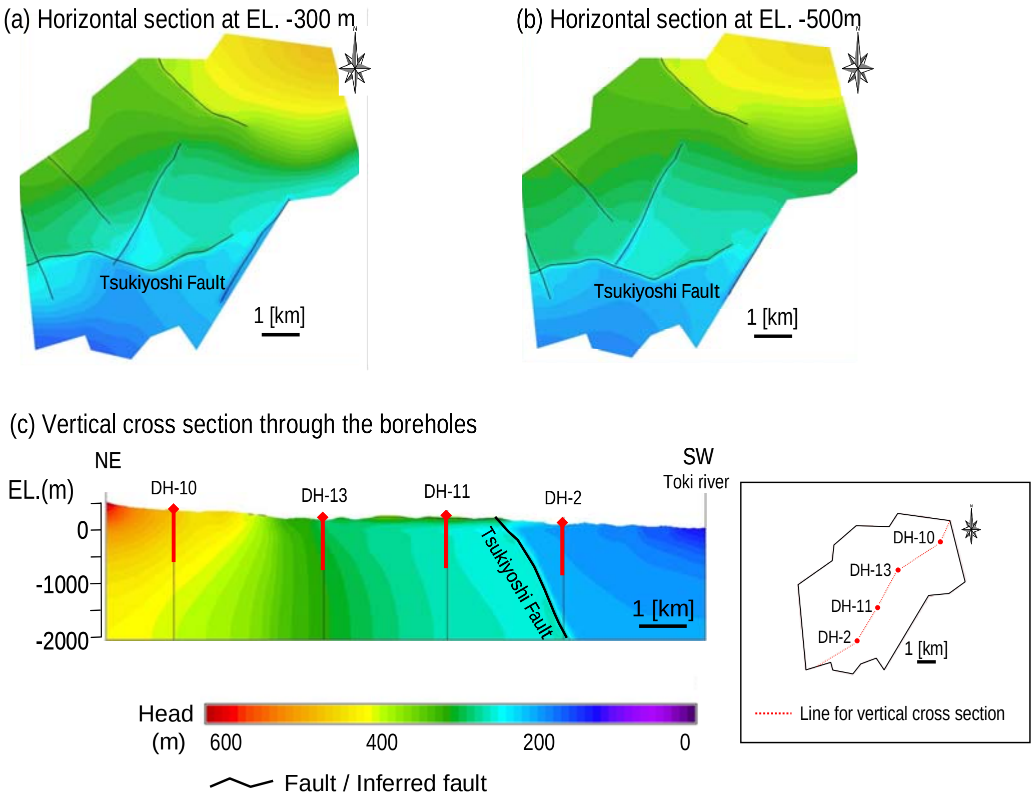


Fig. 3.2-6 Results of groundwater flow simulation on the Local scale[44)]

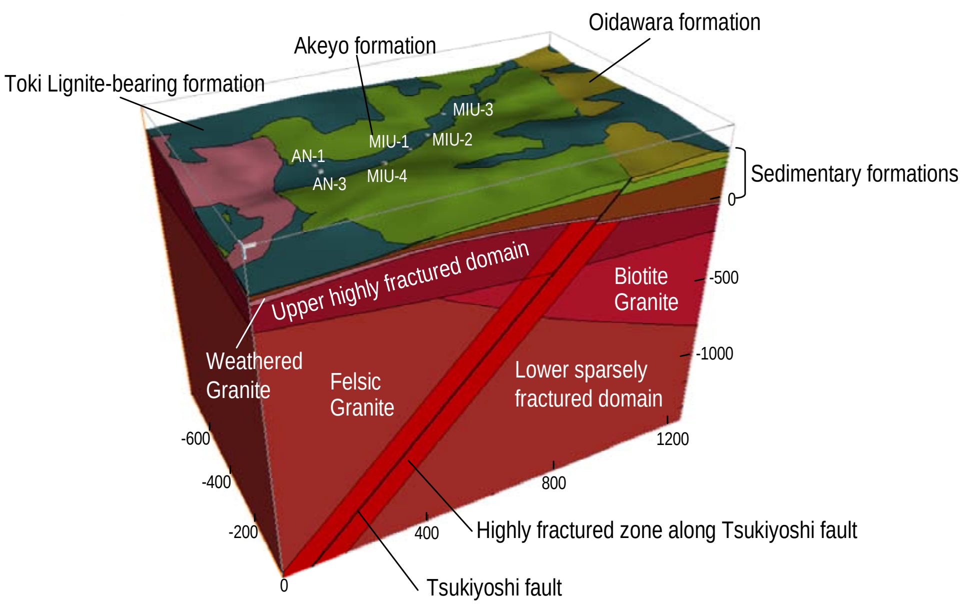
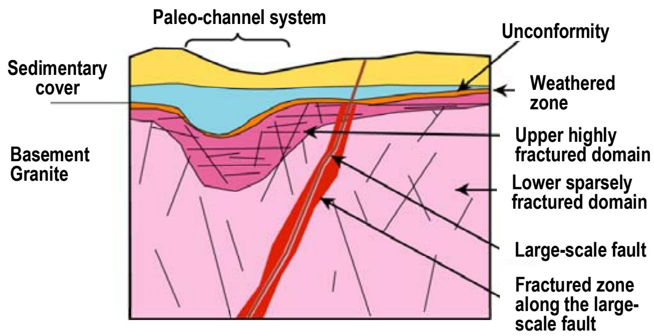


Fig. 3.2-7 Geological model at the Shobasama Site



General description of the conceptual geological model
- Sedimentary rocks widely and unconformably cover the basement granite.
- The eroded surface of the weathered zone of the granite basement is underlain by the unconformity between the sedimentary cover and the basement granite. The paleo-channel systems that has a significant elevational change of the unconformity can be observed in the region with a thick sedimentary cover.
- The basement granite is structurally divided into the upper highly fractured domain (UHFD) and the lower sparsely fractured domain (LSFD) based on the fracture frequency of low-angle fractures.
- Joints and faults of varying scale are formed in the basement granite.
- Some large-scale faults act as major conduits or hydraulic barriers.

Fig. 3.2-8 Geological conceptual model[68]

3.2.1 Geological structure

The studies conducted to determine the 3-D distribution of geological structure (size and geometry of host rock and extent of surrounding formations and spatial distribution and geometry of transport pathways (groundwater flowpaths)) on the site scale based on existing information included collecting data on the distribution of the Toki Granite, the Mizunami Group (Oidawara Formation, Akeyo /Hongo Formation, the Toki Lignite-bearing Formation), the Seto Group and discontinuities that are considered to influence groundwater flow. This step involved developing a geological conceptual model by interpreting existing literature data and the results of the studies conducted on the regional and local scales (Fig. 3.2-8). The 3-D distribution of the geological structure on the site scale was estimated using the local-scale geological model, resulting in an initial geological model on the site scale[22),26),27),69),70)]. In developing the site-scale model, the consistency and adequacy of data and the characteristics of the geological structures at the MIU Construction Site were examined by comparing and scrutinizing existing geological maps[22)].

Results

The distribution of the Toki Granite, the Mizunami Group, the Seto Group and the Tsukiyoshi Fault were considered to be the major geological structures in the site-scale area, based on the local-scale geological model[69)]. Consistency with existing geological maps[5)] was confirmed[70)]. Scaling down from the local to the site scale increased the level of detail that could be identified. The formations of the Mizunami Group and the Seto Group and the upper highly fractured domain occurring in the upper part of the Toki Granite (rock zone with a high density of fractures dipping at low angles (0-30 degrees) were identified and the first site-scale geological model was developed (Fig. 3.2.1-1: geological map (left) and geological model (right))[22)]. One of the reasons for the upper highly fractured domain could be the occurrence of a relatively large stress release at the bottom of the valley covered by thick sedimentary rock, leading to the formation of a horizontal extension joint associated with stress release[71)]. The geological events in the area that provide evidence of such stress release include erosion and denudation[1),2),72)] and the removal of seawater load associated with regression during the deposition of the Mizunami Group and the Seto Group. The unconformity between the undulating Toki Granite and the Mizunami Group (particularly the topography distributed from the Tono mine to the MIU Construction Site – the so-called Tsukiyoshi Channel)[68)] was confirmed as a unique geological structure at the MIU Construction Site (Fig. 3.2.1-2).

During the early stage of the investigation program, it was widely known that lineament surveys are a quite efficient method for basic understanding of large-scale fault distributions in targeted basement rocks. [e.g. 73), 74), 75), 76), 77)] From an examination of previous regional studies (i.e. RHS), around 30 lineaments with lengths of a few hundred meters to a few kilometers were identified in the site-scale area through interpretation of satellite and aerial photographs[9),31)]. With the use of empirical length criterion on fault-related lineaments[78)], one of the lineaments which is longer than 3 km was incorporated into the local-scale geological model.[22)] It was also modeled as a possible fault in the site-scale model.

Conclusions and implications for the next investigation step

The relationship between the length and frequency of the lineaments[31)] (Fig. 3.2.1-3) showed fractal characteristics (Fig. 3.2.1-4), as was found in previous studies[79)], and indicated a distribution trend more or less consistent with the discontinuities that were confirmed or predicted in the local-scale investigations (e.g. geological mapping and borehole investigations)[28),31)]. In addition, considering the accuracy of the identified lineaments (20-60 m uncertainty perpendicular to the length of the lineament[31)]), the lineament distribution on the site scale could be used for overall estimation of the distribution and locations of discontinuities; it provided useful input for selecting the investigation layout in the next and subsequent steps.

The results of petrological and mineralogical characterizations using core samples collected at the Tono mine and around the MIU Construction Site indicated that the Toki Granite plots in the granite field in the quartz-plagioclase-potassium feldspar diagram[80)], its mineral and chemical composition does not change significantly with depth[81)] and the Toki Lignite-bearing Formation in the Mizunami Group consists of quartz, feldspar, biotite, clay minerals and calcite. Identification of the lithofacies was possible by visual inspection of mineral composition[82)]. The fracture-filling minerals of the granite consist of more than 50% quartz and feldspars, a few to several 10% of clay minerals (mica, smectite) and calcite and less than a few % of biotite, chlorite and epidote, which are distributed heterogeneously[70)].

Since the geological model in this step was developed by estimating geological structures on the site scale using local-scale data, in the next and subsequent steps it was considered essential to confirm the distribution of the Toki Granite, the Mizunami Group and the Seto Group on the site scale and to check the existence of possible discontinuities that are not described in existing geological maps. The latter includes also the verification of interpreted lineaments as actual discontinuous features.

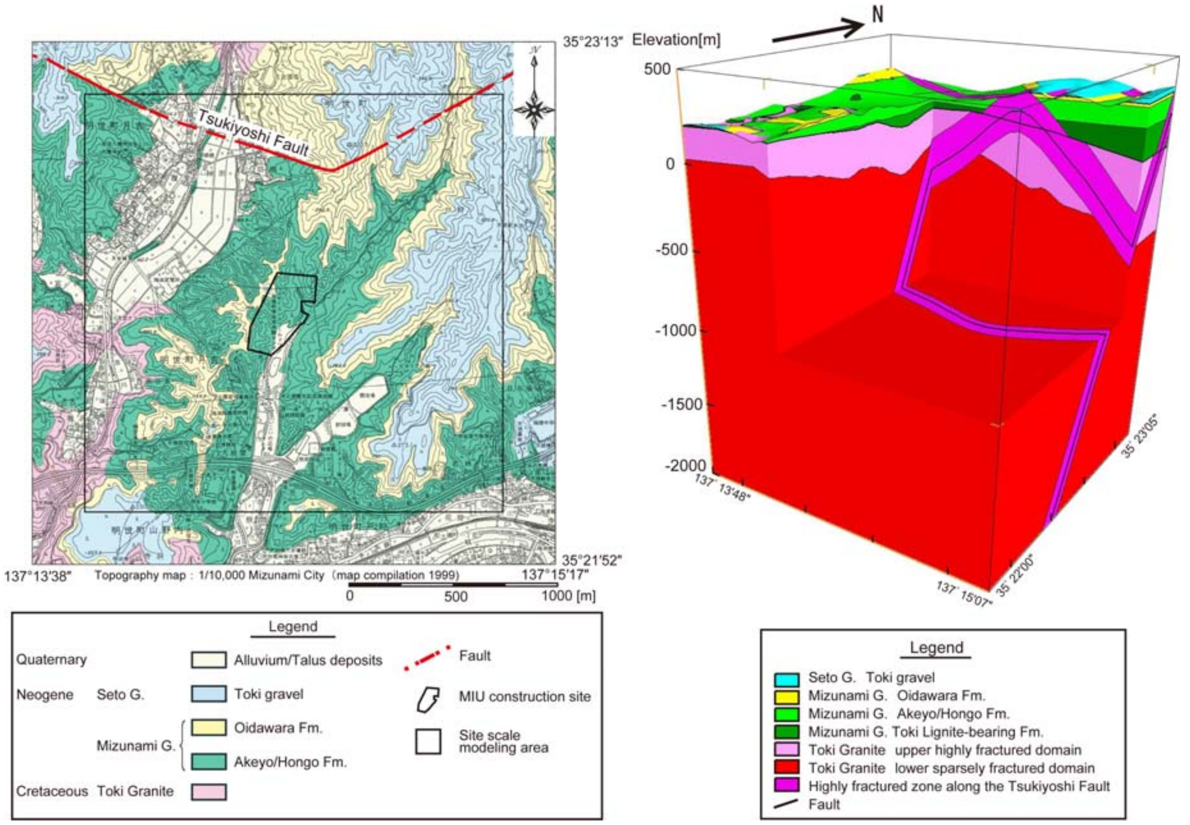


Fig. 3.2.1-1 Geological map and geological model based on the existing geological information[22)]

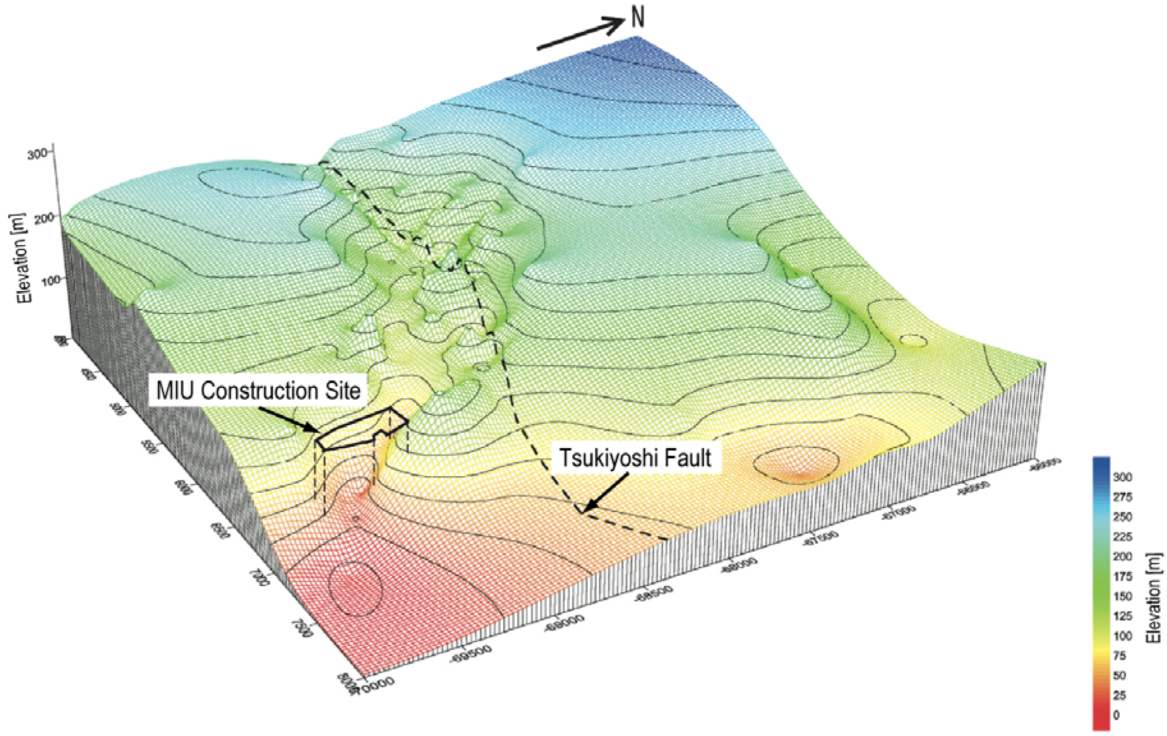


Fig. 3.2.1-2 Elevation of the unconformity between Toki granite and Mizunami Group[68)]

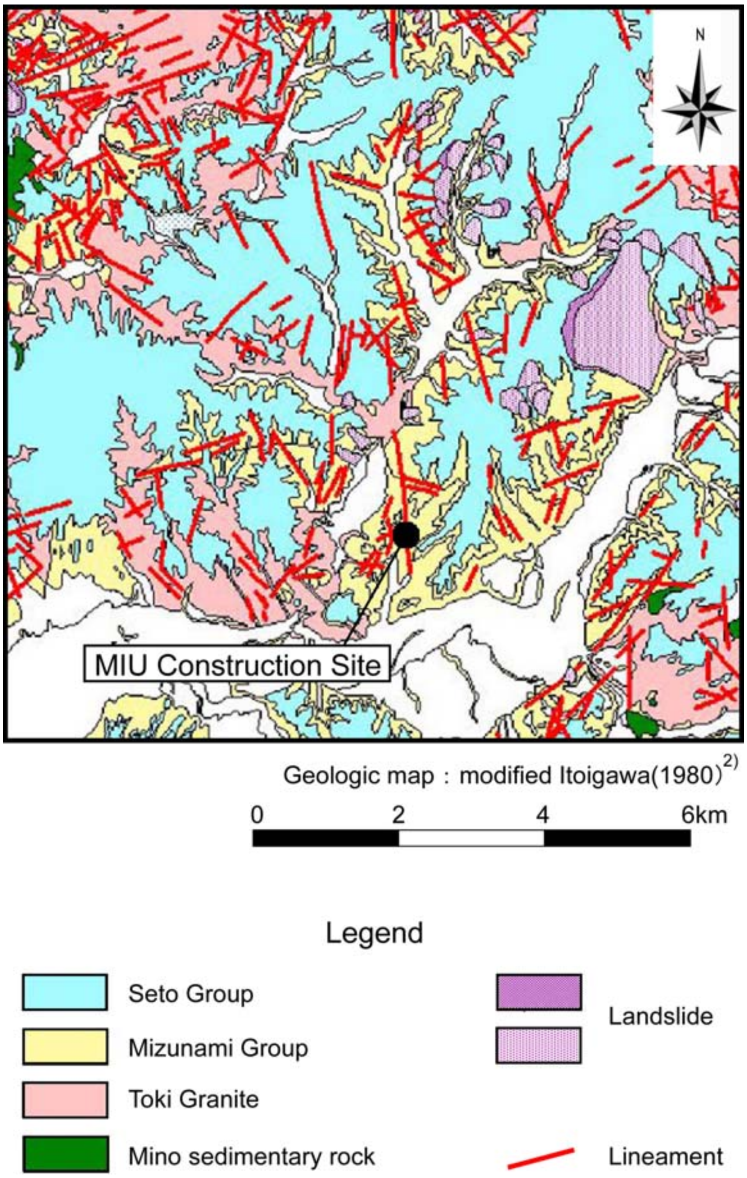


Fig. 3.2.1-3 Lineament interpreted from aerial photographs of a scale of 1:10,000[31)]

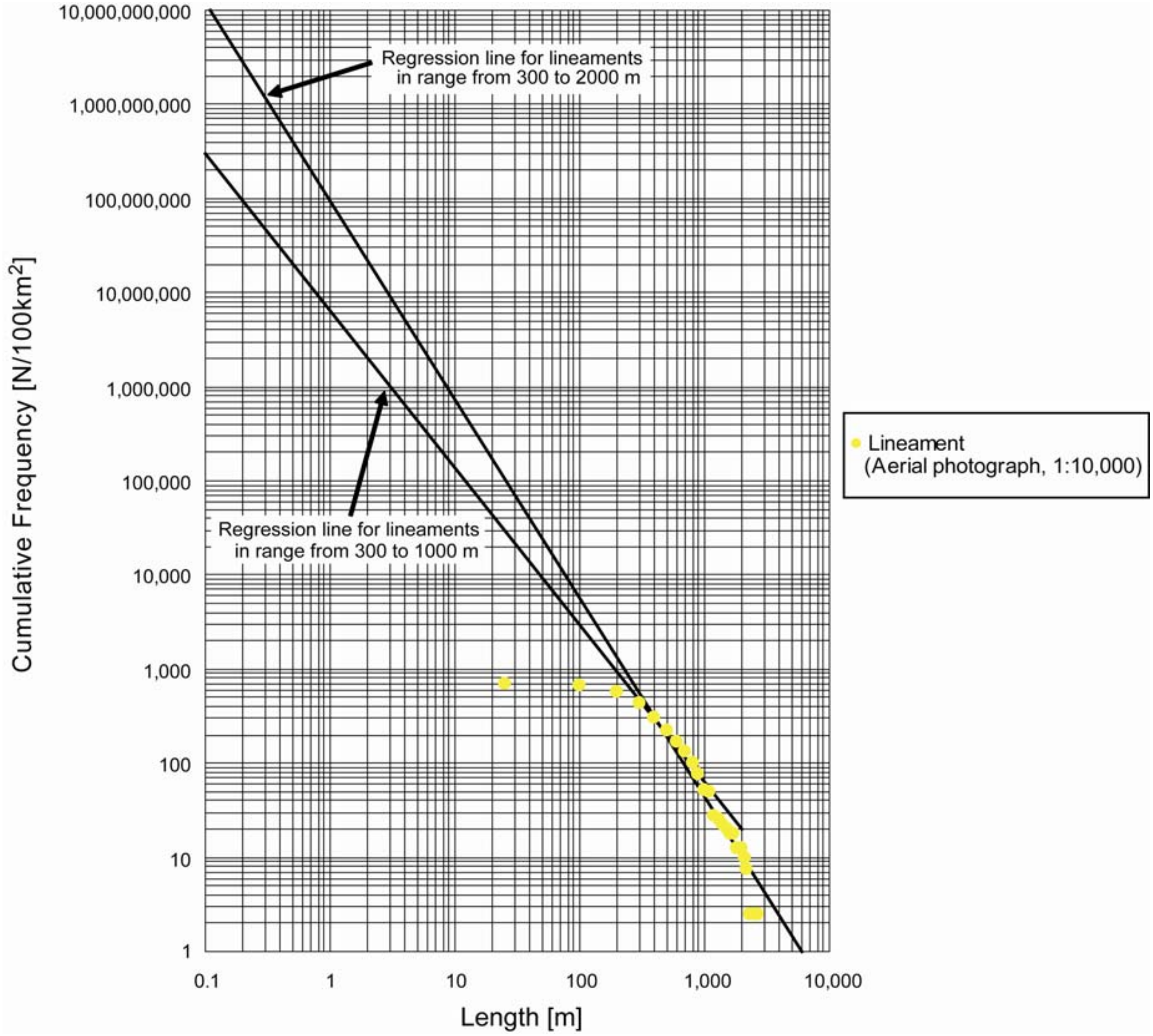


Fig. 3.2.1-4 Cumulative frequency distributions -lineament lengths[31)]

3.2.2 Groundwater flow characteristics

In the studies using existing information, the results of single-hole hydraulic tests were reviewed for each geological unit included in the geological model (see Section 3.2.1) developed in this step and their hydraulic conductivity was determined[83)].

A 3-D hydrogeological model was constructed and groundwater flow analyses were conducted using this model to determine the distribution of the hydraulic gradient on the site scale[83)]. The geological and hydrogeological modeling and the groundwater flow analyses were utilized the GEOMASS system (see Section 4.10).

Results

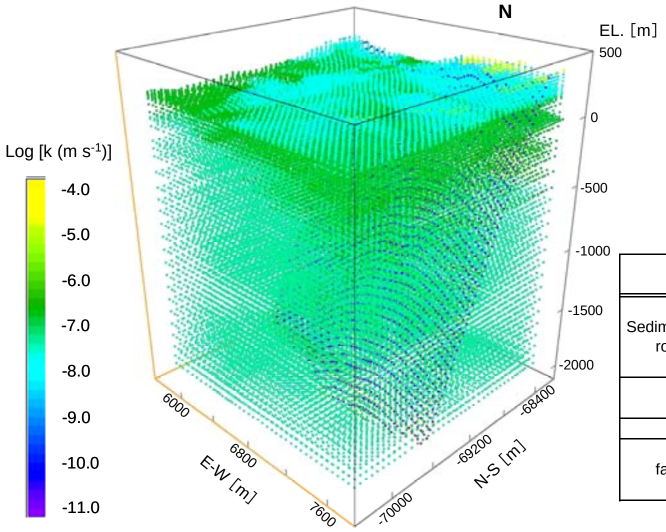
The hydrogeological model developed in this step and the hydraulic conductivity of each geological unit/geological structure are shown in Fig. 3.2.2-1. When developing the hydrogeological model, it is reasonable to classify formations according to the contrast in their hydraulic conductivity. The results of single-hole hydraulic tests were reviewed for each geological unit/geological structure included in the geological model. The variability of the hydraulic conductivities in each geological unit is characterized by a log-normal distribution. A hydraulic contrast of an order of magnitude was defined as the criterion to include a geological unit/geological structure as a separate hydrogeological unit in the model. The geometric mean values were taken as the representative values of the hydraulic conductivity of a unit/structure. As the Mizunami Group consists of sedimentary rocks, from a hydrogeological point of view, a classification based on stratigraphic and lithofacies data is more appropriate for the hydrogeological model; for the Toki Granite which consists of fractured rock, a classification based on fracture density is more appropriate.

To determine groundwater flow characteristics in a particular area of interest, the area should preferably represent a closed groundwater flow system (e.g. watershed) with natural groundwater flow boundaries. However, if the domain boundary was to be set like this also for groundwater flow in the deep underground environment, the analysis domain for characterization of groundwater flow would need to be extended, thus reducing the accuracy of the analysis results. In order to avoid such reduced accuracy when analyzing the groundwater flow on the site scale[77)], the analysis on the local scale was conducted by setting the lateral boundary condition as a distribution of hydraulic head. The local-scale domain for groundwater flow analysis includes the site-scale area as well as the recharge and discharge areas[44)]. Information on recharge rate into the rock, which can be estimated from river flux, precipitation and evapotranspiration, and groundwater levels can be used for setting the top boundary conditions for the groundwater flow analyses.

In order to determine the distribution of the hydraulic gradient on the site scale, the 3-D distribution of the hydraulic head was derived based on the results of the groundwater flow analysis at the site scale (Fig. 3.2.2-2). The principal direction of groundwater flow in the site-scale area is from north-east to south-west, which is in line with the overall topography. This direction on the site scale was confirmed to be consistent with the results of the groundwater flow analysis[44)] on the local scale, suggesting that the method of setting the above lateral boundary condition was appropriate. Fig. 3.2.2-2 shows that the distribution of hydraulic head is significantly different in zones of the Tsukiyoshi Fault, which is characterized as anisotropy of hydraulic conductivity (see Section 3.2 –*Shobasama Site investigations*) also influencing the hydraulic gradient. This indicates that discontinuities such as faults may have a significant impact on groundwater flow characteristics and that determining the distribution and geometry of such discontinuities is essential from a hydrogeological perspective. Furthermore, when the boundary conditions are established based on an analysis of the groundwater flow in a wider area, an analysis should be conducted considering discontinuities including faults that are distributed in the vicinity of the boundary itself.

Conclusion and implications for the next investigation step

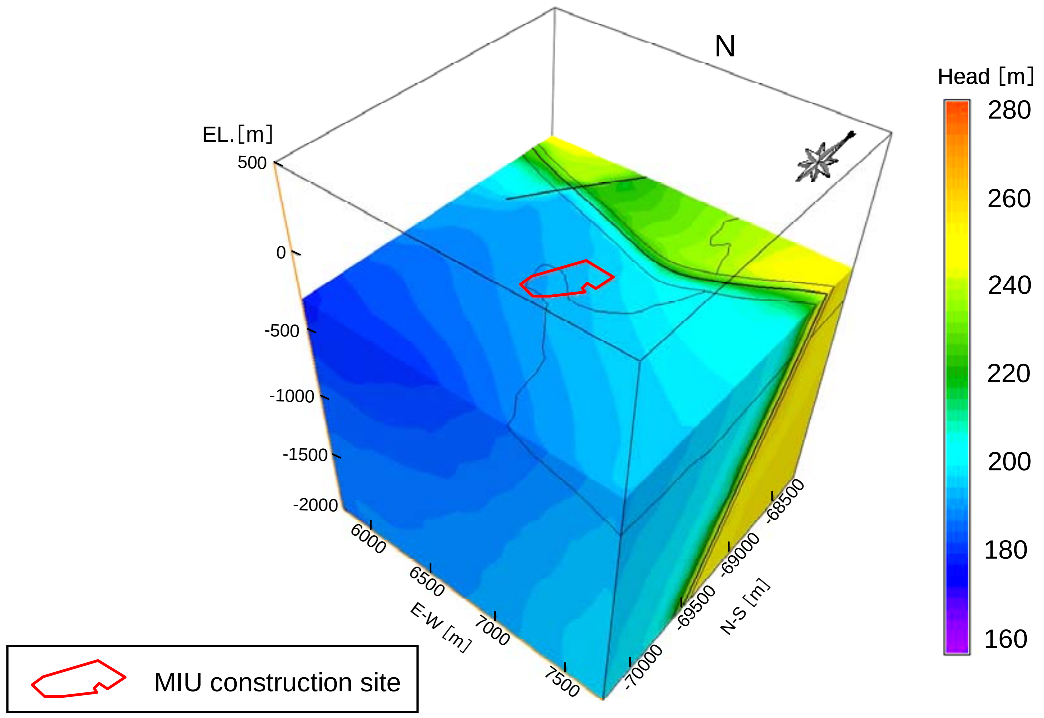
For the next and subsequent steps, it was considered important to determine the distribution and geometry of discontinuities such as faults by investigations in the site-scale area, which should be taken into account in developing a geological/hydrogeological model and analyzing groundwater flow.



Hydraulic conductivity

Geological features and structural elements			Log [k(m s^{-1})]
Sedimentary rock	Seto Group		-5.0
	Mizunami Group	Oidawara Formation	-8.5
		Akeyo/Hongo Formation	-7.8
		Toki-lignite bearing Formation	-7.0
Toki granite		Upper highly fractured domain	-6.7
		Lower sparsely fractured domain	-7.4
Highly fractured zone along the Tsukiyoshi fault			-6.4
fault	Main part of Tsukiyoshi fault		-11.0
	Other faults	Parallel to fault	-5.2
		Normal to fault	-11.0

Fig. 3.2.2-1 Hydrogeological model (3-D distribution of hydraulic conductivity)



※Refer to Fig. 2.2.2-2 for location of Site scale area

Fig. 3.2.2-2 Head distribution (Elevation -300 m : Depth of the shaft 500 m)

3.2.3 Geochemical characteristics of groundwater

During the studies using existing information, the geochemistry of the groundwater in the site-scale area was evaluated and a 3-D distribution of groundwater chemistry was produced based on the results of the hydrochemical analyses and information on geology and groundwater flow[26] on the local scale (including the site scale). The findings were reflected in the planning of borehole investigations and the studies in the research galleries.

Results

For the local scale area, data on groundwater chemistry, groundwater pH value and redox conditions had been obtained mainly from borehole investigations carried out as part of the RHS. Using these data, the spatial distribution of the geochemical characteristics of the groundwater between the boreholes and in the site-scale area were estimated using the kriging method[84] with the SURFER software developed by Gold Software Co.. Based on the available data and the kriging interpolation, the groundwater in the granite in the south part of the site-scale area was found to be Na-Cl type, the concentration of chloride ions increases with depth[48], the pH value of the groundwater is mildly alkaline and the redox conditions were estimated to be weakly to strongly reducing (Fig. 3.2.3-1). Mass balance analysis and multivariate analysis[48] indicated that the geochemistry of the groundwater in the site-scale area could be explained by the mixing of four groundwaters with different chemistries (meteoric water, Na-(Ca)-HCO_3 type groundwater, diluted Na-(Ca)-Cl type groundwater and concentrated Na-(Ca)-Cl type of groundwater). One of the main processes determining groundwater chemistry was thus identified as being the mixing of the groundwaters with different chemistries.

Na-Ca-Cl type groundwater with a salinity of several thousand mg l^{-1} has been pumped from a depth of around 1,300 m at a hot spring (Takasago hot spring in Mizunami City) located 3 km south-east of the site-scale area[13]. The data from this hot spring were not included in Fig. 3.2.3-1 because their quality is not clear. In this figure, data on groundwater chemistry in borehole DH-2 (located at the vicinity of boundary of the MIU Construction Site) collected down to a depth of 500 m were used and the distribution of groundwater chemistry in the zone deeper than 500 m was therefore uncertain. Thus, Na-Ca-Cl type groundwater with salinities higher than the estimated level (a few thousand mg 1^{-1}) shown in Fig. 3.2.3-1 may be present deep underground in the site-scale area. Investigation of the distribution of Na-Ca-Cl type groundwater was identified as an important issue to be addressed in Step 1 and subsequent steps. The distribution of groundwater chemistry (Fig. 3.2.3-1) and their relationship/consistency with the distribution of hydraulic heads (Fig. 3.2.3-2) by comparing the distributions and confirming their consistency was an additional objective for the subsequent investigations.

Conclusions and implications for the next investigation step

For the areas where high-salinity groundwater is present and a depth dependence of the concentration is seen, the evolution process of groundwater chemistry (e.g. mixing of groundwaters with different salinity) could be ascertained from 2-D distributions of the groundwater chemistry calculated with the kriging method, mass balance analysis and multivariate analysis.

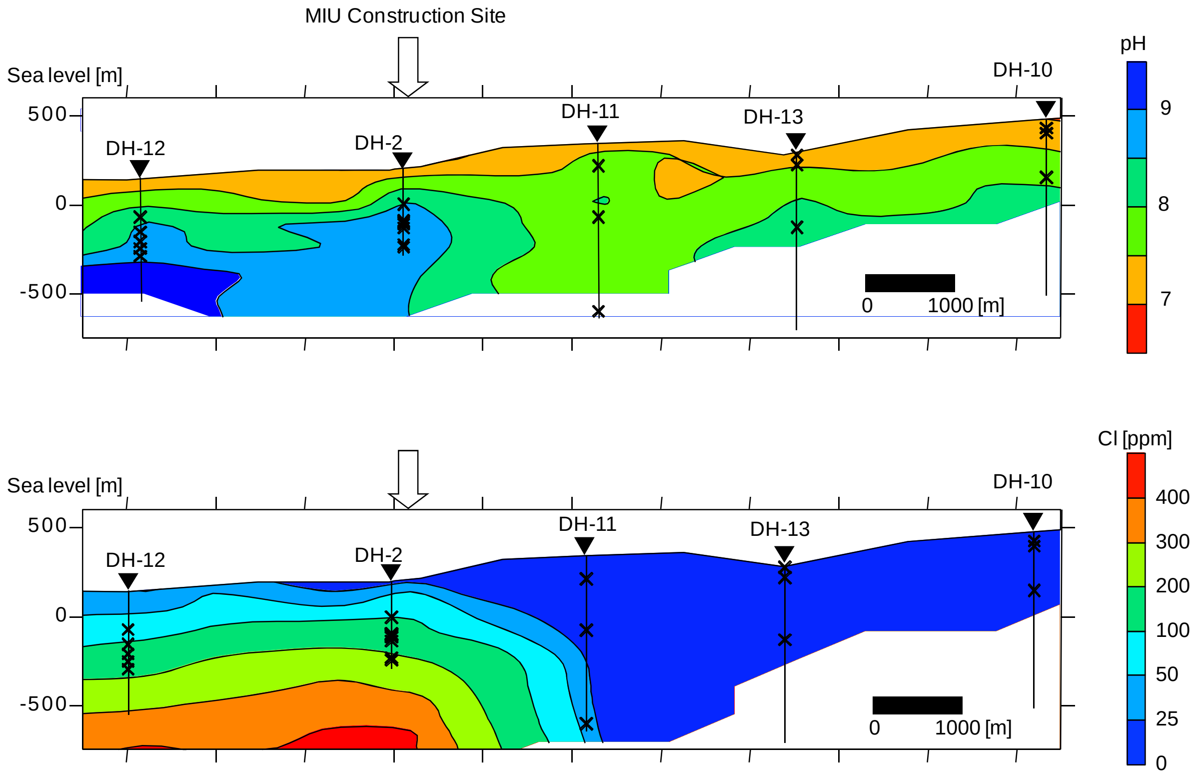


Fig. 3.2.3-1 Estimated distribution of groundwater chemistry (pH, Cl concentration)[48)]

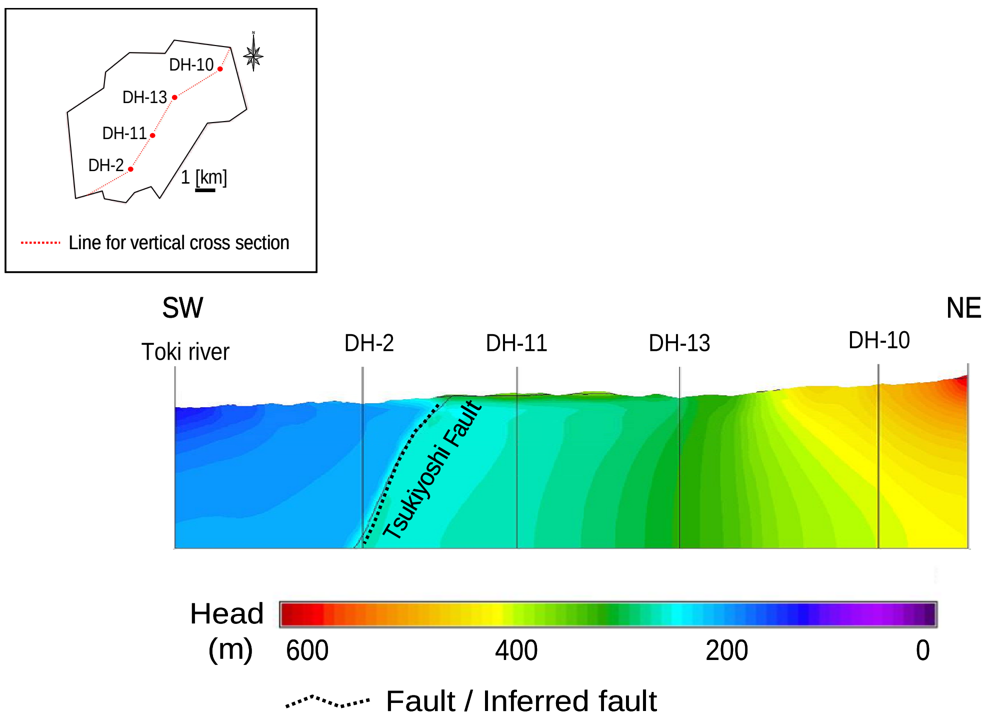


Fig. 3.2.3-2 Simulated head distribution of groundwater

3.2.4 Transport/retardation of nuclides

For the studies using existing information, relevant reference data to be used were compiled from previous investigations in the Tono area, which are RHS, geoscientific studies in the Tono mine and investigations at the Shobasama Site, and also from those on granite (Kurihashi Granodiorite) in the Kamaishi mine[85),86)]. This was done with the aim of understanding the sorption/diffusion characteristics of the rock, solute transport field in the rock (pore structures and porosities that affect solute transport) and the effect of colloids, organics and microbes on solute transport. Retardation of solute transport was evaluated based on information on sorption/diffusion coefficients, the pore structures and the geometry of water conducting fractures and element profiles in the vicinity of the fractures and the types and geochemical characteristics of colloids/organic matter and microbes in the groundwater, as well as petrological and mineralogical characteristics and petrophysical characteristics of rocks and geochemical characteristics of the groundwater obtained by local-scale investigations.

Results

With regard to the characteristics of solute transport in the Mizunami Group, it is understood from various investigations that the natural uranium in the Tono deposit was absorbed and mineralized and retained in the sedimentary rocks for a long period of time[87)]; limited data are available, however, on solute transport characteristics in the Toki Granite. An example is the co-precipitation of natural uranium due to the sedimentation/concentration of iron oxide near water conducting fractured granite[22)]. In the Toki Granite, it is assumed that a network of pore structures (such as mineral grain boundaries and small fractures) that could allow diffusion of materials is present and that a network of open channels contributing to solute transport is formed[87)]. In the matrix near water conducting fractures in the Toki Granite, matrix diffusion has occurred and represents the main retardation mechanism of natural uranium-series nuclides. The process of solute transport in the Toki Granite is the same as that in the Kurihashi Granodiorite[22),86)]. Based on these findings and given the similarity in mineralogical and chemical composition, the groundwater chemistry (Na-HCO_3 type), rock texture and distribution of pore structures[22)], sorption capacity and matrix diffusion in the Toki Granite may be assumed to be similar to those of the Kurihashi Granodiorite. Although data on sorption characteristics in Na-Cl type groundwater have not been obtained for both the Mizunami Group and Toki Granite at the MIU Construction Site, it would be possible to estimate sorption using data on similar rocks contained in the JNC-SDB sorption database[88),89)].

Conclusions and implications for the next investigation step

Data was obtained on the types and volumes of colloids/organic matter and microbes in groundwater[87),90)], but not on their interaction with materials. Also, since no data was available for the environment of groundwater chemistry (e.g. redox conditions and presence of Na-Cl type water) in the rocks of interest, the effects of the conditions of groundwater chemistry on solute transport could not be evaluated. Therefore, any data on the retardation of solute transport obtained in Step 0 was considered to contain a large uncertainty and the characteristics would need to be evaluated in detail through borehole investigations in the next and subsequent steps.

3.2.5 Dilution of nuclides

Concentration of solutes in the groundwater is diluted due to changes in groundwater flux along groundwater flow paths from low permeable rock zones to high permeable zones or high permeable structures[91]. Therefore, in this investigation, 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. The geological structures in the Tono area that could be expected to contribute to such dilution effects are the sedimentary rocks covering the Toki Granite and highly fractured zones along large-scale faults. These structures are considered to function as aquifers containing large volumes of groundwater. To evaluate dilution effects, the groundwater flux needs to be determined, as well as the geological structure (more specifically the cross-sectional area) and the distribution of volume of the groundwater flow. However, the cross-sectional area of an aquifer may not be easily understood due to its spatial heterogeneity. The dilution effect was therefore estimated by comparing the distribution of the Darcy velocity in the hydrogeological units assumed to form the aquifer that extend over a large area.

Results

In the hydrogeological model in this step (see Section 3.2.2), The Seto Group and the formations making up the Mizunami Group, the upper highly fractured domain and lower sparsely fractured domain of the Toki Granite and of the presence of discontinuities and the Tsukiyoshi Fault estimated from lineaments along the Hiyoshi River were modeled. The frequency distributions of the Darcy velocity were calculated for the formations constituting the Mizunami Group, the upper highly fractured domain, the lower sparsely fractured domain and the highly fractured zones along the Tsukiyoshi Fault, based on the results of the groundwater flow analyses discussed in Section 3.2.2 (Fig. 3.2.5-1). Compared to the Darcy velocity in the lower sparsely fractured zone in the Toki Granite, where the hydraulic conductivity is relatively low, the Darcy velocities were relatively high in the highly fractured zones along the Tsukiyoshi Fault, the upper highly fractured domain and the Toki Lignite-bearing Formation. It was thus suggested that these hydrogeological units are important when considering dilution effects.

Conclusions and implications for the next investigation step

In the next and subsequent steps, it was considered important to determine the 3-D distribution of the hydrogeological characteristics of the Toki Lignite-bearing Formation and the upper highly fractured domain. These are the hydrogeological units expected to be widely distributed in the site-scale area and are expected to function as the diluting formations, based on the distribution of the Darcy velocity calculated in this step.

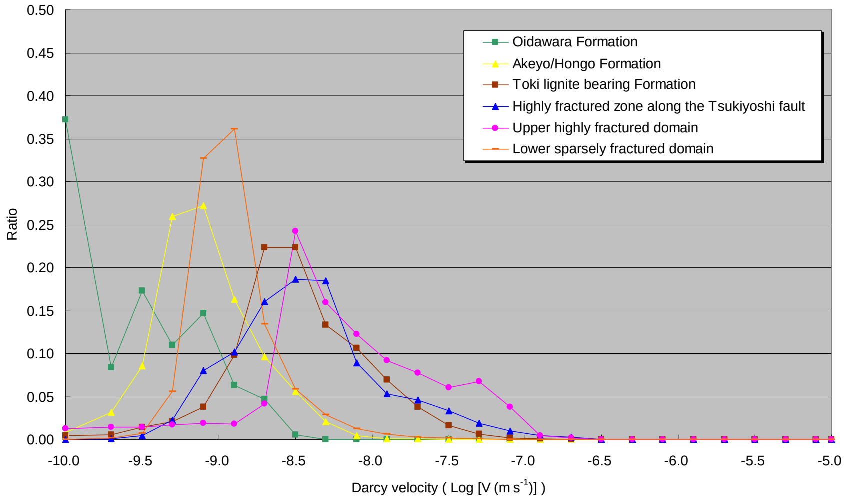


Fig. 3.2.5-1 Darcy velocity distribution
(The vertical axis shows the ratio (cumulative frequency is 1 in each geological formation and domain))

3.2.6 Local stress regime, spatial variability of petrophysical/geomechanical properties of rocks, and size and structure of EDZ

The goals of the studies using existing information are to collect information on the petrophysical/geomechanical characteristics of rock and initial stress states of the Toki Granite at the MIU Construction Site in order to develop a rock mechanical model and to estimate the distribution and evolution of the excavation disturbed zone (EDZ). The latter is defined herein as consisting of three zones: the excavation damaged zone, the unsaturated zone and the stress redistribution zone.

As a first step, the initial stress states and petrophysical/geomechanical characteristics of rock were determined and a rock mechanical model developed using data from the borehole investigations conducted at the Shobasama Site. The effects of tunnel excavation on the rock surrounding the tunnels were analyzed using a method that takes into account rock discontinuities.

Results

As an example of the results of the investigations conducted at the Shobasama Site[65),66),67)], the results of hydraulic fracturing tests using boreholes are shown in Fig. 3.2.6-1. A rock mechanical model for the Shobasama Site (Fig. 3.2.6-2) was produced based on the results of the investigations presented above, laboratory tests on petrophysical/geomechanical characteristics of rock and the geological model developed in this step (Fig. 3.2.7-1). In this model, the domain was divided into four rock units with different petrophysical/geomechanical characteristics of rock, fracture densities and initial stress states (relationship between the different principal stresses and the orientation of the maximum principal stress) as shown in Fig. 3.2.6-2. Since the initial stress states vary depending on depth and geological structure, the evaluation of the initial stress requires a) measurement of the initial stress at different depths taking into account the geological model and the rock mechanical characteristics and b) determination of the 3-D initial local stress regime based on point data, including data on initial stress, geological structure and petrophysical characteristics[92].

In this step, numerical analyses to predict the impact of excavating the underground facilities on the rock surrounding the tunnels were conducted using the rock mechanical model for the Shobasama Site. The numerical models used in the analyses that take rock discontinuities into account include the micro-mechanics-based continuum (MBC) model[93,94], the boundary element method for rock fractures (BEMF)[95], the crack-tensor model(CTM)[96] and the virtual crack model[97]. Of the different zones in the EDZ caused by tunnel excavation, these methods result in a representation of only the stress redistribution zone induced by the release of stress on the rock surrounding the tunnels. They do not include the basic constitutive equation that represents the occurrence of the excavation damaged zone due to blasting or machine excavation, meaning that such phenomena cannot be expressed in the analyses. In practice, an excavation damaged zone would be generated around the tunnel walls and modeling this zone appropriately is important in predicting the characteristics of the EDZ.

Of the analysis methods described above, the MBC method based on the equivalent continuum model and analyses based on the crack-tensor model and the virtual crack model were therefore selected to evaluate the effect of the width of the excavation damaged zone on the results of analysis of excavation damage. The width of the excavation damaged zone was used as input to the analyses. According to the studies at the Kamaishi mine and the Tono mine[99], the widths of the excavation damaged zone were 30 cm for machine excavation and 80 cm for blasting. Therefore, assuming the width of the excavation damaged zone to be 30 cm and 80 cm, the analyses were conducted using the rigidity of the intact rock, the occurrence of fractures (occurrence of new fractures or propagation of existing fractures) and the distribution of fractures (length, density and direction) as input parameters [100].

Conclusions and implications for the next investigation step

The results of the analysis indicated that the displacement of the walls could increase by a factor of two when considering the excavation damaged zone, comparing to the case without consideration of the excavation damaged zone (Fig. 3.2.6-3); the hydraulic conductivity in the excavation damaged zone could be increased by a factor of three compared to that before excavation and the degree of the impact may largely depend on the geometry of newly generated fractures in the excavation damaged zone (Fig. 3.2.6-4). In this step, the width of the excavation damaged zone was used as an input parameter for the analyses; in the excavation impact tests to be conducted in Phase III, direct evaluation of the excavation damaged zone was considered to be an important issue.

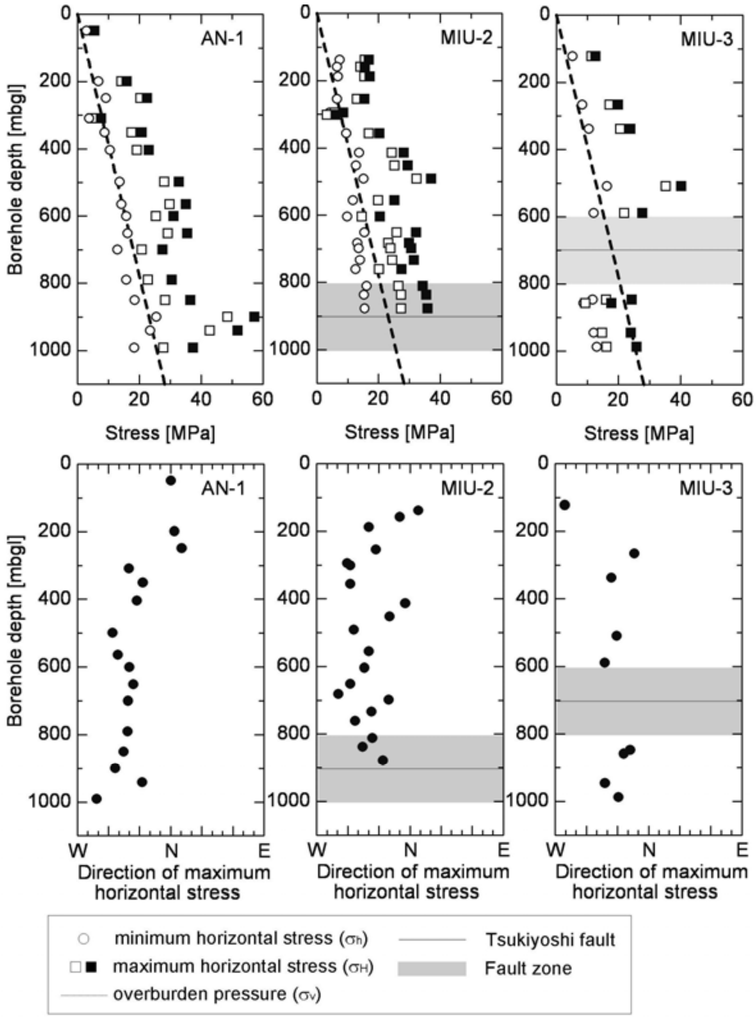
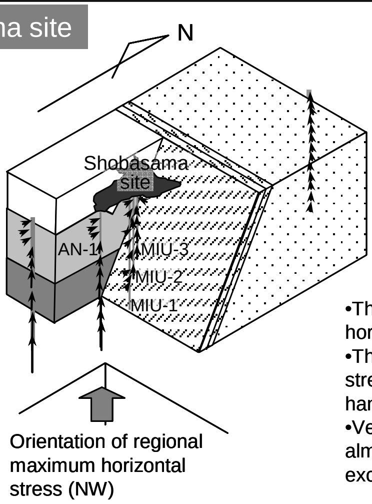


Fig. 3.2.6-1 Results of hydraulic fracturing tests (AN-1, MIU-2, MIU-3)[65),66),67)]

In-situ stress state in Shobasama site

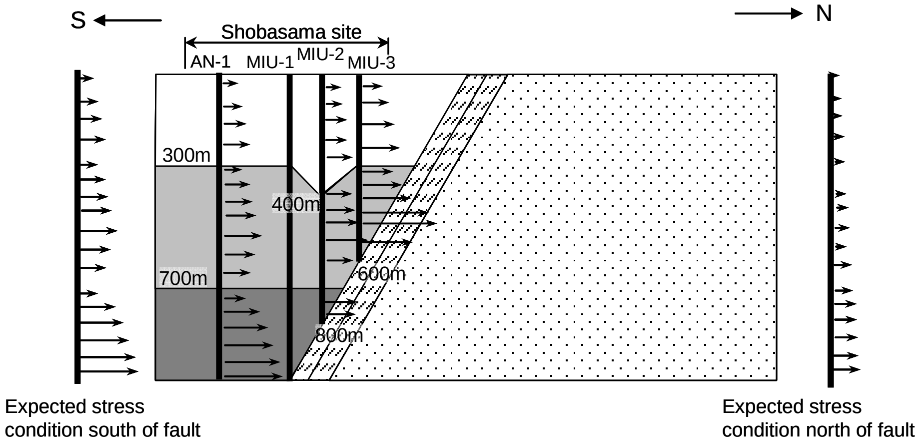
Hanging wall of Tsukiyoshi fault

- The orientations of maximum principal horizontal stresses are NNW-SSE~NW-SE to over 300m depth.
- Stress decoupling occurred.
- The rock mass may be divided into the three zones which have different stress condition.
- Vertical stresses in Shobasama site are almost equal to the overburden pressure expect near Tsukiyoshi fault.



Foot wall of Tsukiyoshi fault

- The orientations of maximum principal horizontal stresses are NNW-SSE~NW-SE.
- The magnitudes of principal horizontal stresses are relatively lower than that in hanging wall of Tsukiyoshi fault.
- Vertical stresses in Shobasama site are almost equal to the overburden pressures except near Tsukiyoshi fault.



Rock properties (Matrix, Rock mass)

	Hanging wall of the fault			Foot wall of the fault	Damage zone near fault
	Zone 1	Zone 2	Zone 3	Zone 4	hanging wall foot wall
Mechanical properties of matrix	•Deformability: Low •Anisotropy: none	•Deformability: High •Anisotropy: large	•Deformability: Low •Anisotropy: small	•Deformability: Low •Anisotropy: very small	•Deformability: Lowest in Shobasama site •Anisotropy: big
Fracture distribution	•High fracture frequency •Horizontal~Sub-horizontal	•Low fracture frequency	•High fracture frequency •Sub-vertical	•Very low fracture frequency compared to hanging wall	•High fracture frequency •The frequency in hanging wall is higher
Expected mechanical properties of in-situ rock mass	•Deformability: relatively lower than zone 2 •Big local variation	•Deformability: highest in the site •Small local variation	•Deformability: relatively lower than zone 2 •Big local variation	•Deformability: almost same in hanging wall •Small local variation (expect damaged zone)	

Fig. 3.2.6-2 Rock mechanical model in Shobasama Site[67)]

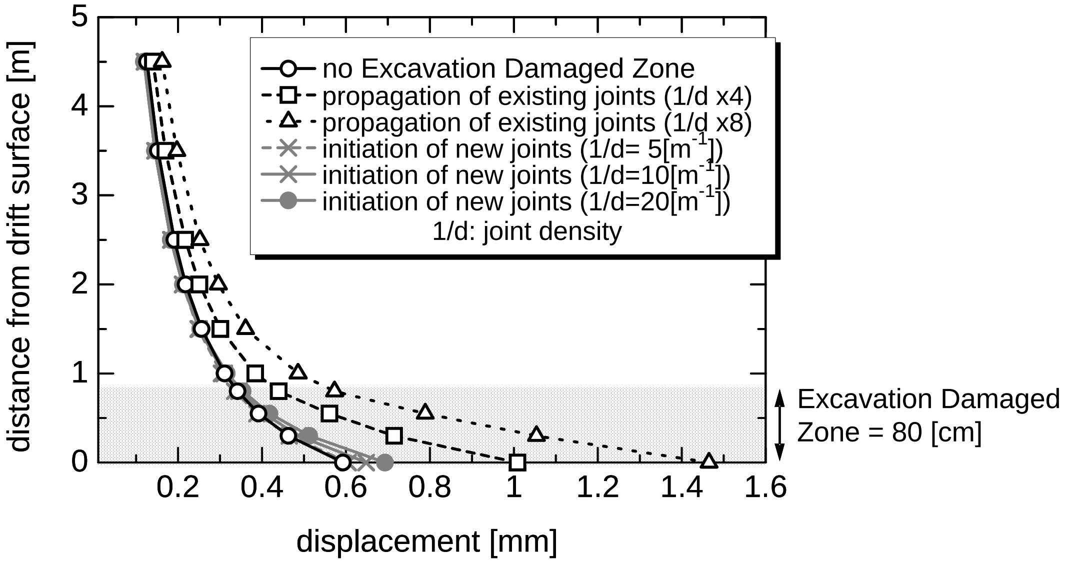
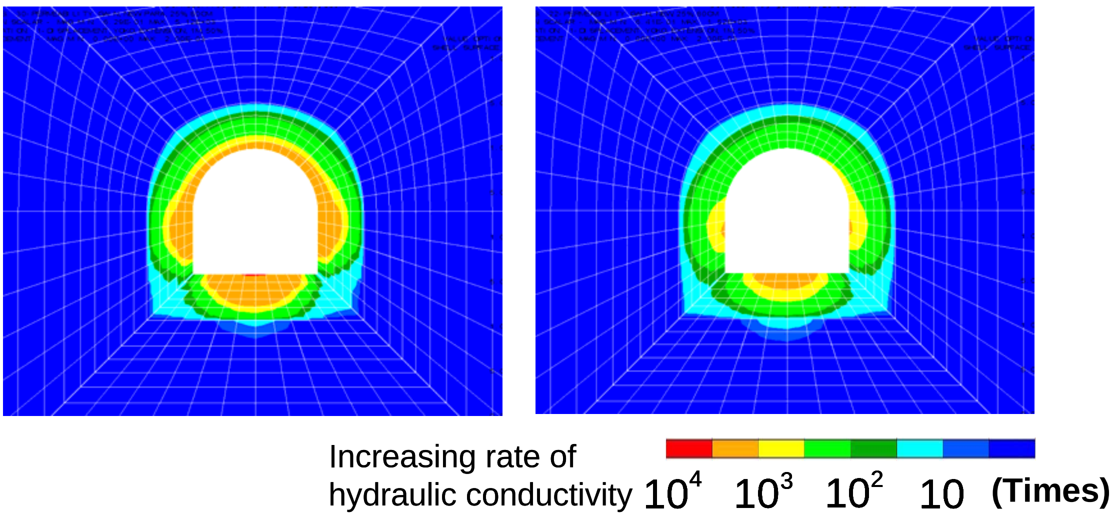


Fig. 3.2.6-3 Distribution of rock displacement around drift (MBC model)



(a) New cracks parallel to the wall (b) New cracks in random orientations

Fig. 3.2.6-4 Distribution of hydraulic conductivity increase around drift
(Crack tensor + Virtual fracture model Analysis)

3.2.7 Volume of inflow into underground tunnels

In order to determine the drainage method for the underground facilities, the inflow rate into underground facilities was calculated using a theoretical formula assuming an isotropic homogeneous medium, since hydrogeological structures such as high permeable and low permeable features in/around the MIU Construction Site that may influence the inflow volume have not yet been understood. In this step, data on hydrogeological characteristics of the granite were determined based on the information presented in

Section 3.2 for the estimation using the theoretical formula.

Results

The distribution of the hydrogeological characteristics of the granite was evaluated using the data examined in this step (Fig. 3.2.7-1). The geometric mean of the hydraulic conductivity (10^{-8} m s^{-1}) was used for calculating the inflow volume of groundwater. The calculations were made for the shafts and galleries (horizontal tunnels) using theoretical formulae assuming isotropic homogeneous media. The number and lengths of the shafts and galleries were based on the facility layout shown in Fig. 1.2.1-2. The inflow volume of groundwater into the underground facilities was estimated to be about 3,000 m^3 per day[101). This estimate was reflected in the design of the drainage system for the research galleries (see Section 5.1.4).

Conclusions and implications for the next investigation step

For the next step, a hydrogeological model considering water conducting features and low permeable features should be developed to predict a more realistic inflow rate.

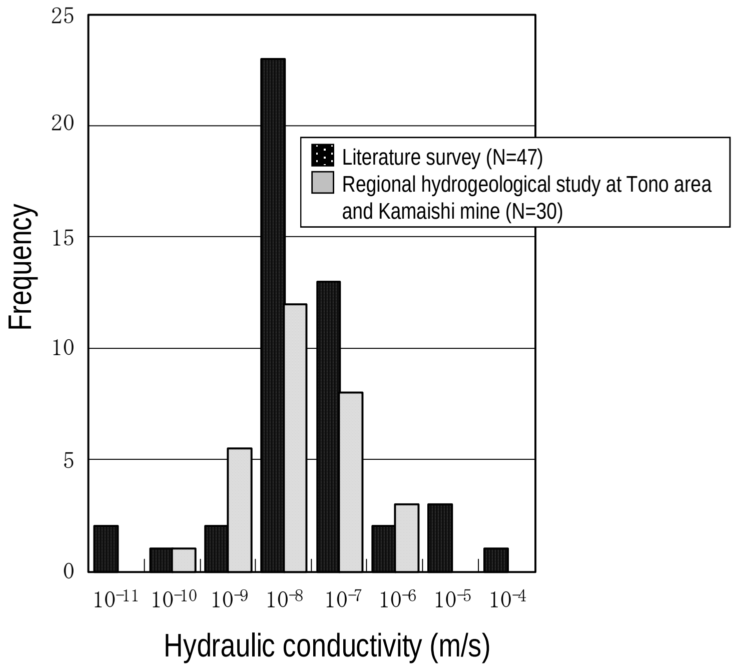


Fig. 3.2.7-1 Distribution of hydraulic conductivity of granitic rocks in Japan

3.2.8 Distribution of discontinuities intersecting underground tunnels

With the aim of acquiring information on discontinuities such as faults and fractured zones that would affect the petrophysical/geomechanical characteristics of rock surrounding the underground facilities, the distribution of such features intersecting underground tunnels was estimated based on the geological model developed in Section 3.2.1.

Results

The results indicated that the Tsukiyoshi Fault, the major discontinuity in the site-scale area, would not be intersecting the underground facilities; the fault was estimated to be approximately 480 m below the deepest part of the underground facilities (Fig. 3.2.8-1).

Conclusions and implications for the next investigation step

When estimating the distribution of discontinuities, modeling the spatial distribution of the Tsukiyoshi Fault described in existing geological maps is relatively straightforward, since a large amount of data, including investigations in the local-scale area, are available on the fault. For discontinuities that are not described in existing geological maps, rough estimates of their frequency and locations may be possible from lineaments, but the associated uncertainties should be taken into account to ensure appropriate modeling (see Section 3.2.1).

For the next and subsequent steps, it was considered important to check for the occurrence of discontinuities that are not described in the existing geological maps.

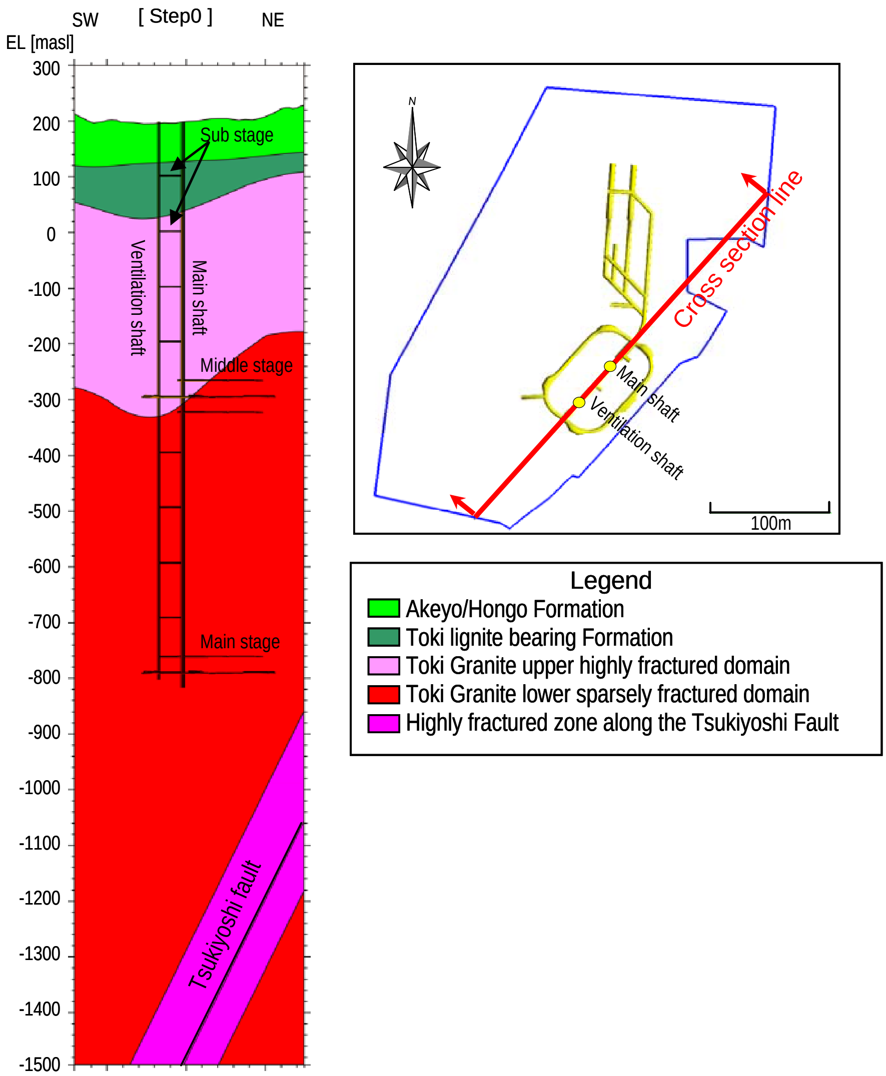


Fig. 3.2.8-1 Predicted geological structure around the MIU facility (Step0)

3.2.9 Subsurface thermal conditions

The goal was to characterize the geothermal conditions in the Toki Granite at the MIU Construction Site by using existing information. The distribution of the geothermal gradient and the thermal characteristics of the rock were compiled as shown in Table 3.1-1.

In this step, the characteristics of the underground thermal environment were determined by referring to existing information from temperature logging that was conducted as a part of the borehole investigations and tests on thermal characteristics using core samples (thermal conductivity, specific heat and the linear expansion coefficient) for the Shobasama Site and its surrounding area (local-scale area).

Results

The average geothermal gradient down to a depth of 1,000 m at the Shobasama Site and in the local-scale area is 2 ºC/100 m (Fig. 3.2.9-1), which is slightly lower than the nationwide average (3 ºC/100 m), except for volcanic zones[21]. Published data[17),18] and thermal characteristics obtained from laboratory tests[49] using cores from boreholes DH-6, 7, 8 and the Shobasama Site are shown in Fig. 3.2.9-2. The peak values for the thermal conductivity and the linear expansion coefficient of the Toki Granite are different from the literature data, but the range of distribution is within that of the published data[21]. The data on specific heat showed a wider distribution than the literature data. With these findings for the underground thermal environment, including the geothermal gradient and thermal characteristics in the range for the local-scale area, as long as there is no local heat source such as a volcanic zone, the geothermal gradient can be determined by temperature logging in a single borehole and the thermal characteristics can be obtained by tests using several core samples.

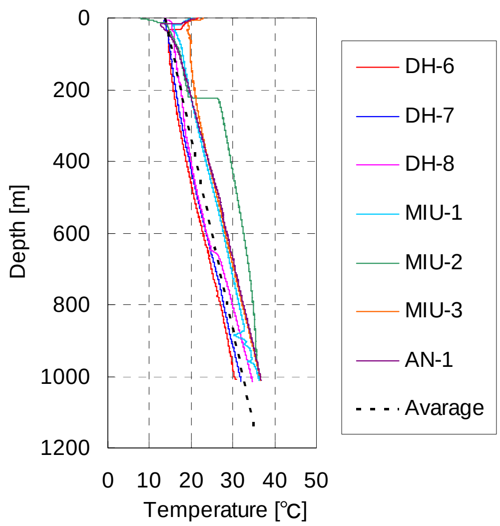


Fig. 3.2.9-1 Result of temperature logging
(Boreholes in the Shobasama Site, and DH-6, 7 and 8 boreholes)

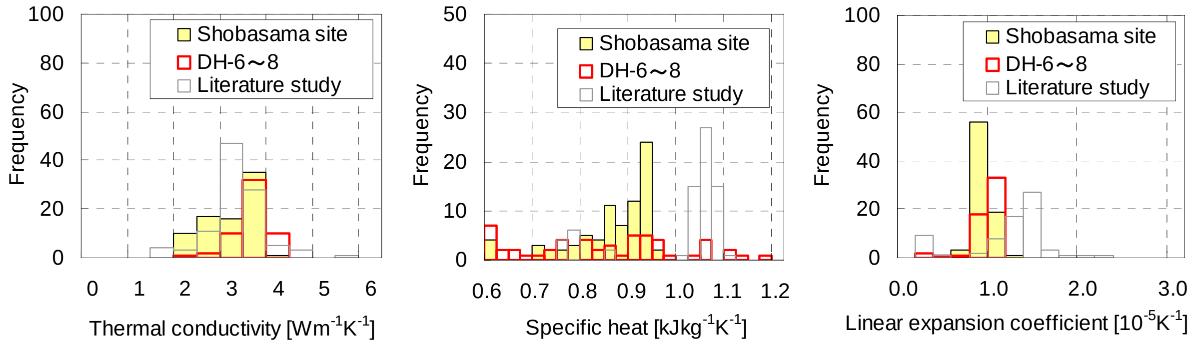


Fig. 3.2.9-2 Result of thermal property test
(Boreholes in the Shobasama Site, and DH-6, 7 and 8 boreholes)

3.2.10 Discussion of result and recommendation for further investigations

For the studies using existing information with the goal of achieving an preliminary understanding of specific aims as shown in Table 3.1-1, information from the literature and geological maps, a RHS and geoscientific studies in the Tono mine and at the Shobasama Site were compiled and reviewed.

A geological conceptual model, a geological model, a hydrogeological model, a hydrochemical model and a rock mechanical model of the site-scale area were developed based on the above data. Groundwater flow analyses and stress/excavation analyses were conducted based on these models to estimate the groundwater flow condition at site scale and rock mechanical conditions around the underground facilities.

Through these investigations, modeling and analyses, the key factors for investigation in subsequent steps were identified as listed below:

- 3-D detailed distribution of geological structures on the site scale.
- 3-D distribution of discontinuities that are not described in existing geological maps.
- 3-D distribution and hydraulic characteristics of faults that may affect groundwater flow in the site-scale area.
- Data on the geochemical characteristics of the groundwater on the site scale.
- Data on the transport/retardation characteristics based on borehole investigations.
- 3-D distribution and hydraulic characteristics of the upper highly fractured domain and the Toki Lignite-bearing Formation that are assumed to be distributed widely in the site-scale area and to function as an aquifer.
- Inflow volume of groundwater into the underground facilities through groundwater flow analyses using a hydrogeological model taking into consideration water conducting features and low permeable features.

<u>Geological structure</u>

Information on formations in the sedimentary overburden and the lithofacies of the granite can be collected by examining existing information. Since fractal characteristics were observed in the relationship between the length and frequency of lineaments and the distribution of the lineaments was, in general, consistent with the discontinuities confirmed or estimated by investigations on the local scale (see Section 3.2.1), the interpretation of lineaments would be useful for acquiring information on the distribution of the discontinuities that are not described in existing geological maps. The lineaments would also be very useful for determining the investigation for the next and subsequent steps. In order to incorporate the lineaments appropriately in models, modeling techniques for discontinuities considering probabilistic aspects (e.g. fractal characteristics of fractures identified from lineaments and outcrops) would need to be developed and evaluated.

Groundwater flow characteristics

In order to conduct groundwater flow analyses, a site-scale hydrogeological model needs to be developed using existing information. Such a model should incorporate data on the hydrogeological characteristics of each of the geological units that were classified in detail from geological information such as stratigraphy and lithofacies.

Data on the recharge rate into the rock that can be estimated from river flux, precipitation and evapotranspiration, and data on groundwater levels need to be collected as these can be used as boundary conditions for groundwater flow analyses.

Groundwater flow analyses for a wider area encompassing the site-scale area allow lateral boundary conditions to be set for the site-scale analyses or evaluation of the reliability of the groundwater flow analyses. For these analyses, the consistency of the hydrogeological models for both spatial scales needs to be ensured. This includes representation of discontinuities such as faults that are expected to affect the characteristics of groundwater flow on both spatial scales.

Geochemical characteristics of groundwater

Groundwater chemistry and its distribution that should be investigated using borehole investigations and the evolution process of groundwater chemistry that should be considered can be identified from literature data for the surrounding area. The conceptual model that is a prerequisite to performing in situ investigations could be developed and the modeling options presented. However, data obtained in this step are fairly uncertain because there is insufficient information regarding the raw data, such as sampling depths methods and hence, quality of the data of our purposes. For the interpretation of the results of the hydrochemical analyses in this step, the evaluation of uncertainties due to the insufficient data quality will be important.

Transport/retardation of nuclides

It is expected that there will be insufficient data available on solute transport/retardation characteristics on the rock formations of interest. The retardation effects can be roughly estimated using databases containing relevant information and/or studies of similar geological environments. However, since retardation characteristics are strongly controlled by the specific conditions in the geological environment, for a detailed evaluation of retardation the above-mentioned databases need to be expanded.

Dilution of nuclides

To understand the dilution effect of aquifers, the groundwater flow velocity of aquifers that could dilute solutes should be estimated. In addition to acquiring basic data for evaluating the dilution effect, groundwater flow analyses should be carried out using a hydrogeological model that classifies the aquifers that may cause heterogeneous velocity distribution from a hydrogeological viewpoint in as much detail as possible, depending on the model scale.

Local stress regime, spatial variability of petrophysical/geomechanical properties of rocks and size and structure of EDZ

Information on the local stress regime and the petrophysical/geomechanical characteristics of rock will form the basis for the design of the underground facilities. It will also be important for establishing input conditions for the numerical analysis to predict the impact of the excavation on the rock around the tunnels to determine the extent and petrophysical/geomechanical characteristics of the EDZ.

For areas where relevant investigation data have been obtained, initial stresses and the spatial distribution of petrophysical/geomechanical characteristics should be determined. Existing information can be used to perform the numerical analysis regarding EDZ.

Volume of inflow into underground tunnels

Applying theoretical formulae developed in the field of civil engineering is suitable for roughly estimating the inflow volume of groundwater based on the limited information available at the time of construction of the actual underground facility when hydrogeological structures are not clear. However, in the case where the hydrogeological structure is found to be heterogeneous due to the presence of discontinuities, development of a hydrogeological model and groundwater flow analyses taking into consideration the estimated distribution of hydrogeological features such as faults would be necessary for more reliable estimation of the inflow volume of groundwater.

Distribution of discontinuities intersecting underground tunnels

In this step, it will be difficult to directly identify discontinuities other than those described in existing geological maps. However, lineaments can be used for the estimation of such features. The information on lineaments allows a rough estimation of the distribution frequency and locations of discontinuities and can also be used as input for establishing the investigation plans for the next and subsequent steps.

Subsurface thermal conditions

The data on the thermal conditions in geological formations will form the basis for determining the underground thermal environment and contribute to the design and construction of the underground facilities. In areas where relevant investigation data are available, the geothermal environment can be determined using such data.

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3.3 Step 1 investigations

Among the key factors identified in Step 0 (see Section 3.2.10), investigations based on ground exploration were conducted giving priority to investigations that contribute to determining the 3-D distribution of geological structures that could affect the characteristics of groundwater flow and groundwater chemistry. The investigations in question are those that determine the outline of the 3-D distribution of geological structures in the wide area, prior to borehole investigations to acquire more detailed data. More specifically, surface geological mapping and reflection seismic surveys (see Section 4.2) were conducted with the aim of acquiring data on the distribution, configuration and mineralogical/petrological characteristics in the Toki Granite, the Mizunami Group, the Seto Group and discontinuities that could affect groundwater flow. These investigations are important for selecting the locations for borehole investigations in the subsequent steps. In this step, investigations with the specific aims shown in Table 3.1-1 were conducted, except for those for which the required data could not be obtained.

Surface geological mapping was conducted for outcrops at and around the MIU Construction Site and the former underground shelter located to the south-east of the MIU Construction Site to determine the distribution of surface geology and faults (Fig. 3.3-1)[1)].

A reflection seismic survey was conducted to acquire data on the geological boundaries within the Mizunami Group, the boundary between the Mizunami Group and the Toki Granite, the lithofacies of the upper part of the Toki Granite and the configuration of faults in and around the MIU Construction Site that were estimated based on the investigations in Step 0 (see Section 3.2), and the geological mapping[2)]. The survey lines were planned along minor roads in and around the MIU Construction Site to cover as much of the area as possible, the aim being to accurately determine the 3-D distribution of discontinuities from the surface to deep underground (Fig. 3.3-2). Efforts were made to ensure that, as far as possible, the survey lines would cross the strikes of the faults that had been confirmed/estimated by surface geological mapping and interpretation of lineaments at right angles. The survey lines were extended outside the MIU Construction Site to allow investigations to 200 m or deeper, where the upper extent of the Toki Granite is assumed to occur; the survey lines within the MIU Construction Site allow investigations only near the surface. The survey lines were also set to pass close to existing boreholes in order to allow a direct comparison to be made of the profile obtained by the reflection seismic survey and the distribution of geological structures determined in the boreholes.

Based on the results of the investigations, the geological model constructed in Step 0 was updated by adding discontinuities other than the Tsukiyoshi Fault and the hydrogeological model was updated accordingly. Sensitivity analyses for groundwater flow were conducted focusing on the uncertainty regarding the hydrogeological characteristics of the faults in the updated hydrogeological model. Based on these results, faults with a NNW strike that were assumed to have a large influence on the characteristics of groundwater flow and the geological and hydrogeological characteristics of faults that would be expected to emerge at the underground facilities were identified as key factors for investigation in the subsequent steps.

The geosynthesis flow diagram that was constructed based on the experience obtained through the studies in this step is shown in Appendix 4 and the detailed approach for the specific aims is summarized in

Sections 3.3.1 - 3.3.4. The key factors for investigation in subsequent steps and recommendation for further investigations in the disposal project that were identified in this step are summarized in Section 3.3.5.

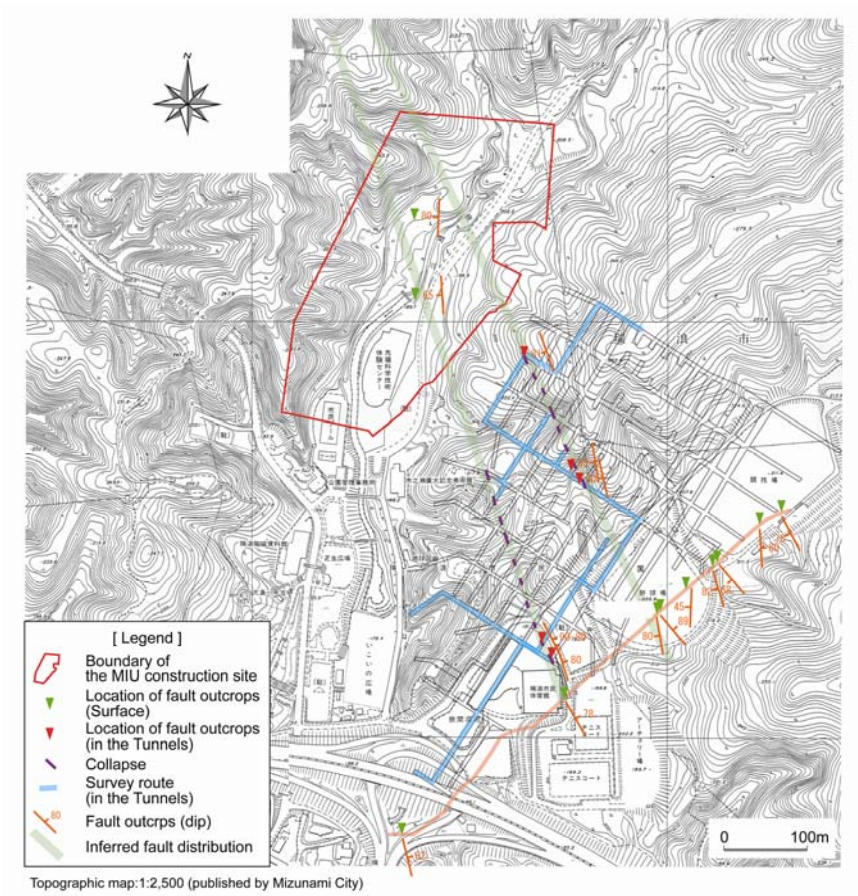
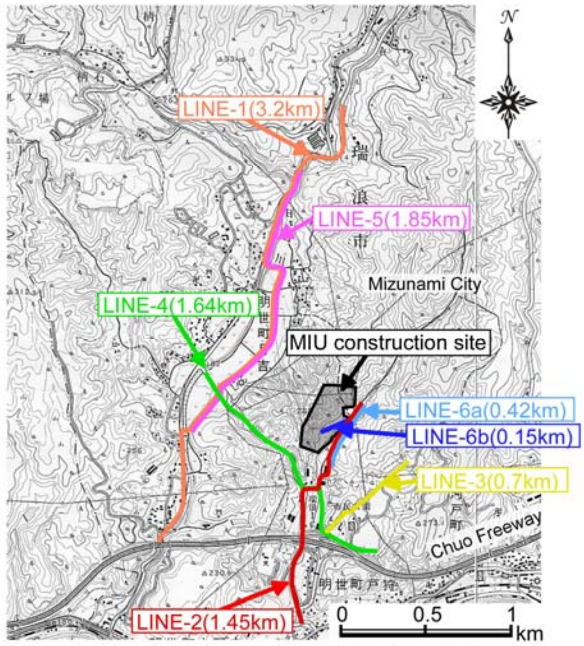


Fig. 3.3-1 Location of fault outcrops identified from the geological survey[3)]



Topographic map:1/25,000 "Toki & Mizunami" (published by Geographical Survey Institute of Japan)

Fig. 3.3-2 Reflection seismic survey lines around the MIU Construction Site[2)]

3.3.1 Geological structure

Surface geological mapping and reflection seismic surveys were conducted with the aim of acquiring data on the distribution and configuration of discontinuities and the mineralogical and petrological characteristics in the Toki Granite, the Mizunami Group and the Seto Group that could affect groundwater flow. Also to determine the distribution of the Toki Granite, the Mizunami Group and the Seto Group on the site scale identified in Step 0 and the existence of discontinuities that are not described in existing geological maps[2),3),4),5)]. Based on the acquired data, the geological model constructed in Step 0 (see Section 3.2.1) was updated[6)]. In this model, around 30 fault-related lineaments identified based on existing information (see Section 3.2.1) with a subsurface distribution estimated based on the data obtained in this step and data obtained for the local-scale area were also included in the model as discontinuities.[3),7)]

Results

Surface geological mapping and reflection seismic surveys were conducted focusing on the geological features unique to the area around the MIU Construction Site[8)] (such as the unconformity between the Toki Granite and the Mizunami Group). As a result, the distribution of the boundaries within the Mizunami Group and the unconformity between the Toki Granite and the Mizunami Group could be determined. Reflection events were found in the zone corresponding to the upper highly fractured domain in the Toki Granite. A new finding was the identification of minor faults with a NS to SSE-NNW strike not shown on existing geological maps (Fig. 3.3.1-1)[2),4),5)]. For the faults identified in this step, their distribution and configuration, and mineralogical and petrological characteristics were confirmed in outcrop[3)] through geological mapping and the extent of the faults at depth was predicted to some extent by combining the results with those from the reflection seismic surveys. In the reflection seismic surveys, displacements of reflection events that could be interpreted as faults were identified at several locations in addition to those that had been correlated to the distribution of faults at outcrop[3),4)]. This would imply the occurrence of faults that do not reach the surface, that have small displacements or that were active a long time ago.

The geological model was updated based on the data obtained in this step (Fig. 3.3.1-2: geological map (left), geological model (right))[3),6)]. In order to represent the distribution of discontinuities in the area where investigations were not conducted in this step, the model was updated by excluding lineaments[3),] that are unlikely to be actual faults, by comparing them with known faults in terms of their direction and distribution. The lineaments included in the model were those derived from existing data (see Section 3.2.1) and the faults were those predicted by the reflection seismic surveys conducted in this step and confirmed by borehole investigations on the local scale (see Appendix 1). The dip angles of the modeled discontinuities in the underground were determined by comparing them with the dips and the strikes of the faults confirmed by the borehole investigations on the local scale[3)].

Conclusions and implications for the next investigation step

Compared with the geological model constructed before Step 0, the updated model includes the distribution of the Toki Granite, the Mizunami Group and the Seto Group and an additional 27 discontinuities. Of these, 5 faults that were not described in the existing maps were confirmed directly, as shown in Fig. 3.3.1-2 (left)), which helps to improve the understanding of the distribution of the discontinuities. The reflection seismic survey is a particularly effective method for predicting the unconformity of the Mizunami Group and the Seto Group and the distribution of the upper highly fractured domain in the Toki Granite; by combining it with the geological mapping, it was possible to identify or predict discontinuities that are not shown on existing geological maps. In areas with highly undulating geology, the horizontal continuity of faults would be difficult to estimate by comparison with the characteristics of displacement obtained from reflection surveys. When surveying such areas with expected high undulation, it is more effective to set the survey lines at close intervals or to conduct 3-D surveys separately. In addition to this, 3-D tomographic analyses using data from reflection seismic surveys and trench excavation survey would also be useful. Since sufficient data on the distribution of faults was not available in this step, it was necessary to refer to the lineament interpretation results in setting the lines for the reflection seismic surveys.

The minor faults confirmed in this step have a NS to NNW-SSE strike, which may influence the primary direction of the groundwater flow (NE - SW direction: see Section 3.2.2). From the results of the geological mapping, it was revealed that there is intercalation of fault gouge and fault breccia containing a large amount of clay that could function as a flow barrier, implying a significant influence on groundwater flow[6),7)].

The data in this step were obtained from limited surface outcrops found along the lines for the reflection seismic surveys. In the future, the accuracy of the estimations of the geological structures made using reflection seismic surveys is expected to be greatly improved by comparing them with the actual distribution of the underground structures. It was considered that the issues in subsequent steps would be to confirm the boundaries estimated or predicted in this step, to confirm the actual subsurface distribution of discontinuities and to determine the distribution of deep geological structures that were difficult to identify in this step.

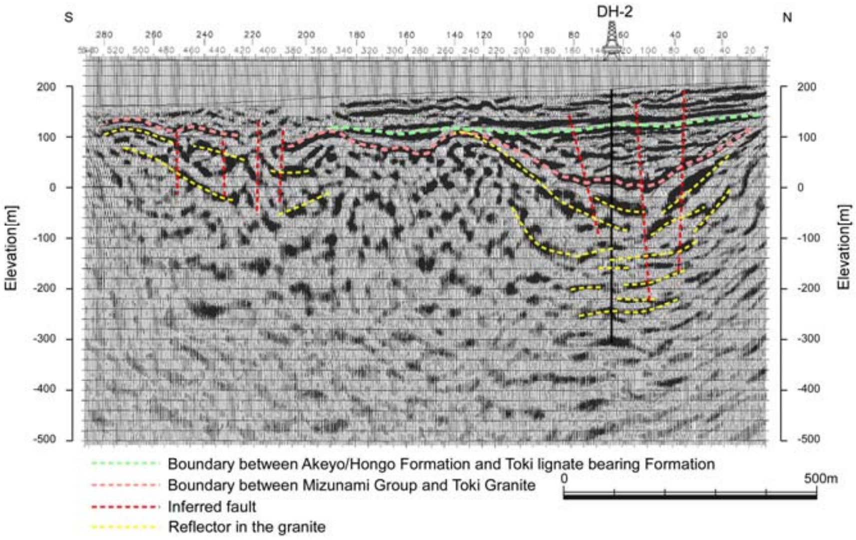


Fig. 3.3.1-1 Geological interpretation of the reflection seismic profile[2)]

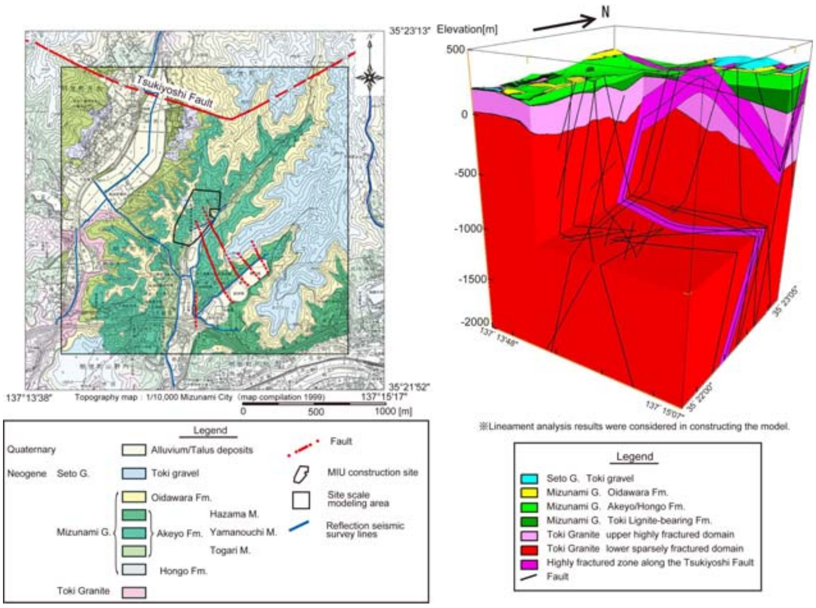


Fig. 3.3.1-2 Geological map and geological model revised with the surface-based investigation phase data[7)]

3.3.2 Groundwater flow characteristics

Data on the distribution and configuration of discontinuities were obtained from the geological mapping and reflection seismic surveys (see Section 3.3.1) as part of the ground explorations. From the groundwater flow analyses conducted in Step 0, faults, such as the Tsukiyoshi fault have a significant influence on the characteristics of groundwater flow. In this step, additional faults identified with the seismic surveys were therefore included in the hydrogeological model (see Section 3.2.2) and the influence of the hydraulic property of these faults on the characteristics of groundwater flow was examined by sensitivity analyses. By including investigation data obtained in this step in the hydrogeological model and the groundwater flow analyses on the local scale, the boundary conditions for the site-scale area could be revised[9]. The geological and hydrogeological modeling and the groundwater flow analyses were utilized the GEOMASS system (see Section 4.10).

In the hydrogeological modeling, the faults with unknown hydraulic characteristics were grouped based on their orientations and, as an initial simplifying assumption, were then assigned the same hydraulic conductivity. Additionally, smaller faults in the vicinity of larger features with similar orientations were also excluded from the hydrogeological model, as they would not be expected to have a significant net hydraulic impact. This process for screening of faults assigning hydraulic conductivity to groups of faults was also applied for the later investigation steps.

Since no additional data were obtained on the hydraulic characteristics of the geological structures in this step, updating the hydrogeological model was based on dataset of hydraulic properties that was made on the Step 0 and the geological model (see Section 3.3.1) that was updated based on data such as distribution depth and the configuration of each formation and fault. For the hydrogeological model shown in Fig. 3.3.2-1, 13 new faults were added in this step, but the hydrogeological characteristics of these features had not yet been obtained by field characterization. Since it is obvious from the results of investigations on the Tsukiyoshi Fault at the Shobasama Site[10),11)] and the groundwater flow analyses conducted in Step 0 (see Section 3.2.2) that the hydraulic anisotropy of the Tsukiyoshi Fault has a significant influence on the distribution of the hydraulic gradient, a sensitivity analysis on the existence of hydraulic anisotropy was performed as part of the groundwater flow analysis and the influence of hydraulic conductivity on the distribution of the hydraulic gradient in each fault group was evaluated[12)].

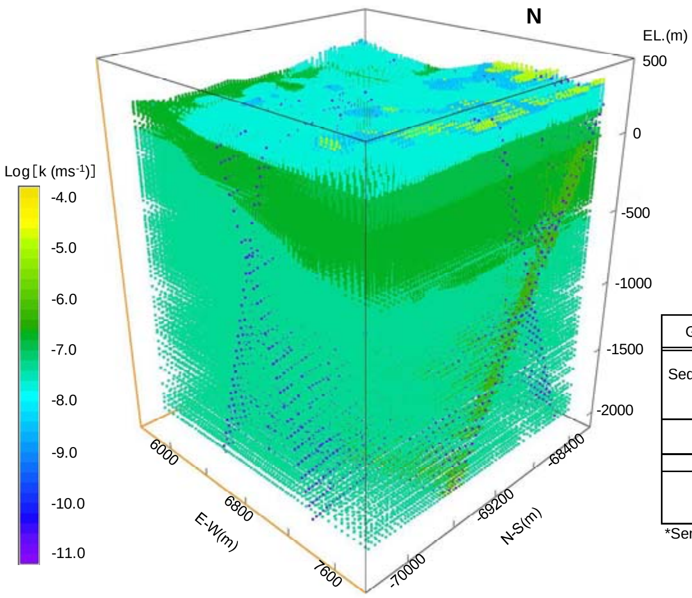
Results

To evaluate the influence of the hydraulic anisotropy in each fault on the distribution of the hydraulic gradient in the site-scale area, the 3-D distribution of the hydraulic head was calculated. Sensitivity case is shown in Section 3.7.2. An example of the results of the sensitivity analysis is shown in Fig. 3.3.2-2. The influence of hydraulic anisotropy in each fault trend on the distribution of hydraulic gradient was determined through comparison with the distribution of the hydraulic head obtained from sensitivity analyses focusing on the existence of the hydraulic anisotropy in each fault trend; i.e. differences in hydraulic head on either side of a fault was caused by a low conductivity perpendicular to the fault plane; the hydraulic gradient in the area surrounded by such faults is small. Groundwater flow analyses focusing on the hydraulic uncertainty of hydrogeological units of faults may be an effective method for evaluating the influence of fault hydraulic conductivity on the hydraulic gradient, for identifying those faults affecting significantly the distribution of the hydraulic gradient in the analysis domain and for prioritizing faults to be hydraulically characterized (hydraulic conductivity and anisotropy).

The result of groundwater flow analysis implies that faults with a longer trace length probably form a hydraulic boundary that would result in a large difference in hydraulic head between the upper and down streams of the fault. When constructing the hydrogeological model, it is important to identify the faults to be modeled by a screening process based on the location and trace length of the fault. It would be efficient to establish the threshold for this screening after acquiring data on the size of the faults that have a significant influence on groundwater flow, in a similar way to the sensitivity analysis. Since faults may exist in areas where data has not yet been obtained, in addition to deterministic models, probabilistic models should also be used to evaluate the influence of the uncertainty of the density distribution of faults and their hydrogeological characteristics on the groundwater flow condition.

Conclusions and implications for the next investigation step

In the next and subsequent steps, it was considered important to determine the geological and hydrogeological characteristics of NNW and NE trending faults that were predicted to have a significant influence on groundwater flow around the MIU Construction Site, based on the groundwater flow analyses conducted in this step.



Hydraulic conductivity

Geological features and geological structure element			Log [k (m s^{-1})]
Sedimentary rock	Seto group		-5.0
	Mizunami group	Oidawara formation	-8.5
		Akeyo/Hongo formation	-7.8
		Toki-lignite bearing foramation	-7.0
Toki granite		Upper Highly fractured domain	-6.7
		Lower sparsely fractured domain	-7.4
Highly fractured zone along the Tsukiyoshi fault			-6.4
Fault	Main part of Tsukiyoshi fault		-11.0
	Other faults	In-plane of fault	See Table 3.2.6(2)-2
		Normal to fault*	

*Sensitivity analysis about hydraulic anisotropy:13faults in 14

Fig. 3.3.2-1 Hydrogeological model (3-D distribution of hydraulic conductivity)

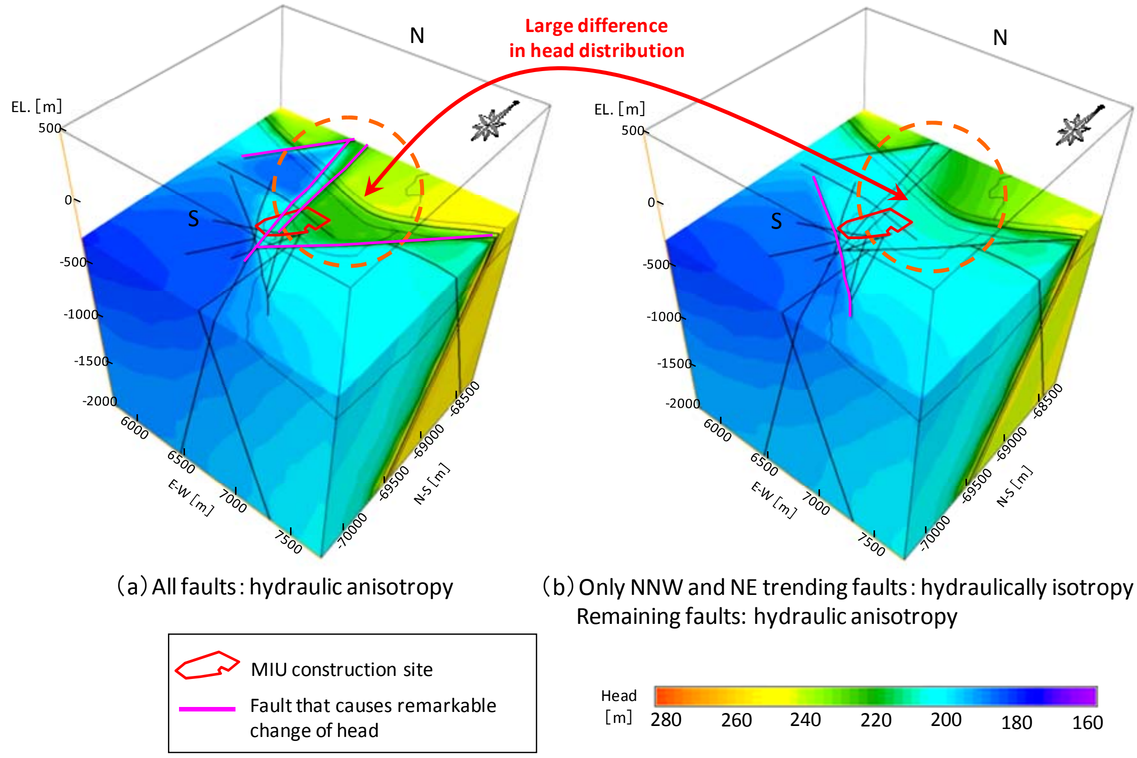


Fig.3.3.2-2 Example of a sensitivity analysis focused on hydraulic anisotropy of faults (Elevation -300 m : Depth of the shaft 500 m)

3.3.3 Dilution of nuclides

The distribution of the Darcy velocity was calculated based on the results of the groundwater flow analysis discussed in Section 3.3.2 in order to determine the dilution effect in each hydrogeological unit.

<u>Results</u>

The frequency distribution of the Darcy velocity (Fig. 3.3.3-1) was calculated for the Mizunami Group, the upper highly fractured domain and the lower sparsely fractured domain of the Toki Granite that have a relatively large spatial distribution in the hydrogeological models, as well as for the highly fractured zone along the Tsukiyoshi Fault (see Section 3.3.2). Although several additional faults were included in the hydrogeological model (see Section 3.3.2) in this step, the trend of the distribution of the calculated Darcy velocity in each hydrogeological unit was similar to that in Step 0. Compared to the Darcy velocity distribution of the lower sparsely fractured domain of the Toki Granite, where hydraulic conductivity is relatively low, the resulting Darcy velocities were relatively high in the highly fractured zone along the Tsukiyoshi Fault, the upper highly fractured domain and the Toki Lignite-bearing Formation. The reason for this is that the hydrogeological model (see Section 3.3.2) was updated using the hydrogeological data from Step 0 without additional data being obtained on the hydraulic characteristics of geological structures in this step; the distribution area of discontinuities newly identified was narrow and the distribution of other geological structures predicted to be aquifers was dominant. This highlights the importance of acquiring accurate data on the hydraulic characteristics of the geological structures distributed widely in the aquifer in determining the dilution effect of aquifers.

Conclusions and implications for the next investigation step

For the next and subsequent steps, it was considered important to calculate a more reliable distribution of the Darcy velocity than in this step by conducting borehole investigations for each formation of the Mizunami Group and the upper highly fractured domain and acquiring data on the 3-D distribution and hydraulic characteristics of these formations and zones and incorporating the data into the hydrogeological model.

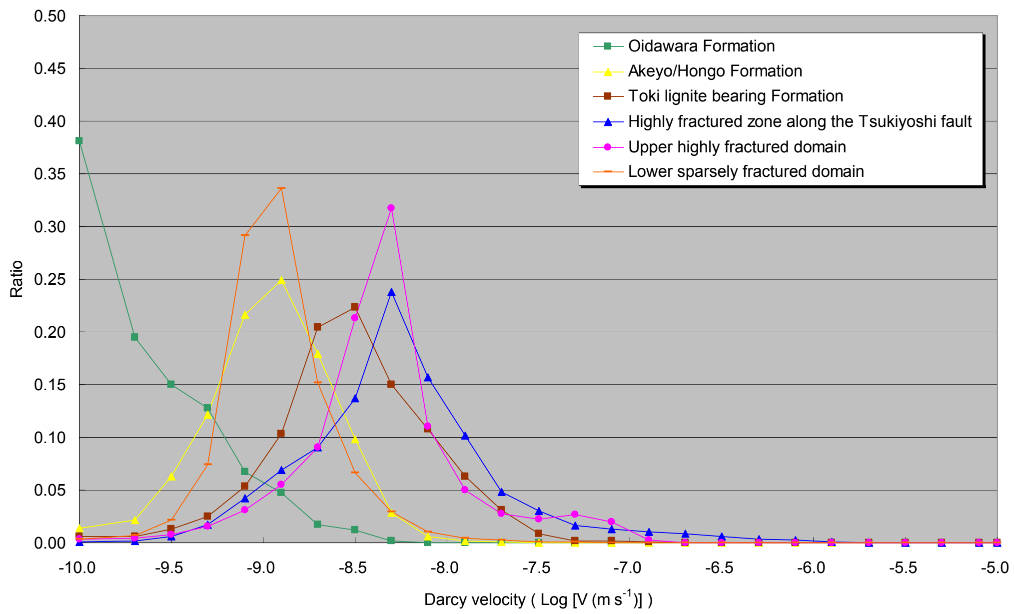


Fig. 3.3.3-1 Darcy velocity distribution (The vertical axis shows the ratio (cumulative frequency is 1 in each geological formation and domain))

3.3.4 Distribution of discontinuities intersecting underground tunnels

As part of ground explorations aimed at acquiring data on the occurrence of discontinuities such as faults and fractured zones[3)] that could influence the petrophysical/geomechanical characteristics of rock at the locations of the underground facilities, predictions were made of locations where such discontinuities could emerge at the planned excavation locations based on the geological model described in Section 3.3.1.

Results

The analysis predicted that seven discontinuities would emerge at the planned excavation locations for the underground facilities, including IF_SB0_002 and IF_SB0_005 both with a NNW strike (Fig. 3.3.4-1) that were confirmed during this step.

In this step, minor faults that are not shown on existing geological maps were included in the model and the accuracy of the fault distribution prediction was improved compared to Step 0.

Conclusions and implications for the next investigation step

The issues in subsequent steps would be to define the actual distributions of the discontinuities underground that were confirmed or predicted in this step and those in deeper zones that would be difficult to identify, as described in Section 3.3.1.

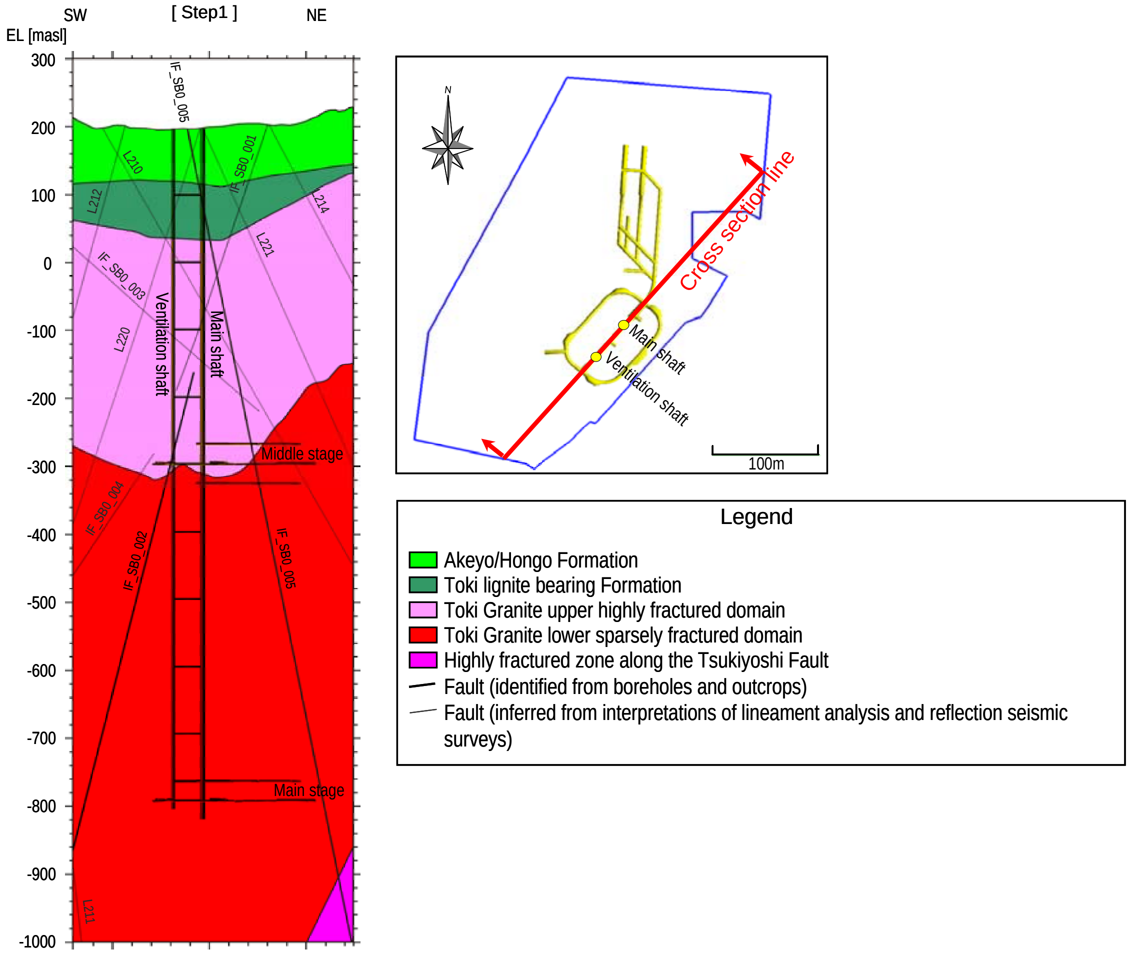


Fig. 3.3.4-1 Predicted geological structures around the MIU facility (Step1)

3.3.5 Discussion of results and recommendations for further investigations

Ground explorations including surface geological mapping and reflection seismic surveys aimed at determining, on wider area, the distributions, configurations and mineralogical/petrological characteristics of the Toki Granite, the Mizunami Group, the Seto Group and discontinuities that would influence groundwater flow. A further aims was to acquire data on the characteristics in order to address the specific aims shown in Table 3.1.-1, namely geological structure, groundwater flow characteristics, dilution of nuclides, and distribution of discontinuities intersecting underground tunnels.

Based on the data obtained in these investigations, the geological model constructed in Step 0 was updated by incorporating discontinuities other than the Tsukiyoshi Fault and the hydrogeological model was updated based on the geological model. Also, sensitivity analyses of groundwater flow were conducted focusing on the uncertainties in the hydraulic characteristics of the faults in the updated hydrogeological model.

Through the investigations, modeling and analyses described above, key factors for investigation in subsequent steps were identified as listed below:

- Acquisition of data on the geological and hydraulic characteristics of the NNW and NE trending faults and faults estimated to emerge at underground facilities that would have a significant influence on groundwater flow in the site-scale area.
- Acquisition of data on the 3-D distribution and hydraulic characteristics of the upper highly fractured domain and on each formation of the Mizunami Group that are likely to function as an aquifer on the site scale.

Geological structure

Surface geological mapping and reflection seismic surveys help to improve the understanding of the distribution of unconformities between the sedimentary rocks and the granite and the accuracy of estimations of the heterogeneity of the granite. They are also effective for identifying relatively minor faults that are not shown on existing geological maps. The evaluation of discontinuities considering the mineralogical/petrological characteristics and the direction of the groundwater flow would be effective in identifying discontinuous features and in reducing the uncertainties associated with the geological model and the hydrogeological model. Since it was difficult to confirm, from the reflection seismic surveys, the continuity of faults in a horizontal direction by comparing the displacement characteristics of reflection events between survey lines in the Toki Granite because of its undulating topography, it would be better to set narrower survey line intervals or to conduct a separate 3-D survey for the area where such continuity is expected. 3-D tomographic analyses using data from the reflection seismic surveys and trench excavation survey are effective if combined with the latter. Since there is only a small volume of data available on the distribution of faults in this step, it would be necessary to refer to the lineament interpretation in establishing lines for the reflection seismic surveys.

Groundwater flow characteristics

If conducted in advance of the borehole investigations, sensitivity analyses of groundwater flow focusing on the hydraulic characteristics of faults predicted to exist and identifying faults considered to have a significant influence on the characteristics of groundwater flow would allow effective formulation of the investigation program in terms of costs, duration and impact due to drilling disturbance.

Also, since faults may be present in areas where data have not been obtained from the investigations, studies using a stochastic approach taking the distribution density of faults into account, as well as a deterministic approach, could be used to evaluate the influence of the spatial uncertainty of faults on the characteristics of groundwater flow, such as the distribution of hydraulic gradients.

Dilution of nuclides

Accurate determination of the dilution effect of additionally identified faults might be difficult due to lack of data on the hydraulic characteristics, despite the fact that the existence of such faults can be estimated from surface geological mapping and reflection seismic surveys. Nevertheless, it is advisable to clarify the influence of such faults on dilution effects. Surface geological mapping and reflection seismic surveys are very effective for determining the detailed distribution of geological structures that, as aquifers, are expected to have a dilution function.

Distribution of discontinuities intersecting underground tunnels

Surface geological mapping and reflection seismic surveys can significantly improve the accuracy of estimations of the distribution of sedimentary rocks, granite and heterogeneities in the granite. They are also effective for identifying relatively minor faults that are not shown on existing geological maps. For the reflection seismic surveys, when undulating topography is expected for the granite basement, it is more efficient to set narrower survey line intervals or to conduct a 3-D survey separately. In setting the lines for the reflection seismic surveys, it is necessary to refer to the results of lineament interpretation, since data on the distribution of faults are not sufficient in this step.

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3. 4 Step 2 investigations

Of the key factors identified in Steps 0 and 1 (see Sections 3.2.10 and 3.3.5), Step 2, involved conducting investigations using existing and new shallow boreholes. Four shallow boreholes (MSB-1, MSB-2, MSB-3 and MSB-4) were drilled with the aim of determining the geological, hydrogeological and geochemical characteristics of the geological environment in the surface to near-surface zone. The shallow borehole investigations were conducted separately from the deep borehole investigations, because long-term hydraulic monitoring in the sedimentary rock zone is generally difficult to perform using deep boreholes due to the casing installed in the section from the surface to the near-surface zone for borehole stability. The results of the investigations in the existing borehole (DH-2) drilled to a depth of 500 m, as part of the RHS (see Sections 4.3 and 4.4), were also used. In this step, investigations with the specific aims shown in Table 3.1-1 were conducted.

The four goals for the shallow borehole investigations were[1]:

- To determine the geometry and hydraulic characteristics of NNW trending faults running through the MIU Construction Site identified in Step 1 as important geological features affecting groundwater flow.
- To understand the initial state of the groundwater flow-field in the sedimentary rock zone and the weathered granite prior to the excavation of the underground facilities.
- To determine the geochemical characteristics of the groundwater in the sedimentary rock and weathered granite.
- To commence long-term monitoring of groundwater to observe changes in groundwater pressure and groundwater chemistry associated with the excavation of the underground facilities.

The number of shallow boreholes and their locations and layout were determined considering the overall objectives outlined above, as well as budget and schedule constraints (Fig. 3.4-1). Specifically, boreholes were located at the upper and down streams in the major direction of groundwater flow that had been estimated from the investigations in Step 0 (see Section 3.2) and Step 1 (see Section 3.3). Also, considering the estimated local groundwater flow along the Tsukiyoshi Channel and the depth of the redox boundary, boreholes were located with the aim of characterizing the hydraulic characteristics and geochemistry of the groundwater in the sedimentary rock and the upper part of the granite at the points where the thickness of the sedimentary rock covering the granite along the Tsukiyoshi Channel significantly varied. Since the NNW trending fault predicted in the investigations/analyses in Step 1 was assumed to dip at a high angle, one of the boreholes was drilled by inclined drilling to intercept this fault. The borehole depths were selected to be between 99 and 201 meters, taking the depth of the upper surface of the granite (thickness of the sedimentary cover) into consideration. The shallow borehole investigations involved core logging, investigations of borehole wall image, geophysical logging (see Section 4.5), fluid logging (see Section 4.6), hydraulic testing (see Section 4.7), and sampling and chemical analyses of groundwater (see Section 4.8). After completing the borehole investigations, long-term hydraulic monitoring was initiated to observe the changes in groundwater pressure and geochemistry of groundwater associated with the excavation of the underground facilities.

For the investigations using the existing boreholes, since the items to be investigated and the level of quality at the time of their drilling differed from the requirements in Phase I of the MIU project, the geological and hydrogeological investigations were conducted again[2)] with the aim of determining the geological and hydraulic characteristics of the weathered granite, the upper highly fractured domain, faults, the distribution and geometry of water conducting features of the Toki Granite down to a depth of 500 meters. In order to identify water conducing features that may affect groundwater flow, several logging runs (see Section 4.6) were performed, including electrical conductivity logging, in addition to geological investigations on cores. Hydraulic tests were also conducted for the identified water conducting features and other borehole sections. Measurement of the initial stress using cores was also conducted (see Section 4.9). To determine the changes in groundwater pressure associated with the excavation of the underground facilities, equipment for monitoring of groundwater pressure was installed and long-term hydraulic monitoring was started after the completion of the investigations in the existing boreholes.

A description of the borehole investigations is provided in Appendix 3 and overview of the results are also provided in Appendices 5 & 7.

Based on the data obtained from the investigations described above, the geological, hydrogeological, hydrochemical and rock mechanical models on the site scale developed in Steps 0 and 1 were updated. In addition, based on these models, analyses of groundwater flow and stress/excavation were conducted. In the modeling/analyses, the consistency of the models and analysis results among different disciplines was checked to improve the credibility of the results and to identify factors that would have a significant influence on the level of uncertainty. Based on the results of the analyses presented above, the geological and hydraulic characteristics of the NNW trending fault in the granite were identified as being important for investigation in subsequent steps.

The geosynthesis data flow diagram constructed based on the experience gained through the investigations in this step is shown in Appendix 4 and the detailed approach for the specific aims is summarized in Sections 3.4.1 to 3.4.8. Also in Section 3.4.9, key factors for investigation in subsequent steps and recommendations for further investigations in the disposal project that were identified in this step are summarized.

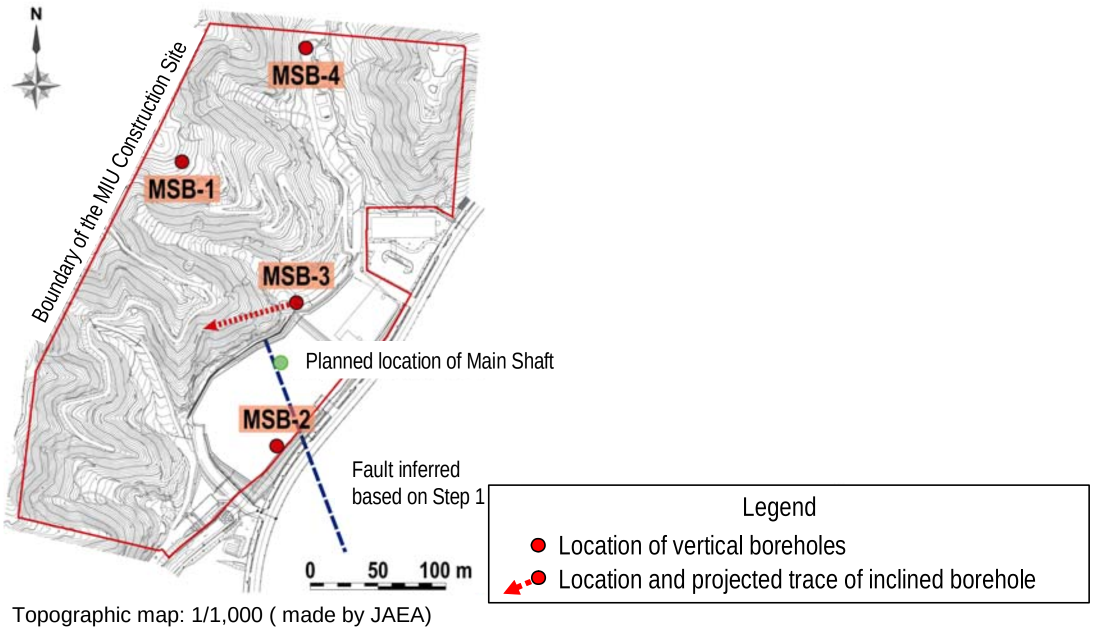


Fig. 3.4-1 Location of the shallow boreholes

3.4.1 Geological structure

Core logging, investigations of borehole wall image, geophysical logging, multi-offset VSP surveys, fluid logging and hydraulic tests were conducted using shallow and existing boreholes in the site-scale area for the zone shallower than 500 m in the Toki Granite in order to directly determine the site-scale 3-D distribution of the geological structures estimated in Step 1[1),2),3),4)]. Based on the geological data obtained in this step, the thickness of the sedimentary rocks, the correlation between the distribution of the Tsukiyoshi Channel (see Section 3.2.1) and the tectonic zonation of the Toki Granite (weathered zone, upper highly fractured domain and low-angle fractured zone to be discussed later), and the relationship between the width and trace length of discontinuities were used to update the geological model[5),6)]. The distribution of water conducting features was estimated by combining the data on the estimated distribution of discontinuities, the distribution of the in/out flow points of groundwater determined by fluid logging and hydraulic characteristics such as transmissivity obtained from the hydraulic tests[2),3)].

Results

A combination of investigations such as core logging, investigations of borehole wall image and geophysical logging in the shallow boreholes allowed definition of the depth profile of each formation of the Mizunami Group and identification of the subsurface distribution of the NNW trending fault identified in Step 1. Fault gouge and breccia were observed in the fault and the nature of the fault was revealed to be consistent with that confirmed in Step 1 (see Section 3.3.1)[1)]. A series of geological investigations were also conducted in the existing boreholes located near the MIU Construction Site, resulting in the identification of two additional faults with an EW strike and confirmation of the continuity of faults with a NS strike in the Toki Granite. It was also found that a weathered zone (where almost all primary minerals are altered or leached and iron-oxidizing minerals and iron hydroxide are precipitated at grain boundaries) with a thickness of a few meters is located in the upper part of the granite; the upper highly fractured domain is distributed down to a depth of at least 500 meters in the granite and there is a zone where fractures dipping at a low-angle are concentrated in the upper highly fractured domain[2),3)] (low-angle fractured zone).The multi-offset VSP surveys in the existing boreholes allowed a clear correlation to be made between the reflection events obtained from the reflection seismic surveys and each formation and the tectonic classification in the granite found in the boreholes (e.g. the fracture concentration zone dipping at a low angle), contributing to improved accuracy of their spatial distribution.[2),3),5)].

The geological model was updated (Fig. 3.4.1-1: geological map (left) and geological model (right)) based on the above data. Compared to the model constructed in Steps 0 and 1, the updated model was more accurate in terms of the distribution of each formation of the Mizunami Group and the understanding of tectonic zonation (weathered zone, upper highly fractured domain and low-angle fractured zone) and the distribution of faults in the Toki Granite.

Conclusions and implications for the next investigation steps

In this step, the depths where each sedimentary formation and the tectonic zones of granite occur were accurately determined and determination of the distribution and nature of the faults in the granite was possible. In particular, the combination of geological investigations using boreholes and the multi-offset VSP survey in the boreholes was found to be effective for accurately estimating the spatial distribution of the faults in the granite.

Fluid electrical conductivity (FEC) logging[7),8)] was effective for determining the distribution of in/out flow points of the groundwater in the granite and, combined with geological investigations and hydraulic tests, it could confirm that the NNW, NE and EW trending faults function as the in/out flow paths for groundwater. The approach of constructing a geological model based only on geological data may overlook small-scale features that are hydrogeologically significant. Therefore, combining the geological investigations with hydraulic tests is effective for constructing models that could be used to determine the distribution and hydraulic characteristics of discontinuities that are important as water conducting features[2),3)].

Issues for subsequent steps would be to determine the distribution and nature of the faults interpreted in this step for the deeper zone in the granite.

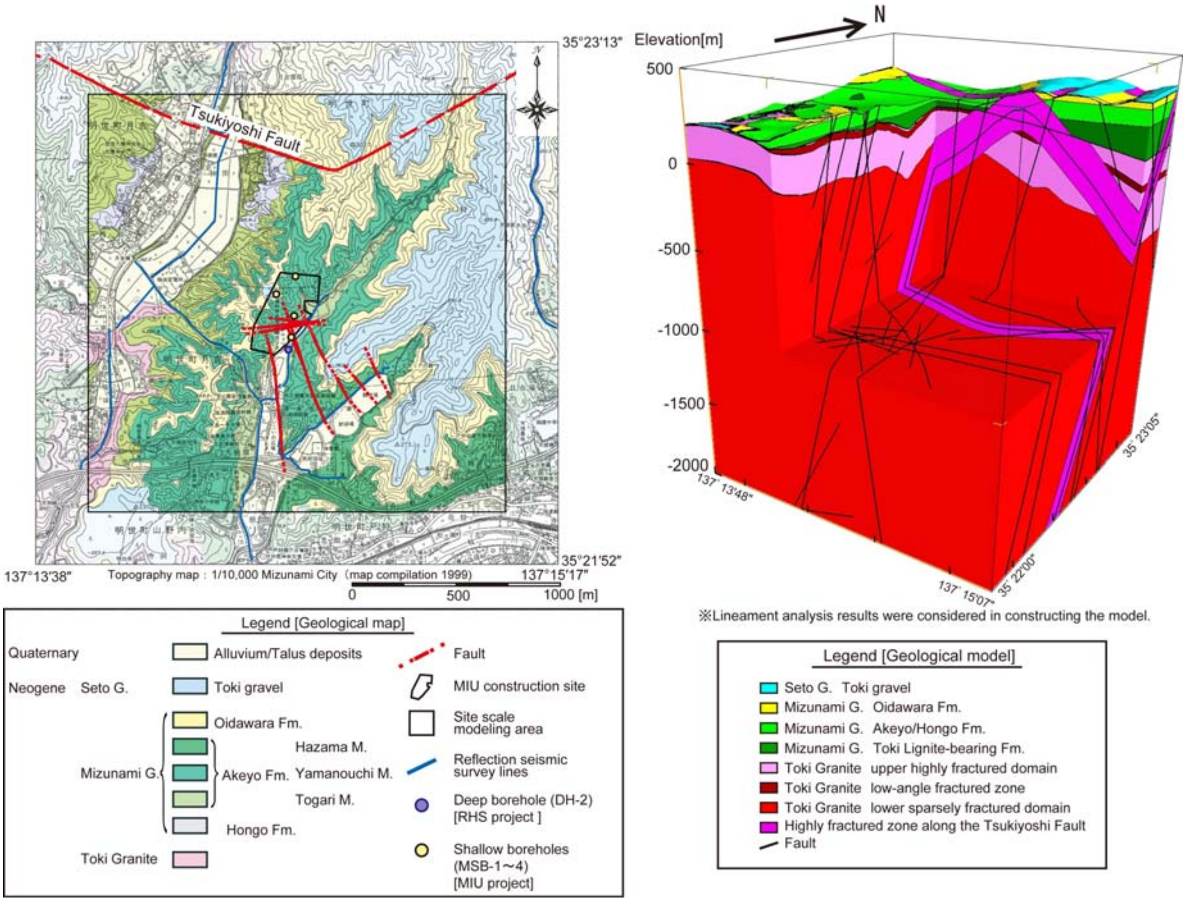


Fig. 3.4.1-1 Geological map and geological model revised using existing and new shallow borehole investigation phase data[6)]

3.4.2 Groundwater flow characteristics

For the NNW trending fault that was predicted from the analysis conducted in Step 1 to have a significant influence on the characteristics of groundwater flow, data needed to be obtained directly from borehole investigations. In this step, fluid logging and single-hole hydraulic tests using existing and new shallow boreholes (see Section 3.4) were conducted with the aim of acquiring data on the hydraulic characteristics of the Mizunami Group, the Toki Granite and the discontinuities[2), 9)]. Also, long-term hydraulic monitoring was conducted in the boreholes used for the above investigations. The aim was to understand the overall distribution of the hydraulic gradient around the MIU Construction Site and to quantitatively test the results of the steady state groundwater flow simulation through comparison with the data from the long-term hydraulic monitoring[10)].

The hydrogeological model was updated by adding the hydraulic characteristics of geological units determined from the individual investigations to the 3-D geological model updated in this step (see Section 3.3.2 [11)]). The results of the groundwater flow analyses in Step 1 (see Section 3.3.2) suggested that the longer the trace of the fault, the greater the effect tends to be on the groundwater flow characteristics. Therefore, screening focusing on the trace length of faults was conducted to allow effective construction of the hydrogeological model and groundwater flow analyses. Similarly to the groundwater flow analysis in

Step 1 (see Section 3.3.2), a sensitivity analysis focusing on the uncertainties associated with hydraulic characteristics of the faults was conducted, using the updated hydrogeological model to determine the effect of faults on the distribution of the hydraulic gradient and also to assess the degree of understanding of the groundwater flow characteristics during the progress of the investigations[11]. The boundary conditions for the site-scale analyses were updated by reflecting the investigation data obtained in this step in the hydrogeological modeling and the analyses of the groundwater flow for the local-scale area[12]. The GEOMASS system (see Section 4.10) was used for the construction of the geological and hydrogeological models and for the groundwater flow analysis.

Results

The hydrogeological model updated in this step is shown in Fig. 3.4.2-1. The low-angle fractured zone in the upper highly fractured domain in the Toki Granite was included in the model and the configuration of formation boundaries and the distribution of faults were updated. The results of the single-hole hydraulic tests conducted in test intervals set up for each geological unit showed variations in the hydraulic conductivity of the different formations of the Mizunami Group by an order of magnitude (see Section 4.7)[2,10]. This illustrates the importance of setting up test intervals based on geological unit as determined by borehole investigations when conducting single-hole hydraulic tests. Of the logging runs conducted (see Section 4.6), the flow volume of the groundwater flow path identified by the fluid electric conductivity logging and the distribution of transmissivity were consistent with the results of the hydraulic tests[13,14]. Therefore, it was confirmed that the numerical analysis based on the results of the fluid electric conductivity logging are an effective method for interpolating the results of the hydraulic tests.

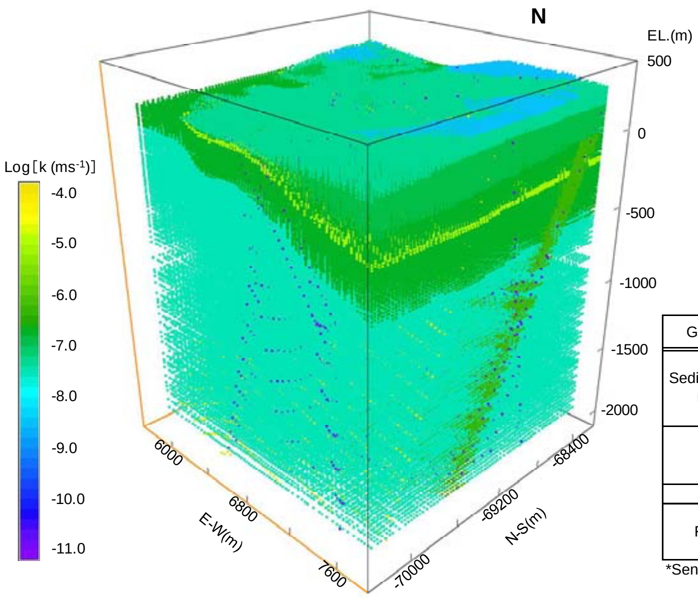
As a result of the long-term hydraulic monitoring using the boreholes, a trend was identified whereby the groundwater pressure decreased by approximately 40 - 50 meters near the boundary between the Akeyo/Hongo Formations and the Toki Lignite-bearing Formation in the Mizunami Group, which would indicate the existence of a hydraulic boundary caused by the sedimentary structure in the Mizunami Group[10]. Large differences in groundwater chemistry in the shallower and deeper zones divided by this hydraulic boundary were observed, also indicating the possibility of the existence of a hydraulic boundary from a geochemical point of view (see Section 3.4.3). These findings confirm the importance of observing in groundwater pressure in each hydrogeological unit in the boreholes and the need to test the observation results and the groundwater flow characteristics based on the groundwater chemistry.

In order to determine the distribution of hydraulic gradient on the site scale and to evaluate the influence of the hydraulic characteristics of the fault on the distribution of hydraulic gradient, the 3-D distribution of hydraulic head was calculated based on the results of the groundwater flow analyses[11]. In the groundwater flow analyses, hydraulic anisotropy of the Akeyo/Hongo Formations were assigned taking into account the hydraulic boundary. A sensitivity case and the results are shown in Section 3.7.2. The comparison of the results from the sensitivity analyses in this step with those from Step 1 (see Section 3.3.2) showed that the distribution of hydraulic head in the analysis area differed greatly (Fig. 3.4.2-2), indicating that the faults considered to significantly affect the groundwater flow-field in/around the MIU Construction Site varied as the hydrogeological model was updated with the progress of the investigations. This confirms the need for sensitivity analyses with the progress of stepwise investigations and the importance of identifying the geological structures to be investigated in the subsequent steps.

The distribution of hydraulic head based on data obtained from the long-term hydraulic monitoring in the existing boreholes was compared with that based on the results of the groundwater flow analysis. The analysis results from Step 1 (see Section 3.3.2) and Step 2 were also compared with each other to confirm the improvement in reliability of the results with the progress of the investigations. Fig. 3.4.2-3 shows the square root of the deviation of the measured and modeled hydraulic head in Step 1 and 2. This figure indicates that the models have been substantially improved reducing the difference by an order of magnitude. The improvement is due to a) the direct acquisition of data on the hydraulic characteristics of geological structures from the borehole investigations and b) the contribution of the data obtained with the progress of the investigations to the improvement of the boundary conditions for the groundwater flow analyses. This suggests that the boundary conditions for the groundwater flow analyses should be updated as required, based on the data obtained at each step when the boundary conditions are being established based on the results of groundwater flow analyses for the wider area and groundwater flow characteristics in the wider area are being updated[12]. The long-term hydraulic monitoring allows determination of the general trend of the depth profile of the hydraulic gradient with a steady state condition and quantitative comparison of measured values with analysis results for the groundwater flow analyses.

Conclusions and implications for the next investigation step

For the investigations in subsequent steps, it was considered particularly important to evaluate the geological and hydraulic characteristics of the NNW, NW and EW trending faults in the granite, for which it was shown based on the groundwater flow analyses conducted in this step that faults with these strikes significantly affect the groundwater flow-field at the MIU Construction Site. It would also be important to obtain data on the geological and hydraulic characteristics of the granite which is predominant in the hydrogeological model.



Hydraulic conductivity

Geological features and geological structure element			Log [k (m s^{-1})]
Sedimentary rock	Seto group		-5.0
	Mizunami group	Oidawara formation	-8.5
		Akeyo/Hongo formation	-7.4
		Toki-lignite bearing foramation	-6.9
Toki granite		Upper Highly fractured domain	-6.7
		Low angle fractured zone	-5.1
		Lower sparsely fractured domain	-7.5
Highly fractured zone along the Tsukiyoshi fault			-6.4
Fault	Main part of Tsukiyoshi fault		-11.0
	Other faults	In-plane of fault	See Table 3.2.6(2)-3
		Normal to fault*	

*Sensitivity analysis about hydraulic anisotropy:10faults in 11

Fig. 3.4.2-1 Hydrogeological model (3-D distribution of hydraulic conductivity)

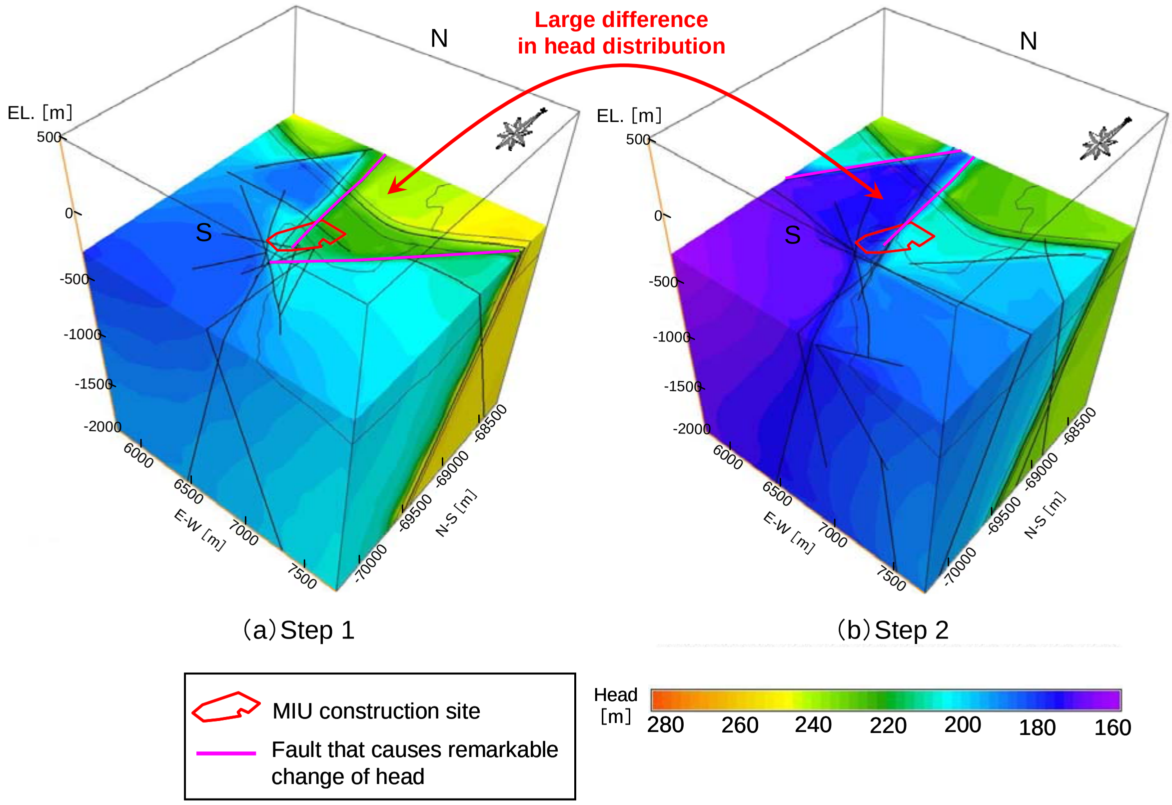


Fig. 3.4.2-2 Comparison of head distribution between Step1 and 2
(All fault : hydraulic anisotropy)

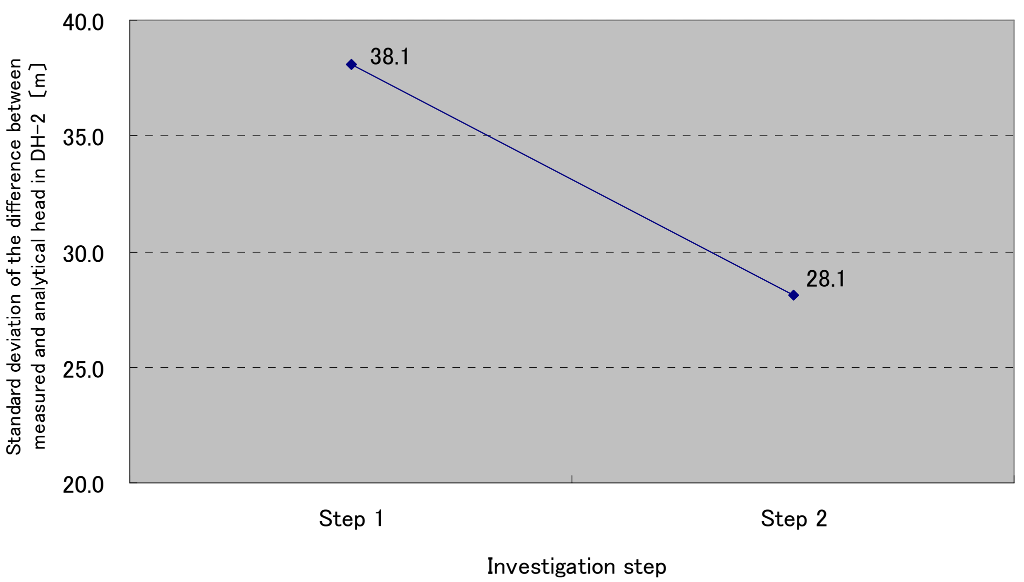


Fig. 3.4.2-3 Comparison between measured and analytical head differences in Step 1 and 2

3.4.3 Geochemical characteristics of groundwater

The goals of the investigations in this step were to test and update the hydrochemical model and to determine the geological environment prior to the excavation of the underground facilities, based on the data and the analysis results obtained in Steps 0 and 1.

Since geochemical data of the groundwater of sedimentary formations around the MIU Construction Site had not been measured up to this point, this step aimed to acquire these data. Therefore, groundwater and rock samples were collected and analyzed for hydrochemical analysis and for updating the model, by conducting borehole investigations for the Mizunami Group with a thickness of a few tens of meters to approximately 200 meters, covering the Toki Granite.

Results

The results of the above investigations indicated that the groundwater in the sedimentary rocks in the site-scale area is Na-Ca-HCO_3 type, rich in silicon and sulphate ions in the shallower part (Fig. 3.4.3-1) and Na-Cl type in the deeper part of the Mizunami Group and the upper part of the Toki Granite. It was also found that the salinity of the groundwater generally increases with increasing depth. A low permeability layer[15)] was found at the depth where the boundary occurs between the Na-Ca-HCO_3 type and the Na-Cl type groundwater in the Mizunami Group. Additionally, a significant lower hydraulic head was observed in the lower part of Mizunami group. The low permeable layer effectively separates the two different groundwater types (Fig. 3.4.3-2). The origin and evolution process of Na-Ca-HCO_3 type groundwater suggests meteoric water and water-rock interaction, respectively[15),16)]. On the other hand, the origin and evolution process of Na-Cl type groundwater is not clear. However, the origin of Na-Cl type groundwater will be different from the Na-Ca-HCO_3 type groundwater[16)].

In the shallower part of the Mizunami Group, the hydrogen/oxygen isotope ratio in the groundwater varies within the fluctuation range of that in the precipitation water sampled around the MIU Construction Site. Tritium was also detected. Thus, the origin of the groundwater in the shallower part of the Mizunami Group is considered to be recent precipitation, with a faster recharge rate compared to the groundwater in the deeper part of the Group[16), 17)]. This finding, combined with that in Step 0 (Sections 3.2.2, 3.2.3), suggests that the flow rate of the groundwater would be very slow deep underground at the MIU Construction Site where it is surrounded by the Tsukiyoshi Fault and the low permeability formations in the sedimentary rocks above. This finding is consistent with the results of groundwater flow analysis.

Conclusions and implications for the next investigation step

At the time of excavating the underground facilities, since the distribution of groundwater chemistry and groundwater flow conditions may have been affected by the distribution of the low permeability formations in the sedimentary rocks, the extent and level of their influence is expected to be different bordering at the low permeability formation. Therefore, observations and analyses for each hydrogeological unit would be essential for evaluating the change in the groundwater regime associated with the excavation in Phase II and subsequent phases. The geochemical characteristics of the groundwater in the Toki Granite would need to be reflected in the investigations using deep boreholes to be conducted in the next step.

In Step 2, information showing the relationship between the distribution of geochemical characteristics of groundwater chemistry and the hydrogeological structures in the Mizunami Group and the adequacy of the results of the groundwater flow analysis in Step 2 was acquired. Guidance for the investigations in the subsequent steps was also established e.g. clarification of the origin of the Na-Cl type groundwater in the lower sedimentary formation. Comparison of the hydraulic characteristics with the distribution of geochemical characteristics of groundwater would allow the results of the groundwater flow analysis to be tested and the credibility of the conceptual hydrochemical model to be improved.

It was considered important to acquire data on the geochemistry of the groundwater in the granite during the investigations in the subsequent steps.

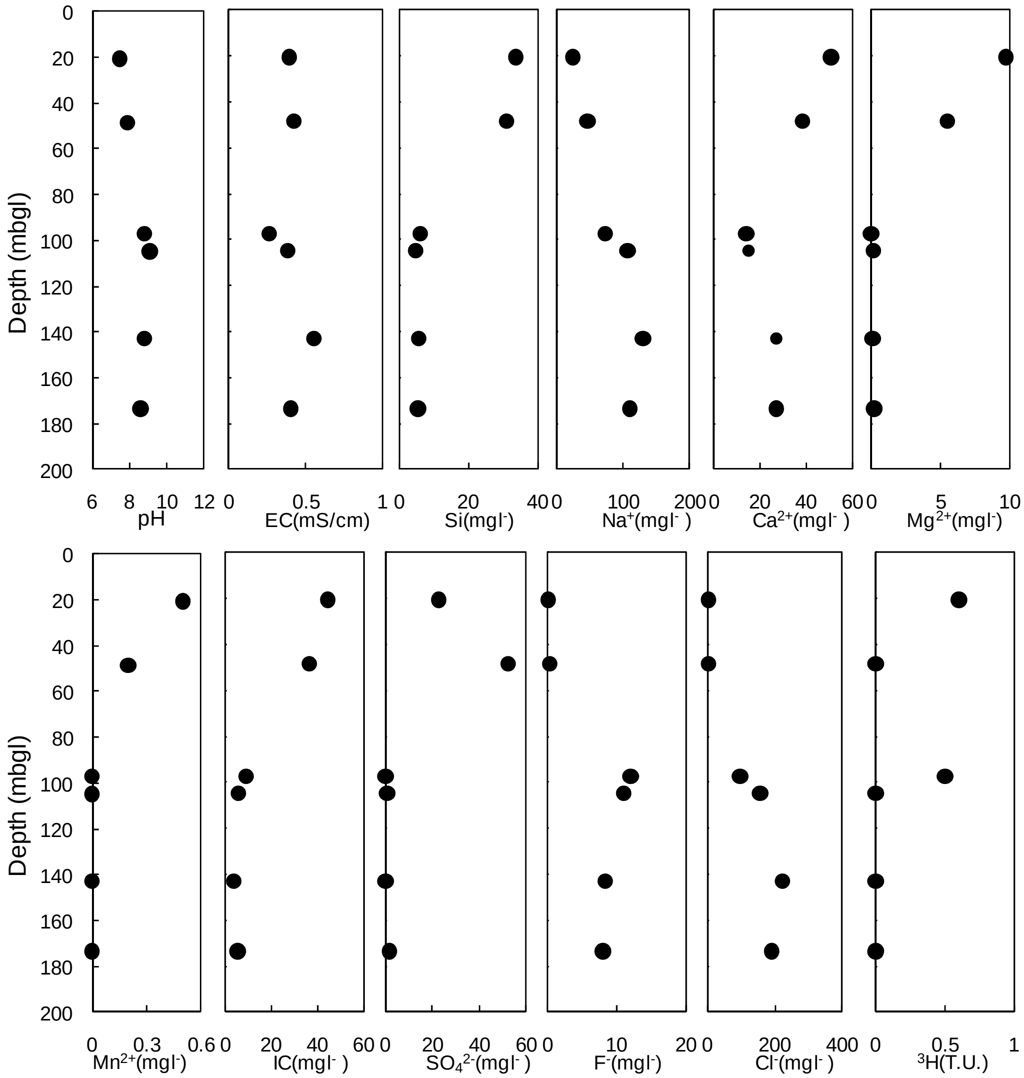


Fig. 3.4.3-1 Depth profile of groundwater chemistry in the borehole (MSB-2,4)[15)]

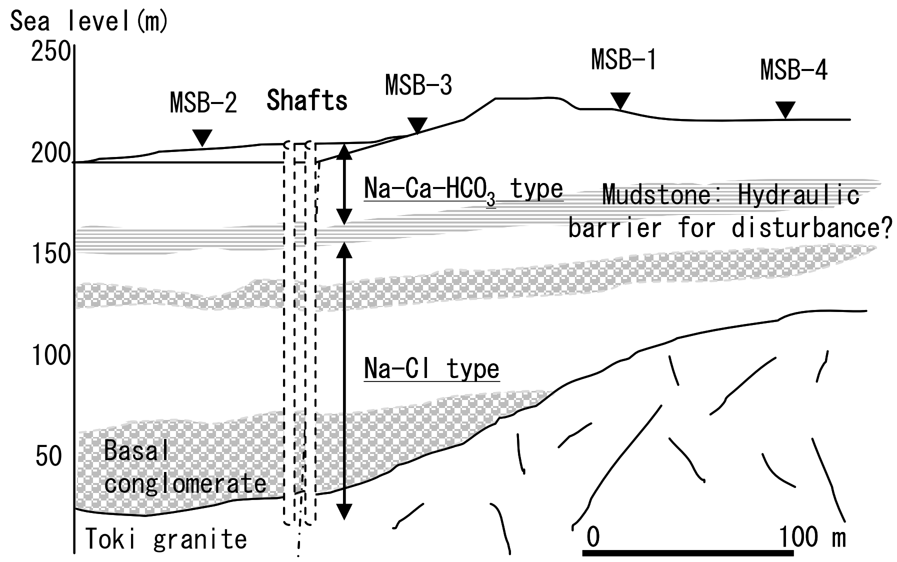


Fig. 3.4.3-2 Schematic view of groundwater chemistry in the sedimentary rock of site scale

3.4.4 Dilution of nuclides

The distribution of the Darcy velocity was calculated based on the results of the groundwater flow analysis presented in Section 3.4.2 to determine the dilution effect of each hydrogeological unit.

Results

By updating the hydrogeological model (see Section 3.4.2) using the data acquired in this step, a low-angle fractured zone with a particularly high hydraulic conductivity in the upper highly fractured domain was identified as the structure assumed in Step 1 to be an aquifer.

The frequency distribution of the Darcy velocity was calculated for the -different hydrogeological units as shown in Fig. 3.4.4-1. The results indicated that the Darcy velocity for the low-angle fractured zone is the highest, followed by the upper highly fractured domain, the Toki Lignite-bearing Formation and the highly fractured zone along the Tsukiyoshi Fault, where velocity tends to be high in general. The Darcy velocity in the Akeyo/Hongo Formations is also high, but is lower than that determined for the lower sparsely fractured domain in Step 1 (see Section 3.3.3). This was because data indicating high hydraulic conductivity were obtained for the Akeyo/Hongo Formations from the investigations in the shallow boreholes. This suggests that borehole investigations that can directly determine the hydraulic characteristics of geological units are very effective for determining the dilution effect. Compared to the Darcy velocity for the lower sparsely fractured domain with relatively low hydraulic conductivity in the Toki Granite, the resulting velocity is higher for the low-angle fractured zone, the upper highly fractured domain, the Toki Lignite-bearing Formation, the highly fractured zone along the Tsukiyoshi Fault and the Akeyo/Hongo Formations. These results indicate that these would be important hydrogeological units in considering the dilution effect.

In this step, the low-angle fractured zone was identified as a separate hydrogeological unit where dilution effects can be expected. For determining the hydraulic characteristics and the dilution effect in the site-scale area with high reliability, it would be useful to conduct borehole investigations and directly acquire data on the distribution of the hydrogeological units deeper underground.

Conclusions and implications for the next investigation step

In the subsequent steps, borehole investigations should be conducted for the zone deeper than that investigated in this step to determine the existence of additional geological units where a dilution effect could be expected. Also, it was considered important to calculate the distribution of the Darcy velocity with higher reliability than in this step, by acquiring data on the distribution range in three dimensions and reflecting the hydraulic characteristics in the hydrogeological model.

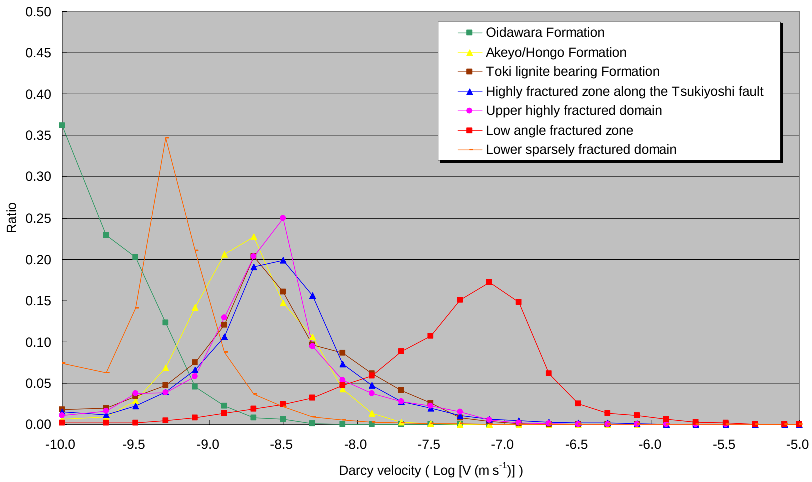


Fig. 3.4.4-1 Darcy velocity distribution
(The vertical axis shows the ratio (cumulative frequency is 1 in each geological formation and domain))

3.4.5 Local stress regime and spatial variability of petrophysical/geomechanical properties of rocks

One of the goals of the investigations in this step was to build on knowledge from the previous steps of the petrophysical/geomechanical characteristics of rock and local stress regime of the Toki Granite in/around the MIU Construction Site- and construct a rock mechanical model for the MIU Construction Site.

Laboratory examinations were conducted to estimate the initial stress state. These included petrophysical/geomechanical examinations using cores from the DH-2 borehole near the MIU Construction Site and examinations using the differential strain curve analysis (DSCA) method[18]. Because several years had passed since the cores were collected from the DH-2 borehole, the DSCA method was selected for the measurements, which, in principle, is not influenced by the age of the cores. It should be noted that the initial stress states obtained using the DSCA method were in the principal stress direction only. Therefore, the information is not sufficient for use as boundary conditions for the numerical analyses to predict the impact of the excavation and such an analysis of the rock surrounding the underground facilities was therefore not conducted.

Results

A rock mechanical model was constructed for the rock around the MIU Construction Site (Fig. 3.4.5-1), based on the results of laboratory examinations using cores from the DH-2 borehole and the geological model updated in this step (Fig. 3.4.1-1). The analysis from the DH-2 borehole showed that the intact rock has a higher apparent specific gravity and lower effective porosity and elastic wave velocity compared to the rock mechanical model for the Shobasama Site in Step 0 (see Section 3.2.6). Concerning the geomechanical characteristics, the uniaxial compressive strength was smaller and the stiffness and the failure criterion were comparable to those of the model for the Shobasama Site. With regard to the initial stress states estimated from the laboratory examinations using the DSCA method, the maximum principal stress direction was N-S to NW-SE and its trend was the same as that of the rock mechanical model for the Shobasama Site in Step 0. As the initial stress states obtained in this step were in the direction of the principal stress, the magnitude of the principal stress was not obtained. Therefore, in-situ rock mechanical tests, such as hydraulic fracturing, using boreholes are required to evaluate the magnitude of the principal stress in the next step. The petrophysical/geomechanical characteristics of rock and stress regime obtained in this step were only for the section extending from the upper highly fractured domain in the Toki Granite down to a depth of 500 meters and the data from Step 0 need to be referred to for the characteristics of the geological units deeper than 500 meters.

Conclusions and implications for the next investigation step

In the investigations in the subsequent steps, the underground facilities will be excavated down to a depth of 1,000 meters. In order to construct a rock mechanical model for the zone extending from the surface to this depth, data on the stress regime and the petrophysical/geomechanical characteristics of the rock would need to be acquired through investigations using boreholes with a depth of approximately 1,000 meters.

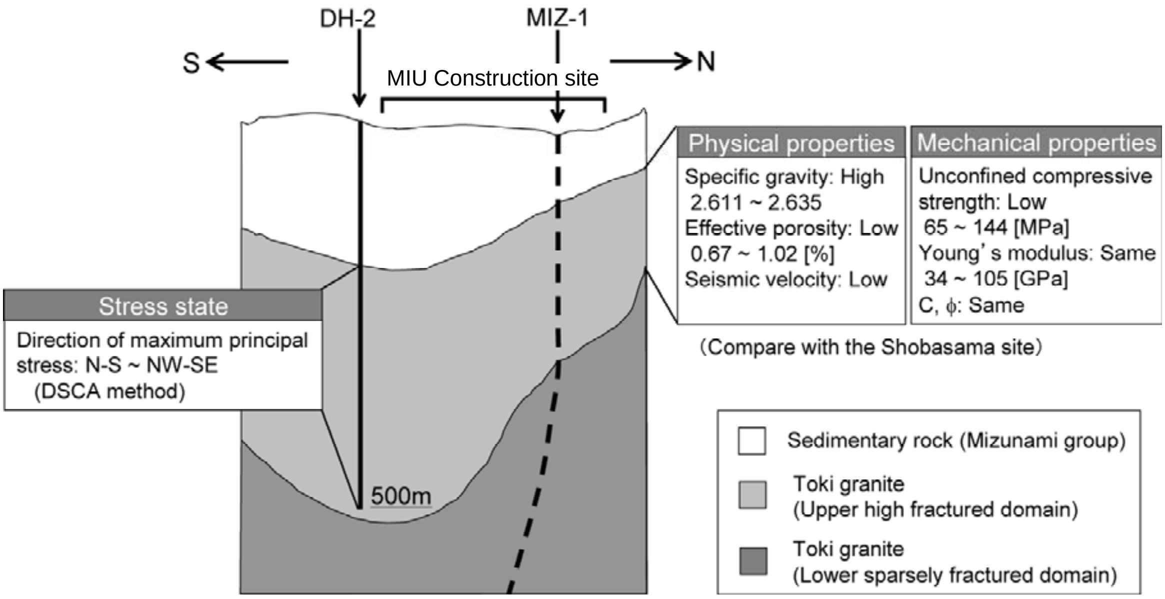


Fig. 3.4.5-1 Rock mechanical model in and around the MIU construction site

3.4.6 Volume of inflow into underground tunnels

Groundwater flow analyses[19] with the aim of predicting the inflow rate into the underground facilities were conducted using the updated hydrogeological model (see Section 3.4.2)[11].

The analyses were conducted by solving a 3-D transient problem for saturated - unsaturated conditions using the equivalent heterogeneous continuum model[20] based on the finite element method. Mesh sizes were determined using a "nested model" whereby the mesh sizes in the area around the MIU Construction Site are smaller than those in the outer area so that the hydrogeological structures around the underground facilities can be modeled in more detail. The Main Shaft, Ventilation Shaft, and galleries (see Fig. 1.2.1-2) were also included in the model and the internal boundary conditions were changed in a transient manner by stepwise simulating the excavation process of the underground facilities. The walls of the underground facilities are considered to represent a boundary condition between a completely open condition and a no-flow boundary due to the effect of the concrete lining or drainage material placed between the lining and the rock. The concept of a “pressure relief factor: α” was introduced to establish this boundary condition at the tunnel, thus taking into account the influence of the tunnel wall on the inflow volume. The water pressure was obtained by multiplying the difference between the initial water pressure, calculated of the tunnel wall before excavation, and atmospheric pressure at the same location by the pressure relief factor α.

For the groundwater flow analyses, a sensitivity analysis (Table 3.4.6-1) was conducted focusing on the differences in the pressure relief factors and the uncertainty in the hydrogeological model (difference in the number of discontinuous structures to be modeled). In Model A, the hydrogeological structure in the site-scale area (see Section 3.4.2) was modeled within the nested model area and the Tsukiyoshi Fault was modeled in the outer area of the nested model area. Model B augments Model A by the inclusion of inferred faults defined by lineaments (> 3 km length) in the outer area of the nested model area in Model A, which could be similar in size to the Tsukiyoshi Fault. Model C was constructed by stochastically modeling the heterogeneity of the hydraulic conductivity of the granite zone of Model B, associated with the distribution of water conducting fractures.

Results

The groundwater flow analyses using the hydrogeological model with different heterogeneities (Models A, B and C) resulted in similar inflow rates into the underground facilities when the pressure relief factors were the same (Fig. 3.4.6-1). As expected, the inflow rate varied greatly, even for the same model, when the factors were different.

Since the upper highly fractured domain has a higher hydraulic conductivity compared to the other hydrogeological unit, 60 - 80 % of the total inflow into the underground facilities was from the zone where the highly fractured domain is present (approximately 200 - 500 meters depth). In the case of smaller the pressure relief factor, the ratio of inflow in the zone shallower than the Middle Stage to the total inflow is larger. While the inflow rate also increased in the zone deeper than the Middle Stage depth (Fig. 1.2.1-2) when the pressure relief factor was small, the inflow rate showed a maximum rate (approximately 4,000 $m^3 day^{-1}$) immediately after completion of excavation of the Middle Stage and then generally decreased when the pressure relief factor was large. From the above results it is shown that the influence of the hydrogeological characteristics near the tunnel on the inflow rate are quite significant, because artificial structural material, such as lining concrete or drainage materials may function as a skin.

Despite differences due to the pressure relief factors, it was suggested in all models that the zone with decreased water pressure due to inflow into the underground facilities was strongly affected by the faults distributed around the MIU Construction Site that are assumed to be hydraulically anisotropic. As the range and level of the decrease in the water pressure would affect the inflow rate, it is important to acquire data on the spatial distribution and hydrogeological characteristics of the faults distributed around the site.

The groundwater flow analysis using the updated hydrogeological model allowed the inflow rate to the underground facilities to be estimated, taking into account the effect of high permeable and low permeable features. This model was compared with that developed in Step 0. In addition, important factors for the investigations in Phase II and subsequent phases were identified, including hydrogeological characteristics near the underground facilities that would have an influence on the inflow rate into the tunnels.

With the findings described above, the influence of the hydrogeological heterogeneity on the inflow rate could be evaluated by conducting 3-D groundwater flow analyses, predicting the range of inflow rates into the underground tunnel based on a hydrogeological model that incorporated heterogeneity. However, 3-D analysis requires a larger amount of time for meshing and calculation compared to predictions based on theoretical analytical formulae. Therefore, the decision on which method to apply will depend on the required accuracy of the predictions for the design/construction of the underground facilities.

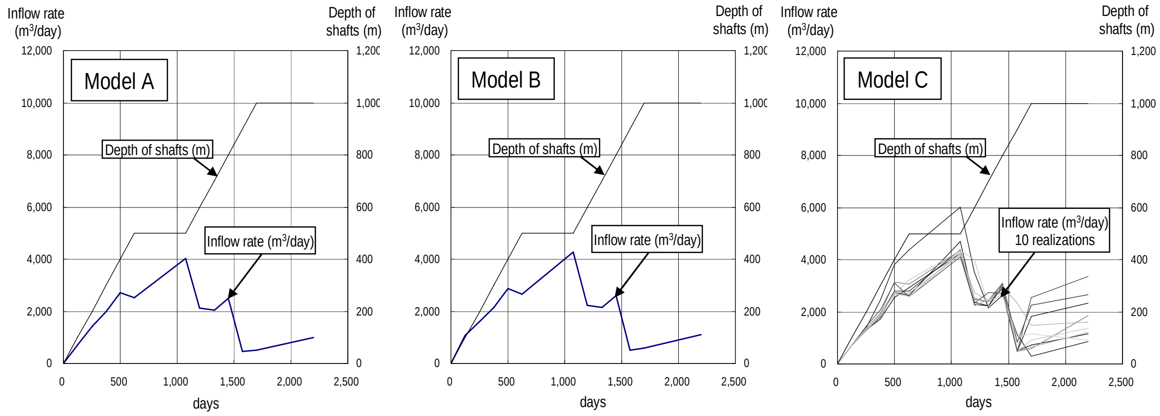
Conclusions and implications for the next investigation step

Since the data in this step on the geological and hydrogeological characteristics of the faults in the granite that are predicted to be encountered by the underground facilities, and on the hydrogeological characteristics of the lower sparsely fractured domain, are not sufficient, acquiring such data was considered important in the subsequent steps. Also, since a high inflow rate from the upper highly fractured domain was predicted, determining the hydrogeological characteristics and the continuity of this domain is important for improving the accuracy of the predictions.

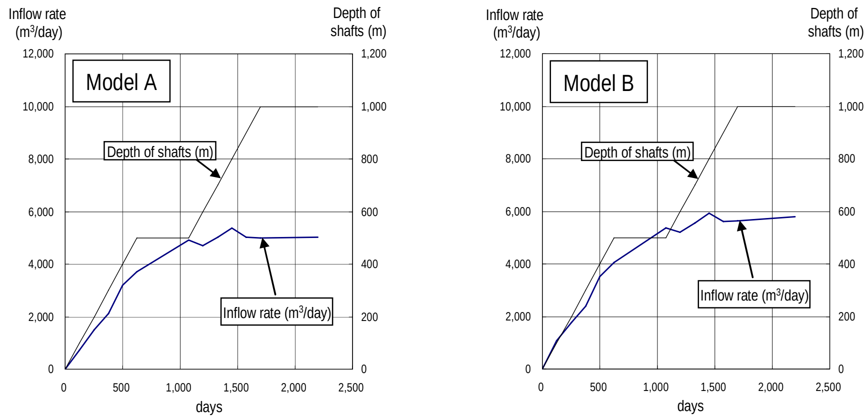
Table 3.4.6-1 Groundwater flow simulations

Case	Modeled fault／WCF	Pressure relief factor
Model A	Tsukiyoshi Fault＋Faults around MIU Construction Site	α =0.2, 0.8
Model B	Model A＋Lineaments with length more than 3km	α =0.2, 0.8
Model C	Model B＋WCF（Modeled using Equivalent Heterogeneous Porous medium）; 10 realizations	α =0.8

WCF: Water Conducting Feature



(a) Pressure relief factor: 0.8



(b) Pressure relief factor: 0.2

Fig. 3.4.6-1 Inflow rate into MIU

3.4.7 Distribution of discontinuities intersecting underground tunnels

The locations where discontinuities would emerge at the planned excavation points for the underground facilities were predicted[6)] based on the geological model presented in Section 3.4.1, with the aim of acquiring information on features such as faults and fractured zones at the underground facilities that may have an influence on the petrophysical/geomechanical characteristics of the rock.

Results

The positions where discontinuities would intersect underground facilities are shown in Fig. 3.4.7-1. The subsurface extent of the fault with a NNW strike identified in Step 1 (IF_SB0_005 in Fig. 3.3.4-1) was confirmed and data on the fault were updated (IF_SB1_004 in Fig. 3.4.7-1). It was predicted that newly identified faults with NS strikes and EW strikes (IF_SB1_001 and IF_SB1_002, 003, 005) may emerge at the planned MIU Construction Sites. Many of these faults were predicted to dip at high angles by the integrated interpretation of data gained by geological mapping, reflection seismic survey and borehole investigations.

Conclusions and implications for the next investigation step

In this step, data on the subsurface extent of the faults was obtained by combining geological investigations with the multi-offset VSP survey. The distribution of faults in the shallower granite zone (to a depth of 500 meters) was determined more accurately compared to that in Step 1.

The issues for subsequent steps would be to determine the distribution and geological characteristics of faults in the deep granite that were predicted in this step to be encountered by the underground facilities.

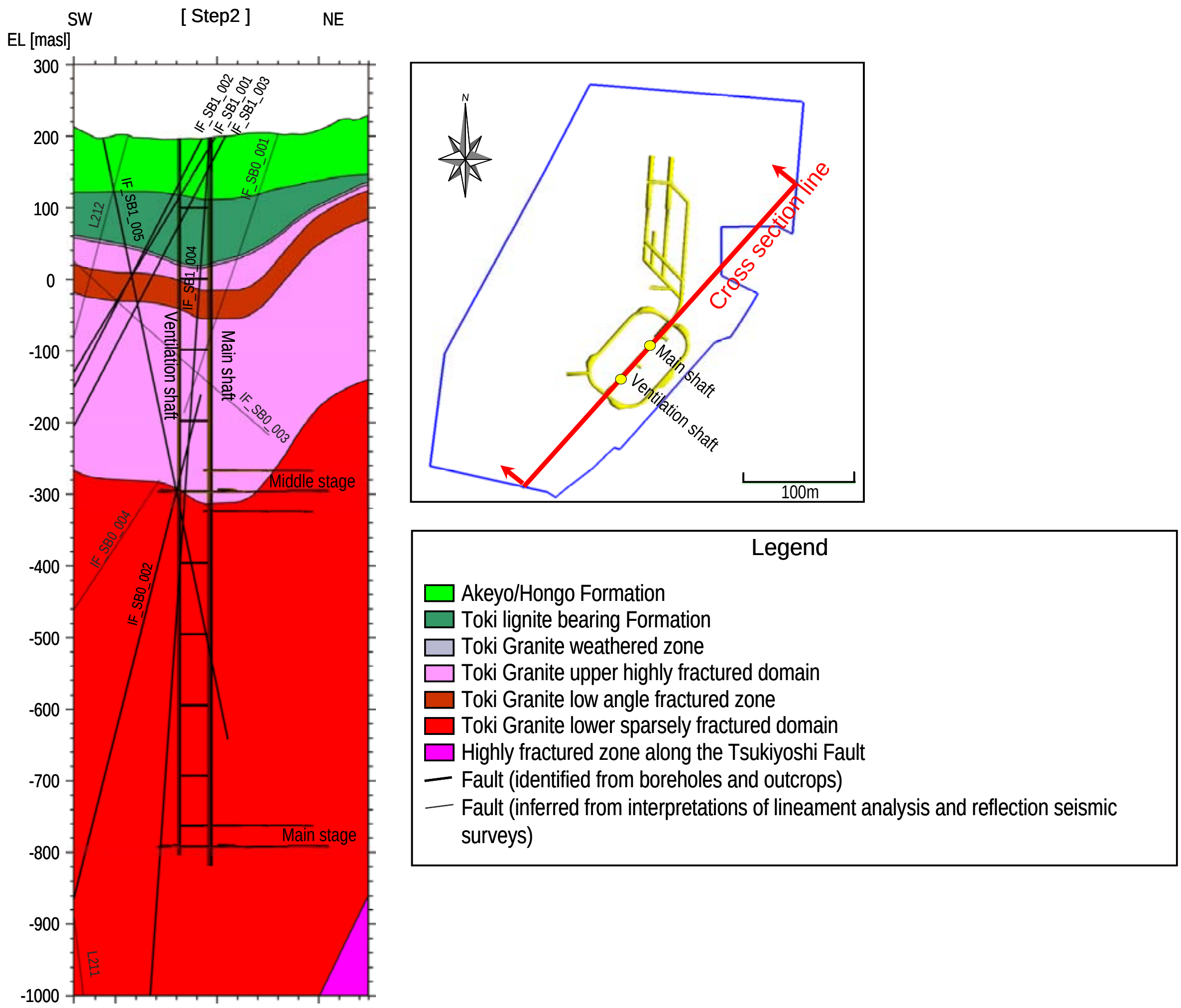


Fig. 3.4.7-1 Predicted geological structures around the MIU facility (Step2)

3.4.8 Subsurface thermal conditions

The goal of this step was to acquire data on the geothermal conditions in the Toki Granite at/around the MIU Construction Site.

In Step 2, temperature logging was conducted to determine the geothermal gradient in the existing boreholes near the MIU Construction Site.

Results

The geothermal gradient in the DH-2 borehole, which reaches a depth of 500 meters was 2 ºC/100 meters, a value consistent with the geothermal gradient in the local-scale area (Fig. 3.4.8-1)[21]. This suggests that the geothermal gradient on the site/block scale could be determined by temperature logging in a single borehole on the local scale, as long as a local heat source such as a volcanic zone is not present.

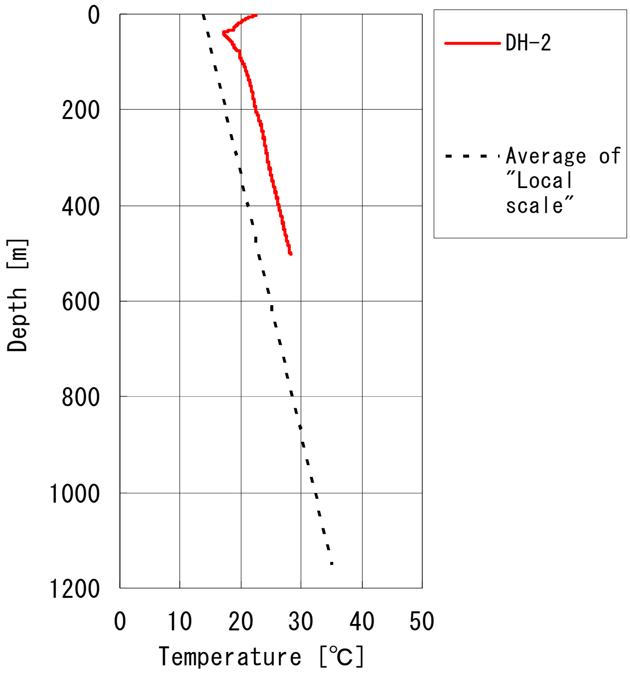


Fig. 3.4.8-1 Result of temperature logging (DH-2)

3.4.9 Discussion of result and recommendation for further investigations

Studies in this step included those using four shallow boreholes and data obtained from existing boreholes drilled as part of the RHS to address the issues listed in Table 3.1-1, with the exception of a) transport/retardation of nuclides, and b) size and structure of EDZ; petrophysical/geomechanical properties of EDZ. The aim was to determine the geological and hydrogeological characteristics in the zone extending from the surface to the shallow geological zone and the geochemical characteristics of the groundwater.

Based on the results of these investigations, the geological model, the hydrogeological model, the hydrochemical model and the rock mechanical model constructed in the two previous steps were updated. Groundwater flow analyses were conducted to estimate the distribution of the hydraulic gradient and the hydrogeological conditions around the underground facilities.

Through the above investigations and modeling and analyses, key issues for the investigations in subsequent steps were identified as listed below;

- Determining the geological and hydrogeological characteristics of a NNW, NW and EW trending faults that are estimated to significantly influence the groundwater flow in the site-scale area and of faults that are predicted to be encountered by the underground facilities in the granite.
- Determining the geological and hydrogeological characteristics of the granite on the site scale.
- Acquiring *in-situ* data on the geochemical characteristics of the groundwater in the granite on the site scale.

- Acquiring data on the local stress regime and the petrophysical/geomechanical characteristics of rock formations by borehole investigations.

Geological structure

Combining the investigations applied in this step was effective for testing and improving the accuracy of the predictions of the geology/geological structural features made in Step 1. It also allowed the distribution of faults in the granite, upper highly fractured domian and water conducting features that were difficult to identify in Step 1 to be determined. The multi-offset VSP survey, in particular, was effective for visualizing the distribution of faults in the deep granite that were difficult to identify with reflection seismic surveys. For a more detailed determination of the distribution of faults, 3-D expansion of the analysis domain would be useful[26)]; this would entail multi-offset VSP surveys with several survey lines in different directions.

Groundwater flow characteristics

Borehole investigations consisting of single-hole hydraulic tests and fluid electric conductivity logging were appropriate for determining the distribution of hydraulic characteristics. For single-hole hydraulic tests, it was important to make working program (including definition of test sections, selection of test methods, etc.) on the basis of the distribution of geological structural features estimated from the geological investigations and the distribution of groundwater in/out flow points in boreholes obtained by fluid logging. In the case where single-hole hydraulic tests could not be performed due to limitations in terms of costs and time, values could be interpolated from the results of numerical analyses based on fluid electric conductivity logging.

An iterative evaluation process consisting of updating the geological model, groundwater flow analyses and evaluations using the same performance index allows evaluation of the influence of specific geological structures on the characteristics of groundwater flow and identification of geological structures that significantly affect the distribution of the hydraulic gradient. Based on the results of such an evaluation, the investigation strategy and program for the subsequent phases can be revised where necessary. For the smooth implementation of iterative investigations and analyses, it is useful to construct a system for geological/hydrogeological modeling and groundwater flow analyses, which is allowing users to quickly construct and modify models in response to the acquisition of new data. When evaluating the characteristics of groundwater flow based on the results of borehole investigations and groundwater flow analyses, it is appropriate to include data on the geochemical characteristics of the groundwater, to better understand the groundwater flow system and to confirm groundwater flow models.

Long-term hydraulic monitoring using boreholes can be used to observe the trend of hydraulic gradient with depth and make predictions of hydrogeological structures such as hydraulic boundaries. Long-term hydraulic monitoring allows quantitative comparisons to be made between measured and analytical values. To acquire data on the overall profile of hydraulic gradient on the site scale at the time of the borehole investigations, it will be necessary to

- conduct long-term hydraulic monitoring for every hydrogeological unit,
- understand the hydraulic characteristics of discontinuities such as faults with significantly different hydraulic conductivities to the background fractured rock
- understand the distribution of groundwater pressure upstream and downstream side of

discontinuities and

- formulate a borehole investigation program aimed at determining the influence of undulating topography that might act as a driving force for groundwater flow.

Geochemical characteristics of groundwater

In this step, it was concluded that a low permeable layer in a sedimentary formation affects not only the hydraulic head distribution, but also influences the mixing and flow paths affecting distribution of groundwater chemistry. Based on the understanding of the geological structures in combination with the determination of hydraulic characteristics (e.g. transmissivity) and head distribution, careful planning of the specific geochemical investigations for the detection of the distribution of different types of groundwater chemistry is recommended.

Dilution of nuclides

Borehole investigations that allow direct acquisition of data on the distribution and hydraulic characteristics of geological units are important for determining dilution effects on the site scale with high accuracy.

Local stress regime and spatial variability of petrophysical/geomechanical properties of rocks

Data on the local stress regime and the petrophysical/geomechanical characteristics of rock not only form the basis for the design of the underground facilities, but are also important for establishing the input dataset for the numerical analyses to predict the impact of the excavation on the rock around the underground facilities that are used to evaluate the distribution and petrophysical/geomechanical characteristics of the EDZ.

The petrophysical/geomechanical characteristics of rock and the depth profile of the initial stress state can be determined by interpreting data from laboratory examinations for petrophysical/geomechanical characterization using the DSCA method using cores sampled at different depths. For the disposal project, laboratory examinations should be conducted using cores from existing boreholes if they are available, to determine the initial stress state and the depth profile of petrophysical/geomechanical characteristics of rock.

Volume of inflow into underground tunnels

It is important to determine the hydraulic characteristics at the construction locations of underground tunnels and to conduct 3-D analyses of groundwater flow based on the hydrogeological model. This is necessary for accurate prediction of the range of inflow into underground tunnels considering the heterogeneous hydrogeological structure and for identification of the factors significantly influencing the estimation of the inflow. In particular, when conducting 3-D groundwater flow analyses, a sensitivity analysis will be required, focusing on uncertain factors that significantly affect the inflow rate into the underground tunnels. However, 3-D groundwater flow analyses require a substantial amount of time for computations compared to estimations based on the theoretical formula. Therefore, the method to be used depends on the estimation accuracy required for designing and constructing the underground facilities.

Distribution of discontinuities intersecting underground tunnels

A combination of the investigations applied in this step is useful for testing and improving the accuracy of the predictions made regarding geological structural features in Step 1. It also allows determination of the distribution of faults in the granite, upper highly fractured domain and water conducting features that were difficult to identify in Step 1. The multi-offset VSP survey in particular is effective for visualizing the distribution of faults in the deep granite that were difficult to identify by reflection seismic survey. For a more detailed determination of the distribution of the faults, 3-D expansion of the analysis domain would be useful[22], which would entail multi-offset VSP surveys with several survey lines in different directions.

Subsurface thermal conditions

Data on the thermal conditions are required for the design and construction of the underground facilities as well as conducting future experiments. For the disposal project, the thermal conditions can be determined by conducting temperature logging in existing boreholes, if available.

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3. 5 Step 3 investigations

In order to address many of the key factors identified in Steps 0 to 2 (see Sections 3.2.10, 3.3.5 and 3.4.9), a deep borehole was drilled and investigations were conducted to determine the geological structures and the hydrogeological, geochemical and rock mechanical characteristics of the deep underground environment (see Sections 4.3 and 4.4). In this step, the results of borehole investigations in borehole DH-15, carried out as part of the RHS, as well as information from the deep borehole MIZ-1 within the MIU Project were used. Also in this step, investigations with the specific aims shown in Table 3.1-1 were conducted, except for those for which the required data could not be obtained.

The objective of the investigations in borehole MIZ-1 was to determine the hydraulic characteristics of the NNW trending fault in the granite that passes through the MIU Construction Site, identified as one of important issues in Step 2 (see Section 3.4), as well as to confirm the spatial distribution of geological structures such as the upper highly fractured domain and to determine its hydraulic characteristics[1),2)]. Particular emphasis was placed on identifying water conducting features and their distribution, and determining petrophysical/geomechanical properties, as well as, determining in detail the 3-D distribution of groundwater chemistry. A further objective was to provide a borehole for the long-term hydraulic monitoring to observe the changes in groundwater pressure associated with the excavation of the underground facilities. In addition to considering the above objectives, the layout and depth of the borehole were determined taking into account budget and construction schedule constraints. Spatial limitations considered were that the borehole should not cross the border of the MIU Construction Site and that the investigations should not interfere with the installation work for the surface facilities during the excavation of the underground facilities (see Appendix 1: Fig. 3.5-1). More specifically, the controlled drilling method was employed which, after initial vertical drilling, proceeds to an inclined alignment controlling the direction and dip angle of the borehole towards the desired direction, in our case towards the fault to be investigated. In order to acquire data on the geology at the greatest depth possible, the length of the borehole was planned to be 1,350 m, which was the maximum depth that could maintain the direction and dip angle required for intersecting with the fault and is the greatest depth possible for excavation within the boundaries of the MIU Construction Site.

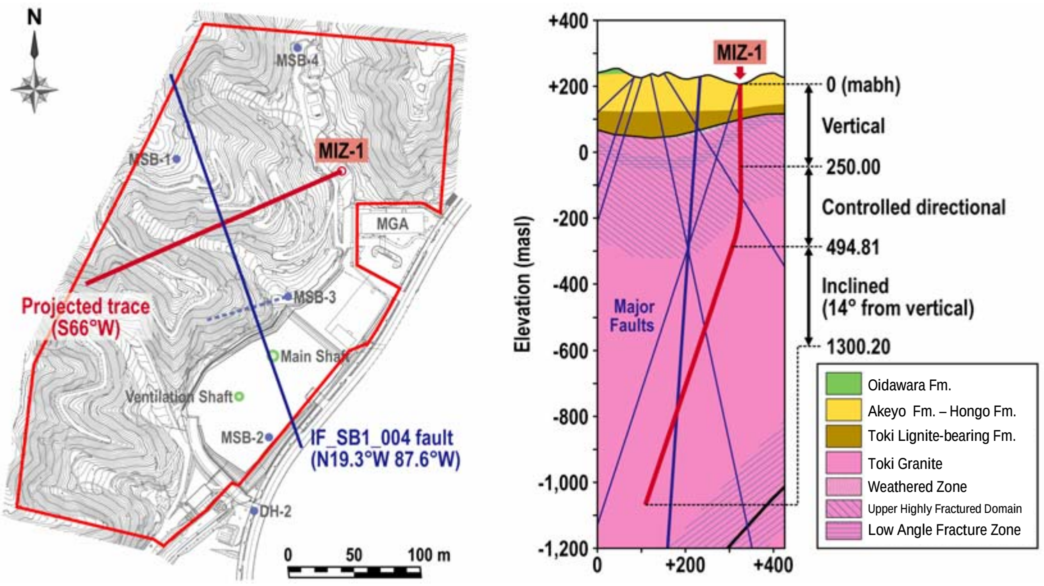
The investigations conducted in borehole MIZ-1 included core logging, investigations of borehole wall image, geophysical logging (see Section 4.5), fluid logging (see Section 4.6), hydraulic testing (see Section 4.7), sampling and chemical analyses of the groundwater (see Section 4.8) and initial stress measurements (see Section 4.9). Hydraulic responses due to borehole drilling and testing activities in MIZ-1 were monitored by using a hydraulic monitoring system installed in the existing and shallow boreholes to confirm hydraulic responses/connections. Finally, a long-term hydraulic monitoring system was installed in MIZ-1 to observe the changes in groundwater pressure associated with the excavation of the underground facilities.

The objectives of the investigations in borehole DH-15 were to determine the hydraulic characteristics of the E-W trending fault in the granite passing through the MIU Construction Site that was identified as one of important issues prior to Step 3 and to determine the influence of the fault on the groundwater chemistry. Initiating a long-term hydraulic monitoring program in DH-15 to determine the change in groundwater pressure associated with the excavation of the underground facilities was also one of the objectives[3)]. The location and layout of borehole was based on considerations of objectives, budget and schedule (see Appendix 1). The borehole was planned to be drilled vertically down to a depth of 1,000 m. The investigation items in borehole DH-15 were the same as those for borehole MIZ-1. After completion of the investigations, a long-term hydraulic monitoring system was also installed.

A description of the borehole investigations is presented in Appendix 3 and the outlines of the investigations in Appendices 5 and 7.

Based on the results of the above investigations, the geological, hydrogeological and hydrochemical models on the site scale and the rock mechanical model on the block scale that had been constructed in Steps 0 to 2 were updated. Using these updated models, analyses of groundwater flow and stress/excavation were conducted to predict the distribution of the hydraulic gradient and geomechanical/hydraulic properties of tunnel near-field environment. The consistency between models and analysis results from different disciplines was checked to improve the credibility of the investigation results. Also, changes in uncertainties and key factors affecting the analysis results were evaluated. Finally, the continuity of the hydrogeological structures affecting groundwater flow was identified as an important issue for investigations in the subsequent steps.

The geosynthesis data flow diagram that was constructed based on the experience gained through investigations in this step is shown in Appendix 4 and the detailed approach for the specific aims is summarized in Sections 3.5.1 to 3.5.9. Key factors for investigation in the subsequent steps and recommendations for further investigations in the disposal project that were identified in this step are summarized in Section 3.5.10.



Topographic map: 1/1,000 (made by JAEA)

Fig. 3.5-1 Location and layout of the planned MIZ-1 borehole[1)]

3.5.1 Geological structure

Core logging, investigations of borehole wall image, geophysical logging, fluid logging and hydraulic tests were conducted in boreholes MIZ-1 and DH-15 to determine the 3-D distribution of the geological structures in the granite zone deeper than 500 m which had not been investigated prior to Step 3[3),4),5),6),7),8)]. Based on the geological data obtained from these investigations the accuracy of the correlation[9)] between the thickness of the sedimentary rock and the distribution of the Tsukiyoshi Channel assumed in Step 2 and preceding steps (see Section 3.2.1) and the tectonic zonation in the Toki Granite (e.g. the weathered zone, upper highly fractured domain and low-angle fractured zone) were improved. Also, the spatial distribution of discontinuities on the site scale was estimated based on newly identified features in order to update the geological model[10)]. The distributions of the water conducting features were predicted[3),5),6),7),8)] by interpreting combined data on the hydraulic characteristics, including the locations of the predicted discontinuities, the points of groundwater in/out flow determined from fluid logging and the transmissivity obtained from the hydraulic tests. Data on the hydraulic characteristics and its connectivity of the discontinuities were acquired from monitoring of hydraulic responses due to borehole drilling in the shallow boreholes where the long-term hydraulic monitoring systems were installed.

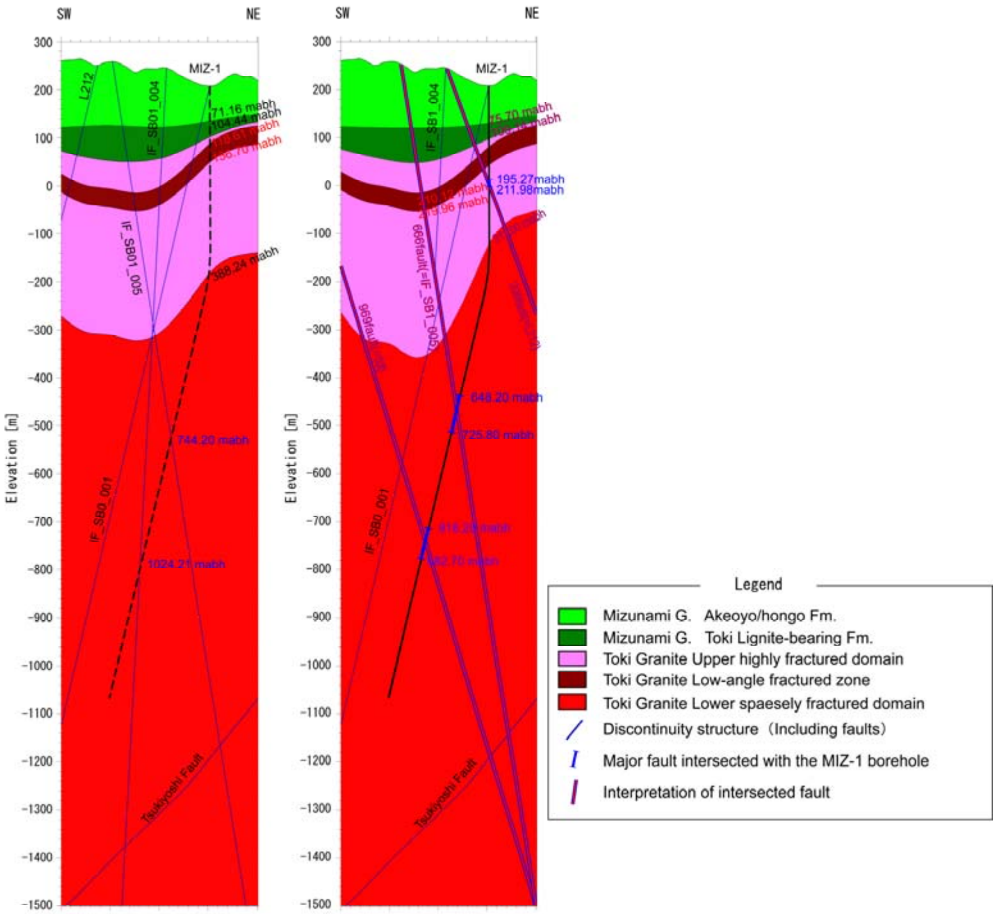
Results

The geological investigations consisted of core logging, investigations of borehole wall image and geophysical logging, which allowed determination of the depth of occurrence of the upper highly fractured domain in the granite, as well as, the nature and the distribution of the lower sparsely fractured domain observed in the zone deeper than the upper highly fractured zone and faults with NW to NNW strikes and an EW strike (Fig. 3.5.1-1). Three large-scale faults (shown with blue lines in Fig. 3.5.1-1) were found[6)], which were significantly altered (characterized by chlorite and clay minerals) and were assumed to cut across the MIU Construction Site. Based on the above data, the geological model was updated (Fig. 3.5.1-2: updated geological map (left) and updated geological model (right))[10)]. The quality of the geological model in terms of its representation was improved by including the tectonic zonation of the granite in the deep underground (the upper highly fractured domain, the low-angle fractured zone and the lower sparsely fractured domain) and data on the fault extending in the deep granite in the geological model constructed in Step 2 and preceding steps. The NNW trending fault identified in Steps 1 and 2 (IF_SB01_004 in Fig.3.5.1-1) was not confirmed in the boreholes in this step.

Conclusions and implications for the next investigation step

The fluid electric conductivity logging allowed high-precision determination of the distribution of groundwater in/outflow points in the granite (transmissivity $>10^{-8}$ m^2 s^{-1}). Combining this with the geological investigations and the hydraulic tests also allowed to determine the occurrence and hydraulic characteristics of discontinuities that are important as water conducting features (Fig. 3.5.1-3)[3),5),6),7),8)]. Through interpretation of the hydraulic responses observed in the surrounding boreholes during borehole drilling[11)] and comparing these with the spatial distribution of the estimated discontinuities, the hydraulic characteristics and its connectivity were determined[4),5),6),7)]. Thus, the hydraulic response due to borehole drilling is considered to be an effective method for evaluating the occurrence of discontinuities and their hydraulic connectivity.

Issues for subsequent steps would be to determine the spatial continuity of the faults identified in this step, which would require detailed definition of the distribution of the faults with NS to NNW strikes and an EW strike that extend near the underground facilities. In order to obtain more information about these faults, cross-hole tomography between boreholes either side of the MIU (e.g. between MIZ-1 and DH-2) as well as additional reflection seismic survey at the northern to north-eastern of the MIU Construction Site and a VSP survey using deep borehole around the MIU (e.g. MIZ-1 and DH-15 borehole) were planned for the next step.



Left : Predicted geological intersection of the MIZ-1 borehole (Based on step2)
Right: Actual geological intersection of the MIZ-1 borehole (Based on step3)
* Depth[mabh] shows the predicted/actual geological intersection of the MIZ-1 borehole

Fig. 3.5.1-1 Result of MIZ-1 borehole investigations[10)]

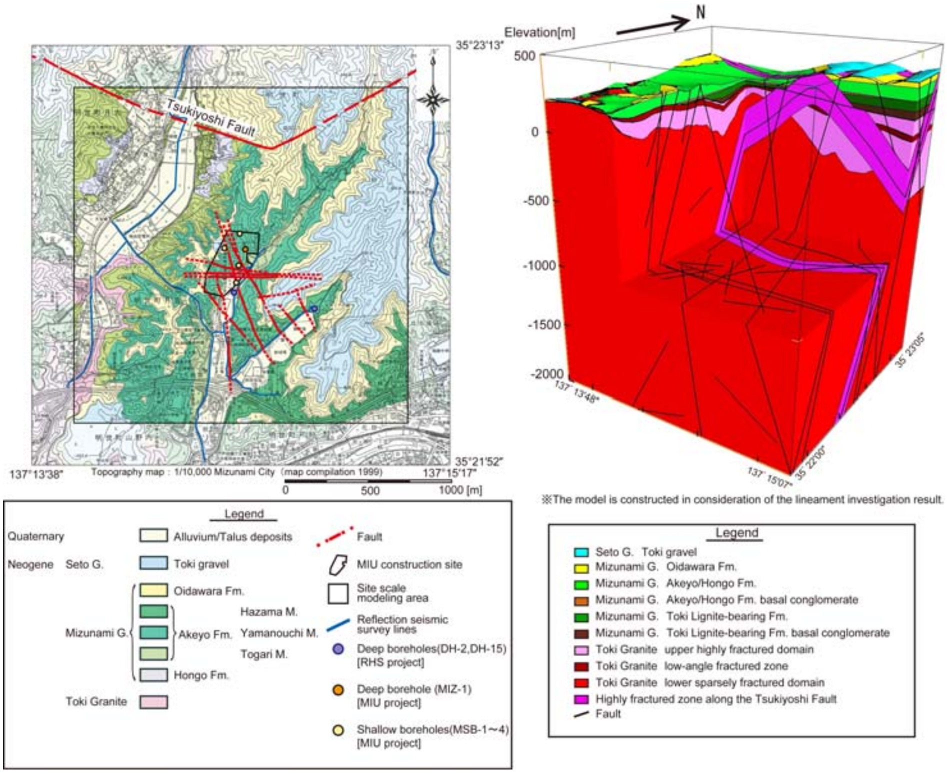


Fig. 3.5.1-2 Geological map and geological model revised using deep borehole investigation phase data[10)]

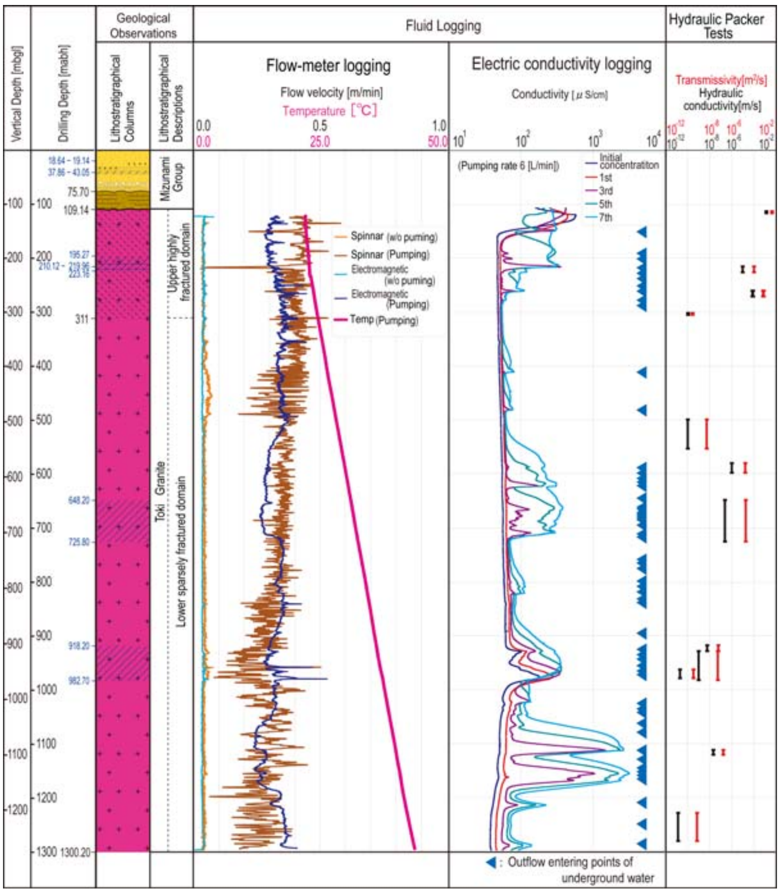


Fig. 3.5.1-3 Result of FEC logging and hydraulic tests in the MIZ-1 borehole

3.5.2 Groundwater flow characteristics

Data on the hydraulic characteristics of the Toki Granite needed to be acquired directly by deep borehole investigations in order to determine the characteristics of groundwater flow in the granite. One of the objectives was to determine the hydraulic characteristics of the major faults that were identified as key features in the preceding steps. Single-hole hydraulic tests and fluid logging were conducted in a deep borehole to acquire data on the hydraulic characteristics of the Mizunami Group, the Toki Granite and the discontinuities[3),5),6),7)]. Monitoring of hydraulic responses due to borehole drilling was also conducted in shallow boreholes where a long-term hydraulic monitoring system was installed in Step 2 to observe the changes in groundwater pressure associated with the deep borehole investigations; this allowed determining the continuity of the hydraulic characteristics and the hydraulic boundary in the rocks[12)].

The hydrogeological model was updated by including the hydraulic characteristics of the geological structures of the updated 3-D geological model (see Section 3.5.1)[13)]. For the modeling of the faults as hydrogeological features, a screening process based on the length of each fault trace was applied, as in Step 2, and the hydraulic anisotropy of the faults was evaluated based on the continuity of the hydraulic characteristics between boreholes estimated from the monitoring of hydraulic responses due to borehole drilling[13)]. Basically, any fault identified as lying between hydraulically connected boreholes was excluded as a potential barrier. Groundwater flow was analyzed using the hydrogeological model, which was calibrated using the distribution of hydraulic head obtained from the long-term hydraulic monitoring in boreholes. A sensitivity analysis was conducted focusing on the hydraulic anisotropy of the faults[13)]. The investigation data obtained in this step were reflected in the hydrogeological modeling in the local-scale area and the boundary condition for the site-scale area was updated[14)]. The GEOMASS system (see Section 4.10) was used for the construction of the above geological/hydrogeological models and for the analysis of groundwater flow.

<u>Results</u>

The hydrogeological model updated in this step is shown in Fig. 3.5.2-1. The results of the deep borehole investigations were used to update, the configuration of the surface of the boundary of geological units, the fault distribution and the hydraulic conductivities of the geological units. The single-hole hydraulic tests indicated a difference in hydraulic conductivity between the upper highly fractured domain, the low-angle fractured zone and the lower sparsely fractured domain in the Toki Granite[3),5),6),7)]. The results of the single-hole hydraulic tests for the water conducting features, which were identified based on core inspections, borehole imaging, geophysical logging and fluid logging, indicated that hydraulic conductivity of fault are not always higher than the hydraulic conductivity of the background fractured rock. Therefore, it can be concluded that some faults, parts of these faults, act as conduits for groundwater flow but others have a function as flow barrier that impedes groundwater flow[13)].

It was confirmed that inflow points can be detected with higher accuracy by fluid electric conductivity logging compared to flowmeter and temperature logging, even at a depth of 500 meters (Fig. 3.5.1-3)[3),5),6),7)]. However, the fluid electric conductivity logging signal is affected by differences in groundwater chemistry such as salinity of inflowing water-conducting features and the borehole fluid, which is replaced by water with a different electric conductivity for the execution of the logging tests (see Section 4.6). Therefore, in the case of execution of the fluid electric conductivity logging in the deep geological zone where the salinity may differ significantly from that in the near-surface zone, results of the detection of water conducting features by the fluid electric conductivity logging would be advisable to be checked by single-hole hydraulic tests. In the sections where mud was used for drilling, the hydraulic conductivity around the boreholes was reduced due to the infiltration of muddy water into the fractures and the hydraulic conductivity calculated from the results of the electric conductivity logging suggested a lower hydraulic conductivity than the actual hydraulic conductivity[5),6),7)], as determined from hydraulic tests in the same section. The fluid logging results (water conducting features) were associated either with faults or with the “background fractured rock”. In the first case, their properties were used as the hydraulic properties of the faults, which were modeled deterministically. In the second case, they were used to determine the hydraulic conductivity values of the “background fractured rock” (e.g. upper highly fractured domain).

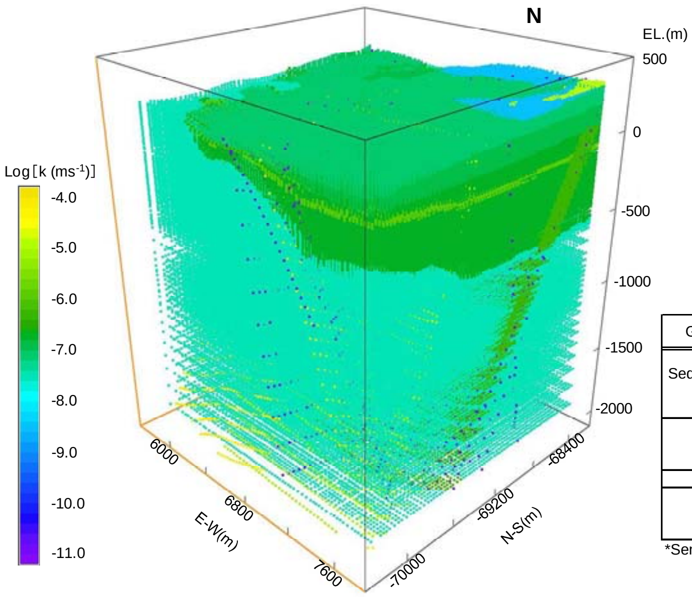
Using the shallow boreholes from Step 2, the continuity of the hydraulic characteristics and the existence of the hydraulic boundary in/around the MIU Construction Site were evaluated by monitoring of hydraulic responses due to the drilling of deep borehole and long-term hydraulic monitoring. Hydraulic effects were observed up to a distance of a few 100 meters. This depends on the distribution and hydraulic conductivity of the geological units in the study area. When investigations are planned in multiple boreholes, it is preferable to investigate the boreholes in sequence rather than at the same time, i.e. to install the hydraulic monitoring system after completing the investigations in one borehole and start the groundwater pressure monitoring before initiating the investigations in the next borehole to make the analysis of the interaction possible[13)].

The 3-D distribution of hydraulic head was calculated based on the groundwater flow analyses and the influence of the hydraulic anisotropy of fault on the distribution on the site scale was evaluated. One example of the results of the sensitivity analysis is shown in Fig. 3.5.2-2. Compared to Steps 1 and 2, the results in this step showed that the variability in hydraulic head was smaller and the difference in the head distribution was significant only when it was due to the hydraulic anisotropy of the NE trending fault. The main reason for the reduction in the variability of the head distribution resulting from the sensitivity analyses is that actual field observations are used to determine the fault properties; for example, the existence of hydraulic anisotropy in the majority of the NNW and EW trending faults was derived based on the results of the monitoring of hydraulic responses due to the drilling. Thus, the distribution of the hydraulic head measured in the boreholes compared with the values based on the results of the groundwater flow analyses with this impact is closer to the actual situation. Fig. 3.5.2-3 shows the square root of the deviation of the measured and modeled hydraulic head in Step 1 and 2 for the DH-2 borehole. This figure indicates that the comparison was improved by approximately 2 m in this step compared to Step 2.

Conclusions and implications for the next investigation step

Since the number of boreholes that could be drilled for the borehole investigations is limited in terms of the cost, time, environmental limitations and disturbance in the area affected by the drilling, it is considered necessary to acquire as much data as possible from a limited number of boreholes. For the investigations in subsequent steps, the optimum use of boreholes that were drilled in this step and Step 2, the acquisition of detailed data on the hydraulic characteristics and its connectivity of the geological structures in/around the

MIU Construction Site and the evaluation of the impact on groundwater flow characteristics were considered to be important.

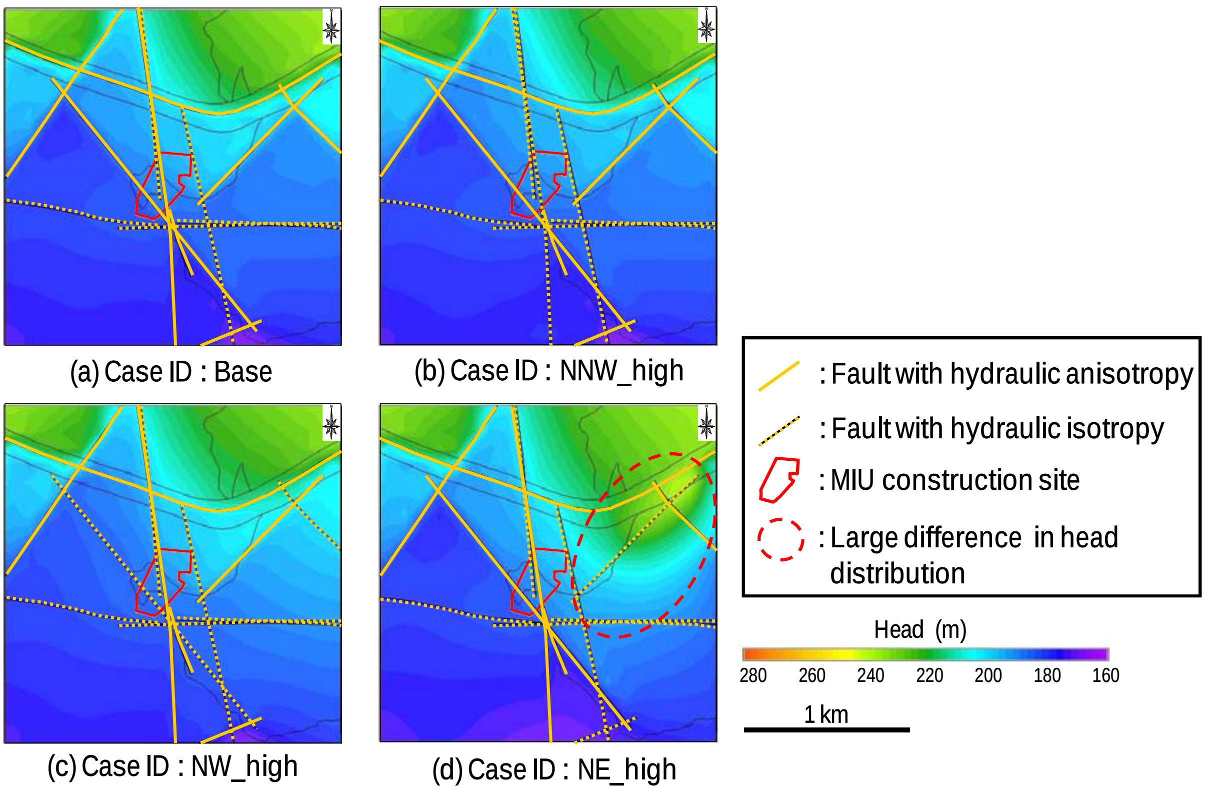


Hydraulic conductivity

Geological features and geological structure element			Log [k (m s^{-1})]
Sedimentary rock	Seto group		-5.0
	Mizunami group	Oidawara formation	-8.5
		Akeyo/Hongo formation	-7.2
		Toki-lignite bearing foramation	-6.9
Toki granite		Upper Highly fractured domain	-6.7
		Low angle fractured zone	-5.9
		Lower sparsely fractured domain	-7.5
Highly fractured zone along the Tsukiyoshi fault			-6.4
Fault	Main part of Tsukiyoshi fault		-11.0
	Other faults	In-plane of fault	See Table 3.2.6(2)-4
		Normal to fault*	

*Sensitivity analysis about hydraulic anisotropy:5faults in 12

Fig. 3.5.2-1 Hydrogeological model (3-D distribution of hydraulic conductivity)



Slice: Elevation -300 m (Depth of the shaft 500 m)

Fig. 3.5.2-2 Example of a sensitivity analysis focused on hydraulic anisotropy of faults
(Sensitivity analysis case: see Table 3.7.2-4)

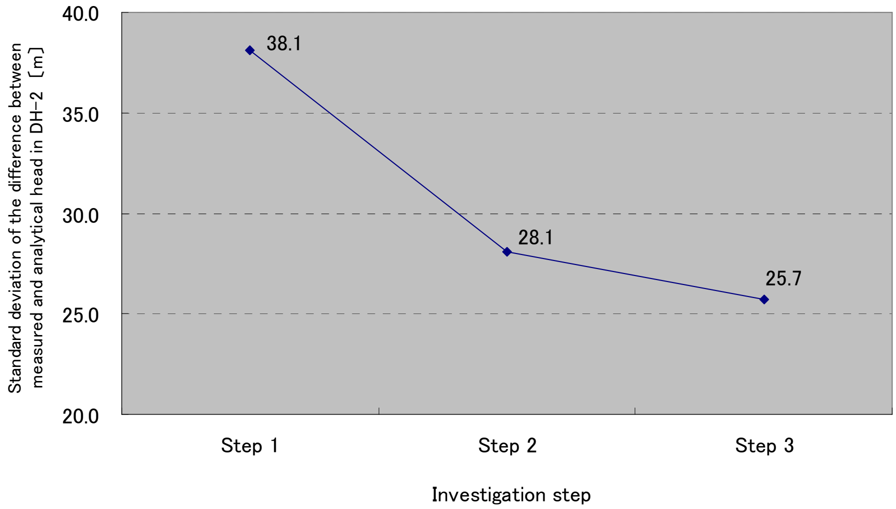


Fig. 3.5.2-3 Comparison between measured and analytical head differences in Step 1 to 3

3.5.3 Geochemical characteristics of groundwater

The objectives of the deep borehole investigations include determining the geochemical characteristics of the groundwater in the granite to a depth of approximately 1,000 meters prior to excavation of the underground facilities in order to incorporate the results in the initial conditions for the analyses of the influence of the excavation on the groundwater regime around the facility in Phase II and subsequent phases. A further objective is to determine geochemical characteristics of the groundwater encountered in the underground facilities as input for planning the investigations in Phase II. To this end, groundwater and rock samples were collected and analyzed and the hydrochemical model based on the investigation results from Step 2 and preceding steps was updated.

<u>Results</u>

Na-Ca-Cl type groundwater with a salinity of approximately 2,500 mg 1^{-1} (one tenth of the salinity of seawater) was found in the granite at a depth of approximately 1,000 meters in the site-scale area (Fig. 3.5.3-1). The quantitative hydrochemical model with the 3-D distribution of the groundwater chemistry was updated to estimate a more detailed distribution of the water chemistry[15)] by repeating the multivariate analysis, with more reliable data on the water chemistry obtained during Step 3 instead of the data used for the multivariate analysis conducted in Step 0. The pH value of the groundwater was almost always in the range of 8 - 9 and this was consistent with the result predicted in Step 0 (see Section 3.2.3). As a result of a thermodynamic analysis using PHREEQ-C, calcite was found to be under-saturated to just saturated at almost all groundwater sampling points. Based on this result and microscopic observation of rock alteration, the water has a major pH buffering capacity due to dissolution/sedimentation reactions with carbonate minerals[16)]. Measurement of redox potential (Eh) was conducted during pumping tests, although, it was difficult to obtain good quality data. However, based on mineral observations and the results of dissolved gas analysis, potential occurrence of redox reactions involving iron minerals, sulphur minerals and hydrogen sulphide gas was indicated. With regard to the origin and residence time based on measurements of ^{14}C and ^{3}H of the Na-Ca-Cl type groundwater, it was concluded from the isotope composition and the ratio of the dissolved chemical components that the groundwater was diluted from saline water that either originated from fossil seawater or from long-term water-rock reactions. Either way, the origin of the Na-Ca-Cl type groundwater will be different from Na-Ca-HCO_3 type groundwater. However, the potential dilution could not be confirmed through investigations in this step, because the salinity of the groundwater was lower compared to that of seawater. Since the origin and residence time of groundwater are useful for validating the results of the groundwater flow analysis, this remains an issue for the investigations in Phase II and subsequent phases e.g. $^{14}C/^{36}Cl$ measurements below 400mbsl.[16)]

Conclusions and implications for the next investigation step

The hydrochemical model of the distribution of groundwater chemistry on the site scale that was constructed in Step 0 was updated using the results from this step (see Section 3.2.3). A quantitative model of groundwater chemistry relating to initial conditions prior to the excavation of the underground facilities was constructed (Fig. 3.5.3-2)[15),16)].

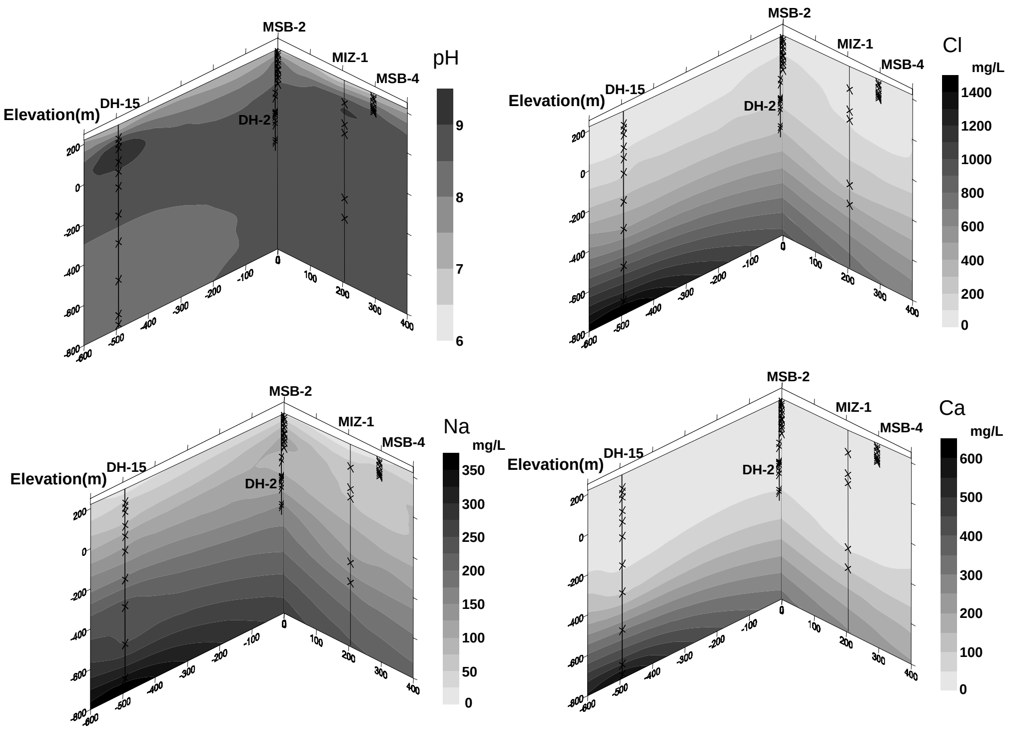


Fig. 3.5.3-1 Three-dimensional distribution of groundwater chemistry in the site scale

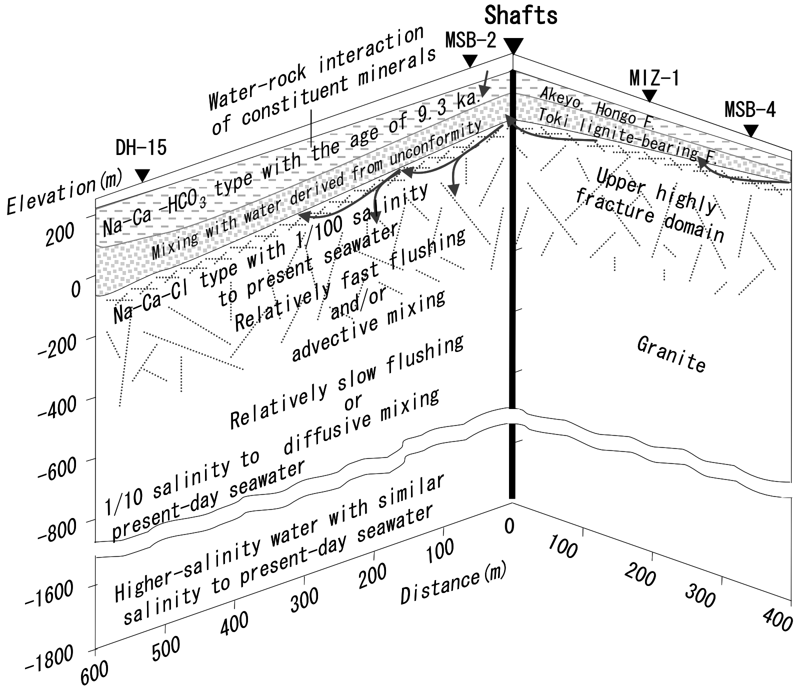


Fig. 3.5.3-2 Hydrochemical conceptual model around site scale.

3.5.4 Transport/retardation of nuclides

The goal of this step in terms of retardation effects of solute transport was to determine the sorption and diffusion properties of the materials in the rocks, the solute transport zone in the rock (pore structures or porosity contributing to solute transport) and the impact of colloid, organics and microbes on solute transport. This was done to update the information on retardation properties obtained in Step 0. Laboratory tests were conducted using cores and groundwater samples from the deep boreholes to determine details of the petrological and mineralogical characteristics of the Toki Granite and the water conducting features, geochemical and petrophysical characteristics and geochemical characteristics of groundwater[5),6),7)]. From laboratory tests using cores from the deep borehole MIZ-1, the sorption coefficients of Cs and Sr for waters with high Na-Cl concentrations were obtained and the depth of matrix diffusion was predicted from the distribution profile of the uranium series nuclides (^{238}U, ^{234}U, ^{230}Th) near the water conducting features[10)]. Based on the data acquired up until this step, the major retardation mechanisms of sorption and matrix diffusion in the Toki Granite were evaluated.

Results

The data on sorption coefficients and the depth of matrix diffusion for the Toki Granite obtained from the laboratory tests using cores were consistent with existing information and estimates based on existing data[10)]. The investigation results and interpretation in Step 0 could also be refined: the sorption capability of the fracture-filling minerals is larger by one to two orders of magnitude than that of the matrix of the Toki Granite and the depth of matrix diffusion near the water conducting features is a few tens of millimeters or more. The study of solute transport and geochemical processes in natural environments similar to those predicted to occur in a geological disposal system (natural analogue studies) are important for verifying the credibility of investigation results[17)]. However, cores are physically disturbed by drilling, sampling and conditioning and the characteristics of the pore structures observed on normal cores are thus clearly different from observations of resin impregnated overcores[18),19)]. Therefore, a detailed evaluation of solute transport characteristics needs to be conducted in the investigations in Phase II and subsequent phases.

Conclusions and implications for the next investigation step

The types and volumes of colloid and organics (e.g. organic-sulfur colloid, fulvic acid, humic acid etc.) and microbes in the groundwater were considered to change with changing groundwater chemistry at the depth of the MIU Construction Site[20),21)]. Due to the borehole investigations, contamination by drilling fluid in the sampled groundwater was a few % to tens of % (ratio of the fluorescent dye concentration in the sampled groundwater to the initial fluorescent dye concentration added to the drilling fluid), which is insufficient for acquiring good quality data on colloid, organics and microbes. Sampling of less contaminated groundwater will not be achievable before Phase II, when long-term sampling will be possible. In Phase III in particular, when less influence due to the excavation of the underground facilities can be expected, the information mentioned above should be collected.

3.5.5 Dilution of nuclides

The distribution of the Darcy velocity for each geological unit was calculated based on the results of the groundwater flow analyses conducted in this step (see Section 3.5.2).

Results

For the hydrogeological model updated in this step (see Section 3.5.2), since no new hydrogeological units that could act as aquifers were added to the hydrogeological model of Step 2 (see Section 3.4.4), the same units as in Step 2 (the low-angle fractured zone, the upper highly fractured domain, the Toki Lignite-bearing Formation, the highly fractured zone along the Tsukiyoshi Fault and the Akeyo/Hongo Formation) were kept as the aquifers that could be expected to have a dilution effect.

The Darcy velocities of the above hydrogeological units were calculated (Fig. 3.5.5-1) and the results indicated that the velocity was highest in the low-angle fractured zone, followed by the upper highly fractured domain, the Toki Lignite-bearing Formation, the highly fractured zone along the Tsukiyoshi Fault and the Akeyo/Hongo Formation. Focusing on the low-angle fractured zone, the variability of the distribution and the values for the Darcy velocity of this zone were smaller compared to those in Step 2. This is due to the fact that new data of the low-angle fractured zone were obtained from the two deep boreholes. Compared to the Darcy velocity for the lower sparsely fractured domain, the Darcy velocity was relatively higher for the low-angle fractured zone, the upper highly fractured domain, the Toki Lignite-bearing Formation, the highly fractured zone along the Tsukiyoshi Fault and the Akeyo/Hongo Formation, as was found in Step 2. This indicates that they are important hydrogeological units when considering the dilution effect.

The accuracy of the Darcy velocity calculated from the groundwater flow analyses will be improved with increasing data on the geological and hydrogeological characteristics of the geological units in future steps.

Conclusions and implications for the next investigation step

Since the number of boreholes that can be drilled for borehole investigations is limited from the viewpoint of costs of the investigations, time limitations, environmental limitations and the disturbance to the area affected by the drilling, it is considered necessary to acquire as much data as possible from a limited number of boreholes. For the investigations in subsequent steps, in order to make optimum use of boreholes that were drilled in this step and Step 2, it was thought to be important to acquire detailed data on the connectivity, 3-D distribution and hydraulic characteristics of the highly permeable layers and structures, the existence of which was confirmed in the boreholes, and to calculate the distribution of the Darcy velocity with higher confidence than was possible in this step through incorporation of the data into the hydrogeological model.

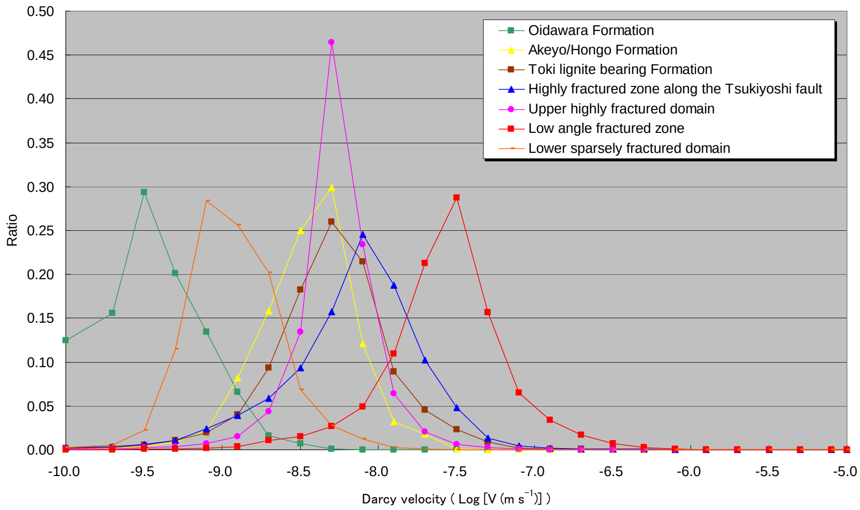


Fig. 3.5.5-1 Darcy velocity distribution (The vertical axis shows the ratio (cumulative frequency is 1 in each geological formation and domain))

3.5.6 Local stress regime, spatial variability of petrophysical/geomechanical properties of rocks, and size and structure of EDZ

The goals of the investigations in this step include improving knowledge of the petrophysical/geomechanical characteristics and initial stress state of the Toki Granite at the MIU Construction Site, improving the rock mechanical model developed in the previous step and making improved predictions of the extent and petrophysical/geomechanical characteristics of the EDZ.

Using the deep boreholes and core samples collected at the MIU Construction Site, initial stress measurements using the hydraulic fracturing method and petrophysical/geomechanical tests in the laboratory were conducted to acquire data for constructing a rock mechanical model. Also, a numerical analysis predicting the excavation effect on the rock around the underground facilities was conducted, considering the excavation damage zone using the method that takes into account the discontinuous rock surface.

Results

The results of the measurements of initial stress using the hydraulic fracturing method[22),23)] in the MIZ-1 borehole are shown in Fig. 3.5.6-1. Based on these results and the geological model updated in this step (see Section 3.5.1), the rock mechanical model for the MIU Construction Site was constructed (Fig. 3.5.6-2). The Toki Granite observed in the MIZ-1 borehole includes the upper highly fractured domain and the lower sparsely fractured domain and contains faults with a high-angle dip. The petrophysical/geomechanical properties, such as uniaxial compressive strength and Young's modulus in the Toki Granite, were generally larger compared to those in Step 0 (see Section 3.2.6) and Step 2 (see Section 3.4.5). B to CM grade moderately hard rocks according to the CRIEPI classification[24) ,25)], were identified at the site. In the zone where faults cross each other at a depth of approximately 200 meters, however, CL grade soft rocks with a high effective porosity, low apparent specific gravity and low geomechanical strength were found. The initial stress state was found to change in the zone near the fault zone at around 600 meters depth[22),23)]. Since the change in the local stress conditions as discussed above can only be determined by in-situ measurements, in-situ tests such as hydraulic fracturing would have to be conducted at several locations taking the distribution of faults into account when determining the initial stress states in detail.

Using the rock mechanical model constructed in this step as a basis, predictions were made of the EDZ with the MBC model[26)], a crack tensor model[27)] and a virtual fracture model[28)] (as was done in Step 0). These analyses involved two-dimensional analyses (at depths of 500 meters and 1,000 meters) and three-dimensional analyses (at a depth of 1,000 meters) to predict the displacement, strain, distribution of fracture apertures and distribution of the shear strain affecting the local safety factors of the rocks around cavities caused by the excavation of the underground facilities. An example of the results of the analyses is shown in Fig. 3.5.6-3 and Fig. 3.5.6-4. Based on the results, the characteristics of the fractures around the underground facilities generated by rock displacement, stress and excavation effects were estimated to be strongly influenced by the initial stress states, the size and direction of existing fractures and newly formed fractures due to the excavation. In order to correctly reflect the effect on the orientation of the fractures and to evaluate rock behavior at the junction of vertical and horizontal tunnels, a 3-D analysis was considered to be more effective than 2-D analysis.

Conclusions and implications for the next investigation step

For the investigations in the next and subsequent phases, it was considered to be necessary to evaluate the validity of the analysis methods and to examine the application of the methods regarding the excavation impact for the discontinuities, by comparing data obtained from various measurements at the galleries (e.g. rock displacement and wall displacement) and the in-situ tests.

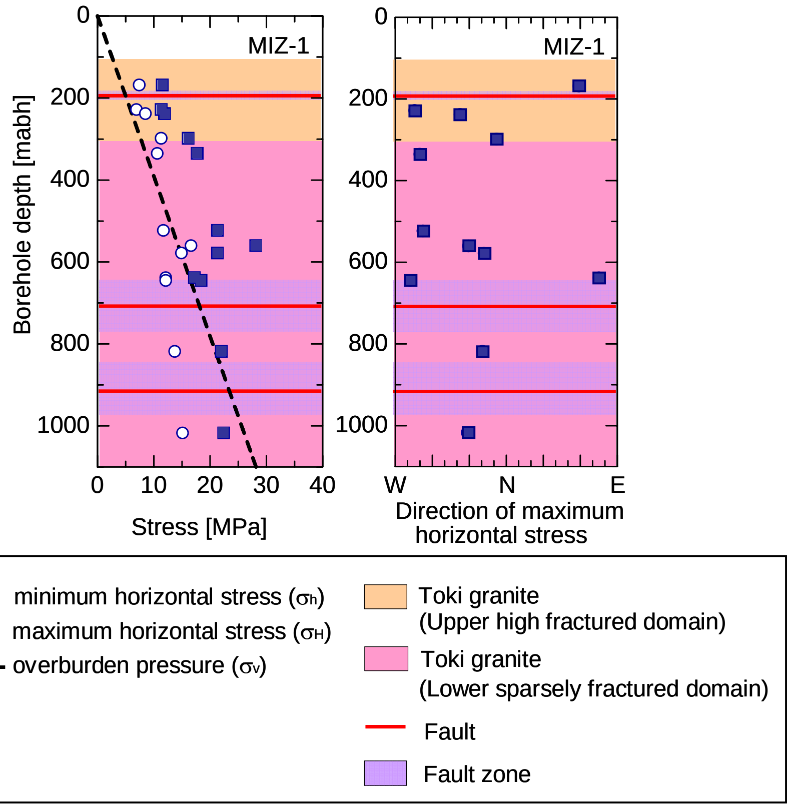


Fig. 3.5.6-1 Results of hydraulic fracturing tests at the MIU Construction site (MIZ-1)

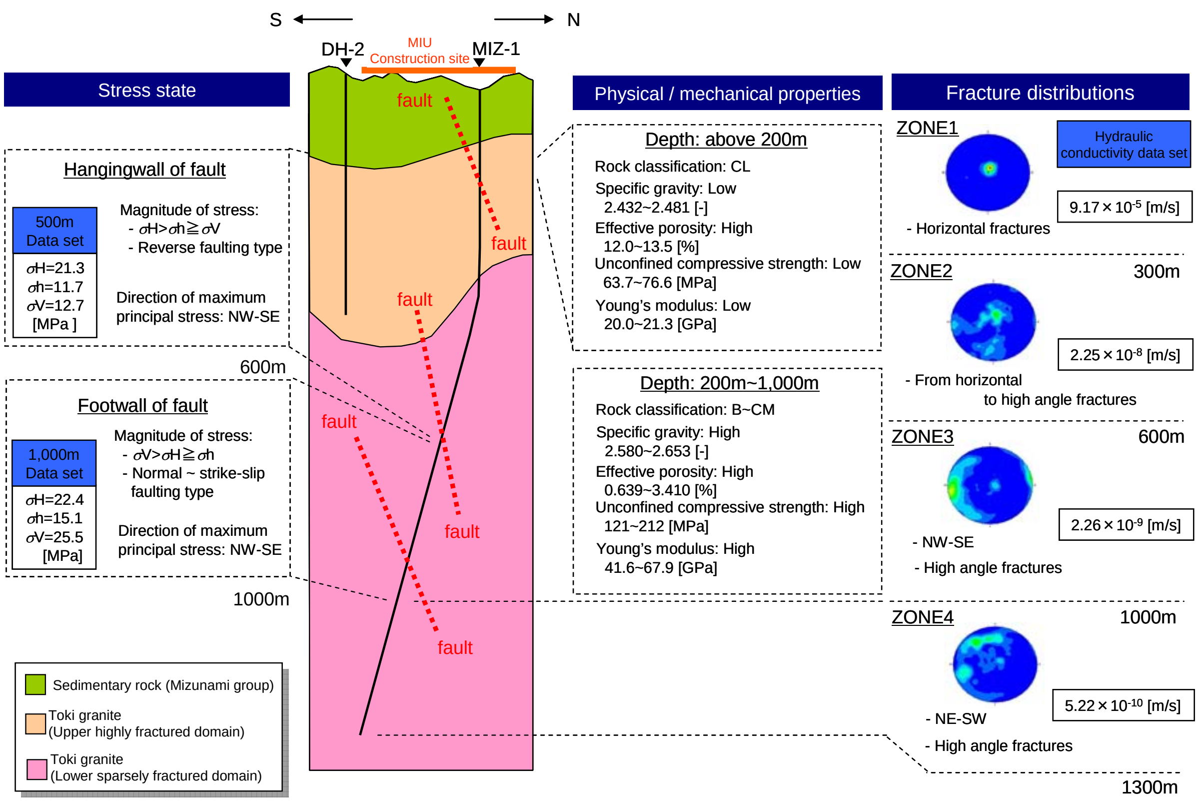
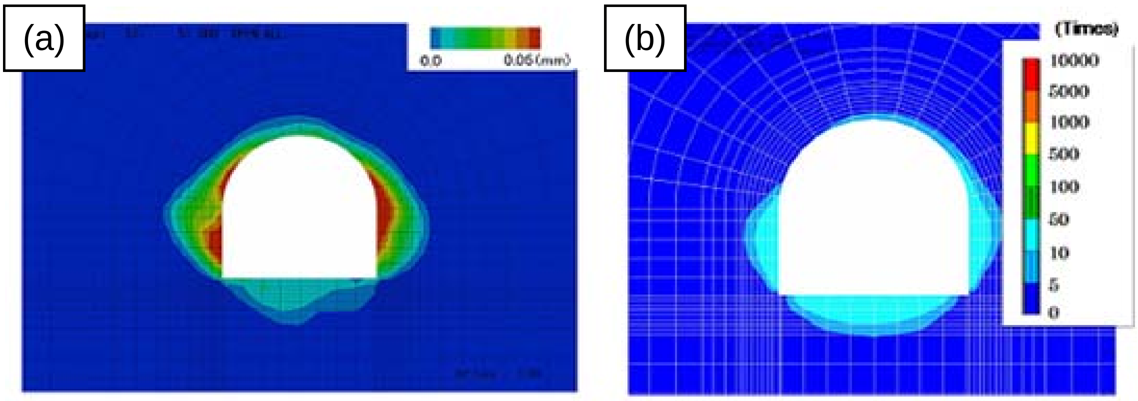


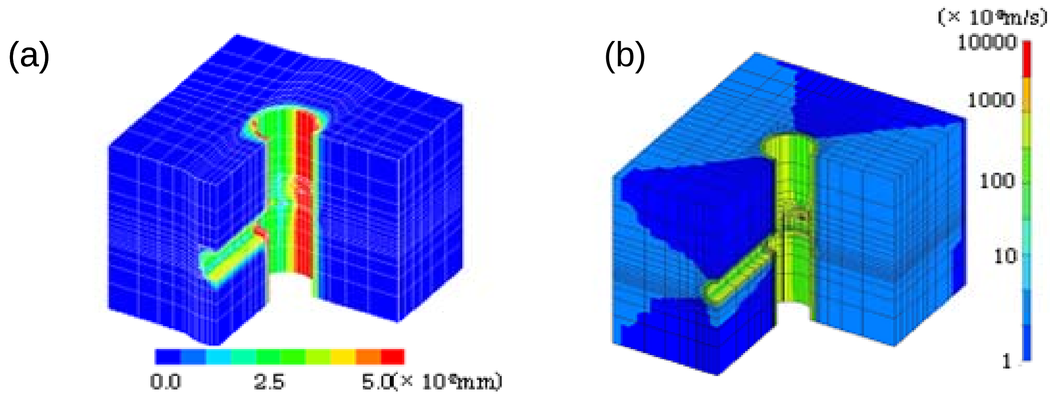
Fig. 3.5.6-2 Rock mechanical model (Step3)



fracture aperture　　　　increase in hydraulic conductivity

(a) MBC model　　　　(b) Crack tensor model and virtual fracture model

Fig. 3.5.6-3 Fracture aperture and increase in hydraulic conductivity (2-D analysis)



fracture aperture　　　　increase in hydraulic conductivity

(a) MBC model　　　　(b) Crack tensor model and virtual fracture model

Fig. 3.5.6-4 Distribution of fracture apertures and hydraulic conductivity (3-D analysis)

3.5.7 Volume of inflow into underground tunnels

A groundwater flow analysis was conducted with the aim of predicting the inflow rate into the underground facilities using the updated hydrogeological model[13] (see Section 3.5.2)[29].

The analyses were conducted by solving a 3-D transient problem for saturated - unsaturated conditions using the equivalent heterogeneous continuum model[30] based on the finite element method, as was done in Step 2 (see Section 3.4.6). A sensitivity analysis was also conducted focusing on the differences in the heterogeneity (difference in the number of the discontinuities for modeling) of the hydrogeological model (Table 3.5.7-1). Since data on the pressure relief factor considering the hydraulic characteristics near the underground facilities (see Section 3.4.6) could not be obtained in the investigations in Phase I, a sensitivity analysis was conducted for this parameter using the same values as in Step 2.

Results

The groundwater flow analysis using the heterogeneous hydrogeological models (Models A, B and C) resulted in similar inflow rates into the underground facilities when the same pressure relief factor was used, despite the differences in the models (Fig. 3.5.7-1). As expected, the rates were very different for the same model when different pressure relief factors were used. These trends are the same as the results of the groundwater flow analyses in Step 2 using different hydraulic parameters.

When the pressure relief factor was 0.8, the overall inflow rate was predicted to be approximately 1,000 - 1,500 m^3day^{-1}, except during periods when the Middle Stage and Main Stage were being excavated (Fig. 3.5.7-1(a)). In the case where highly permeable structures such as faults were encountered during excavation, the local inflow rate would reach approximately 2,000 m^3day^{-1}, an increase of 500 - 1,000 m^3day^{-1} compared to the case with no highly permeable structure.

When the pressure relief factor was 0.2, the inflow rate was greater; it increased with excavation depth and the maximum rate was predicted to be over 10,000 m^3day^{-1} (Fig. 3.5.7-1(b)). The largest inflow rate was from the upper highly fractured domain of the Toki Granite near the zone at a depth of 200 - 500 meters. Although the inflow rate was lower in the lower sparsely fractured domain compared to the upper highly fractured domain, it was larger in the zone where a high permeable fault crosses (Fig. 3.5.7-2). The estimated inflow rate in Step 3 was increased from that in Step 2. This is assumed to be due to the updating of the spatial distribution of the highly permeable structures (number of such structures that emerge in the underground facilities) and the hydraulic characteristics of the structures updated in Step 3. Highly permeable structures that could significantly influence the inflow rate into the underground facilities are expected to occur frequently at the site. For high-precision determination of the number and location (depth) of the highly permeable structures dipping at a high angle that encountered by the underground facilities (particularly in the shafts), priority should be given to acquiring data on the spatial distribution and hydraulic characteristics of the highly permeable structures at the planned excavation point of the underground facilities.

As seen in Step 2, the inflow rate into the underground facilities was significantly affected by the internal boundary conditions and highly permeable structures, compared to the effect of any other factors.

Also, as found in Step 2, all the models suggested that the drawdown of the groundwater level around the underground facilities due to the inflow of groundwater into the facility was significantly affected by the faults located around the MIU Construction Site. These faults were assumed to be hydraulically anisotropic. Since the range and rate of the drawdown will affect the inflow rate, it will be important to acquire data on the spatial distribution and hydraulic characteristics of the faults distributed around the MIU Construction Site.

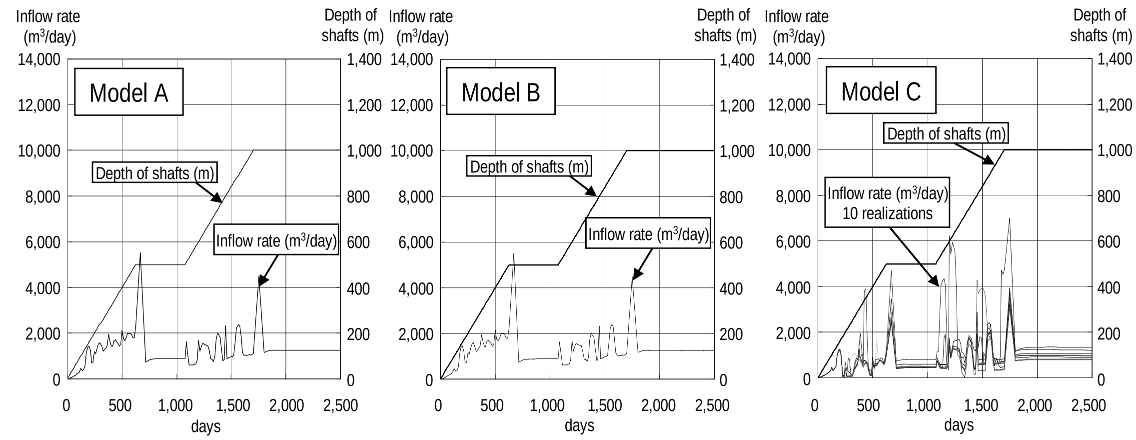
Conclusions and implications for the next investigation step

It was decided that for the investigations in the next and subsequent steps, the accuracy of the predictions of the number and locations of highly permeable structures that emerge in the underground facilities should be improved. Also, that characterization of the geology and hydrogeology of the faults at the excavation points of the underground facilities and around the MIU Construction Site would be important for improving the accuracy of predictions of groundwater inflow rate into the facility.

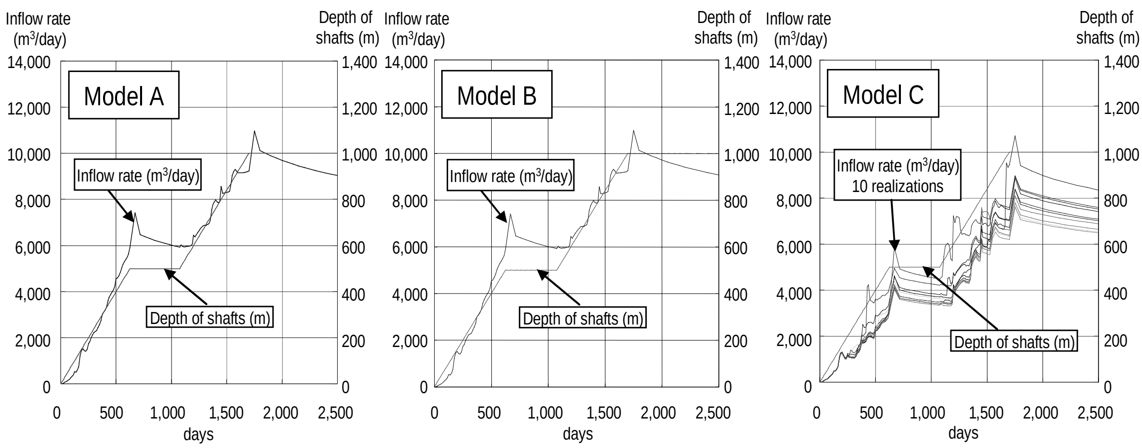
Table 3.5.7-1 Groundwater flow simulations

Case	Modeled fault／WCF	Pressure relief factor
Model A	Tsukiyoshi Fault＋Faults around MIU Construction Site	α =0.2, 0.8
Model B	Model A＋Lineaments with length more than 3km	α =0.2, 0.8
Model C	Model B＋WCF（Modeled using Equivalent Heterogeneous Porous medium）; 10 realizations	α =0.2, 0.8

WCF: Water Conducting Feature

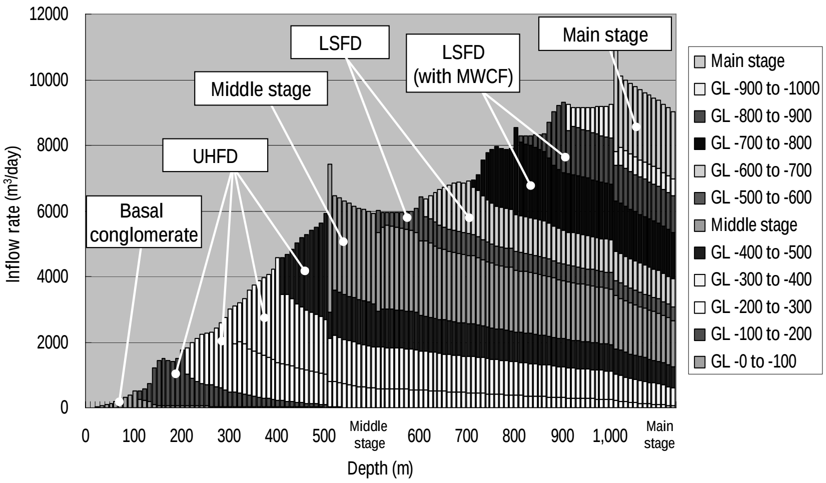


(a) Pressure relief factor: 0.8



(b) Pressure relief factor: 0.2

Fig. 3.5.7-1 Inflow rate into MIU



(MWCF: Major Water Conducting Feature)

Fig. 3.5.7-2 Distributions of inflow rate into MIU (pressure relief factor: 0.2)

3.5.8 Distribution of discontinuities intersecting underground tunnels

The lacations where discontinuities would occur at the planned excavation points of the underground facilities was predicted based on the geological model[10] discussed in Section 3.5.1, including faults and fractured zones that are considered to affect the petrophysical/geomechanical characteristics of the rock.

Results

Using the predictions based on the geological model in Section 3.5.1 (Fig. 3.5.8-1), faults that are considered to be identical to those identified in Step 2 (IF_SB1_002 and IF_SB1_003 in Fig. 3.4.7-1) were identified and their distribution was updated (IF_SB2a_07 and IF_SB2a_08 in Fig. 3.5.8-1). These faults and those additionally identified in this step were determined to be faults that could be intercepted by the underground facilities. Most of the faults were predicted to dip at a high angle according to the interpretation of integrated data gained by geological mapping, reflection seismic survey and borehole investigations.

Data on the locations of the faults in the granite were obtained in this step. In particular, fault occurrence at greater depth was determined more accurately compared to Step 2.

Conclusions and implications for the next investigation step

It was considered that the issues for the subsequent steps would be to acquire data on the spatial continuity of the faults in the deep Toki Granite that were predicted in this step to emerge in the underground facilities.

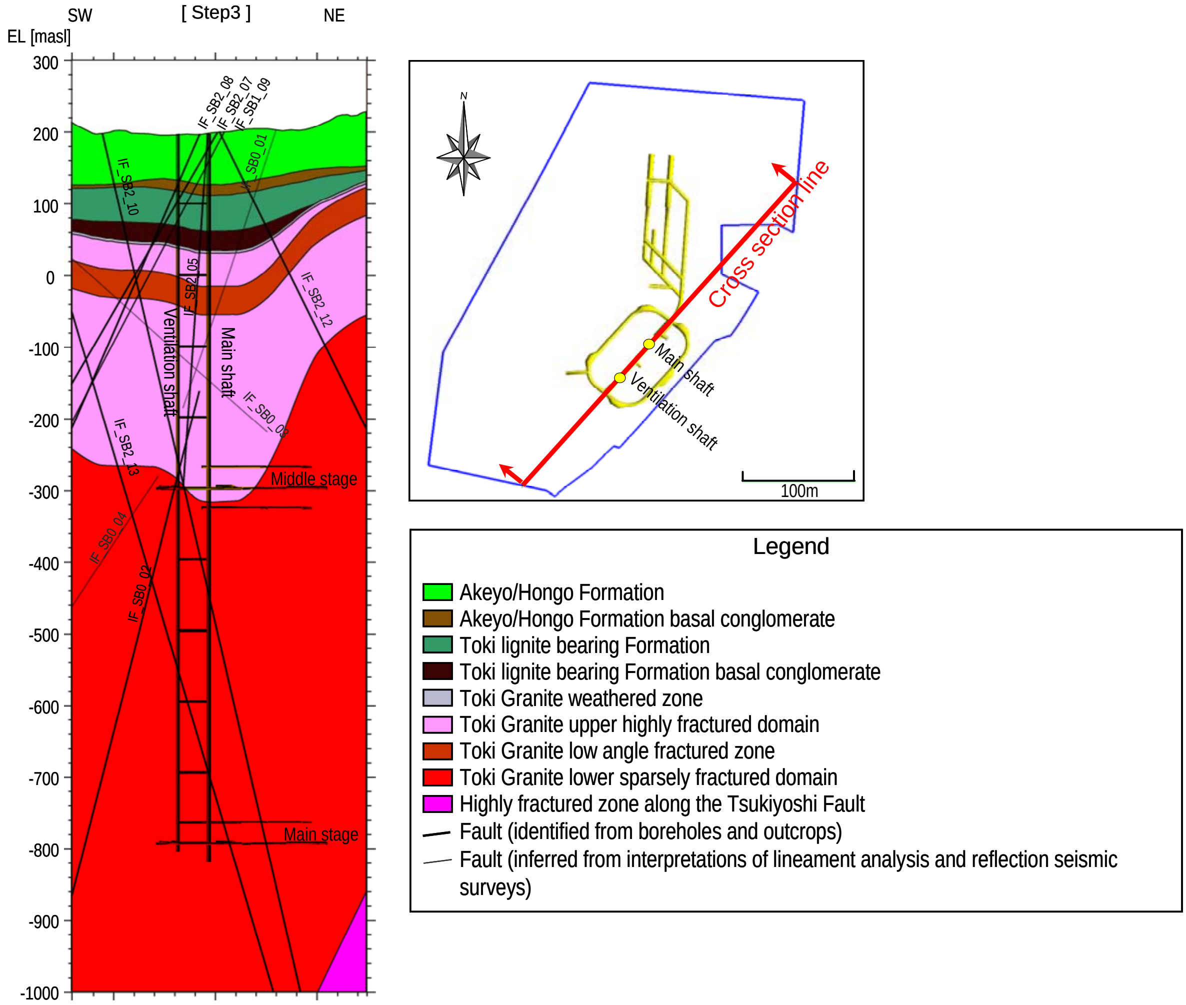


Fig. 3.5.8-1 Predicted geological structures around the MIU facility (Step3)

3.5.9 Subsurface thermal conditions

The goal of this step was to acquire data on the geothermal condition in the Toki Granite at/around the MIU Construction Site.

Temperature logging in the deep MIZ-1 borehole and thermal property tests (measurement of thermal conductivity, specific heat and linear expansion coefficient) using core samples from the borehole was conducted for the MIU Construction Site.

Results

The results of the logging and the tests showed that the geothermal gradient in the MIZ-1 borehole was within the range of the results in Step 0 and Step 2 (Fig. 3.5.9-1)[31]. The distribution of the thermal properties was the same as that on the local scale (Fig. 3.5.9-2). Thus, temperature logging using a single hole is sufficient for determining the geothermal gradient on the local scale, provided there is no local thermal source such as a volcanic zone. The thermal properties could also be determined by the thermal property tests using core samples from a single hole, as long as there are no changes in the pore structure or mineralogical composition of the rock.

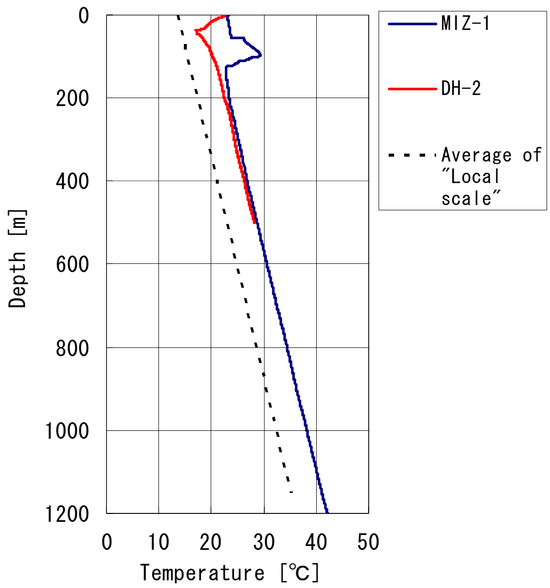


Fig. 3.5.9-1 Result of temperature logging (MIZ-1)

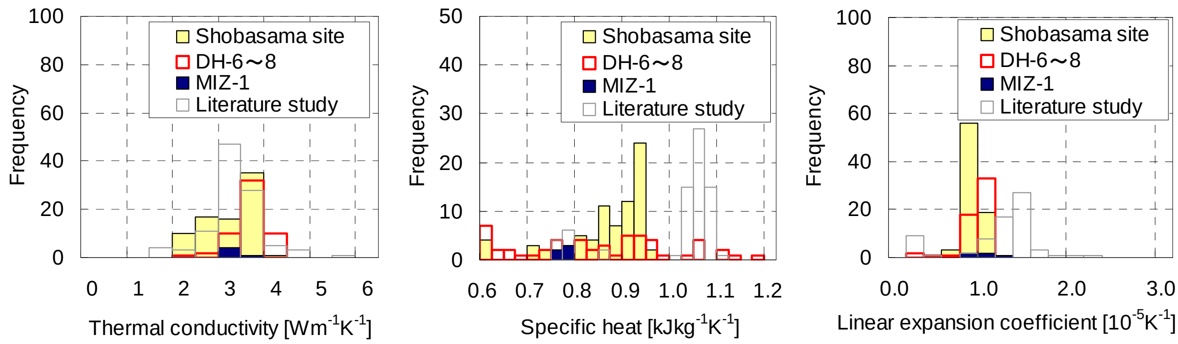


Fig. 3.5.9-2 Result of thermal property test (MIZ-1)

3.5.10 Discussion of result and recommendation for further investigations

Deep borehole investigations were carried out to determine the geological structures, hydrogeological characteristics, geochemical characteristics of the groundwater and geomechanical characteristics from the surface to deep underground in order to achieve the specific aims shown in Table 3.1-1, except for retardation effect in solute transport and influences of colloid, organics and microbes.

Based on the results of the investigations, the models constructed in Step 2 and preceding steps were updated, including the site-scale geological hydrogeological and hydrochemical models and the block-scale rock mechanical model. Based on these models, groundwater flow analyses and stress/excavation analyses were conducted to estimate the distribution of the hydraulic gradient and the geomechanical/hydrogeological conditions around the underground facilities.

The key factors for the investigations and analyses in subsequent steps were identified to include:

- Determining the spatial continuity of faults with N-S to NNW strikes and the E-W strike that were predicted to be distributed around the underground facilities.
- Acquiring data on the hydraulic characteristics and the continuity of the water conducting features between the boreholes.
- Determining the geological and hydraulic characteristics of the faults predicted to be encountered by the underground facilities.

Geological structure

The combination of investigations applied in this step was extremely effective for determining the 3-D distribution of geological structures in the deep Toki Granite. In particular, investigations combining core loggings and investigation of borehole wall image allow detailed determination of the distribution of the geological structures and the characteristics of the Toki Granite. The locations and hydraulic characteristics of discontinuities that are important as water conducting features could also be determined by combining fluid electric conductivity logging and hydraulic testing. The investigations in Step 3 were extremely important for evaluating and confirming the results of Step 2 and preceding steps, including modeling, and for planning activities in Step 4 and subsequent steps.

Groundwater flow characteristics

The geochemical characteristics of groundwater such as salinity in the deep underground environment could differ significantly from those near the surface. Therefore, when determining hydraulic conductivity using single-hole hydraulic tests and fluid electric conductivity logging, an overall evaluation of the hydraulic conductivity distribution from a geochemical viewpoint is necessary in addition to the geological and hydrogeological perspectives.

When investigations were conducted in several boreholes at the MIU Construction Site to determine the hydraulic connectivity and boundary between the boreholes, it was important to formulate a plan for defining the geological structures in the area of interest, the optimum locations for the borehole investigations and the schedule for the investigations. The borehole investigations can be more effective when conducted in series rather than all at the same time, because data on hydraulic connectivity and hydraulic boundaries between the boreholes can be obtained by monitoring of hydraulic responses in the already drilled boreholes.

Geochemical characteristics of groundwater

Where the groundwater chemistry is a result of the mixing of water with different salinities and water-rock interactions as identified on the site scale in the Tono area, effective methods for determining the geochemical characteristics of the groundwater would combine multivariate analysis, thermodynamic analysis of water-rock interactions, the mineral observations and analysis of the chemistry and isotopes of the groundwater that were applied in Steps 0 to 3. Through a combination of these methods, the major processes that lead to the observed groundwater chemistry could be identified (e.g. major water-rock interactions and the conditions for the mixing of the end-members of the groundwater). Also, the reliability of the results for the hydrogeological modeling and the groundwater flow analyses could be demonstrated using data on the origin and residence time of the groundwater. As shown in the investigations in Step 3 and preceding steps, the above investigation methods will gradually improve the degree of understanding of the geological environment through the increasing volume of data, improvement in data quality and consolidation of the existing data from borehole investigations.

Transport/retardation of nuclides

Laboratory tests on cores allow overall evaluation of sorption and matrix diffusion, which are the primary retardation mechanisms for solute transport. Since the test results can be validated by comparison with matrix diffusion properties determined in natural analogue studies, the method of combining laboratory tests and natural analogue studies would be effective. Also, for the evaluation of colloid, organics and microbes in the groundwater in this step, it is essential to collect groundwater samples that have extremely low contamination and that represent in situ conditions. To achieve this, it would be best to collect water samples using the monitoring boreholes over a long period of time.

Dilution of nuclides

Considering the depth of interest, it is effective to conduct borehole investigations down to the deep underground to acquire data on the hydraulic characteristics of geological structures that could contribute to dilution.

Local stress regime, spatial variability of petrophysical/geomechanical properties of rocks and size and structure of EDZ

Data on the local stress regime and the petrophysical/geomechanical characteristics of rock not only form the basis for the design of the underground facilities, but are also important for establishing input conditions for the numerical analysis to predict excavation effects on the rock around the underground facilities.

In this step, a depth profile of the petrophysical/geomechanical characteristics of rock was established by petrophysical/geomechanical tests in the laboratory using core samples from the deep boreholes; the depth profile of the initial stress was determined by investigations such as hydraulic fracturing at different depths using boreholes. For the preliminary investigations, the initial stress states and the depth profile of the petrophysical/geomechanical characteristics were determined by tests in the deep boreholes and in the laboratory using core samples and by measurement of the initial stress using the hydraulic fracturing method. As demonstrated in this step, since the stress conditions vary with the presence of discontinuities such as faults, planning an investigation program focusing on the major geological structures is important. The validity of the analysis of excavation effects on the surrounding rock will be demonstrated only when the investigation results are available after the excavation of the underground facilities. However, the geomechanical impact of excavation on the rock surrounding the underground facilities can be predicted to some extent from the results of the surface-based investigations.

Volume of inflow into underground tunnels

It was found that the spatial distribution and hydraulic characteristics of discontinuities such as faults emerging at the underground tunnels could have a significant influence on groundwater inflow rate. However, in the case where such features dip at a high angle and the underground tunnels extend in a vertical direction, high-precision determination of the depth where highly permeable structures are assumed to be encountered is difficult with borehole investigations conducted at a distance from the construction location of the underground tunnel. Therefore, in order to accurately determine the number and depths of highly permeable structures dipping at a high angle that emerge at underground tunnels, it will be necessary to conduct borehole investigations at the construction points of the underground tunnels.

Since the range and rate of drawdown of the groundwater level are considered to have an influence on the inflow volume, it will be important to acquire data on the spatial distribution and hydraulic characteristics of faults that are considered to affect the drawdown. Because the number of the boreholes will be limited due to various restrictions, the presence of hydrogeological structures such as faults that could significantly influence the inflow rate should be examined using a sensitivity analysis before conducting borehole investigations.

Distribution of discontinuities intersecting underground tunnels

Combining a range of investigations in this step was useful for verifying and improving the accuracy of predictions of the geological features obtained in Step 1. It allowed to determine the occurrence of faults in the deep granite and features that may function as water conduits. The monitoring of hydraulic response during drilling in boreholes located near the borehole being drilled was appropriate for determining the nature of flow barrier or the hydraulic connectivity of the identified discontinuities.

Subsurface thermal conditions

Data on the thermal conditions are required for the design and construction of the underground facilities. Data on the geothermal gradient and thermal rock properties were acquired by temperature logging in deep boreholes and laboratory tests on thermal rock properties using cores. In the preliminary investigations for the disposal project, the thermal condition will also be determined using the same methods. Since significant changes in the geothermal gradient would not be expected within a range of a few km on the local scale provided there is no local heat source such as a volcanic zone, the geothermal gradient on the local scale can be obtained by temperature logging in a single hole. Thermal rock properties can be determined by laboratory tests on several cores from a single hole. However, when the pore structures and the types and volume of the composite minerals of the rocks vary, the thermal rock properties can also change and therefore need to be determined taking the heterogeneity into consideration.

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3.6 Step 4 investigations

In accordance with the key factors identified in Step 3 (see Section 3.5.10), a series of geophysical and hydrogeological investigations were conducted between boreholes in and around the MIU Construction Site with the aim of determining the connectivity of important geological structures and the hydraulic characteristics of the structures that were predicted to influence groundwater flow in Step 3 and the preceding steps (see Section 3.5). The existing borehole DH-2 drilled as a part of the RHS and the deep borehole DH-15 were used for the investigations in this step. Table 3.1-1 shows the investigations and their specific aims conducted in this step.

The objectives of the crosshole investigations were:

(a) To determine the distribution and connectivity of the geological structures between the boreholes that were confirmed by the borehole investigations in Step 3 and preceding steps for the granite near the underground facilities.

(b) To acquire data on the distribution of discontinuities such as faults and fractured zones located at the underground facilities that are considered to affect the geophysical, hydraulic and geomechanical characteristics of the rock.

(c) To determine hydraulic characteristics and connectivity of water-conducting features between boreholes.

Investigations for objectives (a) and (b) above included a seismic tomography survey and a resistivity tomography survey between the deep borehole MIZ-1 and the existing borehole DH-2, a multi-offset VSP survey (see Section 4.2) using the deep boreholes MIZ-1 and DH-15 and a reflection seismic survey with survey lines passing through the vicinity of the deep boreholes MIZ-1 and DH-15. For objective (c), a crosshole hydraulic test was conducted using the deep borehole MIZ-1 as the pumping hole and the shallow boreholes MSB-1 and MSB-3, the existing borehole DH-2 and the deep borehole DH-15 as boreholes for monitoring the hydraulic response.

The seismic tomography survey and the resistivity tomography survey were conducted with the layout shown in Fig. 3.6-1, focusing on determining the detailed distribution of the major discontinuities in the upper highly fractured domain in the Toki Granite and at the MIU Construction Site[1)].

The multi-offset VSP survey was conducted with the layout shown in Fig. 3.6-2, with the objective of accurately determining the distribution of discontinuities that had been confirmed or predicted in Step 3, including the upper highly fractured domain and the low-angle fractured zone near the boreholes[1)].

The objective of the reflection seismic survey with survey lines passing through the vicinity of the deep boreholes was to determine the distribution and connectivity of the discontinuities in the area to the north to north-east of the MIU Construction Site, where the existence of these features had been confirmed or predicted in Step 2, but data had not yet been acquired. The survey was conducted for the two survey lines that passed in the vicinity of the borehole MIZ-1 and the borehole DH-15 with the layout shown in Fig. 3.6-3[1)].

The objective of the crosshole hydraulic tests was to determine the hydraulic characteristics and its connectivity of low-angle fractured zone and discontinuities that had been confirmed or predicted in Step 3 and the preceding steps. Two pumping tests were conducted, one from the low-angle fractured zone in borehole MIZ-1 and one from the discontinuities predicted to extend between the MIZ-1 and DH-2 boreholes[1),2)]. The layout of the pumping section and the monitoring sections are shown in Fig. 3.6-4 and the test conditions in Table 3.6-1.

Based on the test results, the geological and hydrogeological model constructed in Step 3 and the preceding steps were updated. Groundwater flow analyses were conducted using these updated models to predict the distribution of the hydraulic gradient and the groundwater flow conditions around the underground facilities. The reliability of the results was improved by checking the consistency of the models and analyses results. Significant factors that affect the variation in the uncertainties and in the analysis results were evaluated and important factors for the investigations in Phase II were identified (see Section 3.6.6).

The geosynthesis data flow diagram that was constructed based on the experience from the investigations in this step is shown in Appendix 4. The detailed approach used to achieve the specific goals and issues is summarized in Sections 3.6.1 to 3.6.5. The key factors for analysis in the next and subsequent steps and recommendations for further investigations in the disposal project that were identified in this step are summarized in Section 3.6.6.

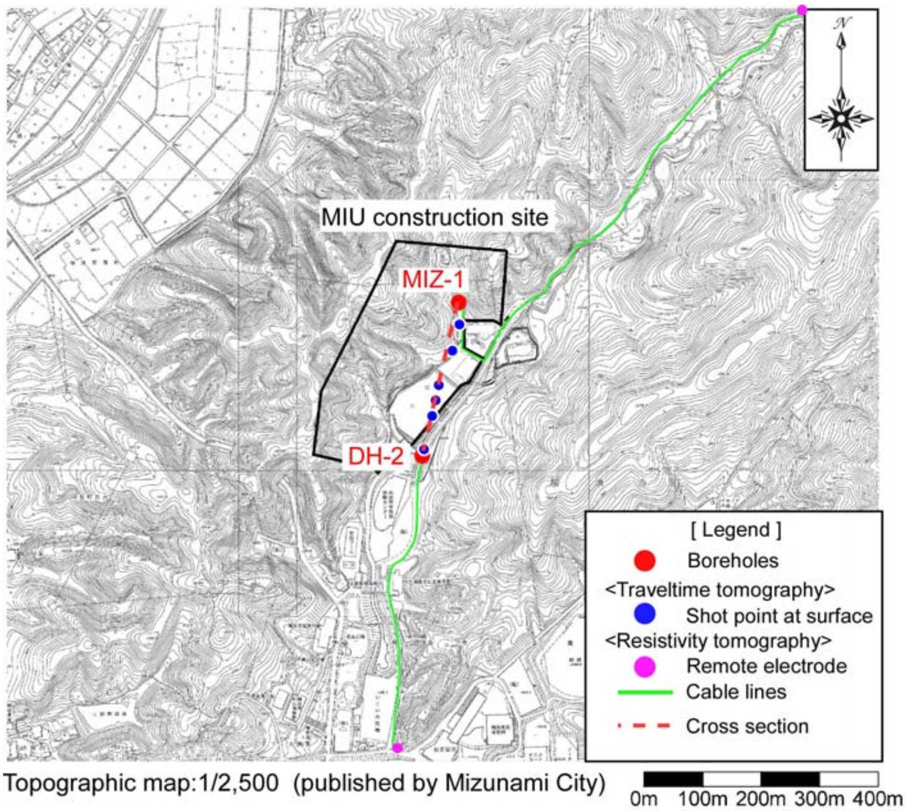


Fig. 3.6-1 Location of the crosshole tomography survey[1)]

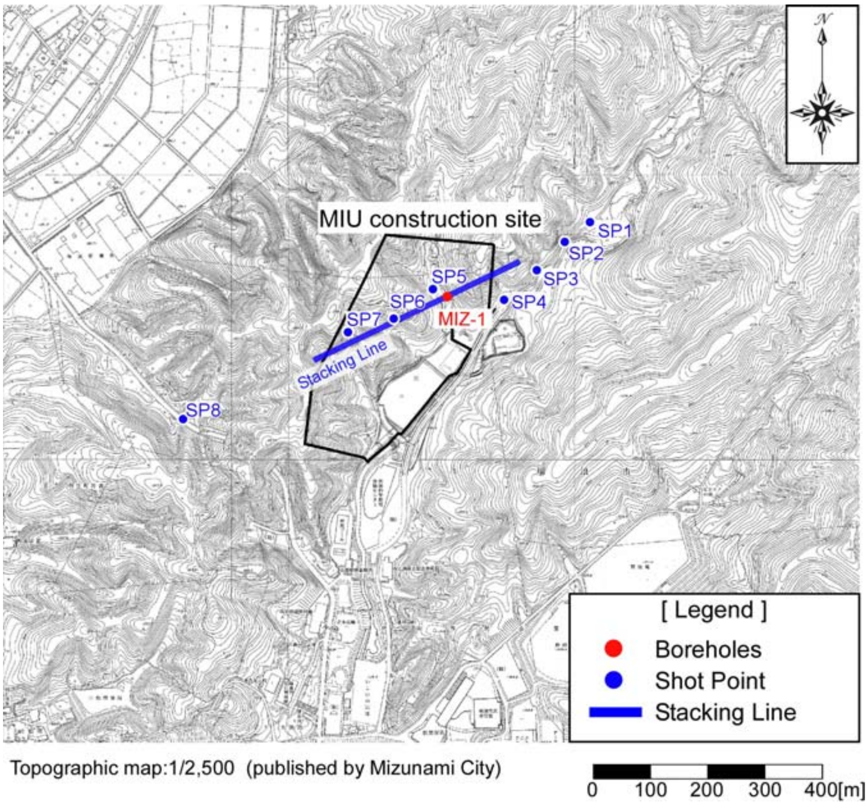


Fig. 3.6-2 Location of the multi-offset VSP survey[1)]

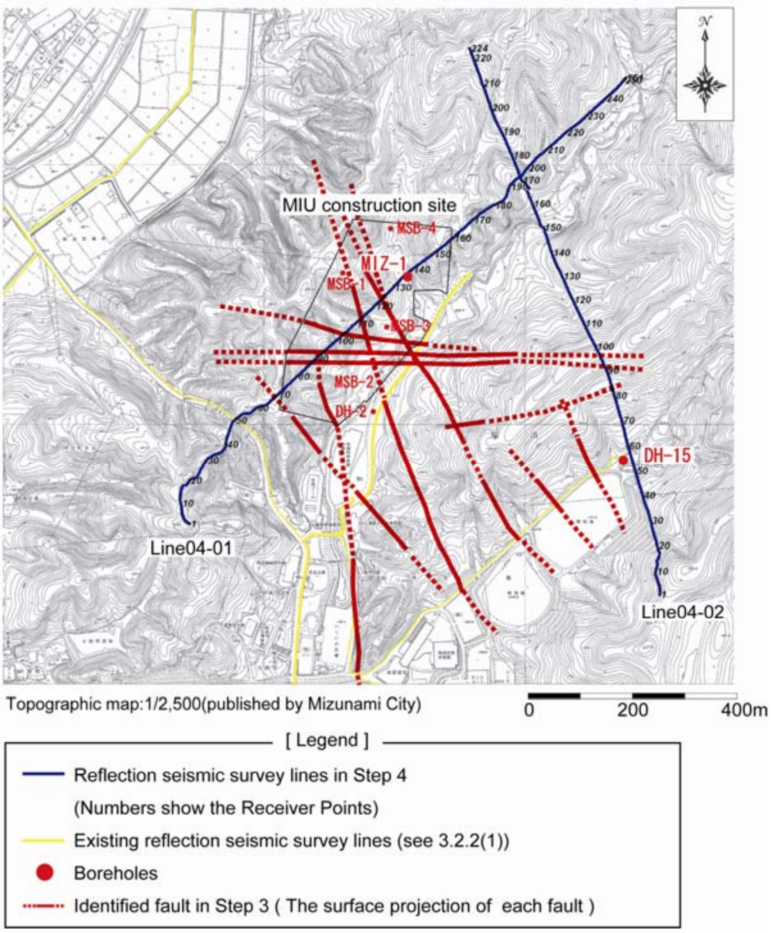


Fig. 3.6-3 Location of lines for reflection seismic survey in Step 4[1)]

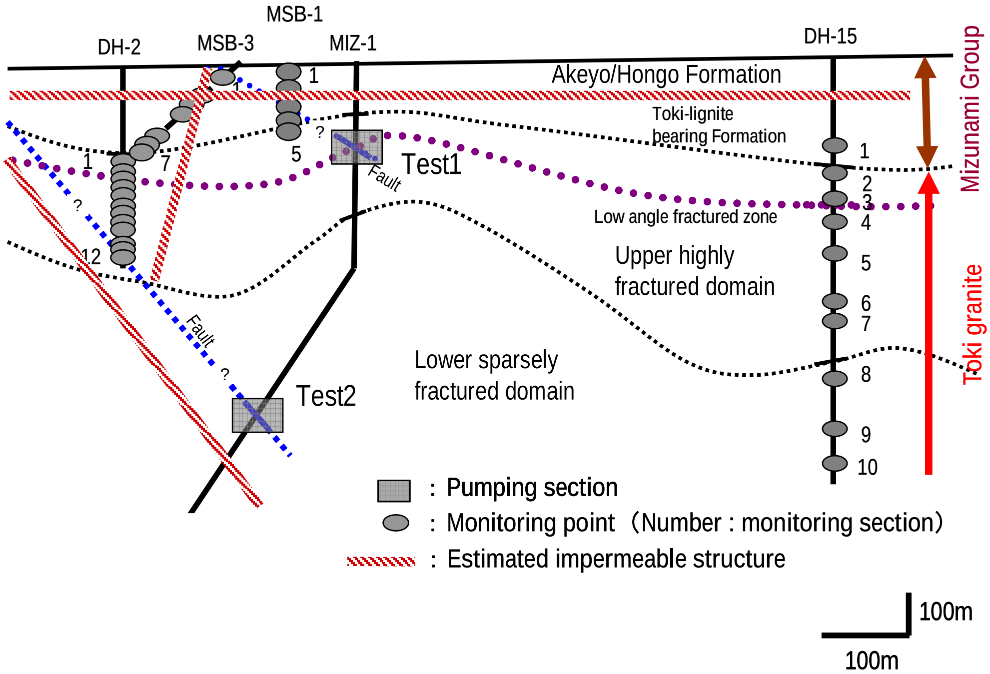


Fig. 3.6-4 Pumping and monitoring points on the crosshole hydraulic test

Table 3.6-1 Specifications for the crosshole hydraulic tests

Test ID	Test interval (meter along borehole)	Main events in the test	Pumping flow rate (l/min)	Pumping time (hour)	Pumping volume (m^3)
Test 1	191.00 – 226.41	PW-SW/SWS-RW1/RWS1-RW9/RWS9	10.8 (RW9)	244.6 (RW9)	157.6 (RW9)
Test 2	662.20 – 706.23	PW-SW/SWS-RW/RWS-PI	5.2	355.2	110.9

＊PW：Pulse withdrawal test, SW：Slug withdrawal test, SWS：Pressure recovery test after slug withdrawal, RW：Constant rate withdrawal test, RWS：Pressure recovery test after constant rate withdrawal, PI：Pulse injection test

3.6.1 Geological structure

Crosshole seismic tomography and resistivity tomography surveys were conducted between the deep borehole MIZ-1 and the existing borehole DH-2 (Fig. 3.6-1)[1] with the objective of determining the connectivity of the discontinuities identified and predicted in Step 3 and preceding steps for the area near the underground facilities. Multi-offset VSP surveys were also conducted using borehole MIZ-1 and borehole DH-15, with the aim of determining the spatial distribution of the faults identified in the deep boreholes (MIZ-1 and DH-15) in Step 3 and the presence of the discontinuities near the boreholes (Fig. 3.6-2)[1),3),4)]. Reflection seismic surveys were conducted for the two survey lines passing in the vicinity of MIZ-1 and DH15, north to north-east of the MIU Construction Site where no investigations were conducted in Step 2. The aim was to determine the connectivity of the NW, NNW and EW trending faults that were confirmed or predicted around the underground facilities in Step 3 and the preceding steps (Fig. 3.6-3)[1).

Based on the geological data obtained in this step, the consistency of the distribution of the tectonic zonation in the Toki Granite (e.g. the upper highly fractured domain and the low-angle fractured zone) that was confirmed or predicted in Step 3 and the preceding steps was checked. A principal component analysis (see Section 4.1) was conducted using the data from the geophysical logging and core logging from the boreholes investigations in Step 3 and the preceding steps (e.g. DH-2, MIZ-1 and DH-15) to define the fault section in detail. The spatial distributions of the discontinuities on the site scale were predicted using additional data identified in Step 4 in order to update the geological model.

Results

Four faults that located between borehole MIZ-1 and borehole DH-2 were predicted by the tomography surveys (Fig. 3.6.1-1). The multi-offset VSP survey using the deep boreholes and the reflection seismic survey showed the geological boundaries in the Mizunami Group located primarily to the north to north-east of the MIU Construction Site and the location of the unconformity between the Toki Granite and the Mizunami Group. With regard to the distribution of the upper highly fractured domain and the low-angle fractured zone in the granite, the geological model in Step 3 and the distribution of the reflection events were generally consistent. By combining the multi-offset VSP survey and the reflection seismic survey, 24 faults in total were predicted (Fig. 3.6.1-2 and Fig. 3.6.1-3). The geological model was updated based on the above data (Fig. 3.6.1-4).

Conclusions and implications for the next investigation step

In this step, the discontinuities located near the Main Shaft were identified particularly by the crosshole tomography survey (Fig. 3.6.1-5). Also, compared to Step 3 and the preceding steps, the locations of the discontinuities near the underground facilities were identified in more detail by the multi-offset VSP survey using the deep boreholes and the reflection seismic survey with the survey lines that surround the area around the underground facilities in Step 3. From the data on the distributions of faults from the near surface to the deep underground that were acquired in this step and the preceding steps (knowledge of the location of the faults and the correlation between the direction and the size of the faults), it was confirmed that the width of the NW trending fault is large around the MIU Construction Site and the distribution of the fault is generally consistent with that of the steep topography of the Tsukiyoshi Channel (see Section 3.2.1). Overall it was possible to interpret fault configurations and their interconnecting relationship from the additional datasets and to improve the accuracy of the predictions of overall fault distributions made in preceding steps.

When conducting the seismic tomography survey in this step, the energy of the seismic source in the boreholes was not transmitted sufficiently between the boreholes due to the long distance between them (approximately 260 meters). Therefore, as an alternative method to the crosshole tomography survey, seismic tomography was conducted between the ground surface and the boreholes, with the seismic source at the ground surface between the boreholes. This approach was effective for identifying the discontinuities between the boreholes in the relatively shallow zones (down to approximately 300 meters in this investigation), although data for the deep underground were difficult to obtain because of the measurement geometry.

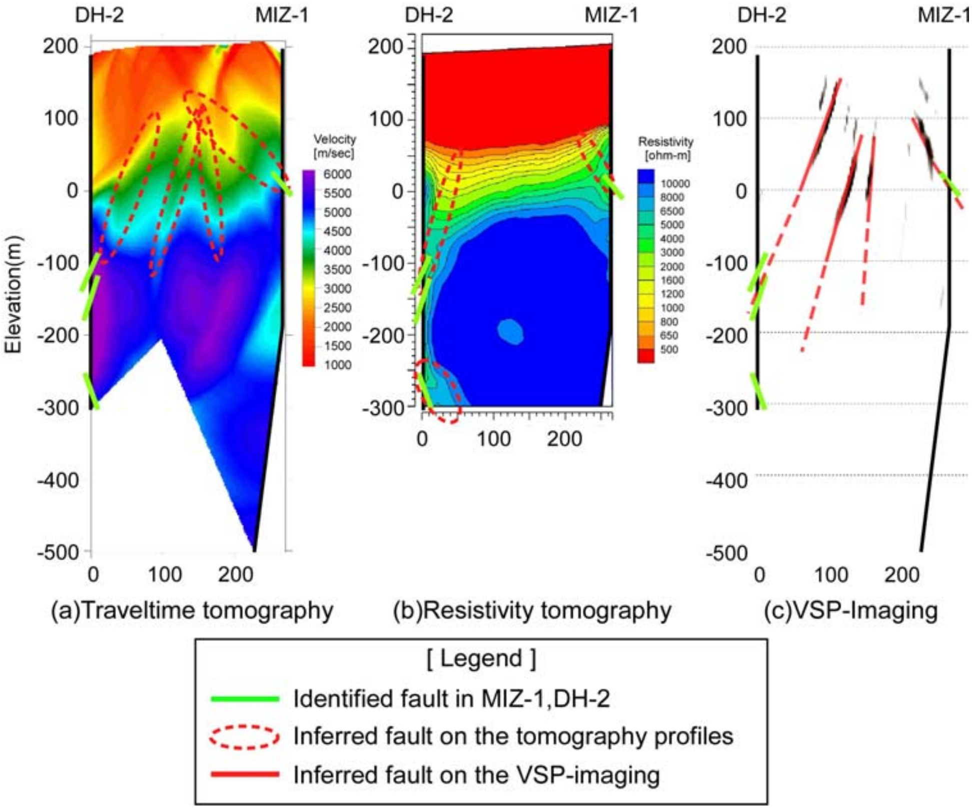


Fig. 3.6.1-1 Geological interpretations based on tomograms and the VSP imaging using seismic data[3)]

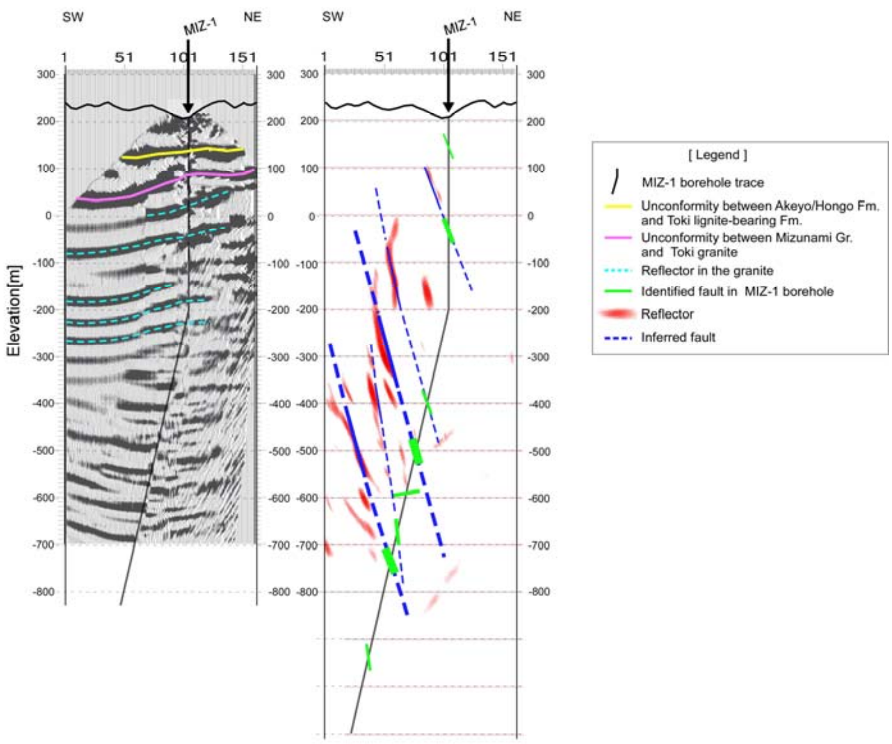


Fig. 3.6.1-2 Geological interpretations based on reflection profiles using the multi-offset VSP[3)]

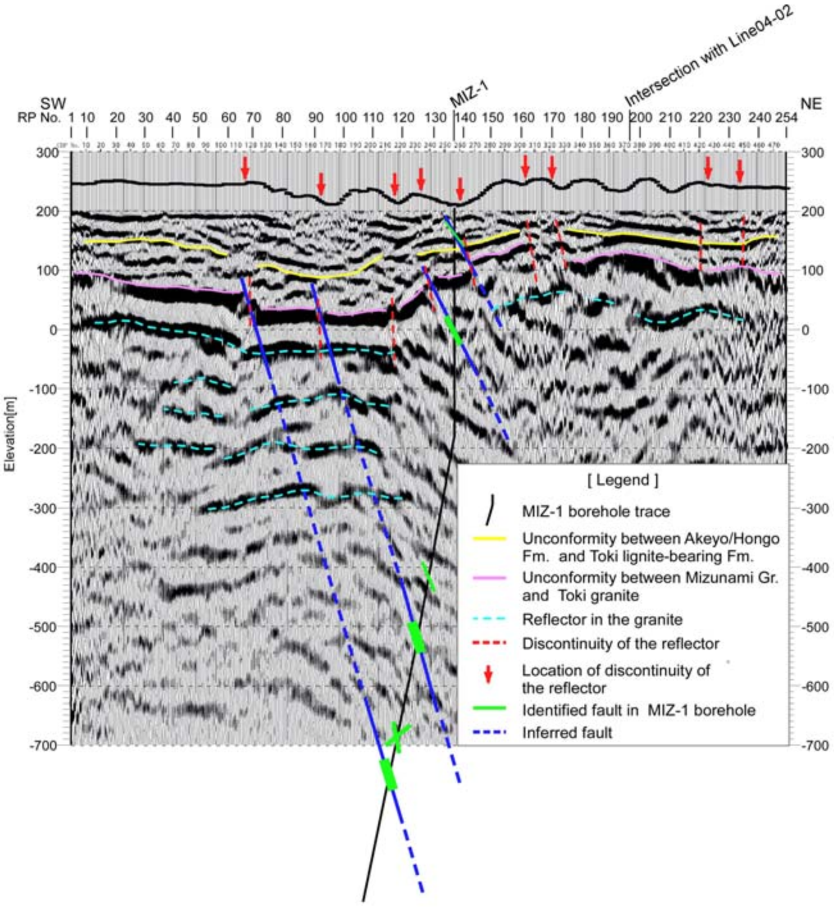


Fig. 3.6.1-3 Geological interpretation based on the reflection seismic profile (Line 04-01)

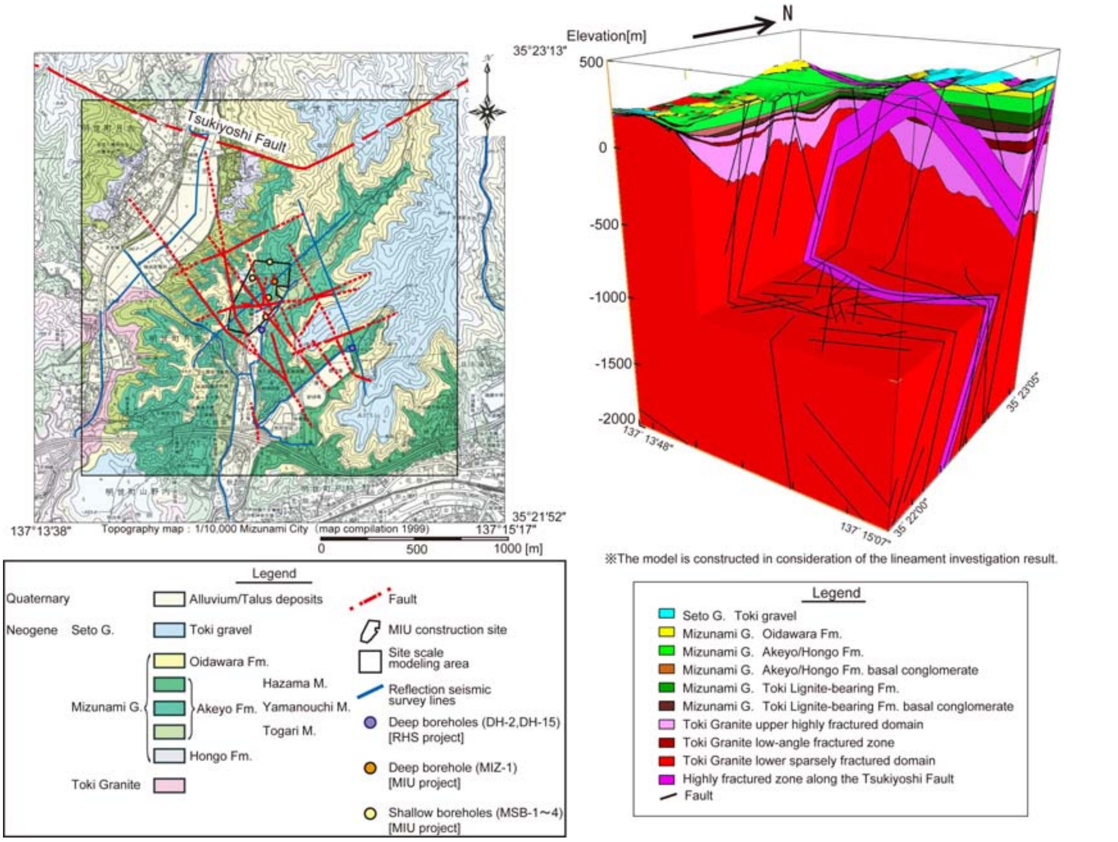


Fig. 3.6.1-4 Geological map and geological model revised using the crosshole investigation phase data

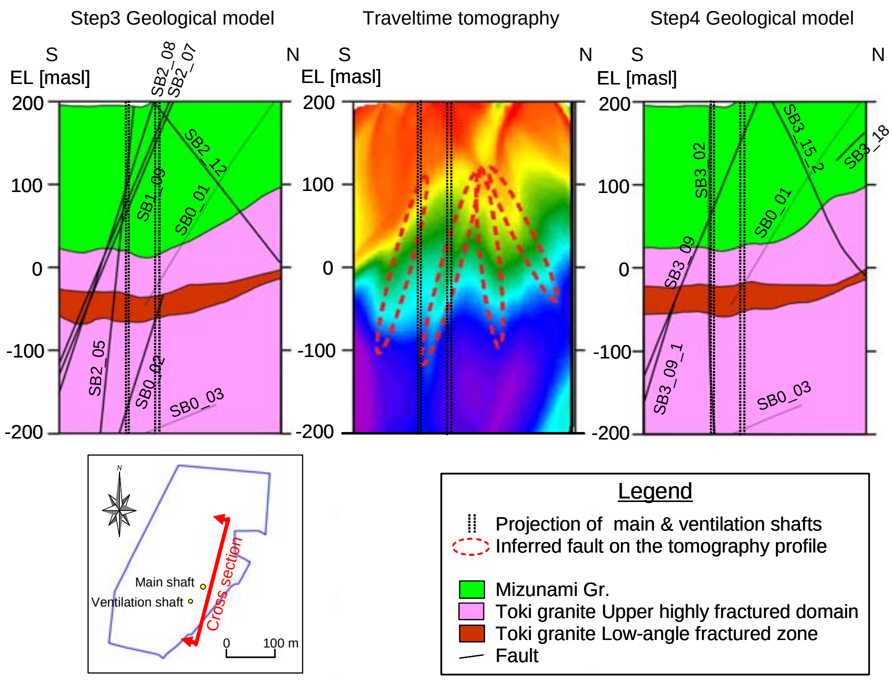


Fig. 3.6.1-5 Comparison between geological interpretation of travel-time tomography profile and geological model

3.6.2 Groundwater flow characteristics

Long-term crosshole hydraulic tests (pumping period of around two weeks) were conducted[2)] using the deep borehole MIZ-1 at the MIU Construction Site as the pumping hole and four boreholes as monitoring holes, namely the shallow boreholes MSB-1 and MSB-3 (around 100 - 200 meters in depth), an existing borehole near the MIU Construction Site (DH-2) and the deep borehole DH-15 (about 1,000 meters in depth), to acquire data on the hydraulic characteristics (hydraulic conductivity and storativity) and its connectivity of the high permeable fractured zone in granite predicted in Step 3 and the preceding steps.

The hydrogeological model was updated based on the hydraulic characteristics of the geological structures determined in the crosshole hydraulic test and the 3-D geological model (see Section 3.6.1) that was updated in this step[5)]. The updated hydrogeological model was calibrated based on the data on the transient groundwater pressures change associated with the crosshole hydraulic tests in each monitoring hole. A sensitivity analysis was also conducted focusing on the hydraulic anisotropy of the faults[5),6)]. The boundary conditions for the site-scale area were updated by incorporating the investigation data obtained in this step in the hydrogeological model for the local-scale area and the groundwater flow simulations[7)]. The construction of the above geological/hydrogeological models and the groundwater flow analyses were based on the GEOMASS system (see Section 4.10).

<u>Results</u>

The crosshole hydraulic test was conducted with a maximum pumping rate of approximately 10 L min^{-1}. The maximum change in pressure at the monitoring holes associated with the test was approximately 2 kPa (about 0.2 meters hydraulic head), comparable to that caused by earth tides. Noise such as the effect of tides, atmospheric pressure and abnormal values due to the resolution of the measuring equipment was filtered from the measured data (see Section 3.8.2) to acquire clear hydraulic responses associated with the crosshole hydraulic tests[2)]. The results of the crosshole hydraulic tests and a schematic diagram of the hydrogeological structure around the MIU Construction Site that was predicted based on these results is shown in Fig. 3.6.2-1 and Fig.3.6.2-2. The hydraulic response at the monitoring holes indicated differences in responses between the shallow zone and the deep zone around the MIU Construction Site and differences bordering the fault that exists in the center of the MIU Construction Site were observed. This suggests the presence of a hydraulic boundary caused by the sedimentary structure and the fault with low hydraulic conductivity, as was suggested by the results of long-term hydraulic monitoring[8)] conducted around the MIU Construction Site to date.

The hydrogeological model was calibrated through the groundwater flow analyses focusing on two aspects; the hydraulic characteristics of geological structures and the distribution and location of the faults[5),6)]. Using data on the transient groundwater pressures change generated by the pumping test for the calibration, the hydraulic characteristics of the geological structures and the distribution ranges and locations that had not been determined before this step could be derived. The hydrogeological model updated in this step is shown in Fig. 3.6.2-3. For the model in this step, as an additional hydrogeological structure, a basal conglomerate was assumed to be present at the base of the Akeyo/Hongo Formations and the Toki Lignite-bearing Formation of the Mizunami Group. The configuration of the surfaces of the geological boundary and that of the fault distributions, as well as the typical hydraulic characteristics (i.e. hydraulic conductivity) of the geological structures were also updated.

The calibration of the hydrogeological model indicated the existence of hydraulic anisotropy for all the faults considered except for the NNW trending fault. For this fault sensitivity runs focusing on the existence of anisotropy of the NNW trending fault were also conducted as in the previous steps and the 3-D distribution of the hydraulic head was calculated each time. The results of the sensitivity analysis shown in Fig. 3.6.2-4 indicated that the distribution of the hydraulic head was generally similar to that in the preceding steps. A full sensitivity case and the results are shown in 3.7.2. The effect on the groundwater flow-field due to the existence of the hydraulic anisotropy of the NNW trending fault located south of the MIU Construction Site was found to be small. The measured distribution of the hydraulic head at the boreholes was compared with that based on the groundwater flow analyses. Fig. 3.6.2-5 shows the square root of the deviation of the measured and modeled hydraulic head difference in this step and Steps 1 - 3. This figure indicates that the fit of the analytical to the measured values was improved by approximately 2 m in this step compared to Step 3, which indicates that the crosshole investigations were effective for acquiring data on the spatial distribution, hydraulic characteristics and its connectivity of the high permeable fractured zone.

The reliability of the hydrogeological model prior to the construction of the underground facilities was improved by adopting an iterative approach in Phase I. This approach repeats a series of types of investigations that involve constructing the hydrogeological model by incorporating the investigation results in each step and identification of the key factors for investigation in the next phase, based on the results of the groundwater flow analyses.

An average difference of approximately 20 meters still remained between the measured hydraulic head monitored in the boreholes and the model results (for example, Borehole DH-2, Fig. 3.6.2-5). The major factor potentially affecting the difference was insufficient understanding of the distribution of the low hydraulic heads in the zone deeper than the Akeyo/Hongo Formations of the Mizunami Group as observed by the long-term hydraulic monitoring (see Section 3.4.2), leading to an inappropriate representation based on the hydrogeological model in this step. Since the hydraulic head in the zone deeper than the Akeyo/Hongo Formations of the Mizunami Group is considered to be similar to that of the Toki River, which is predicted to be the hydraulic boundary of the groundwater passing through the deep underground around the MIU Construction Site, one hypothesis is that a highly permeable geological structure exists which facilitates flow from the deep underground at the MIU Construction Site to the Toki River. Investigations to confirm the above hypothesis have not been conducted due to cost, time and environmental restrictions. The Tono Research Institute of Earthquake Science has been monitoring the groundwater level at a borehole (TGR350) located approximately 250 meters south of the MIU Construction Site since 1998, before the start of the MIU project[9)]. As shown in Fig. 3.6.2-6, the groundwater level has lowered at a rate of 0.4 meters/year since the start of monitoring. The groundwater level in the boreholes in and around the MIU Construction Site is also expected to show the same trend. Thus, the measured values used for the comparison with the results of the groundwater flow analyses in the steady-state may not represent a steady-state condition in the context of long-term evolution. At this point in time, the factors causing the reduction of the water level over a long period of time have not been clarified. As shown in Fig. 3.6.2-6, the fluctuation in groundwater pressure due to earthquakes was monitored at the boreholes around the MIU Construction Site. In order to correctly determine the distribution of the groundwater pressure at any point in time, long-term hydraulic monitoring would be required.

Conclusions and implications for the next investigation step

In order to improve the understanding of the characteristics of groundwater flow, issues that have not been resolved to date should be taken up in the investigations and studies in Phase II and subsequent phases. Prioritizing investigations based on the iterative approach is considered very important.

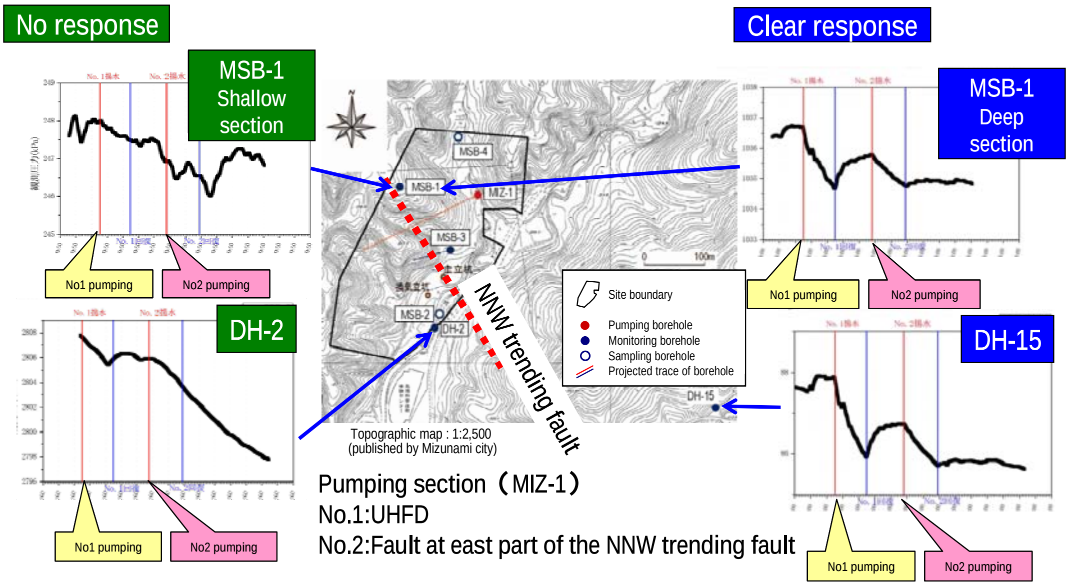
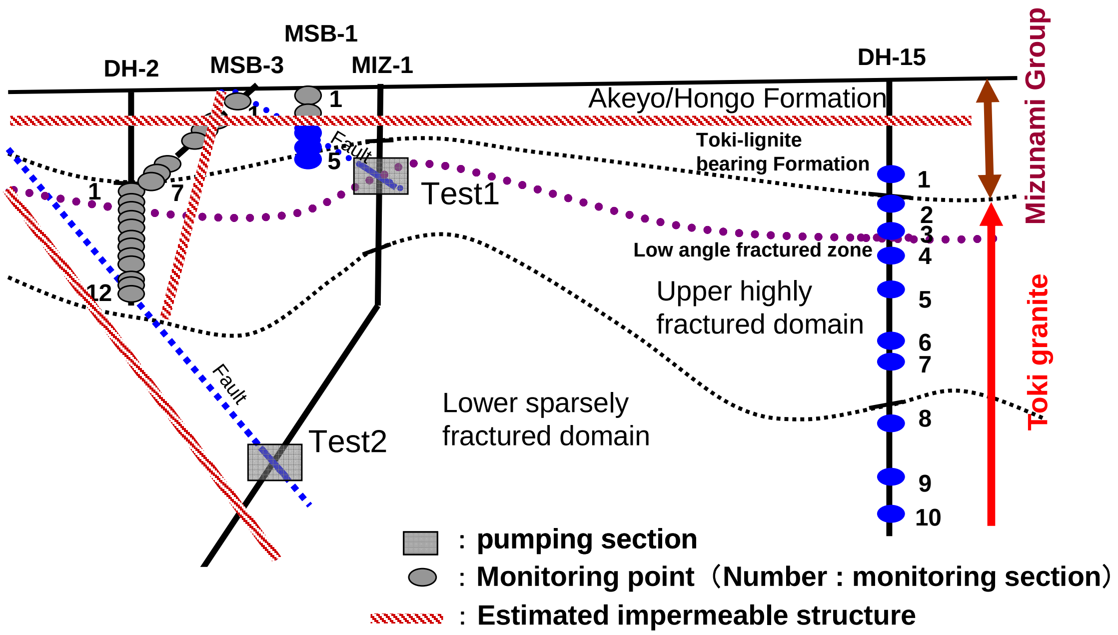
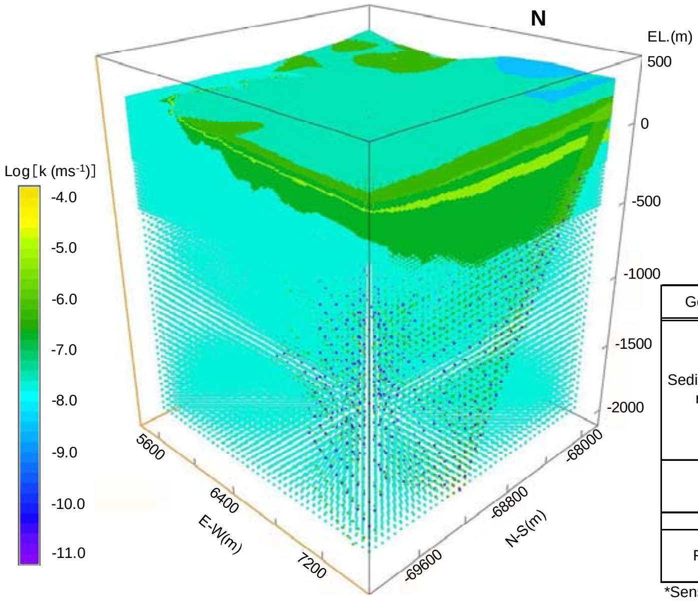


Fig. 3.6.2-1 Results of the crosshole hydraulic tests



※ : monitoring sections with a clear response during the hydraulic tests

Fig. 3.6.2-2 Observed hydraulic response in monitoring boreholes during the crosshole hydraulic tests



Hydraulic conductivity

Geological features and geological structure element			Log [k (m s^{-1})]
Sedimentary rock	Seto group		-5.0
	Mizunami group	Oidawara formation	-8.5
		Akeyo/Hongo formation	-7.6
		Akeyo/Hongo formation Basal conglomerate	-6.3
		Toki-lignite bearing foramation	-6.3
		Toki-lignite bearing foramation Basal conglomerate	-5.9
Toki granite		Upper Highly fractured domain	-6.7
		Low angle fractured zone	-5.4
		Lower sparsely fractured domain	-7.7
Highly fractured zone along the Tsukiyoshi fault			-6.4
Fault	Main part of Tsukiyoshi fault		-11.0
	Other faults	In-plane of fault	See Table 3.2.6(2)-5
		Normal to fault*	

*Sensitivity analysis about hydraulic anisotropy:1faults in 14

Fig. 3.6.2-3 Hydrogeological model (3-D distribution of hydraulic conductivity)

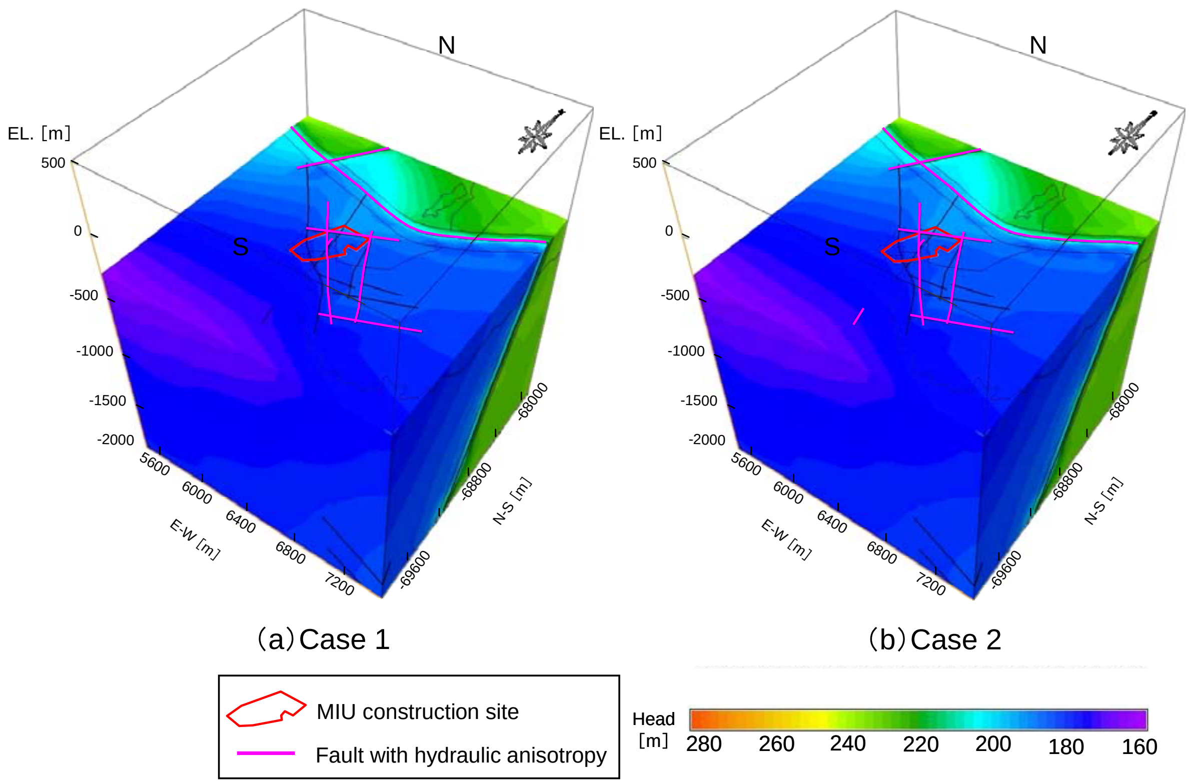


Fig. 3.6.2-4 Sensitivity analysis focused on hydraulic anisotropy of faults (Elevation -300 m : Depth of the shaft 500 m)

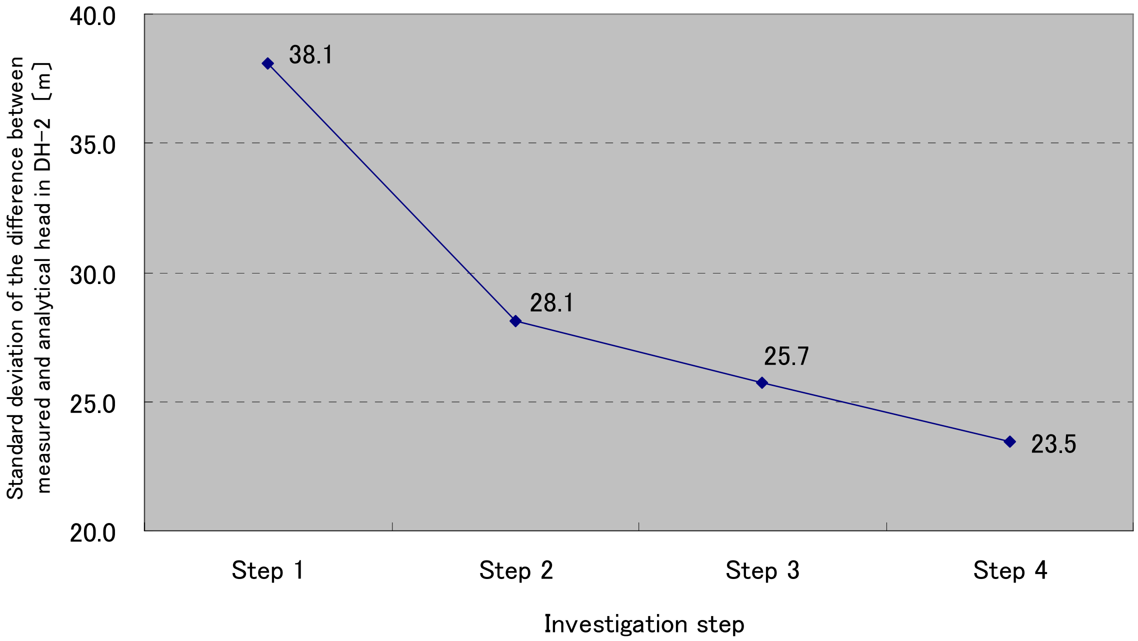


Fig. 3.6.2-5 Comparison between measured and analytical head differences in Step 1 to 4

Fig. 3.6.2-6 Result of long-term water level investigation by TRIES in TGR350 (Modified from Asai et al (2003)[9])

3.6.3 Dilution of nuclides

The distribution of the Darcy velocity was calculated based on the results of the groundwater flow analysis discussed in Section 3.6.2 to determine the dilution effect of each hydrogeological unit.

Results

The hydrogeological model updated in this step (see Section 3.6.2) defined a basal conglomerate as an additional hydrogeological unit at the base of the Akeyo/Hongo Formations and the Toki Lignite-bearing Formation of the Mizunami Group. In this step, therefore, the basal conglomerate was identified as a hydrogeological unit that could be expected to act as an aquifer, in addition to the structures already identified in Step 3 (low-angle fractured zone, the upper highly fractured domain, the Toki Lignite-bearing Formation, the highly fractured zone along the Tsukiyoshi Fault and the Akeyo/Hongo Formation).

The frequency distribution of the Darcy velocity of the above hydrogeological units was calculated (Fig. 3.6.3-1). The result indicated that the low-angle fractured zone showed the highest distribution, followed by the basal conglomerate of the Akeyo/Hongo Formations, the Toki Lignite-bearing Formation and its basal conglomerate and the highly fractured zone along the Tsukiyoshi Fault. The upper highly fractured domain and the highly fractured zone along the Tsukiyoshi Fault showed different trends in the frequency distribution of the Darcy velocity, although their hydraulic conductivities were similar. Also, despite the hydraulic conductivity of the upper highly fractured domain having a similar value to that in Step 3, the frequency distribution for the Darcy velocity of the zone differed greatly from that in Step 3. These results suggest that, even in aquifers with similar hydraulic conductivities, the expected dilution effect may be different depending on their distribution and configuration as well as the configuration, location and hydraulic conductivity of other hydrogeological units. Within the Toki Granite, the Darcy velocities of the low-angle fractured zone, the Akeyo/Hongo Formations and its basal conglomerate, the Toki Lignite-bearing Formation and its basal conglomerate, the highly fractured zone along the Tsukiyoshi Fault and the upper highly fractured domain were relatively high compared to that for the lower sparsely fractured domain with relatively low hydraulic conductivity, which would suggest their importance in terms of dilution effect.

The crosshole investigations conducted in this step contributed to improving the reliability of the hydrogeological model by providing data on the geological structures that had not previously been determined and the 3-D distribution, connectivity and hydraulic characteristics of geological structures that had been either confirmed or predicted to exist in the investigations in Step 3 and the preceding steps (see Section 3.2.5 (3)). The accuracy of the frequency distribution of the Darcy velocity obtained from the groundwater flow analyses conducted based on the model needs to be improved.

Conclusions and implications for the next investigation step

In Phase I, refinement of the hydrogeological model and determination of the dilution effect in the site-scale area were undertaken using an iterative approach. In Phase II, the connectivity, 3-D distribution and hydraulic characteristics of the geological structures that were expected to have a dilution effect in this step would need to be determined or predicted by acquiring data on the changes in ground pressure associated with the excavation of the underground facilities.

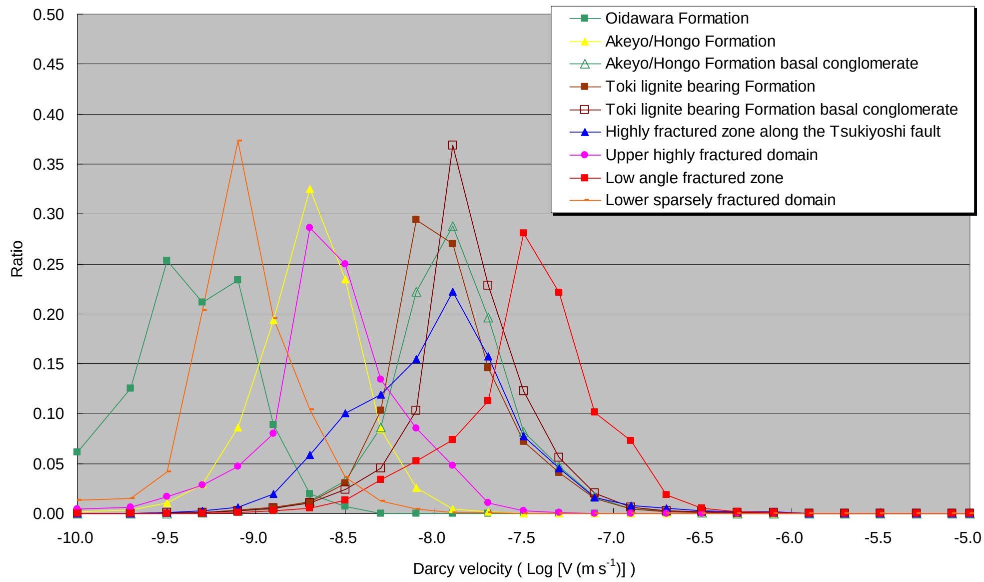


Fig. 3.6.3-1 Darcy velocity distribution
(The vertical axis shows the ratio (cumulative frequency is 1 in each geological formation and domain))

3.6.4 Volume of inflow into underground tunnels

Groundwater flow analyses using the hydrogeological model[5] (see Section 3.6.2) that was updated by calibration using the transient data on groundwater pressure from the crosshole hydraulic test were conducted with the aim of predicting the inflow rate into the underground facilities.

The analyses were conducted by solving a 3-D transient problem for saturated - unsaturated conditions using the equivalent heterogeneous continuum model[10] based on the finite element method as examined in Steps 2 and 3 (see Sections 3.4.6) and 3.5.7). As part of the groundwater flow analyses, sensitivity analyses were also conducted focusing on the differences in the pressure relief factor taking into account the hydraulic characteristics around the underground facilities, as was done in Steps 2 and 3 (Table 3.6.4-1). Since the necessary data could not be obtained in the investigations in Phase I, a sensitivity analysis was conducted using the same pressure relief factor as in Steps 2 and 3. It became clear from the examination in Steps 2 and 3 that the differences in the inflow rate into the underground facilities were small for the different models. The examination in this step was therefore conducted using a single model.

Results

The results of the groundwater flow analyses in Step 4 indicated that the inflow rate would differ significantly even when using the same model when the pressure relief factors are different (Fig. 3.6.4-1), as was indicated in Steps 2 and 3.

When the pressure relief factor was 0.8, the maximum inflow rate was predicted to be approximately 1,000 m^3 day^{-1}. The general trend was for the inflow rate to increase when the excavation of the shaft reached the basal conglomerate of the Toki Lignite-bearing Formation; the trend showed a decrease in the lower sparsely fractured domain of the Toki Granite.

When the pressure relief factor was 0.2, the inflow rate suddenly increased after the excavation of the shaft reached the basal conglomerate of the Toki Lignite-bearing Formation and decreased in the lower sparsely fractured domain of the Toki Granite at depths greater than 500 meters. The maximum inflow rate was predicted to be approximately 4,000 m^3 day^{-1} at the point when the excavation was completed at the Main Stage of 1,000 meters. Although the maximum inflow rate was more than 10,000 m^3 day^{-1} (see Section 3.5.7) in Step 3, the rate based on the analyses in Step 4 decreased to 40 % of that in Step 3. The sudden increase in the inflow rate seen at the time of excavating the Middle Stage and Main Stage in Step 3 was not seen in Step 4. This may be due to the updating of the geological model (see Section 3.6.1) and the calibration of the hydrogeological model using the results of the crosshole hydraulic tests (see Section 3.6.2), meaning that a smaller number of faults with higher hydraulic properties around the MIU Construction Site were considered to intersect the shafts compared to Step 3. Another reason may be that the excavation steps in the groundwater analysis were subdivided into smaller steps to simulate the excavation process in more detail for the analysis.

As in the case in Step 3, all models indicated that the drawdown around the area where groundwater inflows into the underground facilities was strongly influenced by the faults distributed around the MIU Construction Site that are assumed to have hydraulic anisotropy.

<u>Conclusions and implications for the next investigation step</u>

When comparing the results for the inflow in Step 2 to Step 4, the predicted inflow changed significantly because of the updated number and locations of highly permeable structures intersecting the underground facilities and the hydraulic characteristics of these structures, resulting from the increase in data. In order to accurately predict the inflow rate into the underground facilities, it was considered necessary to further characterize these intersecting structures. For this purpose, it was considered important to acquire data on the spatial distribution and hydraulic characteristics of the highly permeable structures at the excavation point of the underground facilities and the area near the facility, as described in Section 3.5.7).

Table 3.6.4-1 Groundwater flow simulations

Case	Modeled fault／WCF	Pressure relief factor
Model B_1	Tsukiyoshi Fault ＋Faults around MIU Construction Site ＋Lineaments with length more than 3km	α =0.2
Model B_2		α =0.8

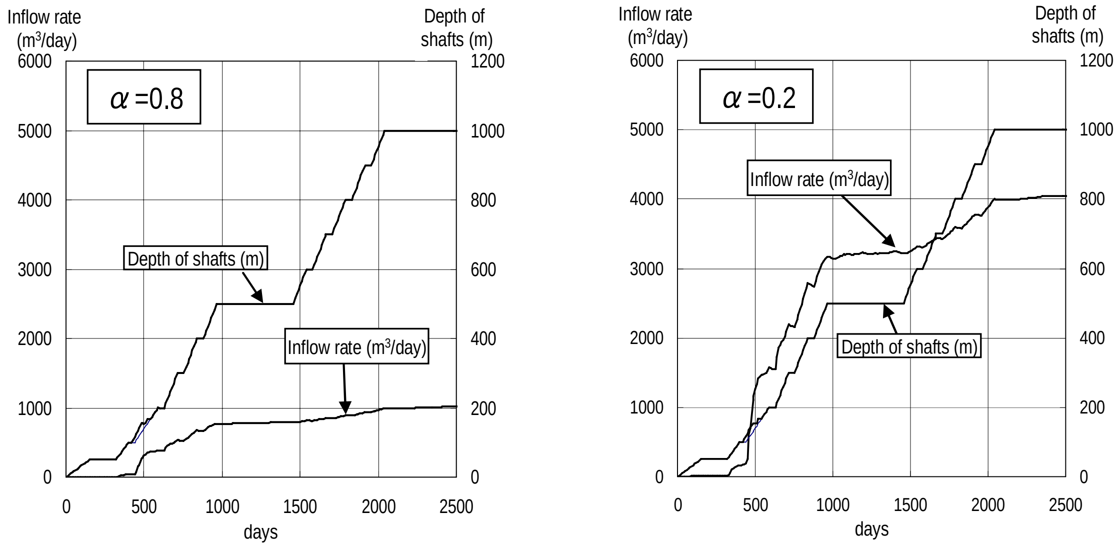


Fig. 3.6.4-1 Inflow rate into MIU (pressure relief factor: 0.8 and 0.2)

3.6.5 Distribution of discontinuities intersecting underground tunnels

The locations where discontinuities would emerge at the planned excavation point of the underground facilities were predicted based on the geological model discussed in Section 3.6.1. The aim was to acquire information on the presence of discontinuities such as faults and fractured zones at the underground facilities that might influence the petrophysical/geomechanical characteristics of the rock.

Results

In terms of the locations where discontinuities would be encountered at the planned excavation points of the underground facilities (Fig.3.6.5-1), 28 faults in total were predicted in Step 4 to be present around the MIU Construction Site from the crosshole tomography survey and the multi-offset VSP survey using the deep boreholes in Step 3 and the reflection seismic survey in the area north to north-east of the MIU Construction Site (where no previous investigations had been done). Most discontinuities were predicted to dip at high angles by the integrated interpretation of data gained until Step 0 to Step 4.

Conclusions and implications for the next investigation step

In this step, the discontinuities located near the Main Shaft were identified, particularly by the crosshole tomography survey. Also, the accuracy of the prediction of the faults that may emerge in the underground facilities was improved from that in Step 3 and the preceding steps by the reflection seismic survey along the survey lines (including the survey lines in Step 1) that surround the underground facilities. From the data on the distribution of the faults from the surface to the deep underground acquired in this and the preceding steps, the distribution of the faults and their connections were interpreted. The accuracy of the predictions was greatly improved.

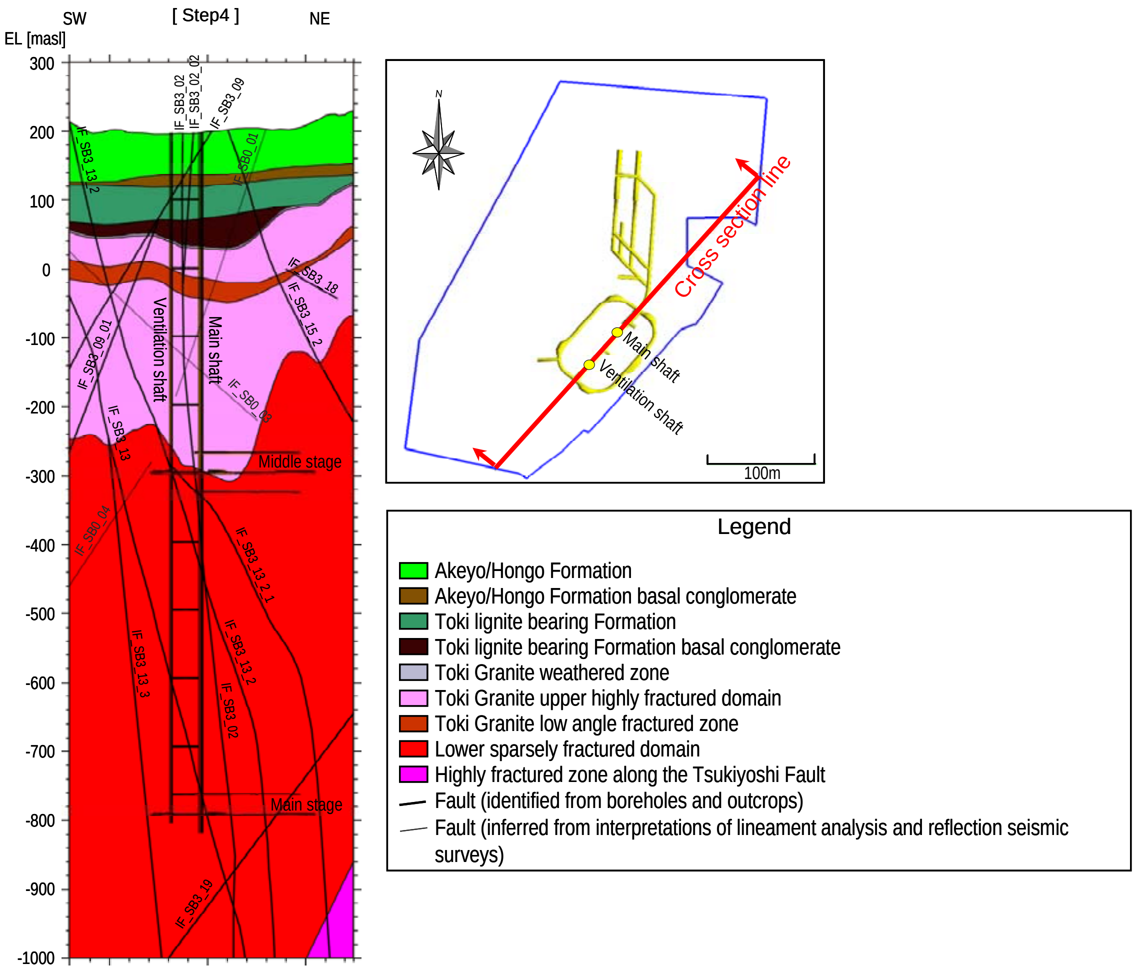


Fig. 3.6.5-1 Predicted geological structures around the MIU facility (Step4)

3.6.6 Discussion of results and recommendations for further investigations

The crosshole investigations were conducted with the objective of determining the connectivity of significant geological structures affecting groundwater flow and their hydraulic characteristics, covering the issues listed in Table 3.1-1 (geological structure, groundwater flow characteristics, dilution of nuclides and geomechanical/hydraulic properties of tunnel near-field environment). The crosshole investigations were included seismic and resistivity tomography surveys using the boreholes in and around the MIU Construction Site, multi-offset VSP surveys using deep boreholes, reflection seismic surveys along survey lines close to the deep boreholes and crosshole hydraulic tests.

Based on the results of these investigations, the geological model and the hydrogeological model on the site scale constructed in Step 3 and the preceding steps were updated. Groundwater flow analyses based on these models were also performed to predict the distribution of the hydraulic gradient and the hydraulic characteristics around the underground facilities.

In Phase I, the key factors for the investigations in Phase II and the subsequent phases were identified through modeling and analyses conducted from Steps 0 to 4. The details are summarized in Section 3.7.

Geological structure

A crosshole tomography survey for a cross-section passing through the vicinity of the underground facilities was effective for predicting the distribution of the faults emerging in the underground facilities. ,Although it would be preferable to conduct the surveys at the same location (along the same survey line), combining the crosshole tomography, reflection seismic survey and multi-offset VSP survey as far as possible in order to accurately predict the distributions of the faults in the zone from the shallow to the deep underground, not all the survey techniques could be applied to the same location. In the seismic tomography survey, due to the long distance between the boreholes (approximately 260 meters), the seismic source energy was insufficient to allow transmission between the boreholes because of the faults present between the boreholes. Therefore, as an alternative method, seismic tomography between the ground surface and the boreholes was conducted, setting the seismic source at the ground surface between the boreholes. The seismic tomography from the ground surface to the boreholes was effective for identifying the discontinuities between the boreholes in relatively shallow zones (down to approximately 300 meters in this investigation). Data for the deep underground were difficult to obtain because of the measurement geometry. For further surveys it should be kept in mind that because the signals in the crosshole tomography may not be sufficiently transmitted, depending on the distance between the boreholes and the geological conditions, it may be necessary to prepare several types of seismic sources prior to conducting the survey. Also, given the investigation costs and the quality control of acquired data, it would be important to select instruments and specifications that are appropriate for the distances between the boreholes and the geological conditions.

Finally to improve the accuracy of the predicted distributions of the discontinuities in areas where investigations have not been conducted, a simulation analysis (e.g. a digital sandbox modeling[11)]) of the geological structure using the acquired geological and geophysical data could be effective.

Groundwater flow characteristics

Since the number of boreholes that can be drilled for the borehole investigations will be limited from the viewpoint of cost, time, environmental limitations and disturbance in the area affected by drilling, it was considered necessary to acquire as much data as possible from a limited number of boreholes.

Crosshole hydraulic tests may be an effective method for predicting the hydrogeological structure between boreholes using holes that have already been drilled, thus avoiding the need for new drilling. In conducting crosshole hydraulic tests, test areas and geological structures to be investigated should be defined based on the hydrogeological model constructed in the preceding steps and the groundwater flow analyses before planning the layout of the pumping and monitoring holes, the pumping rate and period. Even though the change in groundwater pressure associated with crosshole hydraulic tests may be as small as that of background fluctuation due to earth tides, a clear hydraulic response could be obtained by eliminating noise such as the effect of the earth tides and atmospheric pressure changes and by improving the resolution of the measuring equipment.

The calibration of the hydrogeological models using transient data on groundwater pressure obtained from the crosshole hydraulic tests was effective for determining the hydraulic and structural characteristics of geological features (distribution and locations) that have not been determined in the preceding steps.

Since groundwater pressure could fluctuate significantly due to earthquakes, long-term hydraulic monitoring would be necessary to correctly determine the fluctuation of groundwater pressures with time.

Dilution of nuclides

A combination of seismic and resistivity tomography surveys using boreholes, the multi-offset VSP survey and the reflection seismic survey conducted at the same location (along the same survey line) was effective for predicting the distribution of discontinuities from the surface to deep underground. Crosshole hydraulic tests and groundwater flow analyses using transient data for groundwater pressure could be used to determine the connectivity and hydraulic characteristics of aquifers that could contribute to dilution. These techniques would also be appropriate for determining the geological and hydraulic characteristics of the discontinuities that may influence the dilution effect.

Volume of inflow into underground tunnels

Crosshole investigations were capable of determining the spatial extent and hydraulic connectivity of highly permeable structures that could significantly affect inflow into the underground tunnels. However, they are insufficient for accurately predicting the intersections between structures dipping at high angles and underground tunnels extending in a vertical direction. To achieve this goal it is necessary to conduct borehole investigations at the excavation points of the underground facilities.

Distribution of discontinuities intersecting underground tunnels

A crosshole tomography survey for the cross-section close to the underground facilities would be suitable for predicting the distributions of the faults emerging in the facilities. In this step, not all the surveys conducted were performed along the same survey lines. In order to accurately predict the distribution of faults from shallow to deep zones, a combination of crosshole tomography, reflection seismic and multi-offset VSP surveys should be conducted as far as possible at the same locations (along the same survey line). In the seismic tomography survey, due to the large distance between the boreholes (approximately 260 meters), the seismic energy was insufficient for transmission between the boreholes due to the presence of faults. Therefore, as an alternative, a seismic tomography survey between the ground surface and the boreholes was conducted, setting the seismic source at the ground surface between the boreholes. This approach was able to identify discontinuities between the boreholes in the relatively shallow zone (down to approximately 300 meters in this investigation); data for the deep underground were difficult to obtain because of the measurement geometry. Since the signals in the crosshole tomography may not be sufficiently transmitted, depending on the distance between the boreholes and the geological conditions, it was considered important to prepare several types of seismic sources prior to conducting the survey. Also, given the investigation costs and the quality control of acquired data, it was considered necessary to select instrumentation and specifications that are appropriate for the distance between the boreholes and the geological conditions.

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3.7 Conclusions of stepwise investigations and issues for the construction and operational phase

The results of the studies relating to the specific aims relevant to safety assessment and design/construction of the underground facilities are summarized for each investigation step in Sections 3.2 to 3.6. In this section, the relationship between the type and amount of investigations and the improvement in understanding or level of uncertainty is reviewed for each of the specific aims.

3.7.1 Geological structure

Improving understanding with the progress of investigations

In conducting the program for determining the 3-D distribution of geological structures, it was important to characterize the geological structures in and around the MIU Construction Site using stepwise investigations, by developing geological models and evaluating improvements in understanding as well as uncertainties, and then proceeding to the next investigation step. Fig. 3.7.1-1 and Fig. 3.7.1-2 illustrate the evolution of geological models with the progress of investigations in Phase I.

In Step 0, existing literature and the results of investigations conducted for regional-scale and local-scale areas were analyzed in order to develop a geological conceptual model (Fig. 3.2-8). At the same time, the geological structures present in the site-scale area were predicted based on the local-scale geological model. The predicted structures were then checked against existing geological maps and closely examined to check the consistency of models, any omission of key information and those structures that were unique to the MIU Construction Site. As the investigation scale was narrowed down to the site scale, the following were identified as the key geological structures and their continuity was predicted: the formations of the Mizunami and Seto Groups, the upper highly fractured domain in the upper part of the Toki Granite and the lower sparsely fractured domain in the Granite. In addition, the Tsukiyoshi Fault (including the highly fractured zone along the fault) was identified as a major discontinuity. An initial site-scale geological model was thus developed (see also Section 3.2.1). Of the structures shown in the conceptual model (Fig. 3.2-8), the weathered zone of the Toki Granite could not be included in the geological model because the spatial distribution in the site-scale area could not be predicted at the time. Since the geological model at this stage did not include any investigation information on the site-scale area, the depths of the modeled geological structures were characterized with large uncertainty.

(a) Improvement in understanding from Step 0 to Step 1

In Step 1, geological mapping and reflection seismic surveys were conducted to check consistency with existing information on the Toki Granite, the Mizunami and Seto Groups, the Tsukiyoshi Fault and the upper highly fractured domain in the Toki Granite. At the same time, smaller faults not described in existing geological maps, which were not obtained in Step 0, were identified. The geological mapping in Step 1 allowed identification of the faults at surface outcrops and, through combination with the reflection seismic surveys, provided information on the underground distribution of the faults. The faults identified in this manner were mainly those with NS to NNW strikes, and included fault gouge and fault breccia. Since the directions of the faults might influence the main flow directions of groundwater (NE to SW: see also Section 3.2.2), and since fault gouge and fault breccia (containing a large amount of clay that could have a function) are intercalated along these directions, the faults were assumed to have a significant influence on groundwater flow. These faults were defined as a priority target for investigation in the next and subsequent steps. Compared to Step 0, understanding of the distribution of the faults in the geological model was improved in Step 1. Meanwhile, the locations of boundaries between formations in the Mizunami Group, the unconformity between the Toki Granite and the Mizunami Group and the upper highly fractured domain in the Toki Granite were roughly predicted. However, since data from borehole investigations that could be used to check the correlation between reflection events on the reflection profile and actual geological features and their depth were not available at that time, accurate correlation was difficult to achieve. Consequently, the depth profile of the identified geological structures involved large uncertainties. Furthermore, with regard to the weathered zone of the Toki Granite, no significant reflection events were identified on the reflection profile.

(b) Improvement in understanding from Step 1 to Step 2

In Step 2, the depth of the geological structures that were identified previously in Steps 0 and 1 was determined. More specifically, the reflection events assumed to correspond to the boundaries between the formations in the Mizunami Group identified by the reflection seismic survey and the unconformity between the Toki Granite and the Mizunami Group were correlated with the geological distribution observed in the boreholes. The basal conglomerate in each formation and the distribution of the weathered zone in the Toki Granite, which could not be determined in Steps 0 and 1, were identified. The existence of a low-angle fractured zone was also identified in the upper highly fractured domain and its extent was predicted (see also Section 3.4.1). Faults with EW and NS strikes were identified in addition to those with a NNW strike identified in Step 1. Fault gouge and fault breccia were observed in these faults and their properties were found to be consistent with those identified in Step 1 (see also Section 3.3.1). In Step 2, the distribution of the weathered zone in the Toki Granite included in the conceptual model of Step 0 was confirmed for the first time. The existence of the low-angle fractured zone located in the upper highly fractured domain, which had not been determined previously, was identified through investigations in the existing boreholes. The conceptual model and the geological model were updated based on these findings.

(c) Improvement in understanding from Step 2 to Step 3

In Step 3, the depths of the geological structures characterized up until Steps 2 were confirmed. At the same time, the geological structures in the deep granite that could not be characterized until Step 2 were identified. In particular, compared to Step 2, the accuracy of the deeper part of geological model was significantly improved due to the availability of measured data for the deep granite. More specifically, the boundaries of the formations in the Mizunami Group, the unconformity between the Toki Granite and the Mizunami Group and the depth of the low-angle fractured zone were confirmed. The depth of the boundary between the upper highly fractured domain and the lower sparsely fractured domain was also determined. Information on hydraulic characteristics, such as properties of flow barrier and hydrogeological continuity, for the discontinuities confirmed or estimated in Step 2 and proceeding steps was obtained by monitoring hydraulic responses due to borehole drilling in the shallow boreholes where long-term hydraulic monitoring systems were installed. Five large-scale faults assumed to intersect the MIU Construction Site were identified, with strong alteration with chlorite and clay minerals. The NNW trending faults identified in Steps 1 and 2 were not observed in these investigations. This may be because the fault was displaced by one of the above-mentioned large faults supposedly having enough displacement to traverse the MIU Construction Site.

(d) Improvement in understanding from Step 3 to Step 4

In Step 4, the accuracy of predictions of the geological structures in and around the underground facilities was improved by crosshole seismic tomography and resistivity tomography surveys for the area between boreholes MIZ-1 and DH-2 drilled on opposite sides of the planned underground facilities, multi-offset VSP surveys in deep boreholes (MIZ-1 and DH-15) and reflection seismic surveys along the survey line close to the deep boreholes. In particular, information on the location of faults in the area surrounding the underground facilities significantly improved the accuracy of the interpretation compared to the steps prior to Step 3.

With respect to improving the understanding of the 3-D distribution of geological structures, the accuracy of the estimated distribution depth of the respective features of the geological structures was improved stepwise with the progress of investigations. The number of faults identified in the area from the surface to deep underground increased with the progress of the investigations and knowledge of the trend in orientation and scale of the faults in the investigation area was accumulated.

Issues for Phase II and beyond

Information on lineaments that are less likely to be faults was also included in the geological model. The development of improved modeling techniques for quantifying uncertainties is an issue to be addressed in the future. This would necessitate the development of a technology for evaluating uncertainties using a geostatistical method and the formulation of a modeling approach for geological and hydrogeological structures that is capable of incorporating various types of uncertainty. In areas that have still not been investigated, the distribution of discontinuities will be simulated using geological and geophysical data obtained thus far.

In the Phase I investigations, the geological structures assumed to affect groundwater flow, groundwater chemistry and the local stress regime were identified. A geological model incorporating the spatial distributions of these structures was then developed in a stepwise manner. In the Phase II investigations and beyond, the distributions of modeled geological structures will be reviewed to evaluate the systematic investigation methodology employed in the Phase I investigations and the accuracy of predicted geological structures. At the same time, the model will be updated. Geological structures extending into the underground facilities, particularly discontinuities, will be characterized in terms of their geometry, structural type and petrological/mineralogical properties in order to construct a geological model on a block scale.

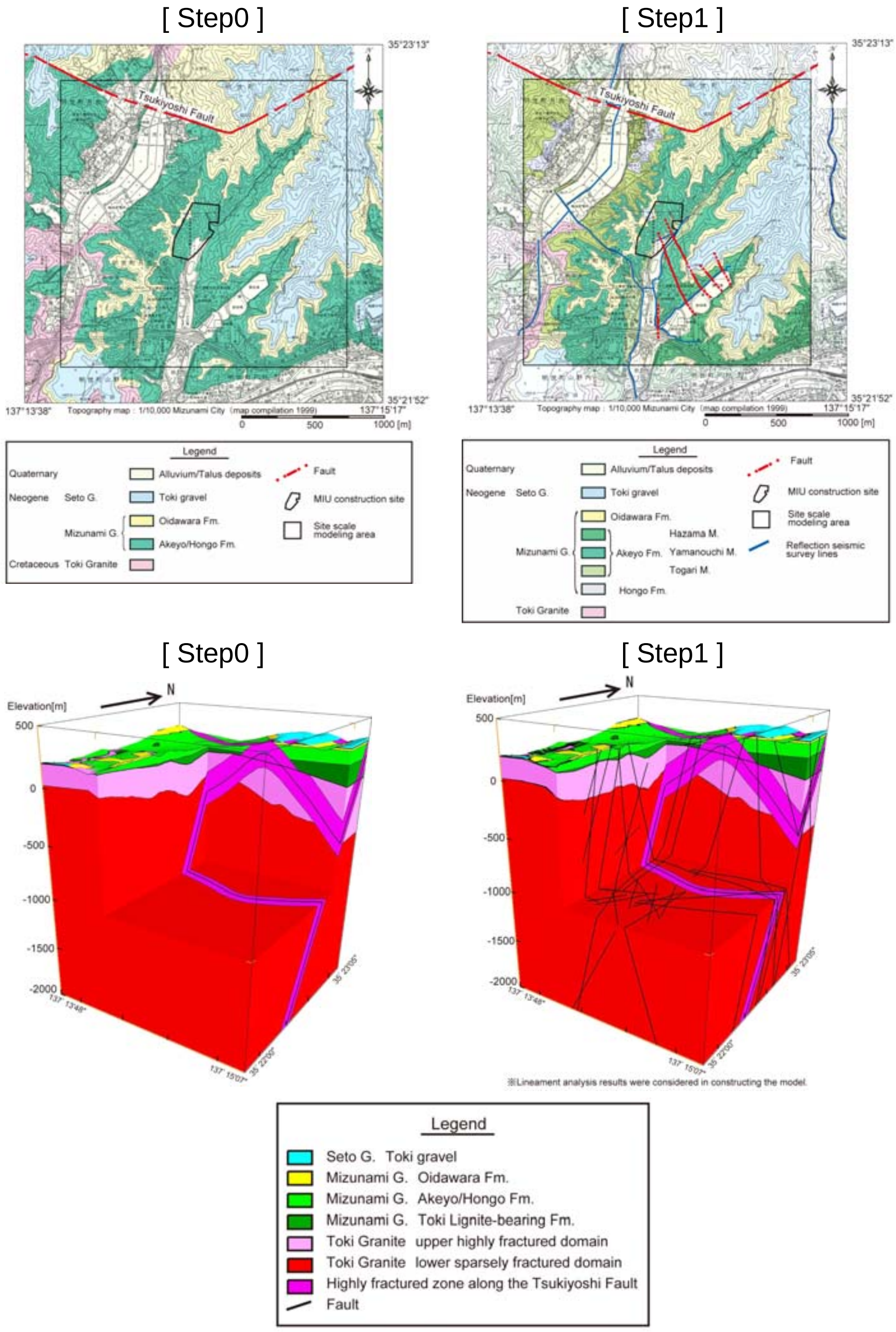


Fig. 3.7.1-1 Evaluation of the geological model with progress in the stepwise investigations (Step0-Step1)

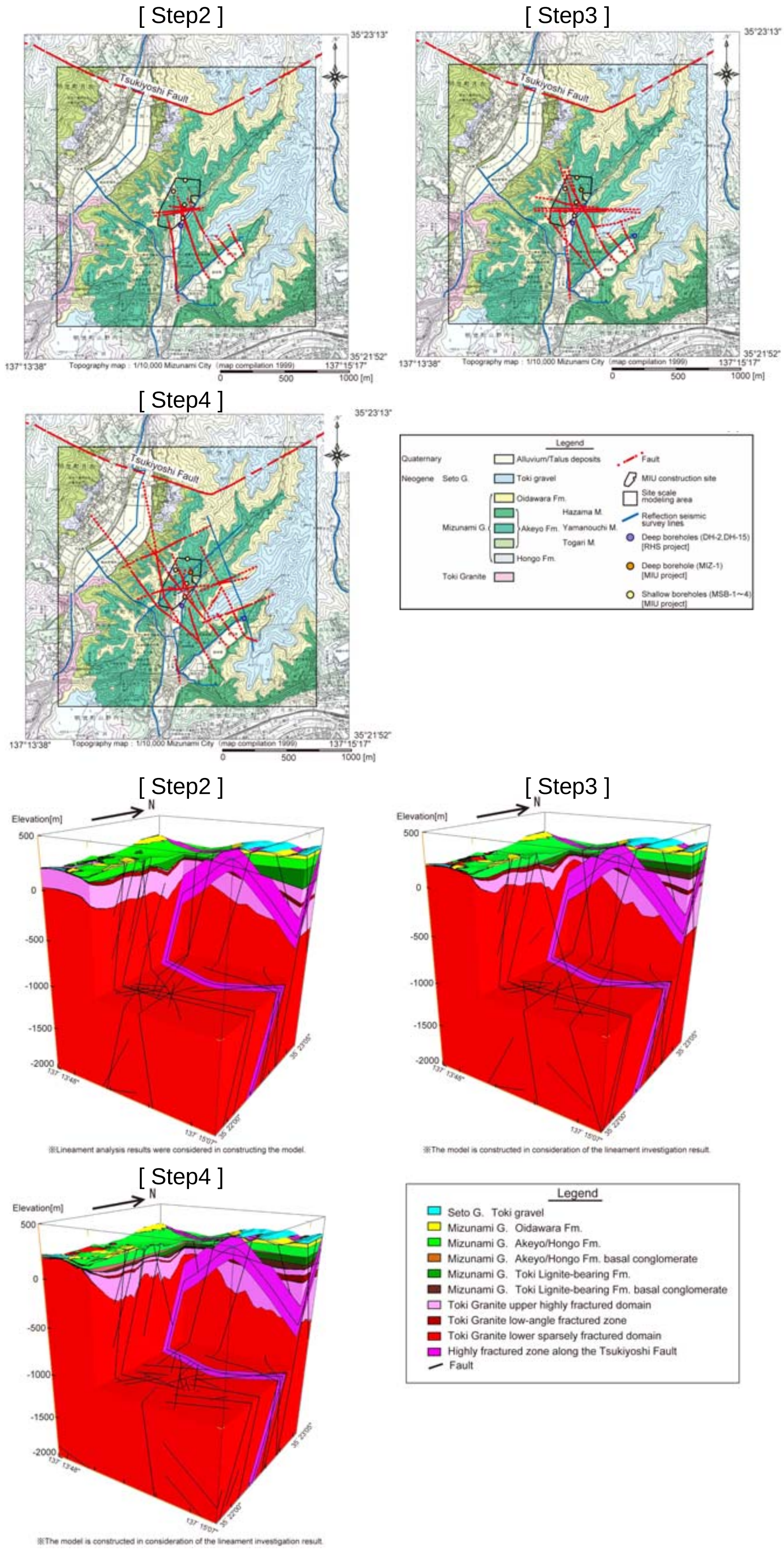


Fig. 3.7.1-2 Evaluation of the geological model with progress in the stepwise investigations (Step2-Step4)

3.7.2 Groundwater flow characteristics

Improvement in understanding with the progress of investigations

To establish a technical basis for the investigation and analysis of the characteristics of groundwater flow, it is important to clarify the relationship between the number of investigations and the associated improvement in understanding or uncertainties. It is also essential to specify key factors to be characterized in subsequent steps. In Phase I, in order to address these issues, the following efforts were made based on the results obtained in the respective investigation steps: first, a hydrogeological model was constructed based on the geological model and groundwater flow analyses were conducted using the model; key factors that are likely to influence the groundwater flow characteristics were then identified. The results obtained in this manner were reflected in the subsequent investigations.

The results from Step 0 indicated that faults would have an impact on the groundwater flow characteristics as well as on the hydrochemistry of groundwater and the volume of inflow into the underground facilities (see also Sections 3.2.2, 3.2.3 and 3.2.7). In particular, the significant effect of the Tsukiyoshi Fault, which has an anisotropic hydraulic conductivity, was confirmed (see also Section 3.2.2). Investigating hydraulic characteristics such as hydraulic conductivity and anisotropic hydraulic conductivity for all faults whose existence was confirmed or predicted by the geological investigations was not practical due to restrictions such as investigation costs, time and the disturbance caused by borehole drilling. Therefore, on the groundwater flow analyses, sensitivity analyses were conducted iteratively in each step with the focus on the anisotropic hydraulic conductivity, in order to identify faults presumed to have a significant influence on the groundwater flow characteristics. When evaluating the improvement in the understanding of groundwater flow characteristics with the progress of investigations, the following criteria were defined based on the results of the above-mentioned sensitivity analyses from the standpoint of the groundwater flow characterization prior to the excavation of the underground facilities, and in view of the hydraulic characteristics that might not have been identified in each of the steps:

- Number of cases in the sensitivity analyses;
- Variation in the hydraulic head distribution among the different cases in the sensitivity analyses; and
- Reproducibility of hydraulic head distribution measured in the boreholes.

Reduction in the number of cases of the sensitivity analysis cases that needed to be analyzed taking into account the number of unknown parameters indicated that, of the faults which influence the groundwater flow characteristics, the number of faults whose hydraulic characteristics could be identified or predicted increased. Reduced variation in the distribution of hydraulic head between the sensitivity analysis cases can be interpreted as a result of having identified or predicted the hydraulic characteristics with a particularly significant effect on groundwater flow. Finally, the improvement in the reproducibility of measured values for hydraulic head distribution in the boreholes points to an improvement of the reliability of the results of groundwater flow simulations. All of the above indicate that the understanding of the spatial variability of hydraulic gradient and hydraulic properties of rocks was improved.

For each investigation step in Phase I, Fig. 3.7.2-1 shows the hydrogeological models and an example of the distribution of the hydraulic head calculated based on the results of the groundwater flow analyses. Fig.

3.7.2-2 shows the square root of the deviation of the measured and modeled hydraulic head in each step. It should be noted that the hydrogeological models and the hydraulic head shown in Fig. 3.7.2-1 are from the analytical case that provided the best fit to the measurements (i.e. with the smallest square root of the deviation in Fig. 3.7.2-2) of all the sensitivity analysis cases conducted in each step. The improvement in understanding with the progress of investigation steps is summarized below.

(a) Improvement from Step 0 to Step 1

Step 0 is the one based on existing information. Therefore, only the Tsukiyoshi Fault and lineaments with a continuity of 3 km or more, which had been identified as faults by the local-scale investigations, were included in the hydrological model (Fig.3.7.2-1). It was known that the Tsukiyoshi Fault has an anisotropic hydraulic conductivity (see also Section 3.2.2). For lineaments with trace length over 3 km, assuming that the hydraulic characteristics would be similar to those of the Tsukiyoshi Fault (which has an equivalent scale), an anisotropic hydraulic conductivity was defined. Therefore, no sensitivity analysis was conducted in Step 0 (Table 3.7.2-1).

The results of groundwater flow analyses conducted in Step 0 confirmed that faults have a significant influence on the groundwater flow characteristics, indicating the importance of determining their distribution and geometry (Fig. 3.7.2-3). Therefore, interpretation of lineaments, geological mapping and reflection seismic surveys were conducted in Step 1. Based on the results of the investigations, 13 additional faults were included in the hydrogeological model and the depth profile of each formation boundary was updated (Fig. 3.7.2-1). Since the hydraulic characteristics had not been determined for these faults, 32 sensitivity analysis cases were conducted (Table 3.7.2-2).

Fig. 3.7.2-2 indicates that the reproducibility of the measured hydraulic heads by the model was significantly lower when the number of analytical cases was increased from Step 0 to Step 1. It seems that the understanding of the groundwater flow characteristics had decreased as the investigations proceeded to Step 1. However, investigations on the site scale were not conducted in Step 0 and geological structures such as discontinuities that have an impact on the distribution of the hydraulic gradient were hardly identified, i.e. Step 0 involved a number of "undetected uncertainties." In contrast, the existence of discontinuities was predicted or identified by the ground exploration and they were included in the hydrogeological model in Step 1. However, the certainty of their existence and distribution range and their hydraulic characteristics were not determined in this step, i.e. Step 1 involved a number of "detectable uncertainties with unknown quantity and quality." The uncertainties in Steps 0 and 1 are thus completely different in nature. The investigations in Step 1 were important as initial investigations for identifying key geological features to be investigated in the subsequent phases, as well as for determining their distribution ranges and hydraulic characteristics. In order to improve the understanding of groundwater flow characteristics, it will be important to identify geological features that may have an influence on the distribution of hydraulic gradient before investigating the distribution of these features and their hydraulic characteristics.

The results of the sensitivity analyses conducted in Step 1 indicated that NNW and NE trending faults have a significant influence on the groundwater flow-field at the MIU Construction Site (Fig. 3.7.2-4). Based on this finding, evaluation of the distribution, geometry and hydraulic characteristics of faults with these strikes was deemed to be essential for investigations in subsequent phases. Therefore, determining the geometry and hydraulic characteristics of the NNW trending faults intersecting the MIU Construction Site was set as one of the goals in planning the shallow borehole investigation program in Step 2. Geological and hydrogeological investigations for determining the distribution, geometry and hydraulic characteristics of discontinuities such as faults were conducted again in the existing boreholes.

(b) Improvement from Step 1 to Step 2

In Step 2, based on the results of the investigations in shallow and existing boreholes, a low-angle fractured zone in the upper highly fractured domain of the Toki Granite was additionally included in the hydrogeological model. Information on the depth profile of the boundaries of other faults and the geometry and hydraulic characteristics of the NNW and EW trending faults was also obtained and included in the model (Fig. 3.7.2-1). In Step 2, 12 sensitivity analysis cases were performed (Table 3.7.2-3).

Fig. 3.7.2-2 shows that the number of simulations decreased by a factor of three in Step 2 compared to Step 1 as the understanding of the spatial variability of hydraulic properties of rocks was improved. In detail, the hydraulic conductivities of the faults hydraulically characterized in basement granite were fixed based on the borehole investigations. Also the revised geological model resulted in the number of different fault groups being decreased. The improvement was derived from the 3-D distribution and hydraulic characteristics of the faults deep underground obtained in Step 2. Thus, borehole investigations capable of directly acquiring such information were effective in reducing the uncertainties regarding the spatial variability of hydraulic properties of rocks, where the number of simulation runs is used an indicator of the uncertainty on the model parameters. A significant improvement in the fit of the calculated heads to the measured values was also observed in some analytical cases and the variation in the hydraulic head distribution among the analytical cases increased. These results indicated that the anisotropy of the fault hydraulic conductivity, which has a significant influence on the groundwater flow-field in and around the MIU Construction Site, had not been determined. Therefore, the understanding of spatial variability of hydraulic gradient and hydraulic properties of rocks may be improved by identifying the anisotropic hydraulic conductivity of such faults.

The results of sensitivity analyses conducted in Step 2 showed that faults with NNW, NW and EW strikes have a significant influence on the groundwater flow-field at the MIU Construction Site (Fig. 3.7.2-5). Based on this finding, evaluating the distribution, geometry and hydraulic characteristics of faults with these strikes was essential for investigations in the subsequent phases and was set as one of the goals in planning the deep borehole investigation program in Step 3.

(c) Improvement from Step 2 to Step 3

In Step 3, information on the depth profile of the boundaries of geological formations and the geometry and hydraulic characteristics of faults with NNW, NW and EW strikes was obtained based on the results of deep borehole investigations and the information was included in the hydrogeological model (Fig. 3.7.2-1). 8 sensitivity analysis cases were analyzed (Table 3.7.2-4).

Fig. 3.7.2-2 and Fig. 3.7.2-6 show that in this step the number of analytical cases and the variation in the hydraulic head distribution among the cases was decreased compared to Step 2; the discrepancy between measured and calculated heads was reduced to approximately 15 m. This indicates that the understanding of spatial variability of hydraulic gradient and hydraulic properties of rocks had significantly improved. The improved understanding can be attributed mainly to: (1) an increase in the amount of information obtained by borehole investigations for the faults identified as important features in Step 2 and (2) the fact that the hydraulic characteristics of most faults with NNW and EW strikes (of the faults estimated in Step 2 to have a significant influence on groundwater flow in and around the MIU Construction Site) were predicted based on the results of monitoring of hydraulic responses due to borehole drilling in long-term hydraulic monitoring systems in the shallow boreholes drilled in Step 2 and the existing boreholes. Any fault identified as lying between hydraulically connected boreholes was excluded as a potential barrier.

The results of the sensitivity analyses conducted in Step 3 indicated that an approach combining investigations in new boreholes and monitoring of hydraulic responses due to borehole drilling in existing boreholes is effective for reducing the uncertainties associated with hydraulic conductivity distribution. Therefore, the estimation of hydrogeological structures in and around the MIU Construction Site and the acquisition of information on their hydraulic characteristics and connectivity using several boreholes in and around the MIU Construction Site are important. For this purpose, for planning the crosshole hydraulic tests conducted in Step 4, pumping and monitoring boreholes were selected taking into account the distribution and geometry of NNW and EW trending faults, which are the main faults intersecting the MIU Construction Site, so that hydraulic characteristics of these faults, e.g. connectivity, could be determined based on the response of groundwater pressures during the crosshole hydraulic tests as input to the groundwater flow analyses.

(d) Improvement from Step 3 to Step 4

In Step 4, information on the depth profiles of the boundaries of the geological formations and the geometry of faults located in the vicinity of the MIU Construction Site were obtained based on the results of crosshole investigations. The reinterpretation of the distribution and geometry of faults, including the geological information obtained from Steps 1 to 3, resulted in a considerable revision of the hydrogeological model. With the aim of constructing a more detailed model, a basal conglomerate was included in the model as an additional hydrogeological structure located at the base of the Akeyo/Hongo Formation and the Toki Lignite-bearing Formation in the Mizunami Group. Groundwater flow analyses were conducted based on the data on the transient groundwater pressures change obtained from the crosshole hydraulic tests. The hydrogeological model was calibrated and the presence of anisotropic hydraulic conductivity in the faults was determined (Fig. 3.7.2-1). In this step, two sensitivity analysis cases were analyzed (Table 3.7.2-5).

Fig. 3.7.2-2 shows that the number of analytical cases was decreased by 25% in Step 4 compared to that in Step 3, whereas the discrepancy between measured and calculated heads was reduced to approximately 5 m. The uncertainties regarding the distribution of the hydraulic conductivity were thus significantly reduced; furthermore, the hydraulic head distributions obtained from the two analytical cases were similar (Fig. 3.7.2-7). The improvement is considered to be due to the fact that the hydraulic characteristics of many of the faults were predicted by calibration of the hydrogeological model using the data on the transient groundwater pressures change obtained by the crosshole hydraulic tests. These data served to identify the temporal changes in groundwater flow in and around the test site and allowed: (1) estimation of hydrogeological structures in and around the test site based on the hydraulic response in the monitoring boreholes and (2) estimation of the distribution, geometry and hydraulic characteristics of geological structures based on the transient groundwater flow analysis. This indicates the importance of hydraulic monitoring that allows acquisition of data on transient groundwater pressures change induced by the excavation of the underground facilities in Phase II. This excavation can be regarded as a large-scale crosshole hydraulic test and through the long-term hydraulic monitoring, the understanding of the spatial variability of hydraulic gradient and hydraulic properties of rocks is expected to be significantly improved.

(e) Summary

Investigations were conducted in each step of Phase I adopting an iterative approach, resulting in stepwise improvement in the understanding of the spatial variability of hydraulic gradient and hydraulic properties of rocks with the progress of the investigations. Collaboration with geology experts was essential because the hydrogeological model depends significantly on the geological model. Combining the iterative approach with enhanced interaction with other disciplines such as geology and geochemistry is therefore a very effective way of also improving the understanding of groundwater flow characteristics.

Issues for Phase II and beyond

One of the issues for the next phase and beyond is testing and revision of the site-scale hydrogeological model by measuring the inflow rate of water from the shaft walls associated with the excavation of the underground facilities and by observing the response of groundwater pressures through long-term hydraulic monitoring. Since the inflow rate of the water from the shaft wall is strongly influenced by the skin effect (hydraulic influence such as reduction of permeability due to engineered structures and grout or increase due to EDZ - see also Sections 3.4.6, 3.5.7 and 3.6.4), information on these impacts on the inflow rate should be acquired. Furthermore, the interpretation and reproduction of the head distributions in formations deeper than the Akeyo/Hongo Formation in the Mizunami Group, which was not resolved in Phase I (see also Section 3.6.2), would also be an issue to be addressed in Phase II and beyond. Although the macroscopic hydraulic characteristics of the rocks and major faults were determined mainly by the borehole investigations, long-term hydraulic monitoring (using the boreholes) and crosshole hydraulic tests conducted in Phase I, the hydrogeological heterogeneity, which is considered important from the viewpoint of retardation in solute transport, was not resolved. In order to evaluate the heterogeneity of rock caused by the presence of discontinuities such as fractures in and around the underground facilities, as well as the one relating to the discontinuities themselves, it will be necessary to develop a hydrogeological model covering an area of several tens to several hundreds of meters around the underground facilities and to conduct groundwater flow analyses for this area.

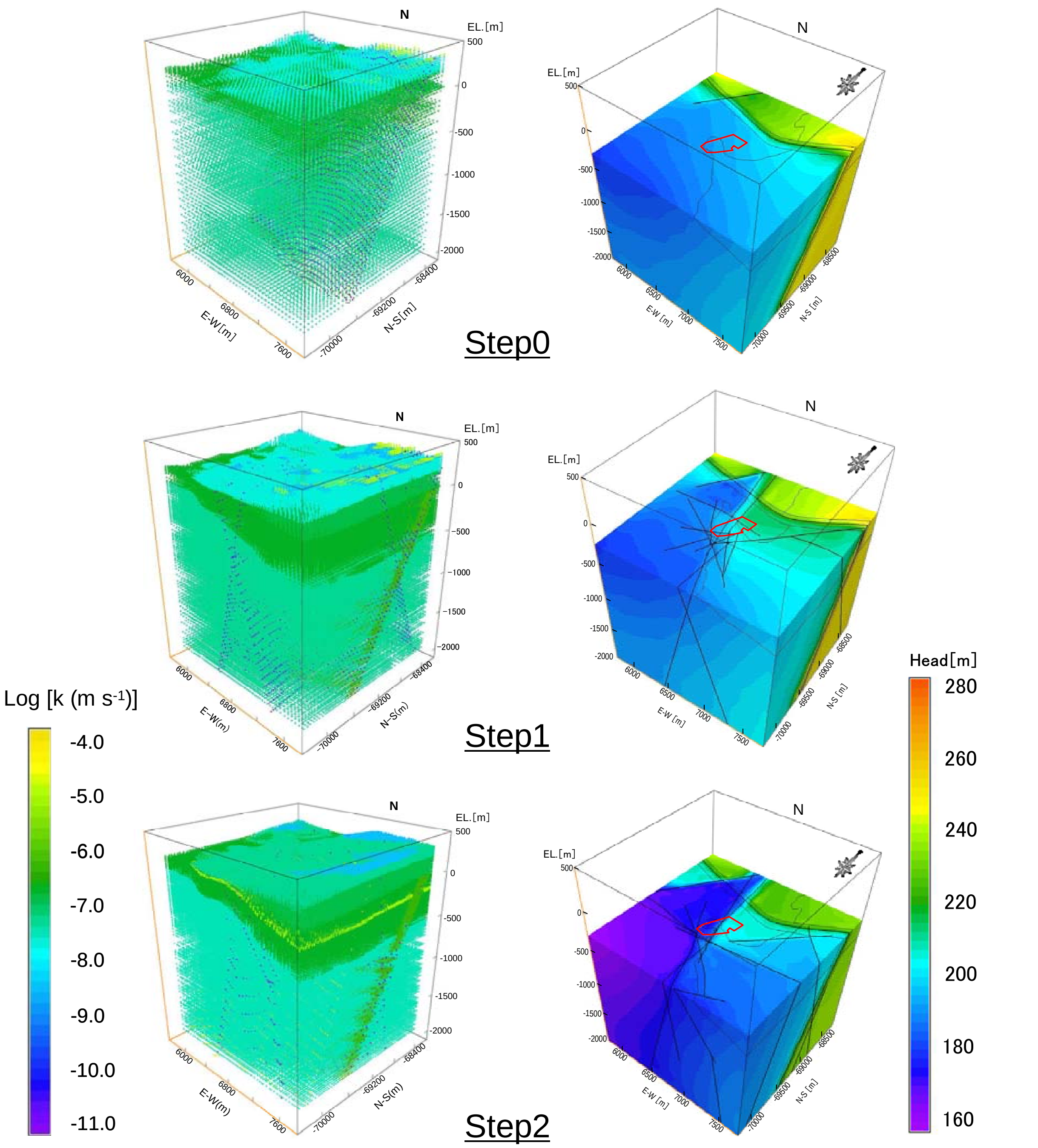


Fig. 3.7.2-1 Iterations in the hydrogeological model and head distributions with stepwise progress of investigations (Left figures are hydrogeological model (3-D distribution of hydraulic conductivity), Right figures are head distribution (Elevation −300 m : Depth of the shaft 500 m))

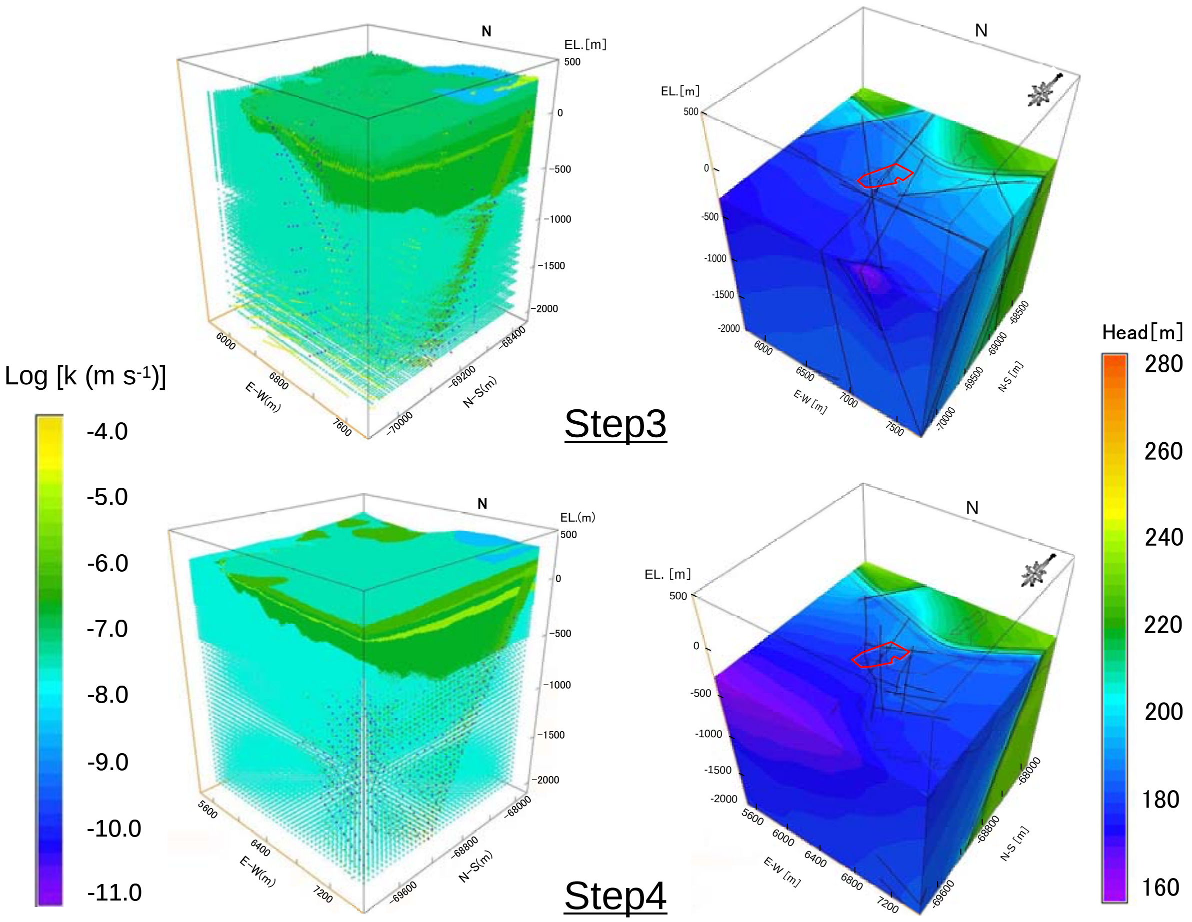


Fig. 3.7.2-1 Iterations in the hydrogeological model and head distributions with stepwise progress of investigations (Left figures are hydrogeological model (3-D distribution of hydraulic conductivity), Right figures are head distribution (Elevation −300 m : Depth of the shaft 500 m)) (Continued)

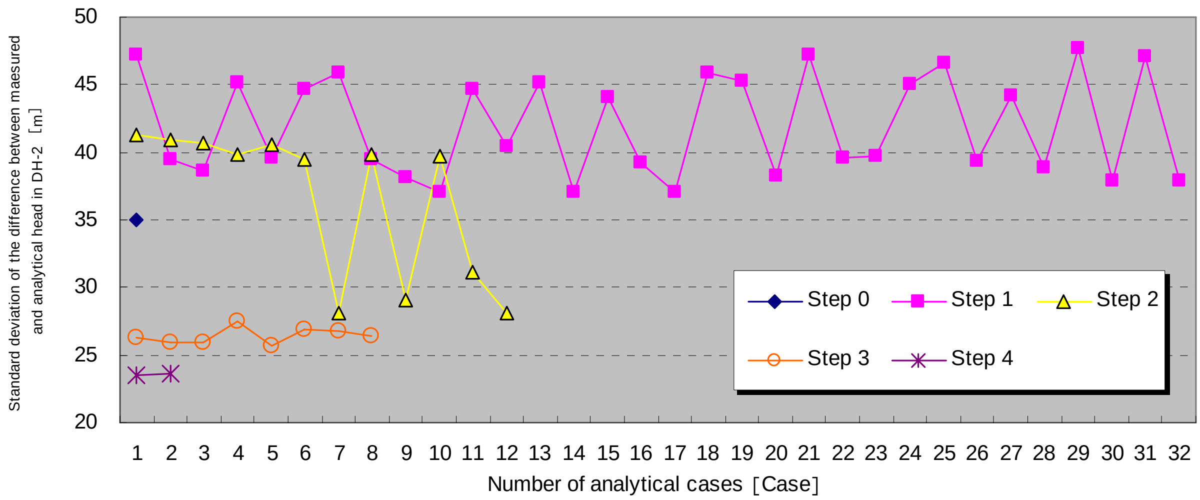
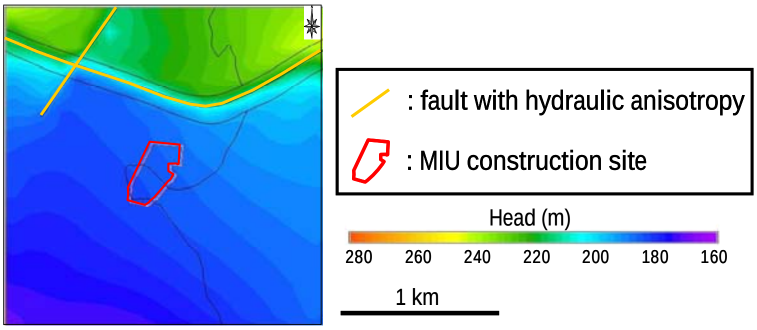


Fig. 3.7.2-2 Improvement of the understanding of groundwater flow conditions with stepwise progress of investigations

Table 3.7.2-1 Hydraulic conductivity of faults in Step 0 (Log [k (m s-1)])

Case ID / Fault	base	
	C	P
Main part of Tsukiyoshi fault	-11.0	
Lineament with length more than 3km	-11.0	-5.2

C : Normal to Fault, P : Parallel to Fault



(a) Case ID : Base

Fig. 3.7.2-3 Head distribution in Step 0 (Elevation -300 m : Depth of the shaft 500 m)

Table 3.7.2-2 Sensitivity analysis cases focused on hydraulic anisotropy of faults in Step 1 (Log k [m s^{-1}])

Case ID / Fault	base		NS_6		NE_6		NNW_6		EW_6		NW_6		NS_NE_6		NS_NNW_6	
	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4
NW trending fault	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4
NE trending fault	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4
EW trending fault	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4
NS trending fault	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4

Case ID / Fault	NS_EW_6		NS_NW6		NE_NNW_6		NE_EW6		NE_NW6		NNW_EW6		NNW_NW6		EW_NW6	
	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4
NW trending fault	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4
NE trending fault	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4
EW trending fault	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4
NS trending fault	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4

Case ID / Fault	EW_NW11		NNW_NW_11		NNW_EW_11		NE_NW_11		NE_EW_11		NE_NNW_11		NS_NW_11		NS_EW_11	
	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4
NW trending fault	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4
NE trending fault	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4
EW trending fault	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4
NS trending fault	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-11.0	-6.4

Case ID / Fault	NS_NNW_11		NS_NE_11		NS_11		NE_11		NNW_11		EW_11		NW_11		All_6	
	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4
NW trending fault	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4
NE trending fault	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4
EW trending fault	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4
NS trending fault	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4	-6.4

C : Normal to Fault, P : Parallel to Fault

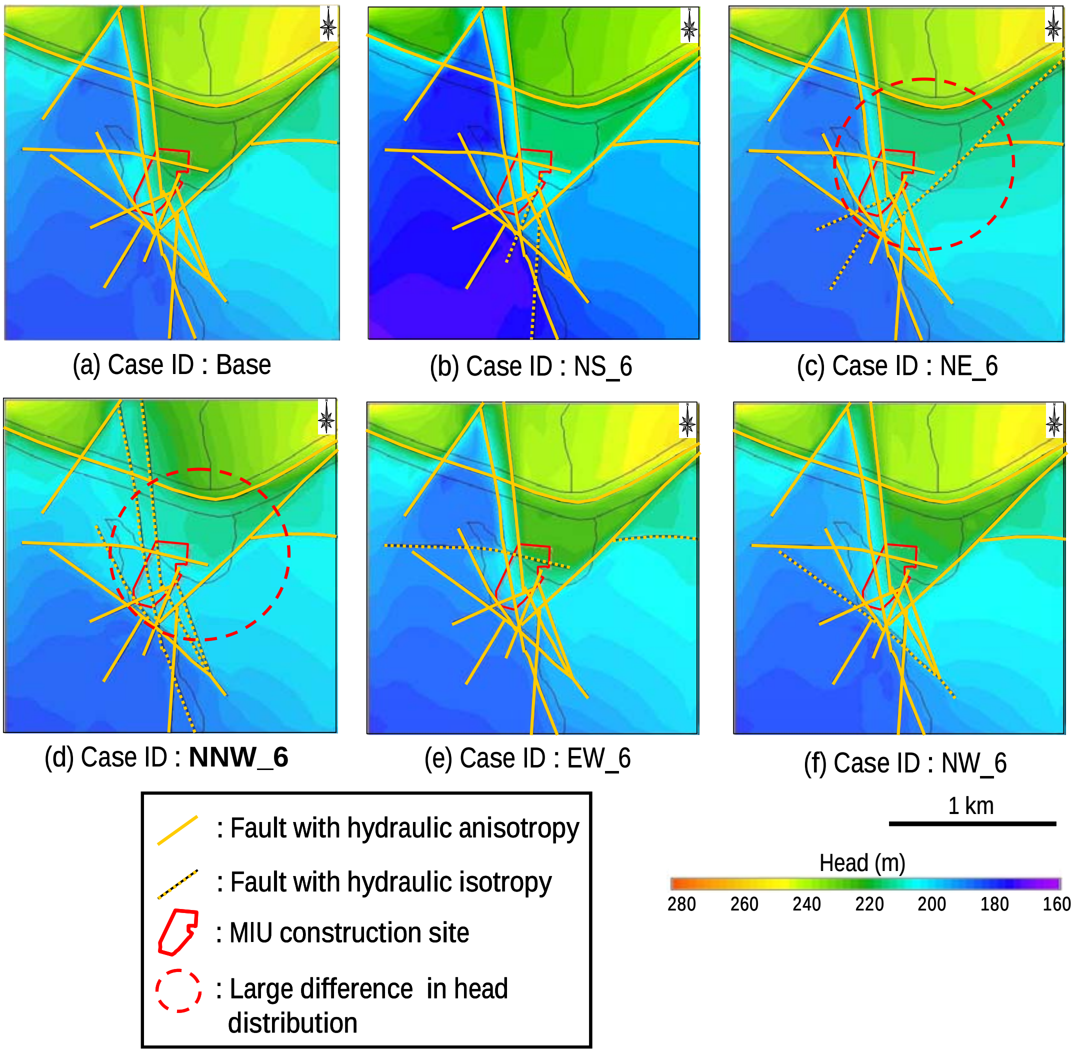


Fig. 3.7.2-4 Example of a sensitivity analysis focused on hydraulic anisotropy of faults in Step 1 (Elevation -300 m : Depth of the shaft 500 m)

Table 3.7.2-3 Sensitivity analysis cases focused on hydraulic anisotropy of faults in Step 2 (Log k [m s^{-1}])

Case ID / Fault	Base		NE_high		NNW_high		NW_high		NE_NNW_high		NE_NW_high	
	C	P	C	P	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-4.9	-11.0	-4.9	-4.9		-11.0	-4.9	-4.9		-11.0	-4.9
NW trending fault	-11.0	-6.4	-11.0	-6.4	-11.0	-6.4	-6.4		-11.0	-6.4	-6.4	
NE trending fault	-11.0	-6.4	-6.4		-11.0	-6.4	-11.0	-6.4	-6.4		-6.4	
EW trending fault	-4.0		-4.0		-4.0		-4.0		-4.0		-4.0	

Case ID / Fault	NE_high_anEW		NNW_high_anEW		NW_high_anEW		NE_NNW_high_anEW		NE_NW_high_anEW		All_aniso	
	C	P	C	P	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-4.9	-4.9		-11.0	-4.9	-4.9		-11.0	-4.9	-11.0	-4.9
NW trending fault	-11.0	-6.4	-11.0	-6.4	-6.4		-11.0	-6.4	-6.4		-11.0	-6.4
NE trending fault	-6.4		-11.0	-6.4	-11.0	-6.4	-6.4		-6.4		-11.0	-6.4
EW trending fault	-11.0	-4.0	-11.0	-4.0	-11.0	-4.0	-11.0	-4.0	-11.0	-4.0	-11.0	-4.0

C : Normal to Fault, P : Parallel to Fault

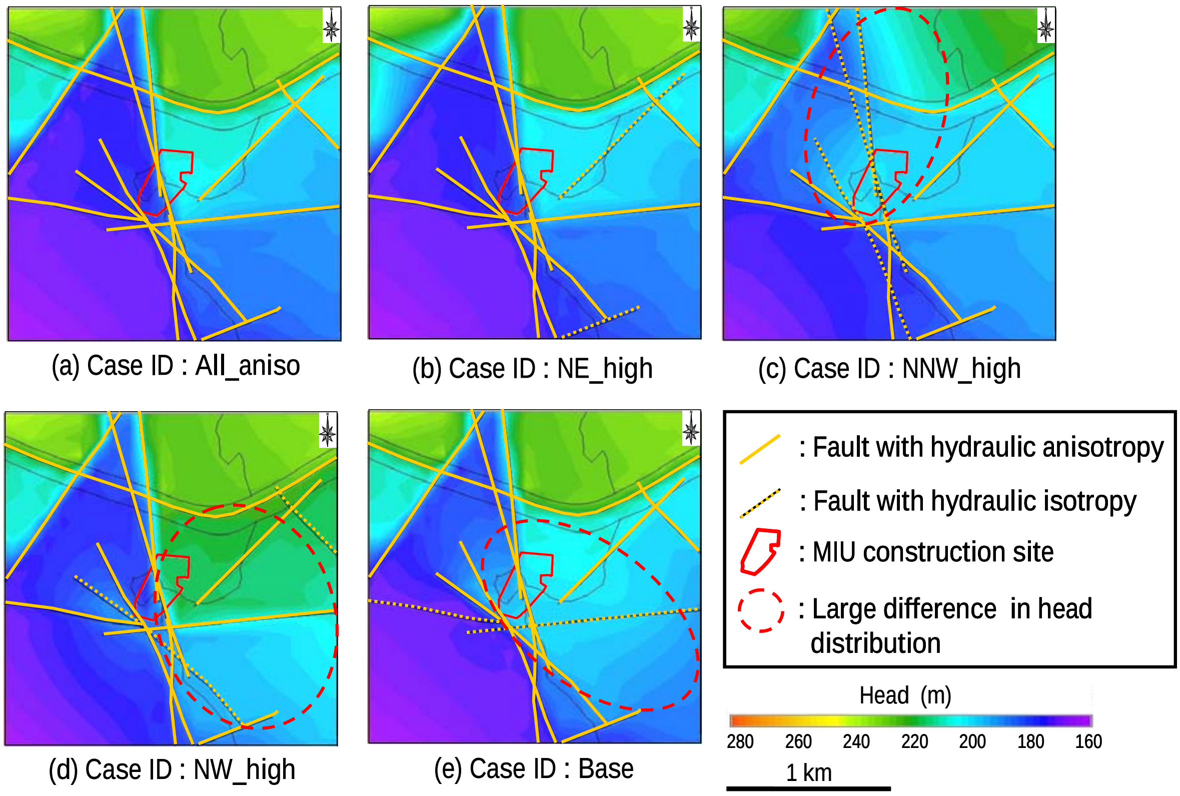


Fig. 3.7.2-5 Example of a sensitivity analysis focused on hydraulic anisotropy of faults in Step 2 (Elevation -300 m : Depth of the shaft 500 m)

Table 3.7.2-4 Sensitivity analysis cases focused on hydraulic anisotropy of faults in Step 3 (Log k [m s^{-1}])

Case ID / Fault	Base		NNW_high		NW_high		NE_high	
	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-5.3	-5.3		-11.0	-5.3	-11.0	-5.3
	-4.7		-4.7		-4.7		-4.7	
	-11.0	-5.1	-11.0	-5.1	-11.0	-5.1	-11.0	-5.1
	-5.1		-5.1		-5.1		-5.1	
NW trending fault	-11.0	-8.0	-11.0	-8.0	-8.0		-11.0	-8.0
NE trending fault	-11.0	-3.9	-11.0	-3.9	-11.0	-3.9	-3.9	
EW trending fault	-5.1		-5.1		-5.1		-5.1	
	-5.0		-5.0		-5.0		-5.0	
	-4.2		-4.2		-4.2		-4.2	

Case ID / Fault	NNW_NW_high		NNW_NE_high		NW_NE_high		All_high	
	C	P	C	P	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0		-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-5.3		-5.3		-11.0	-5.3	-5.3	
	-4.7		-4.7		-4.7		-4.7	
	-11.0	-5.1	-11.0	-5.1	-11.0	-5.1	-11.0	-5.1
	-5.1		-5.1		-5.1		-5.1	
NW trending fault	-8.0		-11.0	-8.0	-8.0		-8.0	
NE trending fault	-11.0	-3.9	-3.9		-3.9		-3.9	
EW trending fault	-5.1		-5.1		-5.1		-5.1	
	-5.0		-5.0		-5.0		-5.0	
	-4.2		-4.2		-4.2		-4.2	

C : Normal to Fault, P : Parallel to Fault

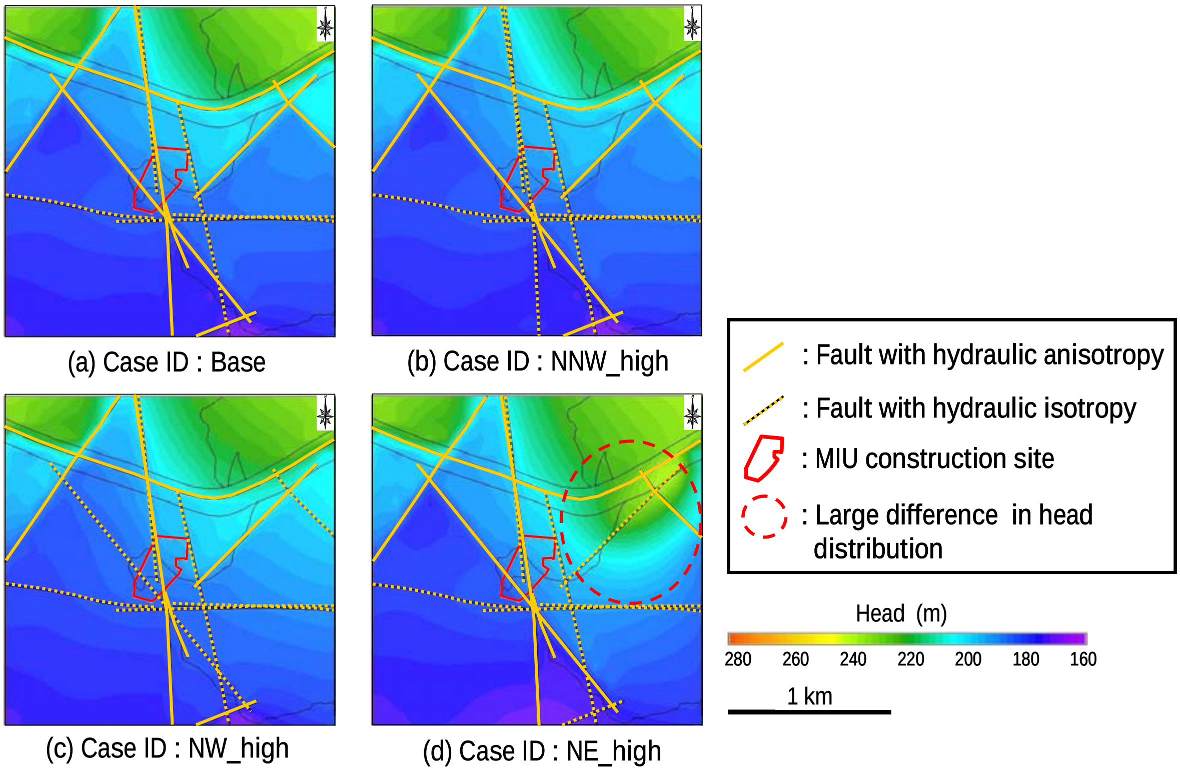


Fig. 3.7.2-6 Example of a sensitivity analysis focused on hydraulic anisotropy of faults in Step 3 (Elevation -300 m : Depth of the shaft 500 m)

Table 3.7.2-5 Sensitivity analysis cases focused on hydraulic anisotropy of faults in Step 4 (Log k [m s^{-1}])

Case ID / Fault	Case1		Case2	
	C	P	C	P
Main part of Tsukiyoshi fault	-11.0		-11.0	
Lineament with length more than 3km	-11.0	-5.2	-11.0	-5.2
NNW trending fault	-11.0	-7.3	-11.0	-7.3
	-5.9		-5.9	
	-4.0		-4.0	
	-6.1		-11.0	-6.1
NW trending fault	-7.7		-7.7	
	-11.0	-8.7	-11.0	-8.7
	-9.0		-9.0	
	-11.0	-8.7	-11.0	-8.7
NE trending fault	-6.2		-6.2	
	-11.0	-4.2	-11.0	-4.2
	-11.0	-5.2	-11.0	-5.2
EW trending fault	-5.1		-5.1	
	-5.9		-5.9	

C : Normal to Fault, P : Parallel to Fault

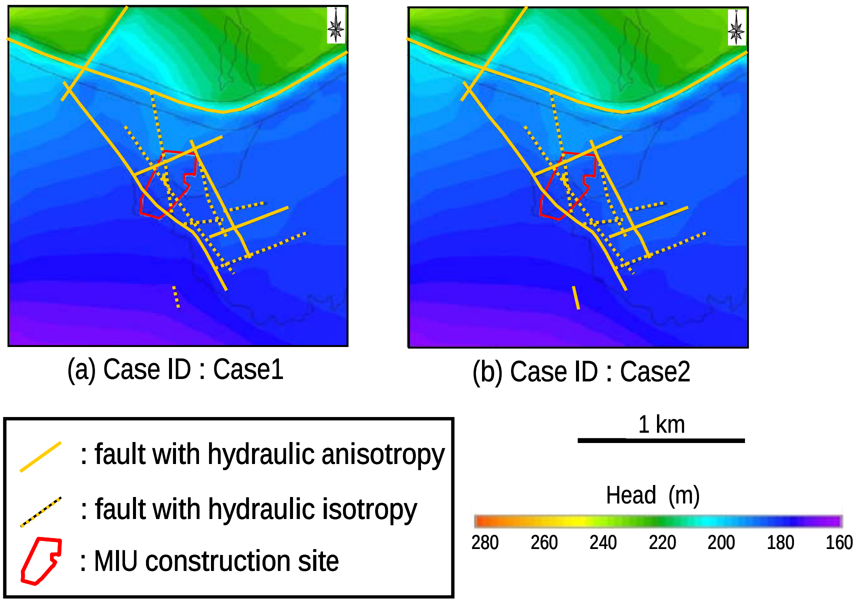


Fig. 3.7.2-7 Sensitivity analysis cases focused on hydraulic anisotropy of faults in Step 4 (Elevation -300 m：Depth of the shaft 500 m)

3.7.3 Geochemical characteristics of groundwater

Improvement in understanding with the progress of investigations

Studies regarding the 3-D distribution of salinity, groundwater pH value and redox conditions allow identification of aquifers with different geochemistry of groundwater, as well as an evaluation of the geochemical characteristics of groundwater in each aquifer. Since the spatial distribution of groundwaters with different chemistries is assumed to relate to the geological structures and groundwater flow conditions, comparison of the spatial distribution with the investigation results on geological structures and groundwater flow characteristics obtained in each step allows the relationship between them to be verified.

In Step 0, 3-D distributions of groundwater chemistry, groundwater pH value and redox conditions were predicted based on the borehole investigations conducted in the RHS (included in the present report as existing information), and literature information on mineral and hot springs (Fig. 3.7.3-1). The literature information served only to qualitatively estimate the groundwater chemistry because the sampling method, depth of sampling, sampling date and time between drilling and sampling, as well as the total volume of groundwater pumped before the acquisition of data, were not specified. In this step, it was possible to state that mainly two types of groundwater were present in the local-scale area encompassing the site-scale area. The Tsukiyoshi Fault, functioning as a flow barrier, occurs between the areas where these groundwaters are present, implying that the distribution of groundwater chemistry is affected by large-scale geological structures such as faults. The groundwater chemistry for the site-scale area was roughly determined in this step, as were the distribution of geochemical characteristics of groundwater and the relationship between groundwater chemistry and the hydrogeology in the local-scale area. However, due to lack of information on groundwater chemistry in the sedimentary rock formations in the site-scale area, its relationship to the hydrogeology could not be specified.

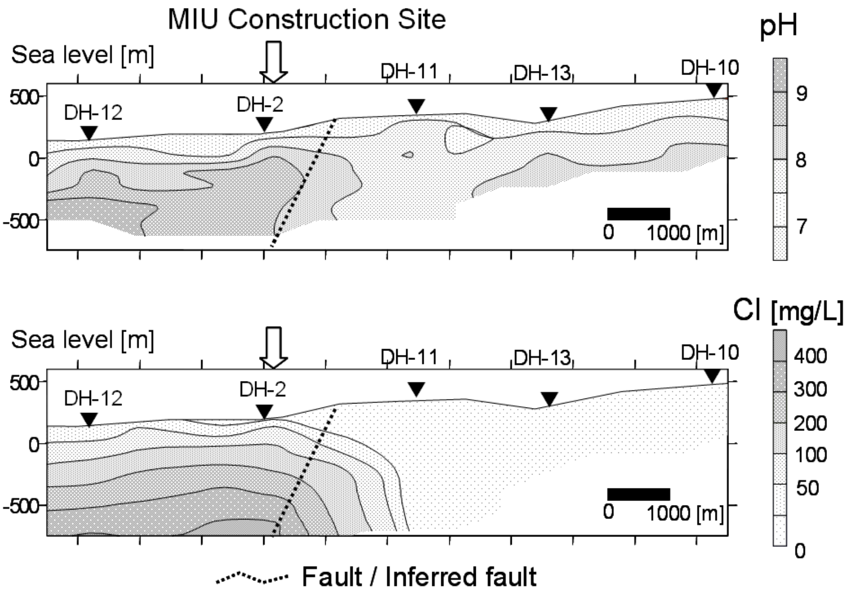
In Step 2, the groundwater chemistry in the sedimentary rock formations and its relationship with hydrogeology, which were not specified in Step 0, were determined. In the sedimentary rock formations present in the site-scale area, the hydrochemistry differed above and below the low permeable formation in the Mizunami Group. An isotope analysis (tritium) indicated the possibility that relatively fast recharge is occurring in the area shallower than the low permeable formation over a timescale of several to several tens of years. The analysis also suggested that the groundwater residence time in the area deeper than the low permeable formation is larger than in the shallower zone (see also Section 3.4.3). As a result, the relationship between the low permeable formation and the distribution of groundwater chemistry was clarified, in addition to the relationship between the faults and the distribution of groundwater chemistry which had been elucidated in Step 0. It was also found that the distribution of groundwater chemistry depends directly on the permeability and spatial distribution of geological structures. Such information would be essential for predicting possible disturbances of groundwater flow and groundwater geochemical characteristics in and around the underground facilities associated with the excavation activities in Phase II and beyond. The impact caused by the excavation of the underground facilities in sedimentary rock is expected to differ between the two sides of the low permeable formation based on the recharge rates, the volume of inflow during the excavation of the underground facilities, the permeability and so forth. Therefore, the excavation of the underground facilities should be planned so as to minimize the disturbances on groundwater environment taking into account their impact.

In Step 3, the groundwater chemistry and its distribution in the granite in the deep formations in the site-scale area predicted by the investigations and analyses in the preceding steps was confirmed (Fig. 3.7.3-1). At the same time, the hydrochemical model for the local-scale area was updated. Thus, a model representing the undisturbed initial state in the site-scale area prior to the excavation of the underground facilities was constructed. The depth profile of salinity was reproduced by repeating the procedure from data acquisition to model revision. The model constructed in this step will serve as the basis for the prediction of possible hydrogeological and hydrochemical changes due to the excavation of the underground facilities in Phase II and beyond (see also Section 3.8.3).

Issues for Phase II and beyond

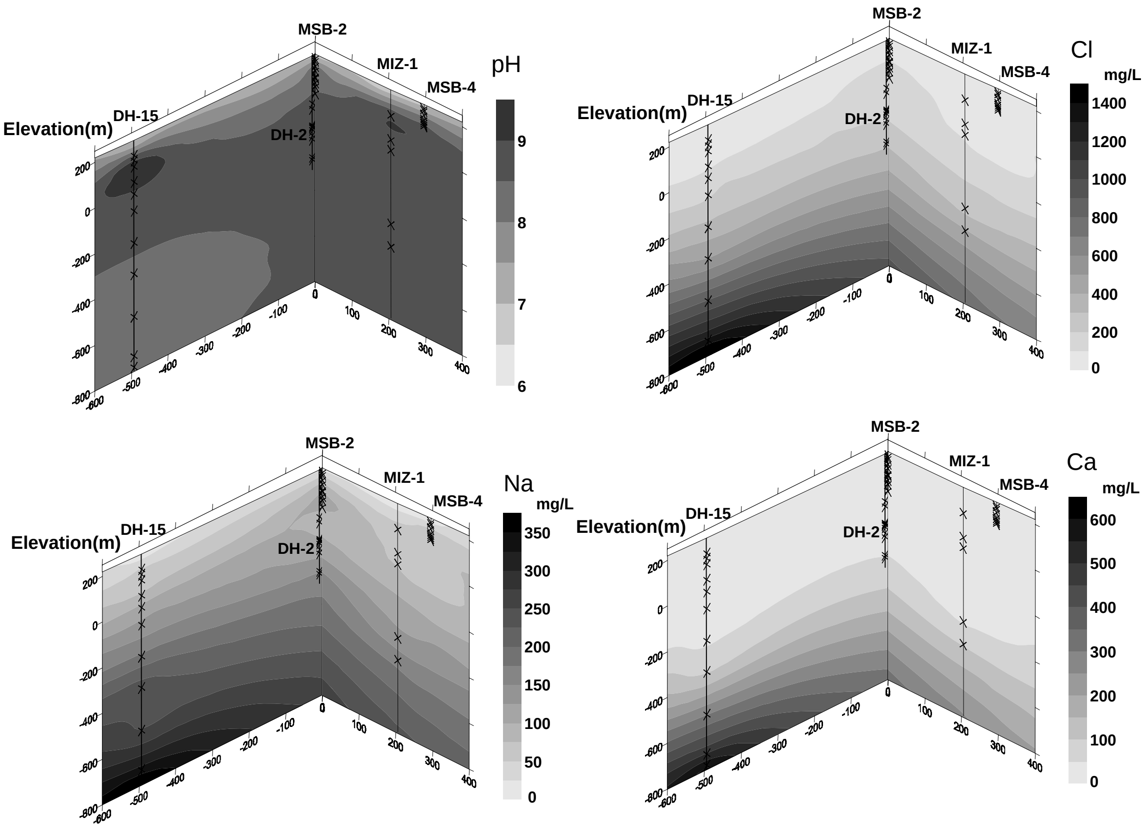
Based on the above results, the following can be identified as issues for Phase II and beyond:

- Testing of the hydrochemical model constructed based on the investigations in Phase I and the hydrochemical changes predicted based on the model through comparison with the results of chemical analyses of groundwater sampled in the underground facilities and of the monitoring of changes of groundwater chemistry due to the excavation of the underground facilities.
- Identification of the general processes and mechanisms involved in the changes in the hydrochemical and hydrogeological environments in and around the underground facilities, which may be induced by the facilities during their construction and operation, in order to clarify the capability of the geological environment to recover from human-induced hydrochemical disturbances, as well as for developing methods for predicting the time required for recovery and steady-state conditions after recovery. These techniques are indispensable for predicting recovery to a steady-state after the closure of a repository and the differences between this new steady-state and that before the excavation of the underground facilities. They will be extremely important for evaluating the uncertainties in various parameters used for the safety assessment and ensuring the reliability of the long-term safety assessment technology.



(a) Estimated distribution of groundwater chemistry after Step 0

Fig. 3.7.3-1 Step-wise understanding of groundwater chemistry around the MIU construction



(b) Estimated distribution of groundwater chemistry after Step 4

Fig. 3.7.3-1 Step-wise understanding of groundwater chemistry around the MIU construction (Continued)

3.7.4 Transport/retardation of nuclides

Improvement in understanding with the progress of investigations

Improvement in the understanding of solute transport and retardation effects, and issues for Phase II and beyond were evaluated based on the results obtained in two steps (Steps 0 and 3) in which data could be acquired.

(a) Sorption capacity and diffusivity of rock matrix and of transport pathways

The validity of the sorption and diffusion coefficients estimated based on the JNC-SDB sorption database[1),2)] and the data on the Kurihashi Granodiorite in the Kamaishi mine were checked by evaluating the values and petrological and mineralogical data obtained in Step 3. The sorption coefficients for Cs and Sr in the Toki Granite matrix and discontinuities were lower than those estimated in Step 0. In addition, groundwater with a high Na-Cl concentration was found to be distributed in the MIU Construction Site. Therefore, the sorption coefficients were set to lower values than those estimated based on the existing information.

(b) Geometry of transport pathways; depth of diffusion-accessible rock matrix

The solute transport field in the Toki Granite was characterized using data on the distribution of the uranium series nuclides (^{238}U, ^{234}Th and ^{230}Th) present in the vicinity of water conducting fractures, in addition to data on pore structures. The values and ranges for the geological structures and pore structures in the solute transport field in the Mizunami Group and the Toki Granite were estimated based on the results of Step 3, which served to reduce uncertainties. However, since the condition of the cores was different from the in-situ conditions because the cores are subjected to geophysical disturbances associated with the drilling, sampling and investigation[3),4)], the data obtained from the cores should be treated as information to be used to understand generic properties and features of the solute transport field.

(c) Effect of colloid/organics/microbes on nuclide transport/retardation

The chemical characteristics of colloids, organic matters and microbes in the groundwater in the Toki Granite could not be determined because it was difficult to acquire suitable data for the following reasons. Firstly, there was no relevant existing information available from Step 0. Secondly, the contamination of the groundwater samples collected during the deep borehole investigations by the drilling fluid in Step 3 reached several to several tens of percent, which was too high to carry out a detailed survey.

Issues for Phase II and beyond

In the Phase I investigations, solute transport and retardation in the Mizunami Group and the Toki Granite, particularly the major mechanisms of solute transport and retardation such as sorption and matrix diffusion, were roughly characterized and evaluated based mainly on the existing information and laboratory tests using cores. However, in order to further reduce the uncertainties in these results, data on sorption and diffusion properties in rock and on the solute transport field in the actual geological environment should be obtained by in-situ tests. For the evaluation of effect of colloid, organics and microbes on nuclide transport/retardation, groundwater samples with extremely low drilling fluid contamination, representing the in-situ conditions underground, should be collected. For this purpose, a long-term water sampling survey using the monitoring holes drilled in the underground facilities would be required. However, since it is assumed that significant hydrogeological and geochemical disturbances will occur in the area in and around the underground facilities to be excavated in Phase II, the area cannot be considered appropriate for in-situ solute transport tests or long-term water sampling survey. Therefore, the development of suitable investigation techniques to be used in Phase III would be the focus for the investigations in Phase II. At the same time, a more efficient investigation program should be promoted through collaborative research with URLs in other countries.

3.7.5 Dilution of nuclides

Improvement in understanding with the progress of investigations

As described in Section 3.2.5, the spatial distribution of groundwater flux has to be determined for evaluating the dilution effect by the groundwater. In order to determine the flux distribution, the areas of aquifers and the distribution of flow velocity in the aquifers are needed to be determined. However, the area of the aquifer would be difficult to reconstruct because of its spatial heterogeneity. Therefore, in Phase I, a geological structure that was assumed to be an aquifer was identified in advance based on the geological/hydrogeological model constructed in each step by using the distribution size of the aquifer. The frequency distribution of the Darcy velocity was then calculated based on the results of groundwater flow analyses, thereby determining the dilution effect of the aquifer. As a result, calculated Darcy velocity distributions in each hydrogeological unit are different. The Darcy velocity distribution was expected to serve as an indicator for determining the dilution effect of the aquifer. Also, the distribution of Darcy velocity showed a different trend with the progress of investigations, even in the same hydogeological unit.

Based on the above, the following were defined as the indicators for determining changes in the distribution trend of Darcy velocity calculated for each hydrogeological unit in each step with the progress of investigations.

- Average Darcy velocity
- Standard deviation of Darcy velocity
- Variation in the average value and standard deviation of Darcy velocity

Fig. 3.7.5-1 illustrates the evolution of the average value and standard deviation of the frequency distribution of the Darcy velocity with the progress of investigations for the main hydrogeological units in the hydrogeological models developed from Step 0 through Step 4. Of the hydrogeological units in the Toki Granite, the lower sparsely fractured domain with a relatively low hydraulic conductivity (average value for Darcy velocity 7.9 x 10^{-10} to 3.2 x 10^{-10} m s^{-1}) was used as the reference for evaluating the dilution effect in other hydrogeological units. The standard deviation and the variation in the standard deviation and average value for Darcy velocity distribution in the lower sparsely fractured domain were judged to be suitable as the reference for evaluation because they were smaller compared to those in other hydrogeological units. The following summarizes the outline of the stepwise process (Fig. 3.7.5-1) of taking into account the mainly hydrogeological units into the hydrogeological model.

(a) Oidawara Formation

The average value for Darcy velocity distribution in the Oidawara Formation was in the range of 3.2 x 10^{-10} to 1.6 x 10^{-10} m s^{-1}, which is lower than that of the lower sparsely fractured domain. Thus, the formation would not be an important hydrogeological unit in the context of the dilution effect.

(b) Akeyo/Hongo Formations

The average value for Darcy velocity distribution in the Akeyo/Hongo Formations was in the range of 2.5 x 10^{-9} to 5.0 x 10^{-10} m s^{-1}. These formations are thus expected to be important hydrogeological units in the context of the dilution effect because the values are higher than those of the lower sparsely fractured domain after Step 2. However, the average value for Darcy velocity distribution in the formations varied significantly with the progress of investigations and decreased from Step 3 to Step 4. Therefore, the formations have a significant uncertainty in dilution effect and understanding of the dilution effect in the formations will need to be improved by investigations in the future.

(c) Basal conglomerate of the Akeyo/Hongo Formations

The basal conglomerate of the Akeyo/Hongo Formations was additionally included in the hydrogeological model in Step 4 and the improvement in understanding of the dilution effect with the progress of the investigations cannot be evaluated at present. The average value for Darcy velocity distribution in the basal conglomerate was 7.9 x 10^{-9} m s^{-1} in Step 4, which was higher than that of the lower sparsely fractured domain. Thus, the basal conglomerate is expected to be an important hydrogelogical unit in the context of dilution effect. The average value for Darcy velocity distribution, standard deviation and their variations will have to be refined based on the results of future investigations.

(d) Toki Lignite-bearing Formation

The average value for Darcy velocity distribution in the Toki Lignite-bearing Formation was in the range of 7.9 x 10^{-9} to 1.6 x 10^{-9} m s^{-1}, which is higher than that of the lower sparsely fractured domain. Thus, the formation is expected to be an important hydrogelogical unit in the context of the dilution effect. However, the average value for Darcy velocity distribution in the formation varied significantly with the progress of investigations and the level of understanding will need to be improved by investigations in the future. The average value for Darcy velocity distribution increased with the progress of investigations from Step 2 to Step 4, while the standard deviation tended to decrease. Therefore, the formation requires further investigation as a hydrogelogical unit of particular importance.

(e) Basal conglomerate of the Toki Lignite-bearing Formation

As with the basal conglomerate of the Akeyo/Hongo Formations, this hydrogelogical unit was additionally included in the hydrogeological model in Step 4 and the improvement of understanding of the dilution effect with the progress of investigations cannot be evaluated at present. In Step 4, the average value for Darcy velocity distribution in the basal conglomerate was 1.0 x 10^{-8} m s^{-1}, which was higher than that of the lower sparsely fractured domain. Thus, the basal conglomerate is expected to be an important hydrogelogical unit in the context of the dilution effect. The average value for Darcy velocity distribution, standard deviation and their variation will have to be refined based on the results of future investigations.

(f) Highly fractured zone along the Tsukiyoshi Fault

The average value for Darcy velocity distribution in the highly fractured zone along the Tsukiyoshi Fault was in the range of 6.3 x 10^{-9} to 2.0 x 10^{-9} m s^{-1}, which is higher than that of the lower sparsely fractured domain. Thus, the fractured zone is expected to be an important hydrogelogical unit in the context of the dilution effect. However, on the basis of its high standard deviation, the zone is estimated to have a highly heterogeneous dilution effect. The average value for Darcy velocity distribution in the zone also varied significantly with the progress of investigations. Therefore, the understanding of the dilution effect needs to be improved by investigations in the future. Meanwhile, the average value for Darcy velocity distribution tended to increase with the progress of investigations from Step 2 to Step 4. Therefore, the zone deserves further attention as a hydrogelogical unit of particular importance.

(g) Upper highly fractured domain

The average value for Darcy velocity distribution in the upper highly fractured domain was in the range of 4×10^{-9} to 1.6×10^{-9} m s^{-1}, which is higher than that of the lower sparsely fractured domain. Thus, the upper highly fractured domain is expected to be an important hydrogeological unit in the context of the dilution effect. The variation in the average value for Darcy velocity distribution with the progress of investigations is comparable to that of the lower sparsely fractured domain. However, the average value for Darcy velocity distribution decreased, while the standard deviation tended to increase from Step 3 to Step 4. Therefore, the upper highly fractured domain has a significant uncertainty in its dilution effect and understanding needs to be improved.

(h) Low-angle fractured zone

The low-angle fractured zone was included in the hydrogeological model in Step 2. The average value for Darcy velocity distribution in the zone was in the range of 2.5×10^{-8} to 2.0×10^{-8} m s^{-1}, which is higher than that of any other hydrogeological unit. Thus, the zone is expected to be an important hydrogeological unit in the context of the dilution effect. However, on the basis of its high standard deviation, the domain is estimated to have a high heterogeneous of dilution effect. Therefore, it deserves further attention as a hydrogeological unit of particular importance and its heterogeneity will have to be evaluated.

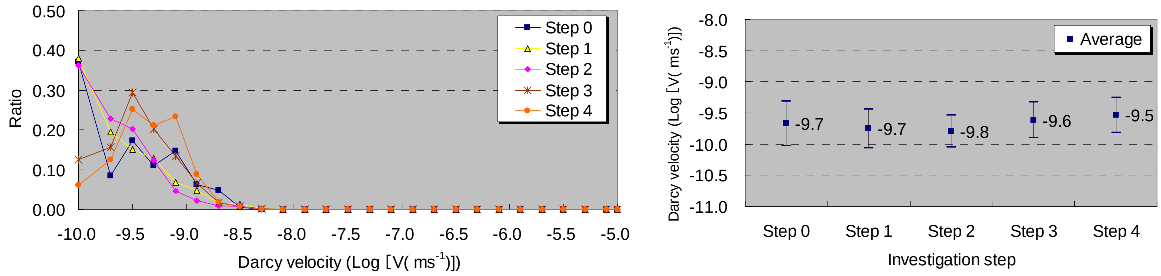
(i) Summary

Fig. 3.7.5-1 shows hydrogeological units whose average value and variation in the standard deviation of Darcy velocity showed a relative increase from Step 2 onwards. This is due to the fact that the hydrogeological model was updated based on the results of borehole investigations, long-term hydraulic monitoring and crosshole hydraulic testing conducted in Step 2 and afterwards. Thus, in evaluating the dilution effect, it is important to conduct borehole investigations as these are particularly suitable for determining the hydraulic characteristics of hydrogeological units.

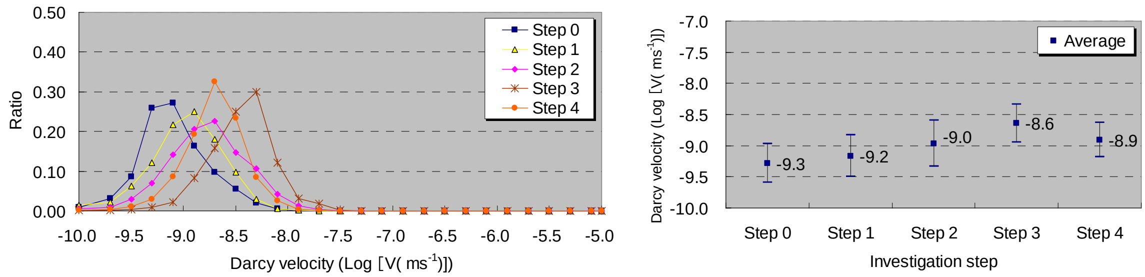
In Phase I, the Toki Lignite-bearing Formation, the highly fractured zone along the Tsukiyoshi Fault and low-angle fractured zone were identified as particularly important hydrogeological units in the context of dilution effect. However, large variations are likely to exist with respect to the dilution effect of these structures. Therefore, the understanding will need to be improved in the investigations in Phase II and beyond.

Issues for Phase II and beyond

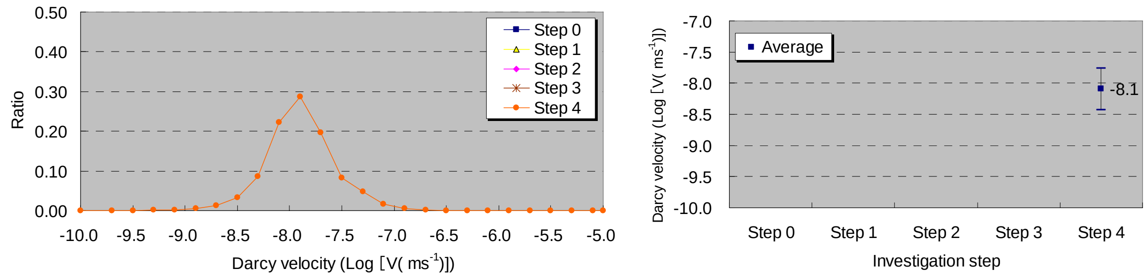
Regarding the issues in Phase II and beyond, the hydrogeological model should be updated based on the information obtained during the excavation of the underground facilities (see also Section 3.7.1) and the Darcy velocity distributions should be calculated using the updated model to evaluate the changes.



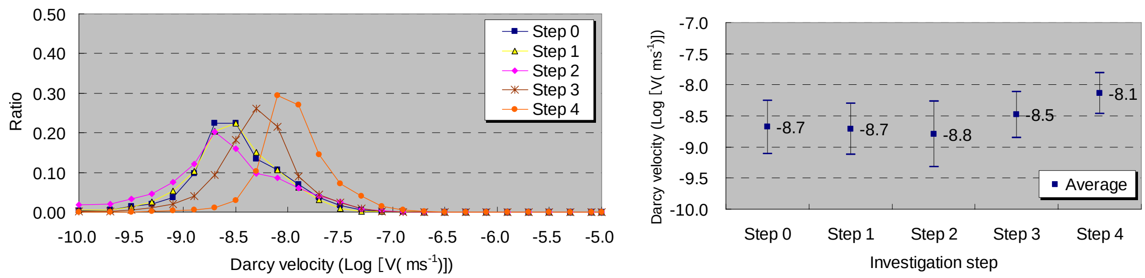
(a) Oidawara Formation



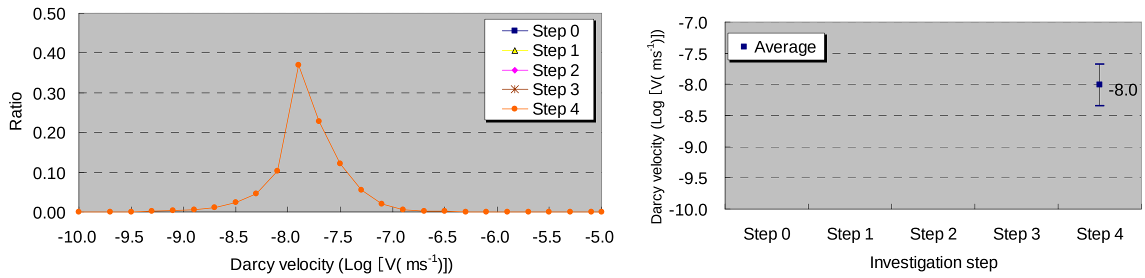
(b) Akeyo/Hongo Formation



(c) Akeyo/Hongo Formation basal conglomerate

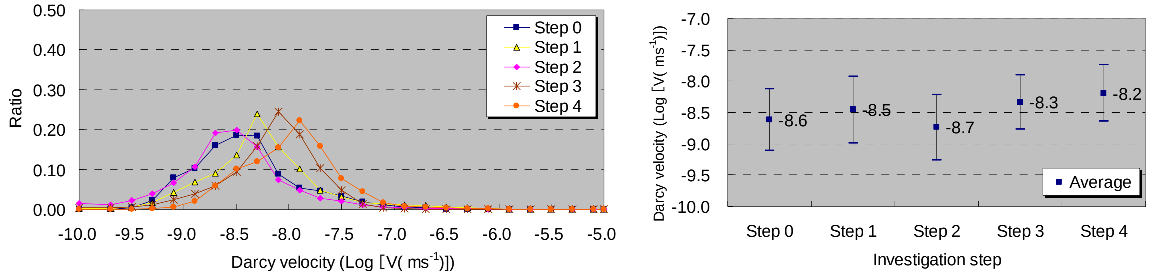


(d) Toki lignite bearing Formation

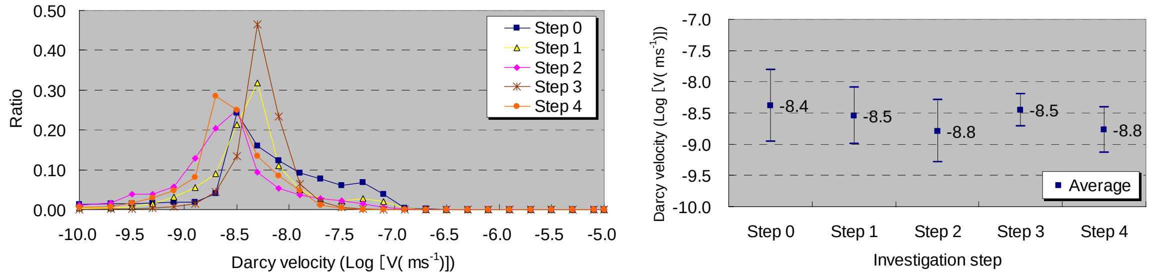


(e) Toki lignite bearing Formation basal conglomerate

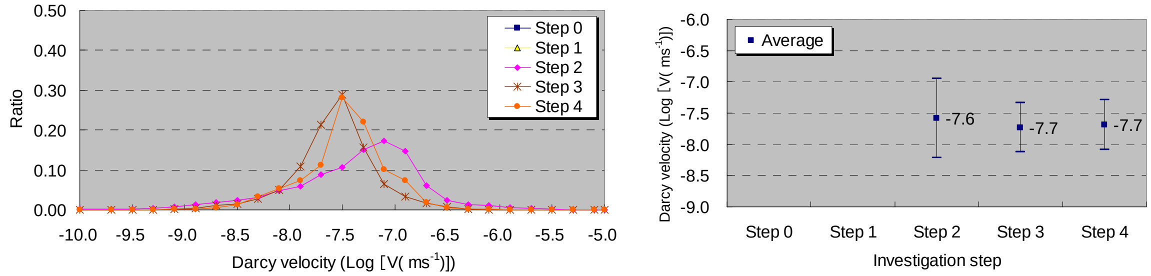
Fig. 3.7.5-1 Darcy velocity distributions in geological units with stepwise progress of investigations



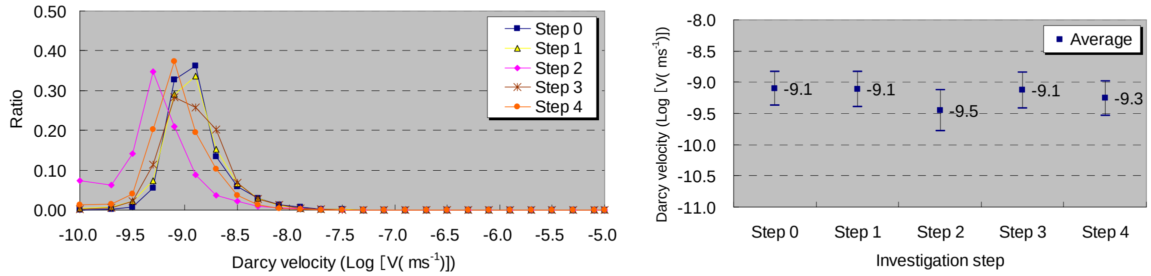
(f) Highly fractured zone along the Tsukiyoshi fault



(g) Upper highly fractured domain



(h) Low angle fractured zone



(i) Lower sparsely fractured domain

Fig. 3.7.5-1 Darcy velocity distributions in geological units with stepwise progress of investigations (Continued)

3.7.6 Local stress regime, spatial variability of petrophysical/geomechanical properties of rocks, and size and structure of EDZ

<u>Improvement in understanding with the progress of investigations</u>

The depth profile and 3-D distribution of initial stress states and petrophysical/geomechanical characteristics of rocks are determined by borehole investigations. Because they are assumed not only to be depth-dependent but also to be related to geological structures, a rock mechanical model has to be constructed taking these factors into account. The extent and petrophysical/geomechanical properties of the

EDZ are predicted by simulating the excavation of the underground facilities based on the numerical analysis method and defining input data based on the rock mechanical model.

(a) Improvement in understanding from Step 0 to Step 2

In Step 0, the initial stress states and petrophysical/geomechanical characteristics of rocks were obtained by referring to existing information, namely the data obtained by the borehole investigations conducted at the Shobasama Site and their interpretation in a rock mechanical model.

In order to evaluate the extent and petrophysical/geomechanical properties of the EDZ, a sensitivity analysis was conducted to predict the influence of the excavation of the underground facilities on the rock around the underground facilities using a numerical analysis method that could take into account the influence of discontinuities in the rock.

In Step 2, the principal stress ratio and the direction distribution were determined as the petrophysical/geomechanical characteristics of rocks and initial stress states in the Toki Granite by conducting laboratory tests using core samples obtained from an existing borehole (DH-2) near the MIU Construction Site. As a result, new information on the upper highly fractured domain in the Toki Granite in and around the MIU Construction Site was obtained and the rock mechanical model for the MIU Construction Site was constructed based on these results.

(b) Improvement in understanding from Step 2 to Step 3

In Step 3, the petrophysical/geomechanical characteristics of the Toki Granite were evaluated using core samples obtained from the deep borehole MIZ-1 at the MIU Construction Site. At the same time, the distribution of the initial stress states was determined by in-situ hydraulic fracturing tests. As a result, additional information on the lower sparsely fractured domain in the Toki Granite was obtained and the rock mechanical model of the MIU Construction Site was updated based on these results.

With regard to the extent and petrophysical/geomechanical properties of the EDZ, the rock mechanical model was updated by adding the EDZ to the numerical analysis method that can take into account the influence of discontinuities in the rock. Analyses were then made to predict the impact of excavation on the rock around the underground facilities.

(c) Summary

In order to evaluate the local stress regime and petrophysical/geomechanical characteristics of rocks, a rock mechanical model was constructed and updated using the characteristics and initial stress states in the Toki Granite obtained in each investigation/analysis step (Fig. 3.7.6-1). An analysis was conducted to predict the impact of excavation on the rock around the underground facilities. With the progress of the investigation steps, the understanding was improved through the following: (1) The location of the investigation boreholes used in the modeling were closer to the MIU Construction Site; (2) Information on the lower sparsely fractured domain in the Toki Granite was additionally obtained in Step 3, although information on the granite was limited to that on the upper highly fractured domain in the Toki Granite in Step 2; (3) The results of in-situ initial stress measurements were obtained; (4) The comparison with the geological model made it possible to confirm that the initial stress states differ on both sides close to discontinuities such as faults and (5) Additional information on fractures was obtained.

However, the information on the petrophysical/geomechanical characteristics and initial stress states in the Toki Granite obtained at the MIU Construction Site were derived only from one deep borehole at a distance from the excavation locations of the underground facilities and the characteristics at the excavation locations might be significantly different. Thus, in order to accurately evaluate the local stress regime and petrophysical/geomechanical characteristics at the planned excavation locations of the underground facilities, it would be better to acquire information by conducting deep borehole investigations at the planned excavation locations or in their vicinity.

When conducting a predictive analysis of excavation impact on the rock around the underground facilities using a numerical analysis method taking discontinuities in the rock into account, the relevant discontinuities will be selected by identifying preferential fractures from among the fractures identified in borehole investigations or by performing statistical processing. In considering the excavation damaged zone, the degree and extent of excavation damage will be defined based on the hypotheses developed based on previous cases, etc. However, such information is difficult to acquire in the Phase I investigations and the above-mentioned parameter settings would have to be based on existing knowledge.

Issues for Phase II and beyond

In Phase II, information on the local stress regime and petrophysical/geomechanical rock characteristics around the underground facilities (site/block scale) should be acquired in order to test the rock mechanical model constructed in Phase I.

The test will be performed by comparing analytical and measured data. The measured data include those from investigations using borehole drilled in the underground facilities, initial stress measurements using the boreholes and petrophysical/geomechanical tests using core samples. The validity of the result of the predictive analysis in Phase I regarding the extent and petrophysical/geomechanical characteristics of the EDZ is needed to be evaluated against the excavation effect tests in the underground facilities.

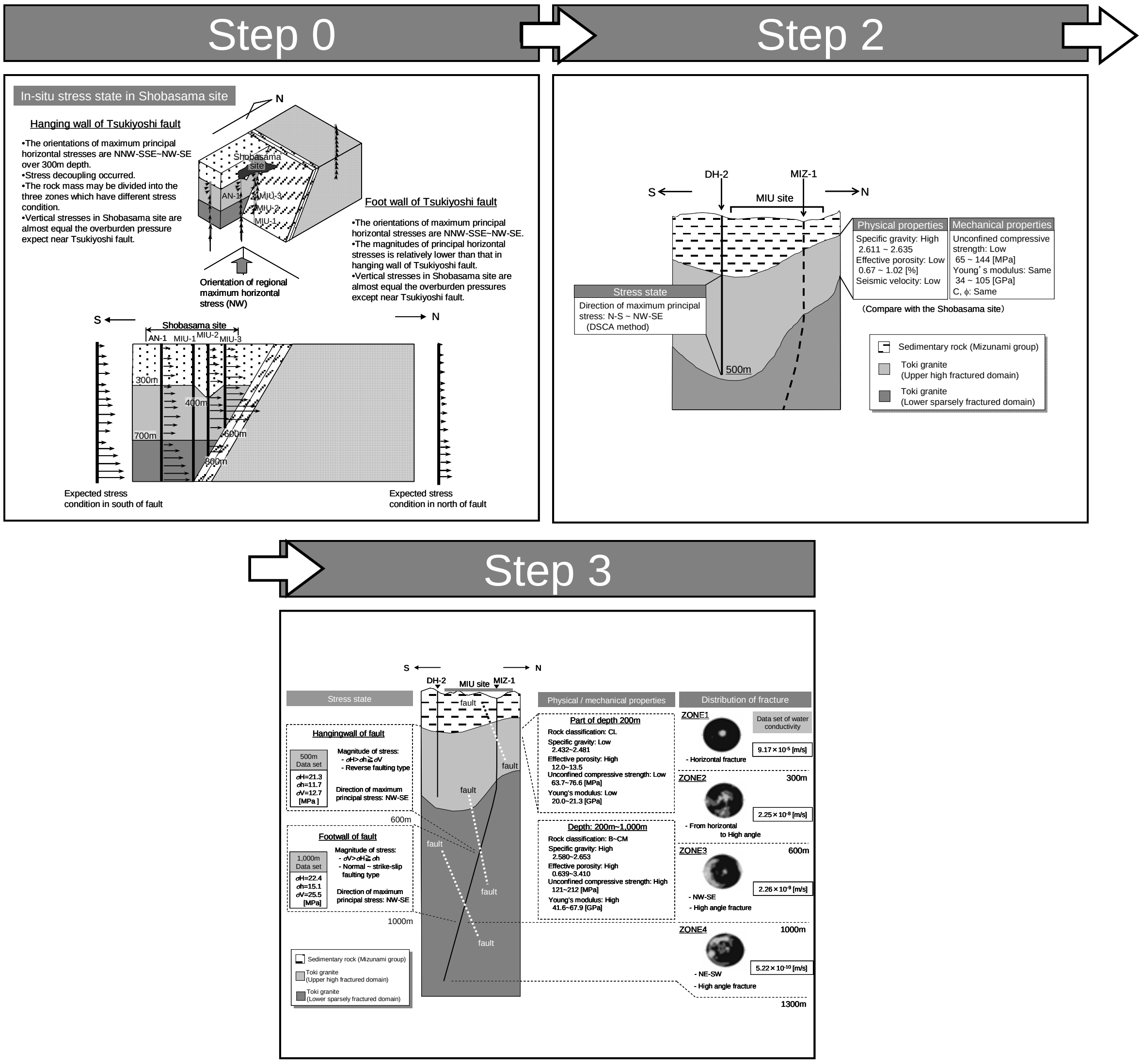


Fig. 3.7.6-1 Evolution of rock mechanical model

3.7.7 Volume of inflow into underground tunnels

Improvement in understanding with the progress of investigations

Methods for estimating the volume of inflow into the underground facilities include a theoretical formula based mainly on an isotropic homogeneous medium and groundwater flow analyses. The groundwater flow analysis is a method in which the excavation of the underground facilities is simulated analytically based on a hydrogeological model constructed using information from borehole investigations, etc. For evaluating the inflow rate based on an anisotropic hydrogeological medium, 3-D groundwater flow analysis is required. The volume of inflow into underground facilities could be estimated with higher accuracy by using such a 3-D analysis. However, compared to the estimation based on a theoretical formula, 3-D groundwater flow analysis is more time-consuming in terms of mesh generation and calculation. Thus, these methods should be used selectively depending on the required accuracy needed for the design and construction of underground facilities.

In Step 0, the groundwater inflow rate into the underground facilities was predicted using a theoretical formula based on an isotropic homogeneous medium, because no information had been obtained on hydrogeological structures such as faults in and around the MIU Construction Site.

From Step 2 onwards, the estimation of the volume of inflow into the underground facilities was based on 3-D groundwater flow analysis. In this instance, the reliability of the hydrogeological model, which forms the basis of the groundwater flow analysis, should be improved in order to increase the accuracy of the estimated volume of the inflow.

In Step 2, the distribution and hydraulic characteristics of sedimentary rock formations, the upper highly fractured domain in the Toki Granite and major discontinuities that were not identified in Step 0 were determined and the hydrogeological model was constructed based on this information (see also Section 3.4.2). In Step 3, the distribution and hydraulic characteristics of sedimentary rock formations, the Toki Granite including the zone deeper than 1,000 m and major discontinuities were determined and the hydrogeological model was updated based on this information (see also Section 3.5.2). In Step 4, the spatial connectivity of major discontinuities and their hydraulic characteristics were determined and the hydrogeological model was again updated based on this information (see also Section 3.6.2).

The comparison between the results of groundwater flow analysis for the conditions prior to the excavation of the underground facilities using these hydrogeological models and the improvement obtained when comparing these to measured groundwater pressure distributions demonstrated the improved reliability of the hydrogeological model with the increased amount of information (see also Section 3.7.2). The accuracy of the groundwater flow analysis based on these hydrogeological models for estimating the volume of inflow into the underground facilities was therefore considered to have improved.

The updating of the hydrogeological model resulted in a change in the number of highly permeable structures that had been predicted to intersect the underground facilities (see also Section 3.7.8), which would significantly influence the estimation of the volume of the inflow (Fig. 3.7.7-1). As described above, it was confirmed that the highly permeable structures found to significantly affect the volume of the inflow dip at high angles at/around the MIU Construction Site. Therefore, the number and locations of the highly permeable structures intersecting the underground facilities (shaft, in particular) will be influenced strongly by the uncertainty in the geometry of the highly permeable structures. Thus, in order to accurately determine the number of highly permeable structures intersecting the underground facilities, it will be a priority to acquire information on the spatial distribution and hydraulic characteristics of highly permeable structures at the excavation points of the underground facilities. However, borehole investigations for this purpose were not conducted at these points in Phase I, because priority was assigned to characterizing groundwater flow in the entire site-scale area, and also because of budget and time restrictions. Thus, the accuracy of the estimation of the volume of inflow into the underground facilities was insufficient.

In estimating volume of inflow rate using the groundwater flow analysis, the effect of the lining concrete and drainage mats installed between the lining and rock was considered. As a result, the hydraulic characteristics vicinity of the underground facilities which are influenced by a skin effect, including that generated by engineered structures, were found to significantly affect the volume of the inflow (see also

Sections 3.4.6, 3.5.7 and 3.6.4). However, the hydraulic characteristics vicinity of the underground facilities were not determined accurately in the Phase I investigations. The results of groundwater flow analyses suggested that a large volume of inflow would possibly occur in the highly permeable zone, requiring measures such as grouting to reduce inflow rate where this is expected to be significant. Grouting also affects the hydraulic characteristics vicinity of the underground facilities, similarly to the lining concrete and drainage mats installed between the lining and the rock. Grouting in particular would change the groundwater pressure vicinity of the underground facilities significantly compared to the case without grouting.

Issues for Phase II and beyond

The results of predictive analyses of the inflow indicated that phenomena such as groundwater inflow and drawdown of groundwater pressure were significantly influenced by the skin effect, including that generated by engineered structures, grouting and other impacts associated with construction (such as excavation work). Therefore, in order to measure the volume of inflow into the shafts associated with the excavation of the underground facilities in Phase II, and also to confirm the validity of the hydrogeological model constructed in Phase I based on the results of long-term hydraulic monitoring around the shafts, it is important to acquire accurate information on the hydraulic characteristics vicinity of the underground facilities. These zones are subject to the impact of the skin effect, including that generated by engineered structures such as lining concrete and drainage mats areas treated by grouting. Long-term hydraulic monitoring using the boreholes drilled in Phase I will also be continued to determine the drawdown of groundwater pressure caused by groundwater inflow into the underground facilities.

For testing and calibrating the hydrogeological model constructed in Phase I based on the information described above, a groundwater flow analysis taking into account human-induced impacts associated with construction will be conducted, and then measurements and calculated drawdown will be compared.

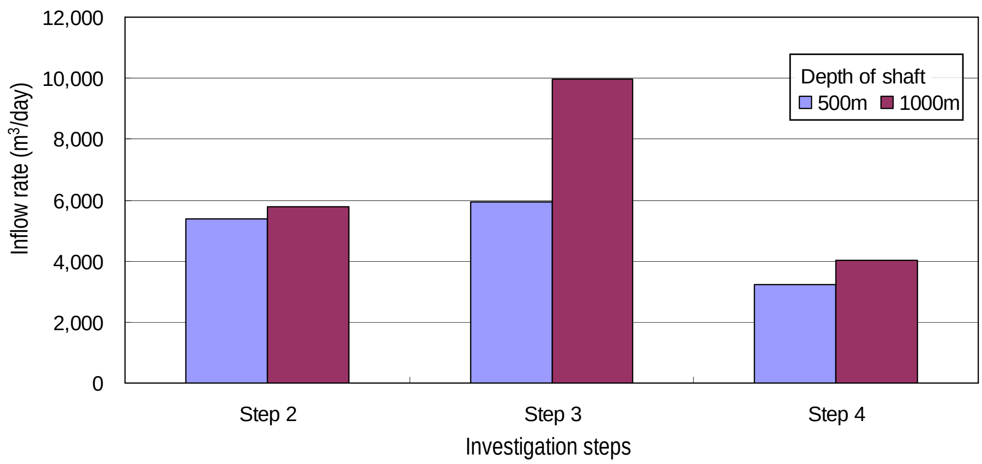


Fig. 3.7.7-1 Inflow rate into MIU estimated by using groundwater flow simulations in the each investigation step (pressure relief factor: 0.2)

3.7.8 Distribution of discontinuities intersecting underground tunnels

Improvement in understanding with the progress of investigations

To determine the presence and extent of discontinuities around the underground facilities, it is important to construct a geological model that reflects the progress of investigations and to check the improvement in understanding and uncertainties before proceeding to the next step. Fig. 3.7.8-1 illustrates the cross-section of the geological models developed from Step 0 to Step 4 along the line crossing the underground facilities.

In Step 0, information on discontinuities was compiled based on existing information and the Tsukiyoshi Fault, which was described in existing geological maps, was modeled. As a result, it was confirmed that the fault would not intersect the planned excavation positions of the underground facilities (see also Section 3.2.8).

In Step 1, the consistency between the subsurface distribution of the Tsukiyoshi Fault and existing information was checked by the geological mapping and reflection seismic surveys. At the same time, the presence of smaller-scale faults in the site-scale area, which had not been identified based on the existing information, was predicted (see also Section 3.3.4).

In Step 2, the actual subsurface distribution of faults previously confirmed or predicted was determined; the subsurface distribution and petrophysical/mineralogical characteristics of faults with a NNW strike predicted in Step 1 were confirmed and the distribution of faults with NS and EW strikes in the granite was also predicted. As a result, the accuracy of the estimation of the location of the faults with the NNW strike was improved compared to that in Step 1. It was also predicted that an additional fault with an EW strike is likely to be present (see also Section 3.4.7).

In Step 3, the faults present in the deep granite, which had not been investigated until Step 2, were identified as a result of deep borehole investigations. In this step, the distribution of the faults with a NW-NNW strike and their petrophysical/mineralogical characteristics obtained from boreholes intersecting the fault planes, in addition to the fault assumed to have an EW strike identified in Step 2, were determined. The accuracy of the estimation of the presence of faults at the planned excavation points of the underground facilities in the deep granite was improved compared to that in Step 2 (see also Section 3.5.8).

In Step 4, a multi-offset VSP survey and a crosshole tomography survey were conducted in the deep boreholes from Step 3. A reflection seismic survey was also carried out in the north to north-east part of the MIU Construction Site, which had not been investigated before. Consequently, a detailed evaluation was made of the connectivity of the fault intersecting the MIU Construction Site, as well as the distribution of faults around the underground facilities. As a result, the accuracy of the estimation of the presence of faults at the planned excavation points of the underground facilities was significantly improved compared to that in Step 3 (see also Section 3.6.5).

Issues for Phase II and beyond

As indicated by the discussions in Step 1 to Step 4 (see also Sections 3.3.4, 3.4.7, 3.5.8 and 3.6.5) many of the discontinuities were estimated to dip at high angles. In order to accurately predict the positions at which these structures encounter the underground facilities, it will be useful to acquire information on the distribution of discontinuities at the planned excavation points of the underground facilities (e.g. from pilot borehole investigations in the shaft).

Meanwhile, as described in Section 3.3.1, lineaments which are unlikely to be faults when compared with the faults predicted by the geological mapping, geophysical surveys and/or borehole investigations were also included in the geological model. Therefore, the improvement of modeling techniques including those for quantitatively evaluating the uncertainties of such information would be one of the future issues. A simulation analysis of geological structures based on the geological/geophysical data obtained so far could prove important as a method for estimating the distribution of discontinuities in uninvestigated areas.

In the Phase II investigations, the distributions of the discontinuities modeled thus far will be confirmed. In addition, the validity of predictions of the 3-D distribution of the geological structures in the Phase 1 investigations will be evaluated and the model updated. Focusing particularly on discontinuities such as the detailed geological structures occurring in the underground facilities, their distribution, geometry, structural type and petrophysical/mineralogical properties will be characterized. At the same time, a more detailed geological model for the block-scale area will be developed.

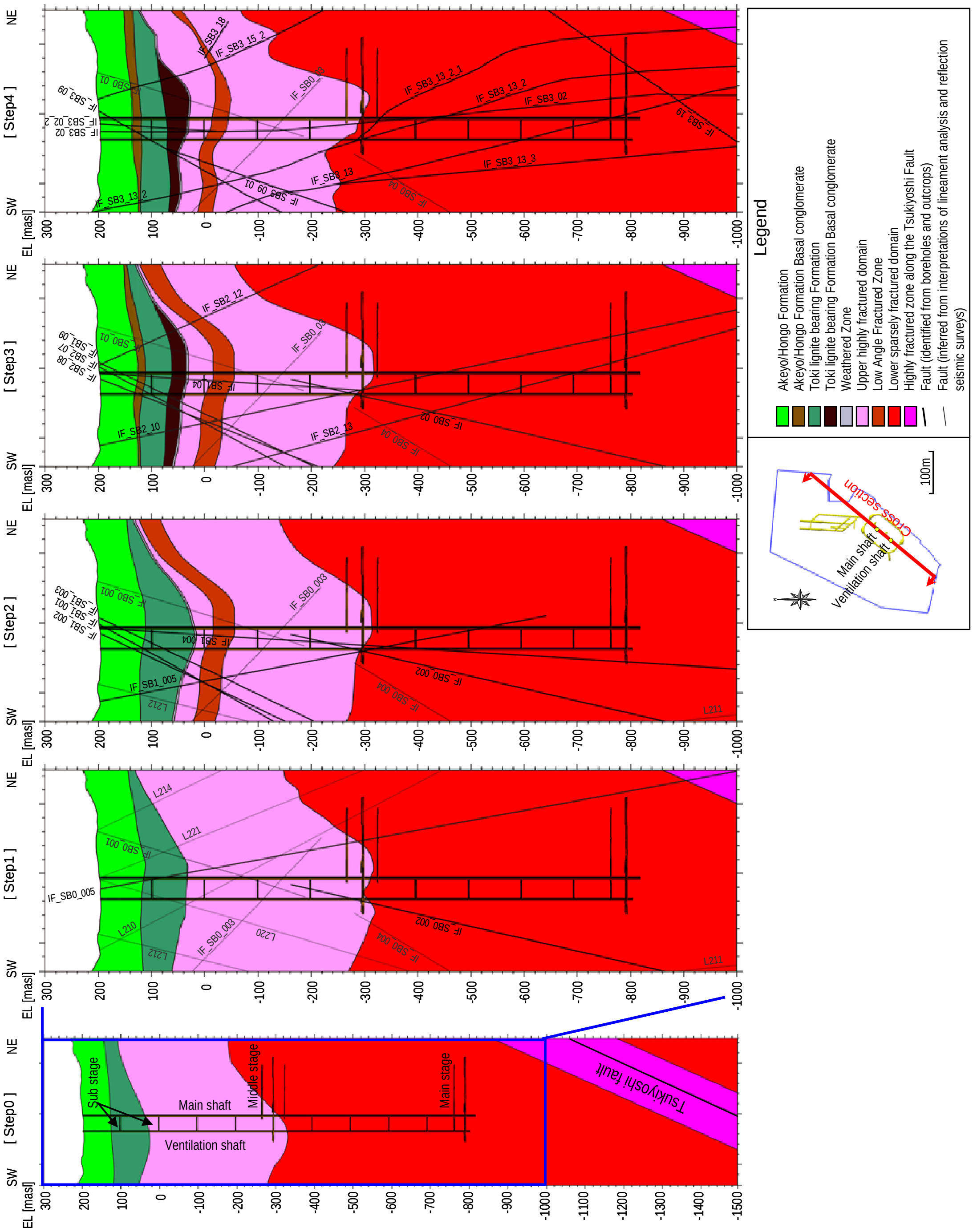


Fig. 3.7.8-1 Predicted geological structures around the MIU facility with stepwise progress of iterative investigations

3.7.9 Subsurface thermal conditions

Improvement in understanding with the progress of investigations

The depth profiles of the geothermal gradient and thermal characteristics in the area of interest can be determined by temperature logging and tests on thermal characteristics using core samples.

Based on the data on the geothermal environment obtained through the investigations from Steps 0, 2 and 3, there were no significant changes in the assessment of the geothermal gradient in the local-scale area unless a local thermal heat source is present (Fig. 3.7.9-l). Thus, on the local scale, the geothermal gradient could be determined by temperature logging in one borehole and the thermal properties could be characterized by performing tests on thermal characteristics using core samples obtained from one borehole.

Issues for Phase II and beyond

For the issues for Phase II and beyond, the thermal characteristics of rocks determined in Phase I would need to be validated by tests on thermal characteristics using core samples obtained by borehole investigations in the underground facilities.

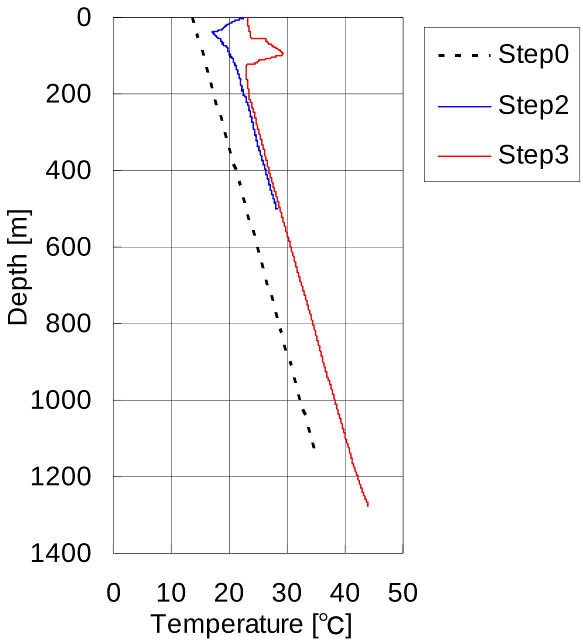


Fig. 3.7.9-1 Transition of the temperature logging result

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3.8 Determination of potential environmental impacts

The results of investigations on the specific aims relating to the safety assessment and design/construction of the underground facilities were summarized in Sections 3.2 to 3.7. This section summarizes the results of investigations on specific aims relating to the environmental impact induced by construction of underground facilities.

3.8.1 Strategy and monitoring approach

As described in Sections 3.2 to 3.7, the development of investigation and assessment techniques for characterizing the geological environment in terms of suitability for geological disposal is an essential aspect of the MIU project. It is also necessary to establish the technical basis for comprehensive assessment of environmental and societal aspects (environmental impact assessment)[1),2),3)] with a view to achieving public acceptance of the disposal project.

The construction of deep underground facilities may cause various types of impacts, not just on the geological environment from the near-surface to deep underground but also on the surface environment. However, the types and significance of the impacts, their influence on the safety assessment and techniques for reducing or dealing with them have not yet been fully clarified. In the future, an environmental impact assessment as mentioned above is considered to be required for the disposal project, similarly to conventional environmental impact assessments for large-scale infrastructure projects on the surface.

The activities in the MIU project involve actual construction of underground facilities. Therefore, technical know-how can be accumulated and techniques for evaluating the impact of excavating the underground facilities on the surrounding environment can be developed based on case studies that assess the impact of excavation on the surrounding deep geological environment.

The phenomena that may be induced by the construction of the large-scale underground facilities are expected to vary depending on the scale and layout of the facilities, the construction techniques applied, operating period, distance from the facilities, timing of the observations, etc. These phenomena can be classified into two categories: one relating to changes in the field conditions (e.g. groundwater flow conditions and groundwater chemistry) and one concerning changes of a system controlling field conditions (e.g. hydraulic conductivity and mineralogical composition) (Fig. 3.8.1-1). The MIU project focuses on environmental and social aspects considered to be important for implementing the project. The following monitoring items were thus defined, although they are exempt from the provisions of the Environmental Impact Assessment Law[4)]:

- Groundwater level and groundwater pressure
- Groundwater chemistry
- Near-surface soil moisture content
- River flux and
- Noise and vibration.

In Phase I of the MIU project, the above items have been monitored in order to acquire data on the initial conditions to be used for determining the changes in the surrounding environment associated with the excavation of underground facilities. The investigation of the impact of the excavation of the underground facilities on the surrounding environment in the near-surface zone will be described in Section 5.2. This section discusses technologies for monitoring the impact associated with the excavation of the underground facilities on the groundwater pressure and groundwater chemistry from the near-surface to deep underground.

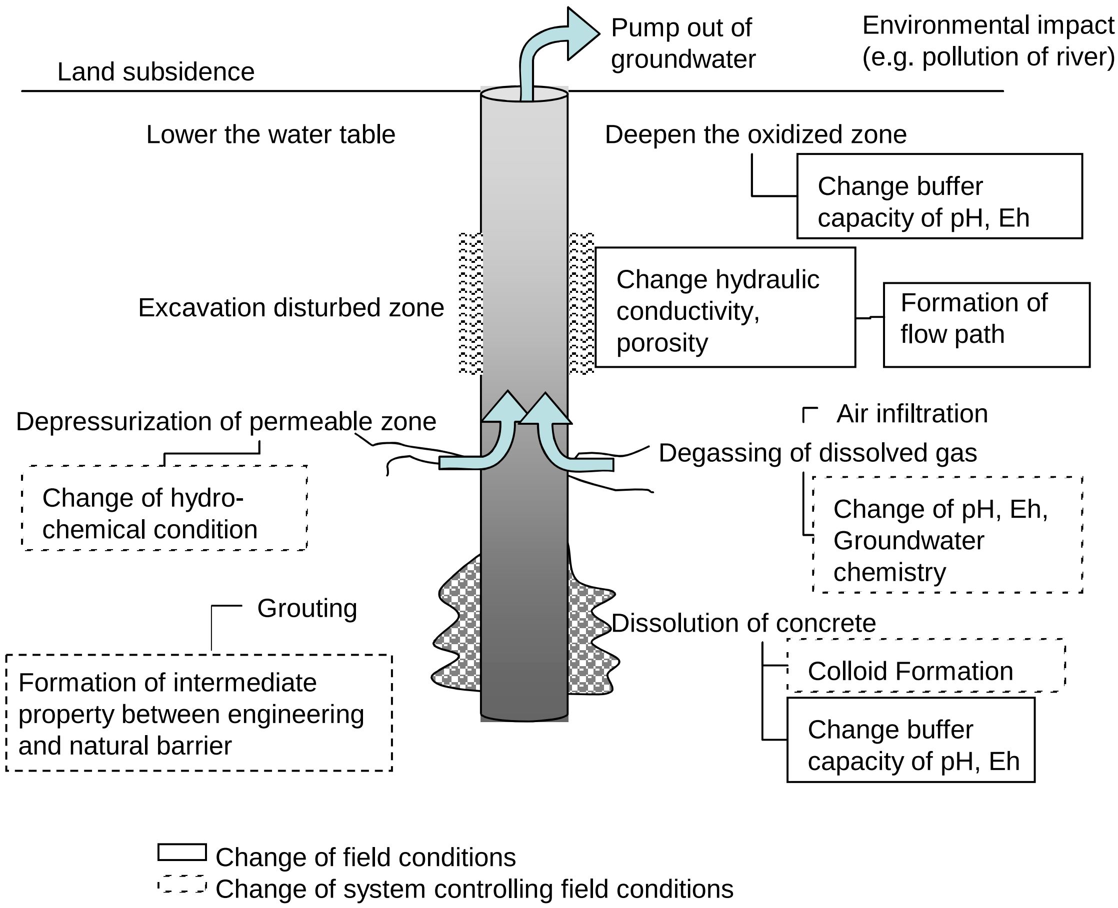


Fig. 3.8.1-1 Hydrogeological and hydrochemical changes resulting from shaft construction

3.8.2 Determining changes in groundwater pressure

Groundwater pressure has been monitored in the MIU project in order to determine the impact of the excavation of underground facilities on groundwater flow characteristics. Groundwater pressure monitoring techniques using a multi-packer system include two types, 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 (Fig. 3.8.2-1). Both types have been used for continuous monitoring in and around the MIU Construction Site in order to determine their respective advantages and disadvantages.

For the multi-packer system, if two or more zones with different groundwater pressures are present in one monitoring interval, the average value of these different pressures is obtained, preventing accurate characterization of the impacts associated with the excavation of the underground facilities. Thus, when installing the multi-packer system in a deep borehole, the monitoring intervals were selected in such a way as to separate zones expected to have different groundwater pressures from one another, based on geological and hydrogeological information obtained in previous investigations in the borehole. Installation of the multi-packer system based on this approach allows acquisition of initial values and accurate determination of the subsequent impact associated with excavation.

Information from various types of borehole investigations prior to installation of the multi-packer system provide the technical justification for the definition of the monitoring intervals and the required geological and hydrogeological information should therefore be acquired continuously along the depth of the borehole.

The time interval for data acquisition using the multi-packer system is presently set at approximately 5 minutes. With the setup described above, data on the initial conditions without the impact of excavation, including seasonal variations, earth tides, atmospheric pressure variations and variations associated with large-scale earthquakes, were obtained (Fig. 3.8.2-2). The time interval for data acquisition should be reconsidered and reset appropriately, taking into account the distance between the underground facilities and the borehole, the timing of operations that may cause changes in groundwater pressure (e.g. blasting intervals for excavation of the underground facilities) and the changes occurring at the time of excavation of relevant geological structures.

The monitoring data thus obtained relate to the influence of natural phenomena such as earth tides and atmospheric pressure variations, as well as digital noise (irregular components generated by the monitoring system). If the change in groundwater pressure induced by excavation of underground facilities is small, it may not be identified because it will be superposed by the above-mentioned noise components. Removing this noise is therefore essential for determining small changes in groundwater pressure[5),6)] (Fig. 3.8.2-3). When human-induced impacts such as the drilling of boreholes, hydraulic testing and excavation of underground facilities are included in the monitoring data, the quantitative evaluation of the impact becomes important. A monitoring data analysis technique using an artificial neural network model[7)] (Fig. 3.8.2-4), which can predict changes in groundwater pressure based on the monitoring data, would be one method to quantitatively identify the effect of artificial fluctuations to groundwater pressure[8)].

For monitoring changes in groundwater flow conditions and groundwater chemistry associated with the construction of the underground facilities, boreholes would be required for monitoring the surrounding area to allow measurement of groundwater pressure and sampling of groundwater in the vicinity of the underground facilities. As described above, systems capable of continuous monitoring of groundwater pressure and batch-style sampling bottles are installed in the boreholes at the MIU Construction Site for the continuous monitoring of groundwater pressure and the sampling of groundwater in the surrounding monitoring holes.

In Phase II, the effect of grouting and the changes in groundwater pressure near the shafts should be monitored continuously. Because large differential pressures are expected in the borehole, monitoring equipment that is applicable in such an environment should be developed.

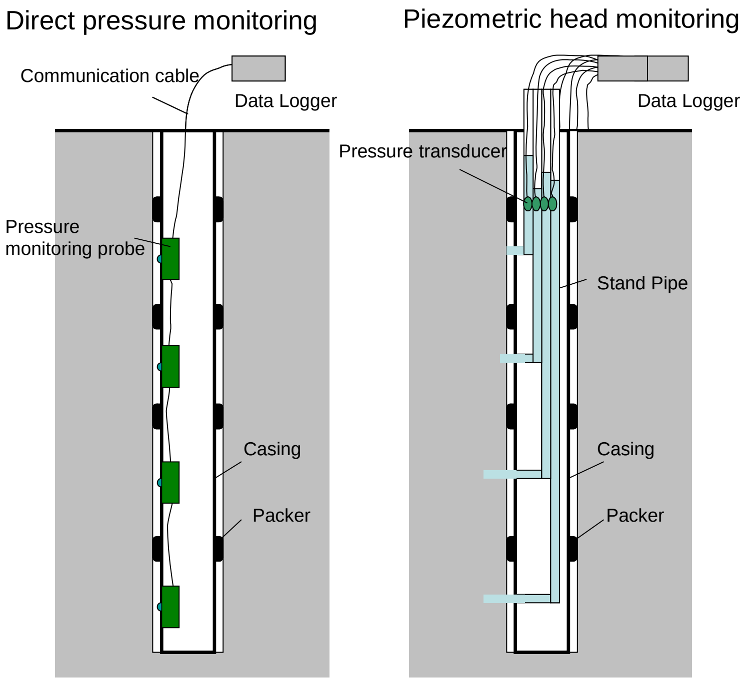
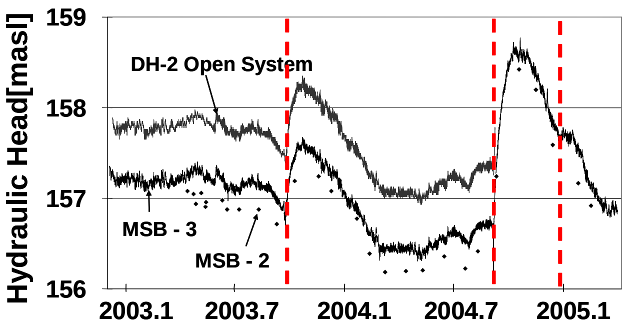


Fig. 3.8.2-1 Schematic of Long-term Monitoring System Configuration [6)]



(Red dashed vertical lines indicate earthquakes)

Fig. 3.8.2-2 Example result of hydraulic head monitoring

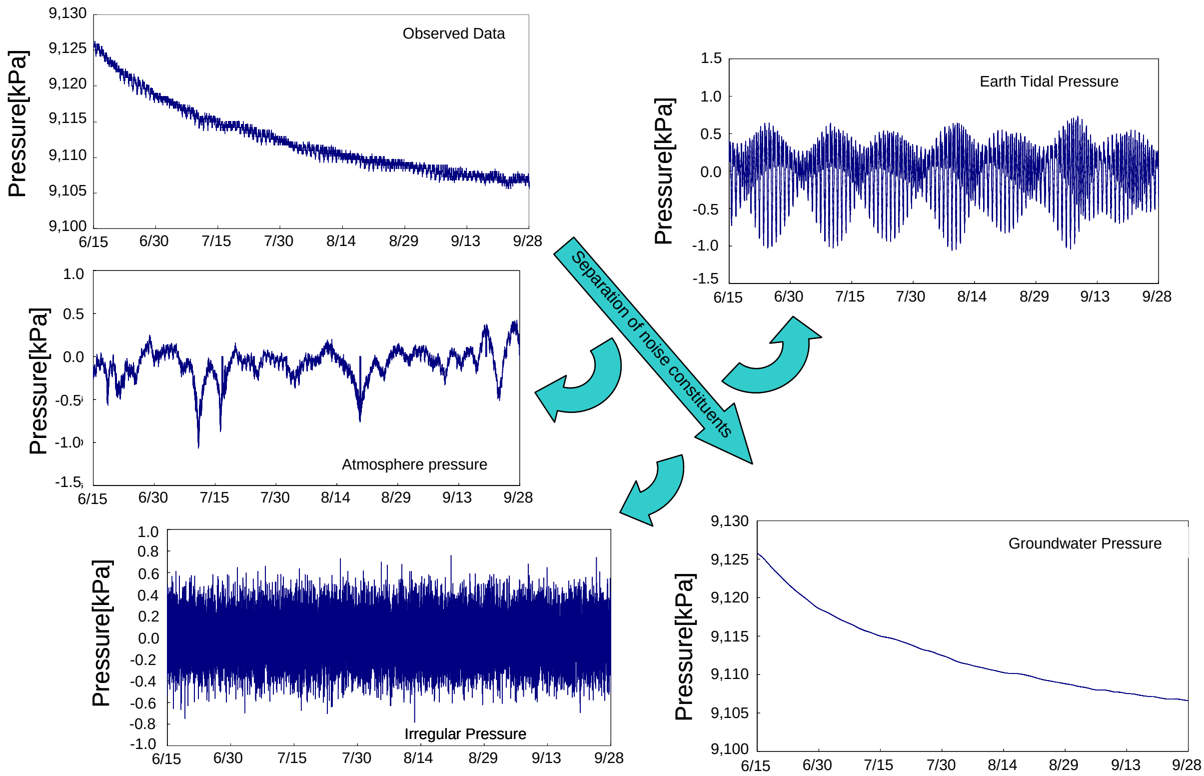


Fig. 3.8.2-3 Elimination of noise constituents from groundwater pressure [6)]

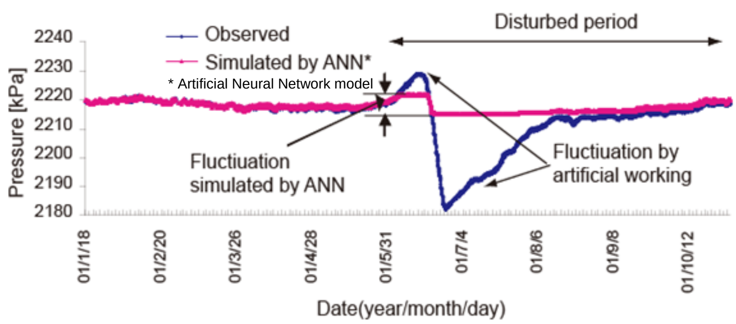


Fig. 3.8.2-4 Comparison between observed and computed hydraulic pressure fluctuations during disturbed period (Modified from Gautam et al, 2003 [8)]).

3.8.3 Determining changes in groundwater chemistry

Determining the initial geochemical characteristics of groundwater in and around the MIU Construction Site and changes in the groundwater chemistry associated with the excavation of the underground facilities is one of the goals of monitoring groundwater chemistry. At the time of the excavation of the underground facilities, phenomena such as changes in the redox conditions at shallow depth, changes in concentrations of dissolved species due to the change in the redox conditions and degassing of dissolved gas are expected due to the reduction in groundwater pressure resulting from the inflow of groundwater into the tunnels from the surrounding rock. Of the monitoring systems available, a piezometer measurement system is highly likely to disturb the groundwater pressure in the monitoring intervals through continuous pumping in order to collect groundwater samples. A pumping system would cause degassing of dissolved gas at the time of sampling. Therefore, in order to monitor phenomena associated with the excavation, it would be preferable to collect groundwater using batch-type sampling bottles in order to keep the in-situ pressure of water samples. However, when dissolved gas is not used as an indicator, it would be possible to monitor geochemical characteristics of groundwater utilizing a pump system.

In order to evaluate changes in the groundwater chemistry for the area extending several tens to several hundreds of meters from the underground facilities, sampling of groundwater and chemical analysis of the sampled groundwater have been carried out since Step 2 for the groundwater in the Mizunami Group once a month in a deep borehole at the MIU Construction Site. The monitoring system used was a direct measurement system for groundwater pressure capable of using batch-type sampling bottles. The sampling frequency was determined based on the number of monitoring sections (around ten) and the time required for the monitoring (1-2 days per section). The basic data thus obtained will be used to evaluate the groundwater chemistry under natural conditions and the changes associated with the excavation of the underground facilities. For quantitative analysis of the changes in groundwater chemistry, the range of variation under natural conditions should be evaluated in advance to allow such variations to be distinguished from excavation-induced changes. Fig. 3.8.3-1 shows monitoring results for the variation in pH and concentration of chemical components in the groundwater in the Mizunami Group under natural conditions obtained in the borehole MSB-2 approximately 70 m distant from the Main Shaft location before the start of excavation[9)]. The figure shows the monitoring results obtained over a period of 14 months from January 2003 to March 2004, with the average, maximum and minimum values in each monitoring interval. It can be seen that the variation range of each chemical component is different even though this includes errors generated in the process from groundwater sampling to analysis. The variation for pH value in the groundwater was larger at shallower depth, which may reflect the difference in recharge rate of surface water depending on the timing of the sampling. It also indicates that the variation is smaller at larger depths close to the low permeable formation. Therefore, when constructing underground facilities, it is important to determine the natural variation range for each chemical component before evaluating the presence of excavation-induced disturbances in each geological structure.

Changes in groundwater chemistry around the underground facilities will be evaluated using seepage water samples collected from the shaft wall immediately after the excavation. The shafts were designed such that groundwater outside the lining concrete can be collected using water collection rings mounted on the shaft wall.

In Phase II, for evaluating the effect of grouting on the groundwater chemistry and changes of the system controlling field conditions around the underground facilities, effort will be made to establish a technique for sampling rock and groundwater from boreholes drilled in the underground facilities and to develop and improve monitoring of geochemical characteristics of groundwater using boreholes with high differential pressure vicinity of the underground facilities.

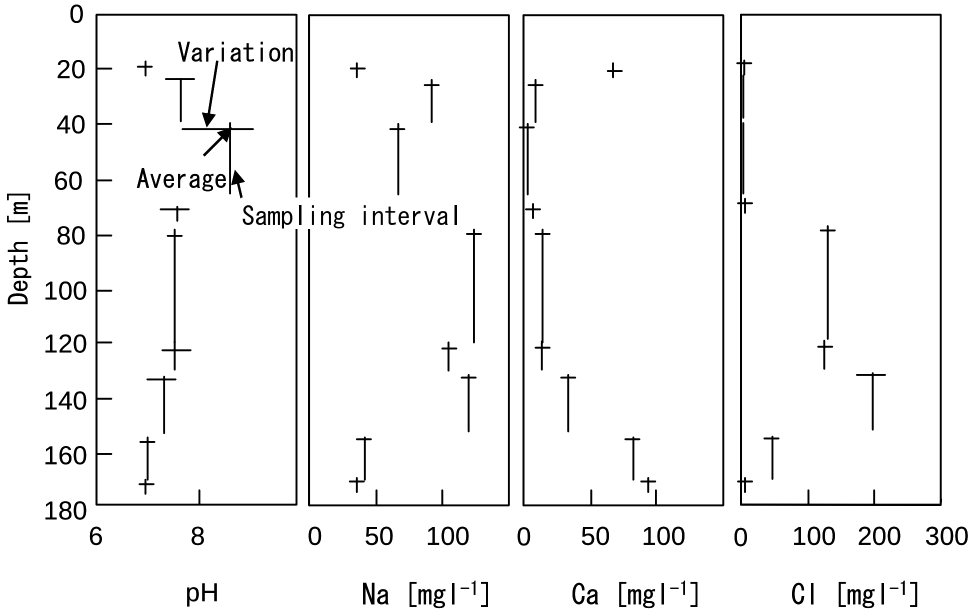


Fig. 3.8.3-1 Monitoring results of groundwater chemistry before shaft excavation[9)]

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3.9 Model predictions for excavation effect of underground facilities

This section summarizes the results of predicting the changes in the deep geological environment due to excavation of the underground facilities for the Phase II investigations based on the results of the Phase I investigations described in sections 3.2 to 3.8.

3.9.1 Geological structures around the underground facilities

Geological structures around the underground facilities were characterized (Fig. 3.9.1-1 and Fig. 3.9.1-2) based on the geological model developed in Phase I (see also section 3.6.1).

The sedimentary rock formations concerned include, from the top, the Akeyo Formation, the Hongo Formation and Toki Lignite-bearing Formation. These overlie the Toki Granite, separated by an unconformity. The Toki Granite can be divided into a weathered zone and an upper highly fractured domain; the latter can also be subdivided into a highly fractured zone dipping at a low angle and a lower sparsely fractured domain. The upper highly fractured domain and lower sparsely fractured domain are predicted to occur in the granite at a depth of about 500 m, where the Middle Stage will be constructed (Fig. 3.9.1-2). Meanwhile, the granite at a depth of about 1,000 m where the Main Stage will be constructed is predicted to be the lower sparsely fractured domain.

The discontinuities generally have NNW, NW, EW and NE strikes, with the NW and NNW strikes being predominant. The features with NW and NNW strikes are predicted to intersect the area between the Main Shaft and Ventilation Shaft from the near-surface. They are also expected to be encountered at the Middle Stage. The NW and NE strikes are predicted to encounter the Main Stage. Since all the discontinuities thus predicted dip at high angles, the following conclusions can be drawn. First, the actual depths where these discontinuities are encountered in the shafts may differ greatly from the predictions and extensive fracture zones may occur along the shafts because of the small angles between the faults and the shafts. (The fractured zones are indicated in blue in Fig. 3.9.1-1; their widths were calculated based on the information from borehole investigations.)

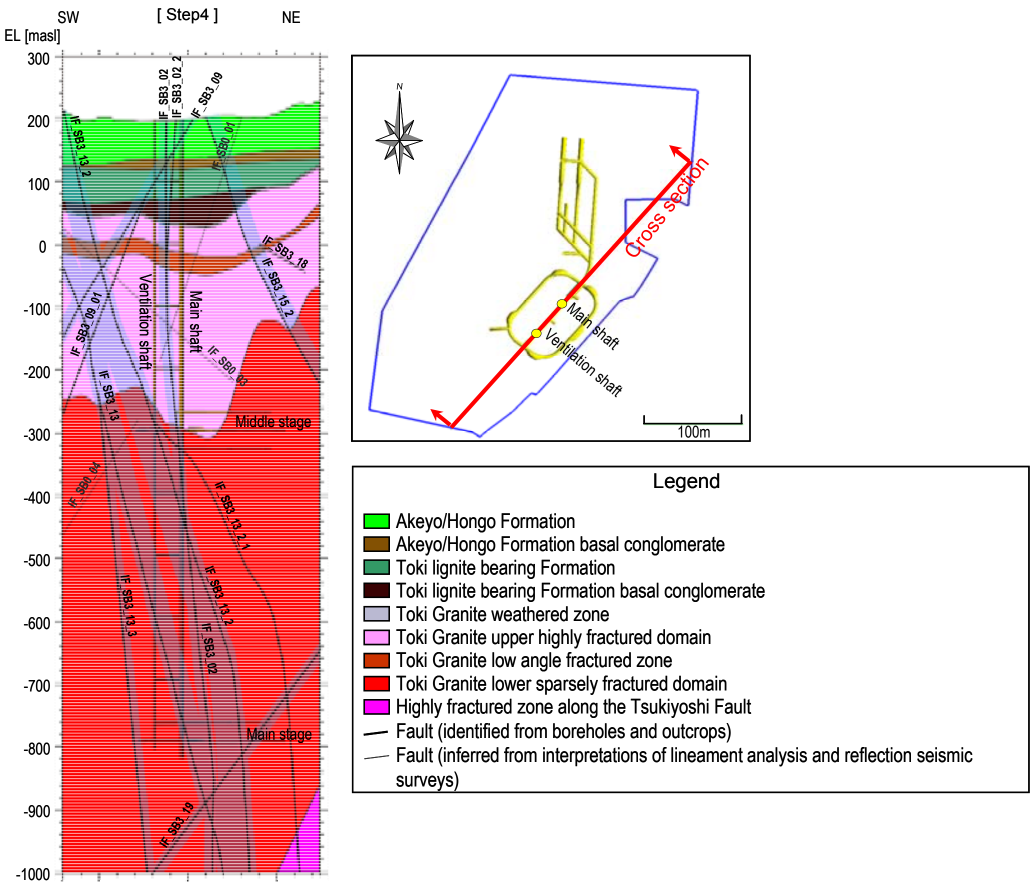


Fig. 3.9.1-1 Predicted geological structures around the MIU facility (Step4)

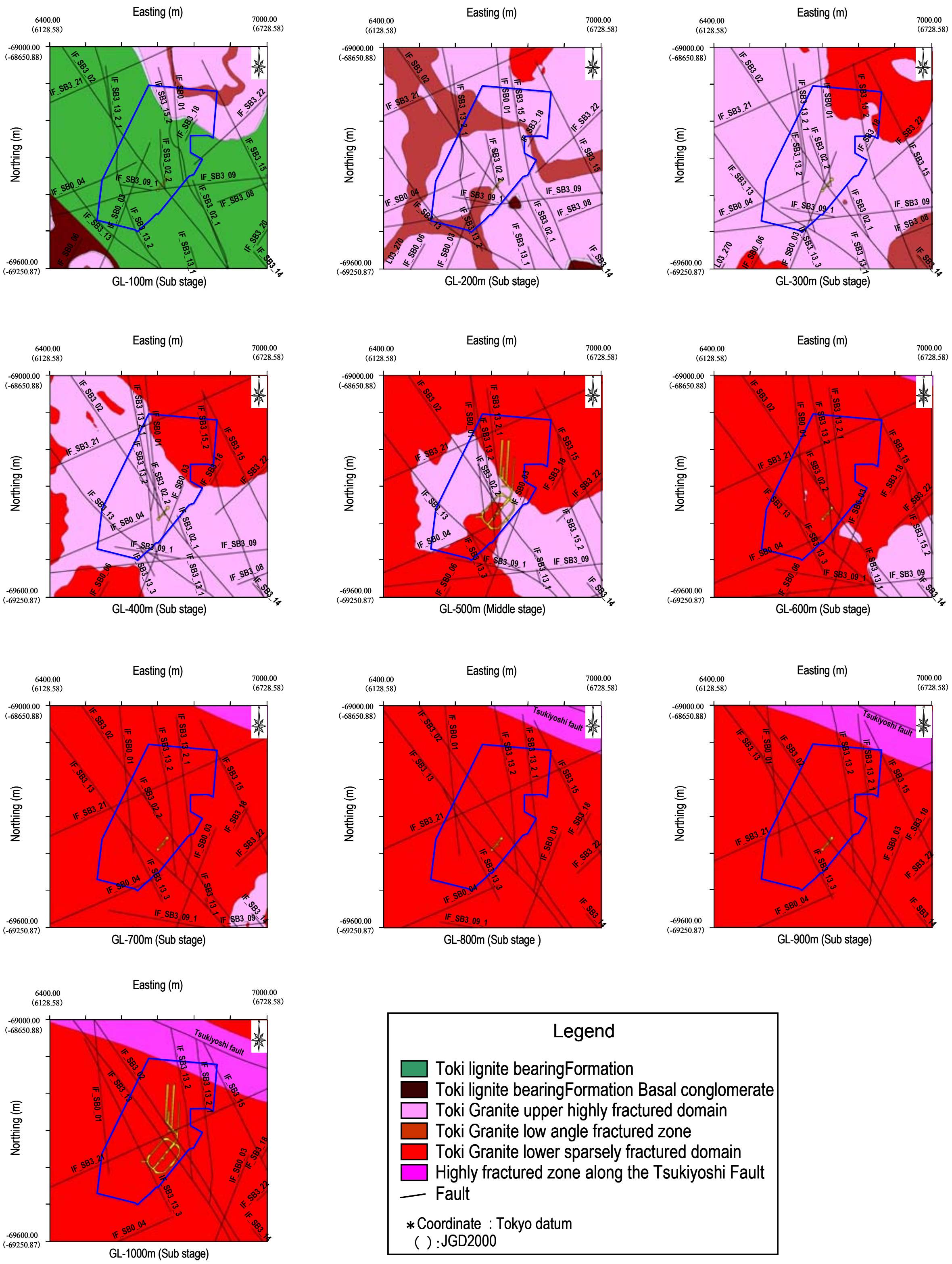


Fig. 3.9.1-2 Horizontal sections through the Step4 Geological model (100 m intervals)

3.9.2 Hydrogeological structures around the underground facilities and changes in groundwater flow-field associated with excavation

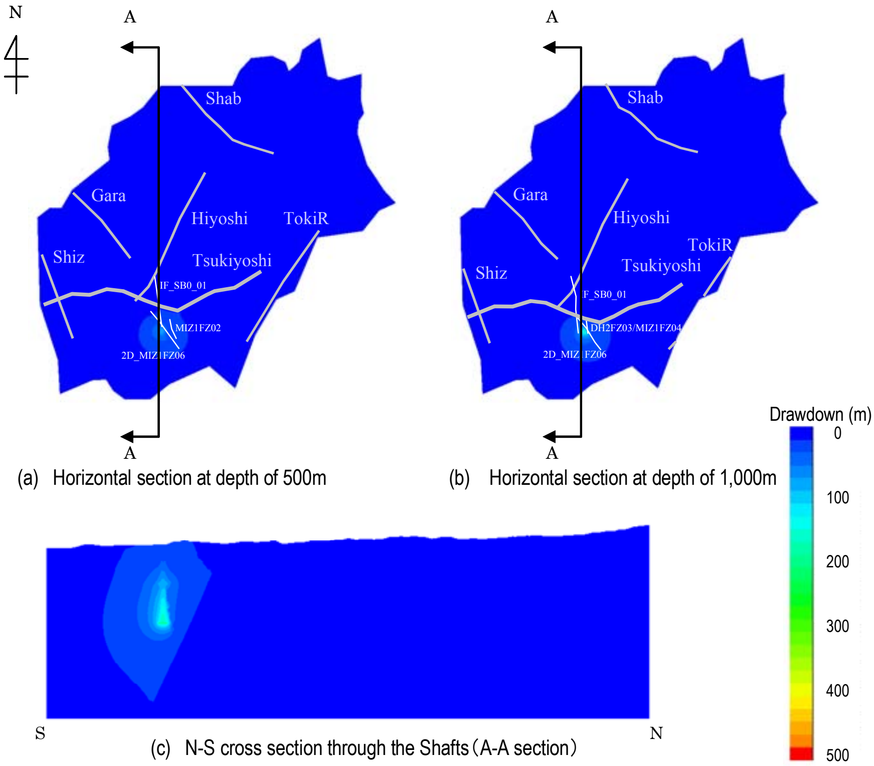
Hydrogeological structures around the underground facilities were predicted in Step 0 to Step 4 (see also sections 3.2.2, 3.3.2, 3.4.2, 3.5.2 and 3.6.2. In addition, based on the hydrogeological model, a groundwater flow analysis taking into account the excavation of the underground facilities was conducted to predict the volume of groundwater inflow into the underground facilities (see also sections 3.4.6, 3.5.7 and 3.6.4). In order to include the effects of the concrete lining and drainage mats installed between the lining and the rock on the groundwater inflow rate from the wall, the concept of the pressure relief factor α was introduced. This was defined as the internal boundary conditions in the groundwater flow analysis so that the boundary condition of the wall was set to that between the atmospheric pressure condition and no-flow boundary condition.

The result of the analysis indicated that, when the pressure relief factor is large (i.e. close to the impermeable boundary; pressure relief factor = 0.8), drawdown of the head is limited to the area around the MIU Construction Site, surrounded by several modeled faults (Fig. 3.9.2-1(a)). However, when the pressure relief factor is small (close to complete atmospheric pressure conditions; pressure relief factor = 0.2), drawdown of the head is found to extend over a wider area. Although dwardown of a head in the order of a few tens of meters does not reach the north side of the Tsukiyoshi Fault, which is a low permeable structure present to the north of the MIU Construction Site, drawdown of the head increased in an east-west direction (Fig. 3.9.2-1(b)).

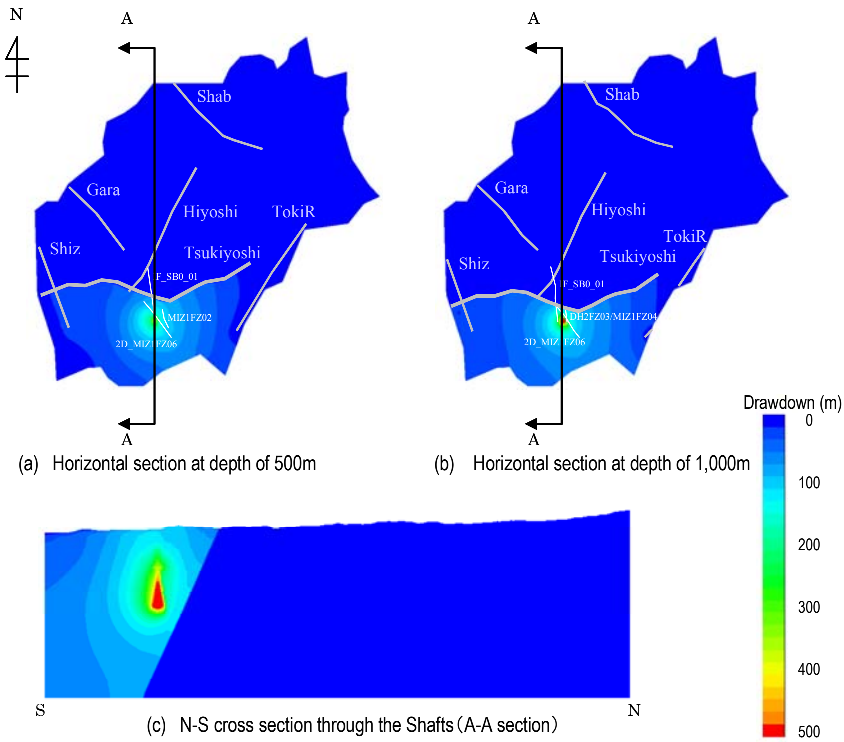
The results of the above analysis indicated that a large volume of groundwater would inflow into the underground facilities from the highly permeable zones, particularly when the pressure relief factor is small. Thus, measures for reducing water inflow, such as grouting, should be applied in areas where a high groundwater inflow rate is expected. As described above, the permeability of the rock around the shafts can be reduced by grouting only the areas where a lot of seepage occurs.

Drawdown in the case of a low pressure relief factor would come close to drawdown in the case of a high pressure relief factor when the internal boundary condition takes into account the grouted zone as well as concrete lining and drainage mats. The drawdown area would then be limited around the MIU Construction area.

Thus, as described in section 3.7.7 and elsewhere, changes in the groundwater flow-field associated with the excavation of the underground facilities, such as a reduction in the groundwater pressure, may be strongly influenced by the skin effect generated by artificial structures, grouting and human impacts associated with the construction and excavation work. Therefore, a groundwater flow analysis should be performed using the hydrogeological model developed in Phase I and internal boundary conditions reflecting the in-situ conditions for the impacts associated with construction. The hydrogeological model should then be tested by comparing the analysis results with the measured values.



(a) Pressure relief factor: 0.8



(b) Pressure relief factor: 0.2

Fig. 3.9.2-1 Drawdown distribution after construction of underground facilities

3.9.3 Distribution of groundwater chemistry around the underground facilities and changes associated with excavation

The distribution of groundwater chemistry around the underground facilities was estimated by deep borehole investigations as described in section 3.5.3. In order to predict the hydrochemical impact on the surrounding environment associated with the excavation of the underground facilities, a thermo-hydro-geochemical coupled analysis was conducted using the codes TOUGHREACT[1),2)] and PHREEQC[3)], based on the estimated distribution of groundwater chemistry and the hydrogeological information.

For the predictive evaluation of the evolution of the EDZ over a long period of time, a cylindrical two-dimensional model with a diameter of 8 km and a depth of 2 km, including the existing groundwater monitoring boreholes, was used in the analysis, assuming that a shaft with a diameter of 6.5 m is excavated in the center of the model to a depth of 1,000 m at a constant excavation rate over a period six years. The model domain was meshed into 29 formations (2 to 500 m) x 23 ring elements (5 cm to 1,600 m), which totals 667 meshes. Changes in the conditions around the shafts were predicted with the boundary conditions set as follows to be consistent with the existing groundwater flow analysis: the pressure at the upper surface is fixed to be constant at 0.1 MPa, the lateral boundaries are permeable with constant temperature/pressure and the bottom boundaries are no-flow with constant temperature and closed conditions[4)]. It should be noted that the sealing effect of the lining concrete in the shafts and the distribution of hydraulic conductivity in the Toki Granite were factored into the assumption.

The results indicated that the groundwater pressure around the shafts would be reduced several months after the start of excavation due to seepage from the shaft walls and that the groundwater pressure immediately beneath the low permeability formation would drop below atmospheric pressure, resulting in 43 kPa absolute pressure after one year. It was also predicted that air would start to infiltrate into the shallow formations due to seepage from the shaft wall, leading to expansion of the unsaturated zone with the progress of excavation. Degassing from the groundwater was predicted to start in the granite around the shafts three years after the start of excavation. The extent of degassing is expected to be around 20 m from the shaft; gases presently observed in the groundwater, such as methane, carbon dioxide and hydrogen sulphide, are expected to be degassed. Furthermore, pH, Eh and groundwater chemistry are expected to change due to infiltration of air, degassing and groundwater flow.

The results of the predictive analysis described above (on the timing and extent of these phenomena) may vary depending on changes in work processes, such as the excavation rate. However, the phenomena predicted by this analysis were also observed during other borehole investigations conducted to date and are therefore highly likely to occur during the excavation of the underground facilities. The rate at which these phenomena occur is predicted to depend on the difference in hydrogeological structures. Thus, the predicted phenomena should be reflected in the plans for the Phase II investigations referring to the 3-D spatial distribution of faults and impermeable layers around the planned excavation areas for the underground facilities. In addition, the validity of the predictive analysis results will require confirmation through future monitoring.

A more reliable predictive analysis methodology would be one of the technologies used for estimating geochemical characteristics of groudnwater in the period after closure of the repository. The reliability of the results of predictive analyses should be improved by ongoing validation using other calculation codes.

3.9.4 Geomechanical properties of rock around the underground facilities and changes associated with the excavation

The geomechanical properties of rock at the MIU Construction Site estimated in Phase I are represented by the rock mechanical model constructed in Step 3 (see also section 3.5.6). Specifically, rocks from classes A to CL according to the rock mass classification applied by CRIEPI are assumed to be present around the underground facilities. The petrophysical/geomechanical characteristics of the rocks in each class were defined based on data from the investigations in Step 3 (Table 3.9.4-1). Data required for the predictive analysis of rock behavior around the underground facilities resulting from excavation may include initial stress states, fracture characteristics and hydraulic conductivity, as well as petrophysical/geomechanical properties. These input data were also defined based on the data from the investigations in Step 3.

Predictive analyses of rock behavior around the underground facilities associated with excavation were conducted based on the data mentioned above. The predictive analyses for the Main Shaft Inset at a depth of 500 m consisted of 3-D analyses using the MBC model, the crack tensor model and the virtual fracture model (Fig. 3.9.4-1 and Fig. 3.9.4-2). The MBC and crack tensor models are equivalent continuum models capable of taking the influence of discontinuities into account.

For the case where the excavation damaged zone was considered, analyses using the MBC model showed no significant differences regarding behavior such as rock deformation (Fig. 3.9.4-3), maximum shear stress, local safety factor, fracture aperture distribution (Fig. 3.9.4-4), etc. from the case without consideration of the excavation damaged zone. Comparing the results obtained using the crack tensor model and the virtual fracture model, no significant differences were recognized in the maximum shear stress and safety factor, although rock deformation (Fig. 3.9.4-3) and the increase in hydraulic conductivity (Fig. 3.9.4-5) differed between the models. Thus, it was confirmed that differences between the models used may result in different outcomes. The cause of these differences can probably be attributed to the fracture modeling technique.

In the next phase and beyond, the initial stress data and petrophysical/geomechanical data should be acquired by borehole investigations in the sub-stages; ground displacement and convergence should be measured with a range of instrumentation in the underground facilities. By comparing the measured data with analysis results, as well as through in-situ tests on excavation damage, the appropriateness of input values and analytical methods will be evaluated, while examining the applicability of discontinuity analyses.

Table 3.9.4-1 Average of petrophysical / mechanical properties (MIZ-1)

Rock mass classification*	Apparent specific gravity	Moisture content (%)	Effective porosity (%)	Unconfined Compressive Strength (MPa)	Rock Young's modulus **(GPa)	Rock mass Young's modulus *** (GPa)	Poisson's ratio	Cohesion (MPa)	Angle of internal friction (°)
A	2.63	0.37	1.10	143.0	50.6	50.6	0.29	39.7	51.1
B	2.62	0.40	1.12	159.6	50.3	50.3	0.27	39.3	52.6
CH	2.63	0.36	0.98	181.3	55.8	49.3	0.27	34.3	52.4
CM	2.59	0.92	2.43	174.7	53.7	50.5	0.18	37.6	49.3
CL	2.34	5.31	12.65	71.8	20.9	20.9	0.24	25.2	30.1

* :Method by Central Research Institute of Electric Power Industry (CRIEPI)
** :50% tangential Young's modulus
***: Revised using the following expression

Rock mass's E =Rock's E × Fracture coefficient

where; fracture coefficient = $(Vp_{(site)} / Vp_{(lab.)})^2$

$Vp_{(site)}$: P-wave velocity by sonic wave logging

$Vp_{(lab.)}$: P-wave velocity by ultrasonic wave velocity test in laboratry

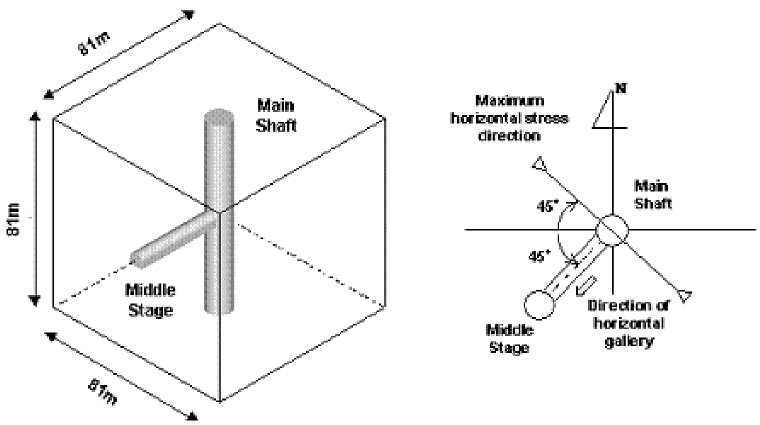
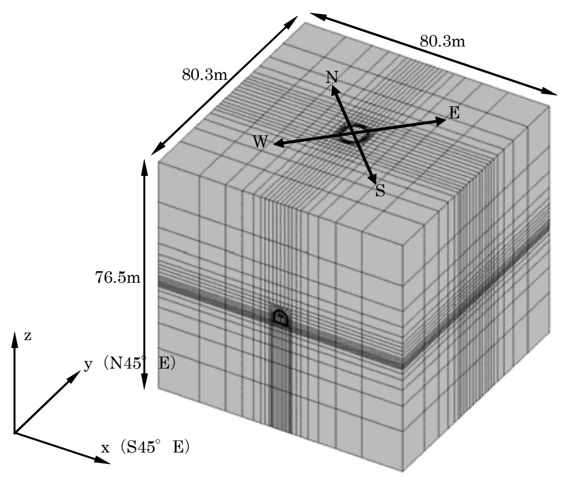
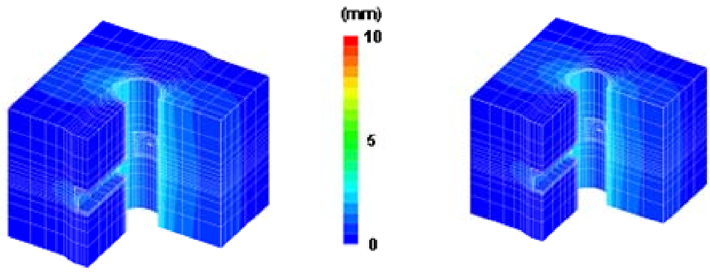


Fig. 3.9.4-1 Direction of horizontal gallery



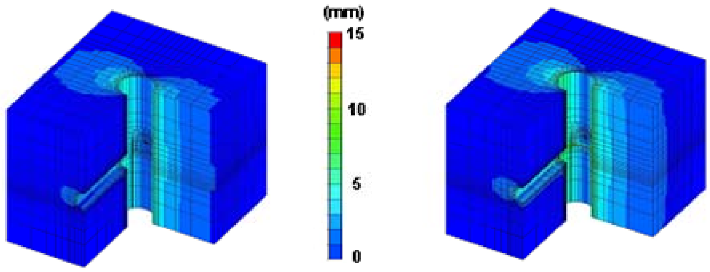
(Crack tensor model and virtual fracture model)

Fig. 3.9.4-2 Example of analysis mesh



No Excavation Damaged Zone　　　Includes Excavation Damaged Zone

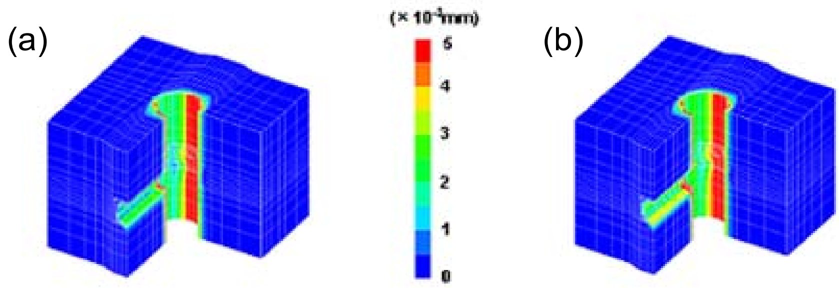
(a) MBC model



No Excavation Damaged Zone　　　Includes Excavation Damaged Zone

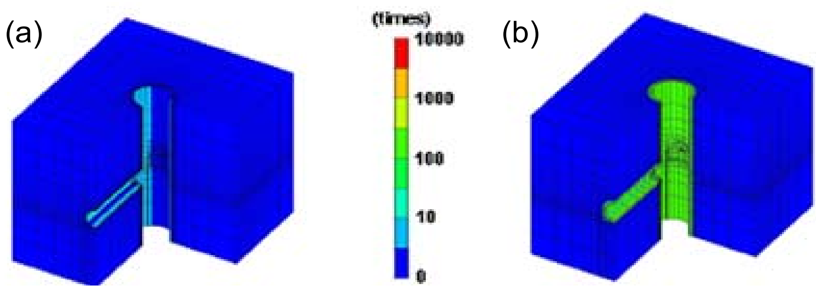
(b) Crack tensor model and virtual fracture model

Fig. 3.9.4-3　Distribution of rock displacement (Class CH)



(a) No Excavation Damaged Zone　　　(b) Includes Excavation Damaged Zone

Fig. 3.9.4-4　Distribution of fracture aperture based on MBC model (Class CH)



(a) No Excavation Damaged Zone　　　(b) Includes Excavation Damaged Zone

Fig. 3.9.4-5　Increase in hydraulic conductivity based on Crack tensor model and virtual fracture model (Class CH)

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4. Geoscientific study: Technology and technique development

In the MIU project, various types of studies were carried out to improve, in a stepwise manner, the understanding of the characteristics of the geological environment as described in sections 3.2 through 3.7. The technologies and techniques required for investigation and analysis were also developed and improved. Technologies and techniques whose applicability was confirmed in Phase I include those for predicting the spatial distribution of discontinuities based on a combination of lineament survey and surface geological mapping, various ground geophysical surveys for accurately determining the spatial distribution of geological structures and discontinuities and a series of geological, hydrogeological and geochemical investigations during borehole drilling and in completed boreholes. Geological and hydrogeological modeling approaches and analysis/estimation techniques for groundwater flow and groundwater chemistry distribution were also established.

This section overviews the technologies and techniques, which are considered to be important for effectively and accurately investigating, analyzing and assessing the characteristics of the geological environment and managing the quality of study results in Phase I. The technical know-how regarding these technologies and techniques are also described. Appendix 8 summarizes the objectives, background, troubles and/or achievements, know-how and issues of the respective investigation/analysis techniques for the geological environment.

4.1 Lineament surveys

Determining the spatial distribution of discontinuities that may affect groundwater flow and groundwater chemistry is important. Lineament surveys were conducted on several occasions to identify discontinuities in the local-scale area. When the displacement of faults dipping at high angles exceeds normal weathering and erosion rates, or when they are subjected to differential erosion, linear topographic features such as linear valleys or kern-cols would be formed at the surface. The lineaments can be interpreted based on these topographic features. Lineament surveys are used mainly to identify active faults. Based on experience to date, it has been reported that lineaments with a length of 3 km or longer correspond almost 100% to discontinuities such as faults or fractured zones identified by surface geological mapping conducted in locations where lineaments were interpreted[1)]. However, there are a few cases in which the correlation between small-scale lineaments shorter than several kilometers interpreted from large-scale images and discontinuities identified by other investigations have been evaluated. Therefore, it is not clear how short an effective lineament can be for the estimation of discontinuities. Lineaments were interpreted from images with the largest scale among those commonly used (1:10,000 scale aerial photographs) and an evaluation was made to determine the limit of the identifiable lineament scale, interpretation accuracy, etc.[2)]. A comparison was made with faults and fractures identified by surface geological mapping and borehole investigations conducted prior to this in order to evaluate whether or not small-scale lineaments are effective in estimating faults and fractures.

In the lineament interpretation using 1:10,000 scale aerial photographs covering the RHS area, 472 lineaments with lengths of around 100-3,000 m were identified and the trends (direction, distribution density, length, etc.) of the lineaments were found to differ depending on the surface geological conditions. A fractal analysis of the results suggested that the size of lineaments that could be interpreted correctly was about 300 - 1,000 m in the bedrock (late Cretaceous granite) and about 400 - 1,000 m in the Mizunami Group (Neogene Tertiary sediments) (regions approximated by straight lines in Fig. 4.1-1; Table 4.1-1). The images used in this interpretation were on the largest scale of those commonly used for lineament interpretation. The above-mentioned scale (length of about 300 - 400 m) would therefore be the shortest limit for small-scale lineament interpretation. As described above, since lineaments are interpreted based on particular topographic features, the possible width of such features (such as valley width) is in the order of 20 - 60 m, and was taken to represent the uncertainty of the position of the underlying structure. A comparison between lineaments extending over around several hundred meters in length and the faults and fractured zones identified (or inferred) by the existing investigations (surface geological mapping, borehole investigation, etc.) indicates that the distributions and directions of the lineaments and the faults or fractured zones were more or less consistent in several cases (lineaments indicated by blue lines in Fig. 4.1-2). This suggests that lineaments extending over around several hundred meters in length may reflect faults and fractured zones. The results of statistical analyses of fractal properties indicated that the lineaments and fractures observed in bedrock outcrops have similar fractal properties (Fig. 4.1-3). Thus, the distribution of fractures with a scale of several to several tens of meters, which are difficult to identify by outcrop or lineament surveys, may be inferred using the relationship between the lineaments and fractures.

Lineament surveys and their analysis involve several uncertainties. An increase in interpretation errors may result from changes in the possible width of the position perpendicular to the extension of the lineament depending on the difference in scale of the image used in the interpretation, the resolution of the image and the scale of the topographic map onto which the lineament is transferred. In addition, a lineament cannot be identified if the topography artificially alters. Differences in the skill of the interpreters are also a cause of uncertainty and the results of lineament interpretation always contain potential error. Therefore, the method of inferring the distribution of medium-scale discontinuities based on the relationship between lineaments and fractures at outcrop inevitably contains a certain degree of error. Regarding future tasks, the effectiveness of this method should be improved and the uncertainty in the method should be reduced, for example by acquiring and analyzing data on fractures with a length of several to several tens of meters at the time of excavation of the underground facilities.

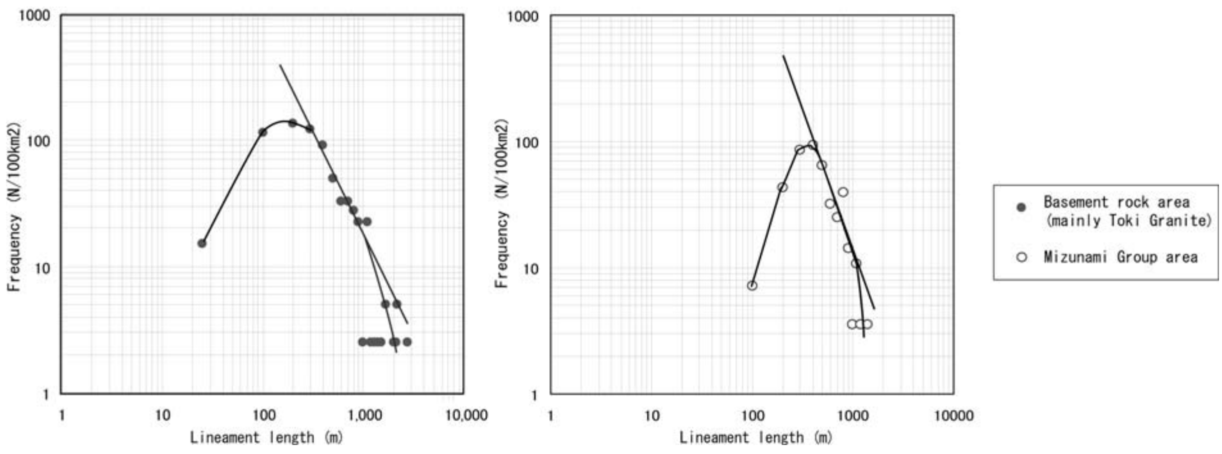


Fig. 4.1-1 Lineament length frequency distribution[2)]

Table 4.1-1 Lineament length defined from 1:10,000 scale aerial photographs[2)]

Class	Possible	Partly possible *1	Difficult *2	May be impossible *3
Basement Rock	300~1,000m	Over 1,000m	100～300m	Under 100m
Mizunami Group	400~1,000m	Over 1,000 m	300～400m	Under 300m

＊1 It is possible to define, but estimation of continuity is difficult.
＊2 Scale of lineament that can be interpreted in some case.
＊3 Scale of lineament that can be hardly interpreted.

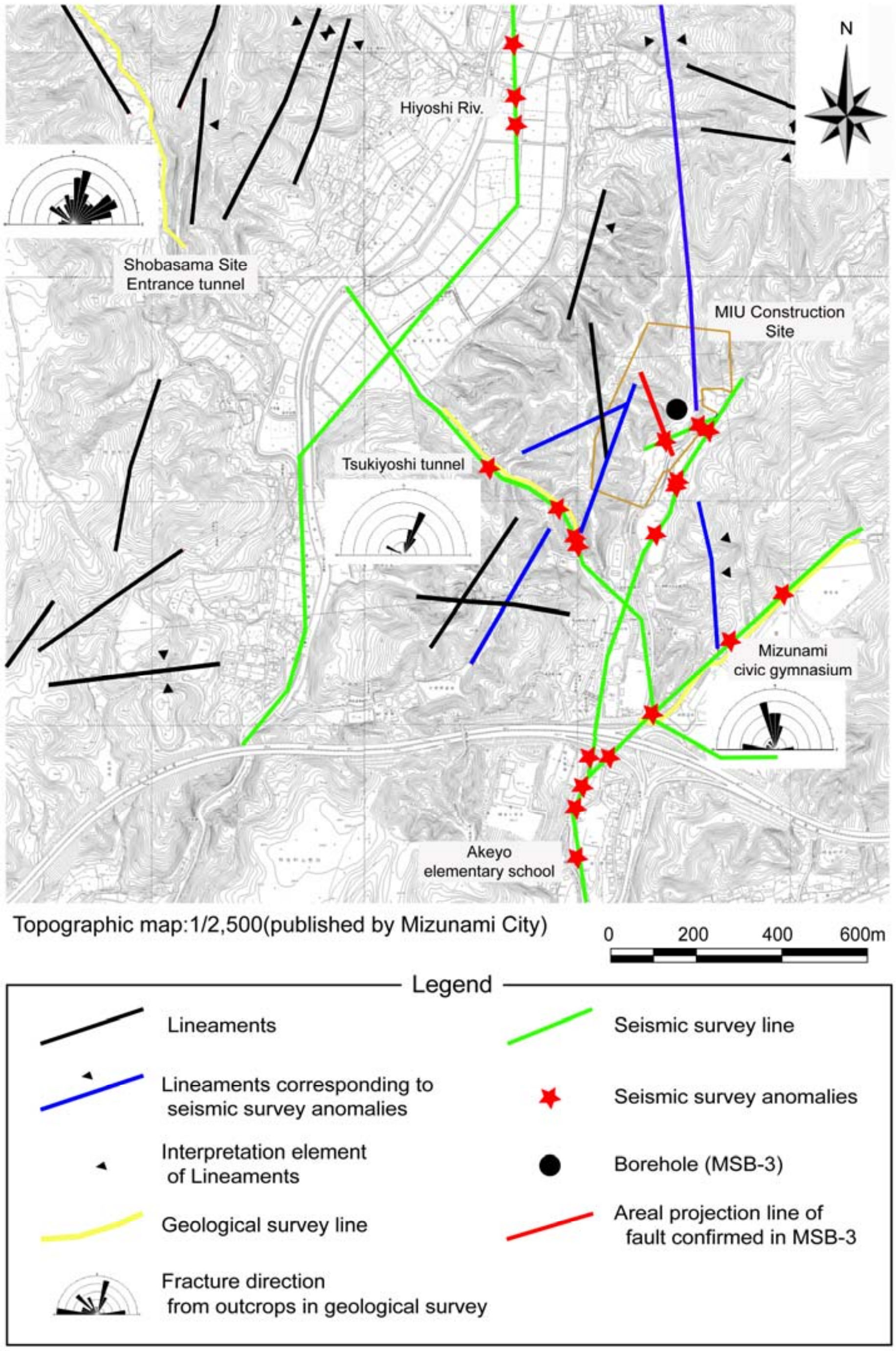


Fig. 4.1-2 Comparison between lineament analysis and other investigation results[2)]

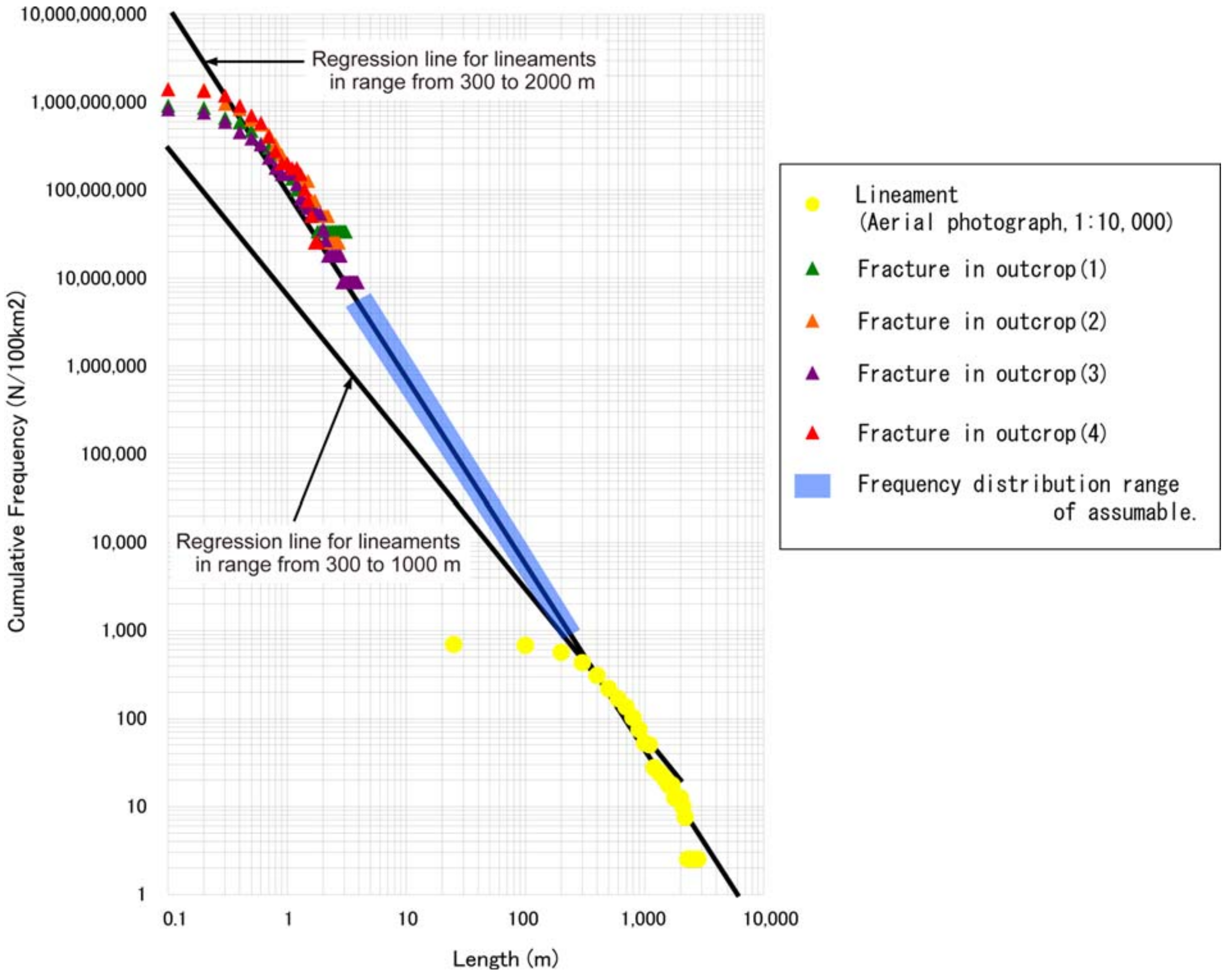


Fig. 4.1-3 Cumulative frequency distributions − lineament and fracture lengths[2)]

4.2 Geophysical survey techniques

<u>Reflection seismic survey</u>

The reflection seismic survey has been developed mainly for characterization of geological structures such as formation boundaries in sedimentary rock. Thus, the applicability of the method to sedimentary rock formations is relatively well understood and data obtained using this method and by borehole investigations are often compared as part of resource exploration carried out in the oil industry and related sectors. In contrast, the applicability of reflection seismic surveys in granite has not been fully evaluated.

In Phase 1, reflection seismic surveys were conducted on the local and site scales, with the source/receiving spacing set to 10-20 m and 2-5 m, respectively[3)]. The reflection profile showed reflection events with good continuity, corresponding to the formation boundaries in the Seto and Mizunami Groups and the unconformity between the sedimentary rock and the Toki Granite, as well as several reflection events at depths corresponding to the upper highly fractured domain in the Toki Granite (see also Fig. 4.2-1(a)). Seen overall, the reflection events observed in the granite seemed to be consistent with the geological structures identified in Steps 0 and 2. However, when compared in detail, some of the geological structures were not consistent with the individual reflection events[4),]. Therefore, as part of developing a technique for more detailed interpretation of geological structures in the granite, several processing and analysis methods were tested to enhance the signal-to-noise (S/N) ratio of reflection events in granite and the reflection imaging accuracy.

A sharp velocity contrast between the sedimentary rock and the granite implied problems such as degradation of imaging due to drastic changes in the waveform obtained in the vicinity of the boundary at the time of normal move-out (NMO) correction and a relative increase in the amplitude of various types of noise due to the reduction of reflection amplitude in the granite. Therefore, the NMO correction and deconvolution parameters focused on the granite were applied without consideration of sedimentary rocks formations as a simple processing/analysis technique. As a result, compared to the reflection profile obtained using regular processing/analysis (Fig. 4.2-1 (a)), the reflection profile obtained using data processing/analysis focused on the granite (Fig. 4.2-1 (b)) agreed better with the events seen in the synthetic seismogram of the granite created based on data obtained by geophysical logging[4)].

Processing and analyses techniques such as surface wave suppression, surface-consistent deconvolution, relative amplitude preservation and pre-stack time migration were also applied. As a result, reflection events in Fig. 4.2-2 (b) (particularly in the area encircled by red dashed lines in Fig. 4.2-2) agreed better with the synthetic seismogram that was calculated from geophysical logging data (sonic and density logging) compared with the result obtained using the regular processing and analyses (Fig. 4.2-2 (a))[5)].

High-density electrical survey

In regions where the granite outcrops, discontinuities dipping at high angles would be difficult to identify using reflection seismic survey compared to regions where the granite is covered with sedimentary formations, because clear reflection events such as formation boundaries in the sedimentary rock that may serve as indicators cannot be obtained. As part of the development of techniques for investigating discontinuities under such conditions, a high-density electrical survey was tested in an area where granite is exposed at the surface[5),6)]. The high-density electrical survey is expected to detect discontinuities based on the difference in resistivity between intact rock in the granite that presents a high resistivity and fractured zone that presents a low resistivity. As a result, a prominent low-resistivity body with approximately several tens of Ωm, which suggests the existence of a fault, was detected at the edge of the analysis profile. However, borehole investigations conducted to check the structure of this low-resistivity body identified no fault at the corresponding depth and also showed an extremely high resistivity (2,000-5,000 Ωm) (Fig. 4.2-3).

The data obtained by the high-density electrical survey were therefore reanalyzed using results obtained by electrical logging in the borehole, which was validated by a simulation analysis[6)]. Reanalysis was carried out using smoothness constrained 2-dimensional inversion[7),8)]. As a result, an artifact image was found to appear at the end of the survey line in the low-resistivity region in the north-east area when a low-resistivity formation was present near the surface along the extension of the survey line. The re-analysis constrained by the results of the electrical logging identified a boundary between the intact rock and the weathered zone in the granite and three discontinuities dipping at medium to high angles (Fig. 4.2-4). Thus, accurate results could be obtained by the high-density electrical survey using the information obtained in the borehole to constrain the analysis. Therefore, such an approach would be effective for accurate interpretation of geological structures in terms of the distribution of weathered zones and discontinuities in the granite. In order to further improve the accuracy of the interpretation, it would be useful to correlate the information obtained in the borehole to the data obtained by the high-density electrical survey by conducting a resistivity tomography survey for the zone between the borehole and the surface. When planning investigation programs, it is also important to set the layout of the survey lines considering the uncertainties of the geological structure concerned.

Multi-offset VSP survey

The multi-offset VSP survey is expected to help in determining the distribution of discontinuities and fractured zones in greater detail than reflection seismic surveys by supplementing the results obtained by the latter. As part of the effort to develop techniques for investigating discontinuities, multi-offset VSP surveys were conducted using boreholes where detailed geological and hydrogeological investigations had been carried out. As a result, discontinuities in reflection events were identified in the profile obtained by stacking offset VSP profiles to which the VSP migration had been applied. The discontinuities were assumed to be faults dipping at a high angle in the deep granite that had been confirmed/inferred by the surface geological mappings and reflection seismic surveys (Fig. 4.2-5(a)(b))[9]. For these faults, a VSP profile was obtained by analyzing and stacking two horizontal components of the 3-component geophone used in the multi-offset VSP survey, in the same way as for the regular offset VSP survey. Reflection events estimated to be directly reflected from these faults (arrows in Fig. 4.2-5 (c)) were identified in the profile thus obtained. Consequently, the distribution of faults dipping at high angles around the borehole was inferred.

The multi-offset VSP survey is thus useful for supplementing the results obtained by reflection seismic surveys. In addition, the distribution of discontinuities dipping at high angles in the deeper part of the geological environment that are difficult to identify by reflection seismic survey can be determined by the multi-offset VSP survey.

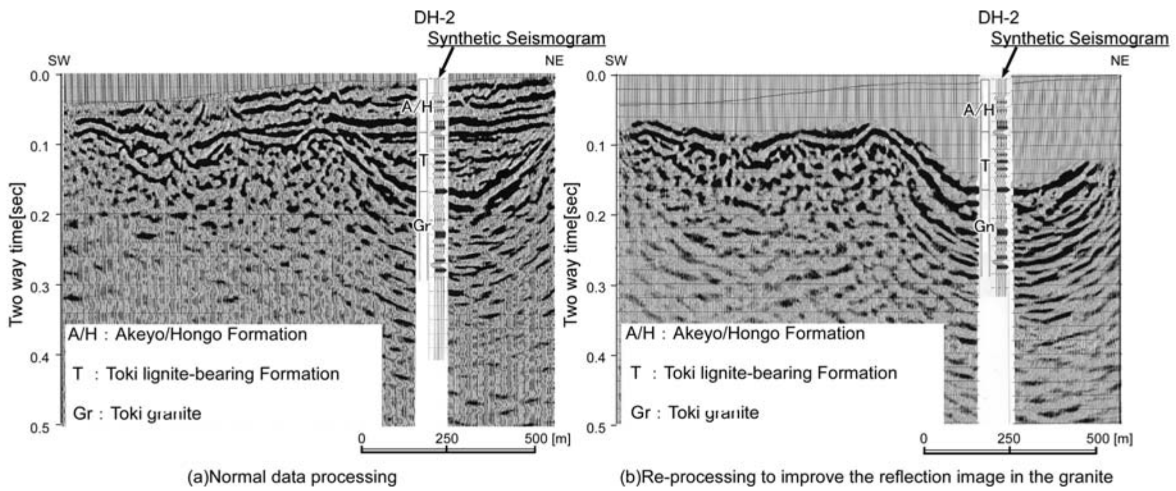


Fig. 4.2-1 Comparison between reflection seismic profiles (1)

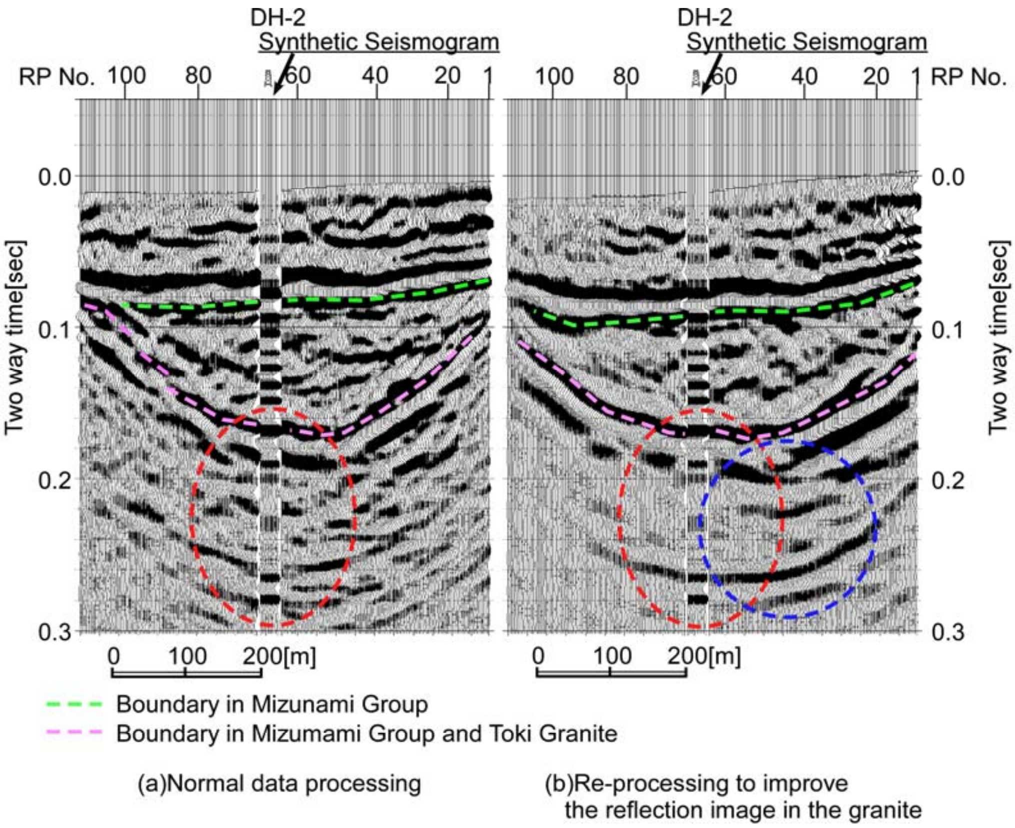


Fig. 4.2-2 Comparison between reflection seismic profiles (2)[5)]

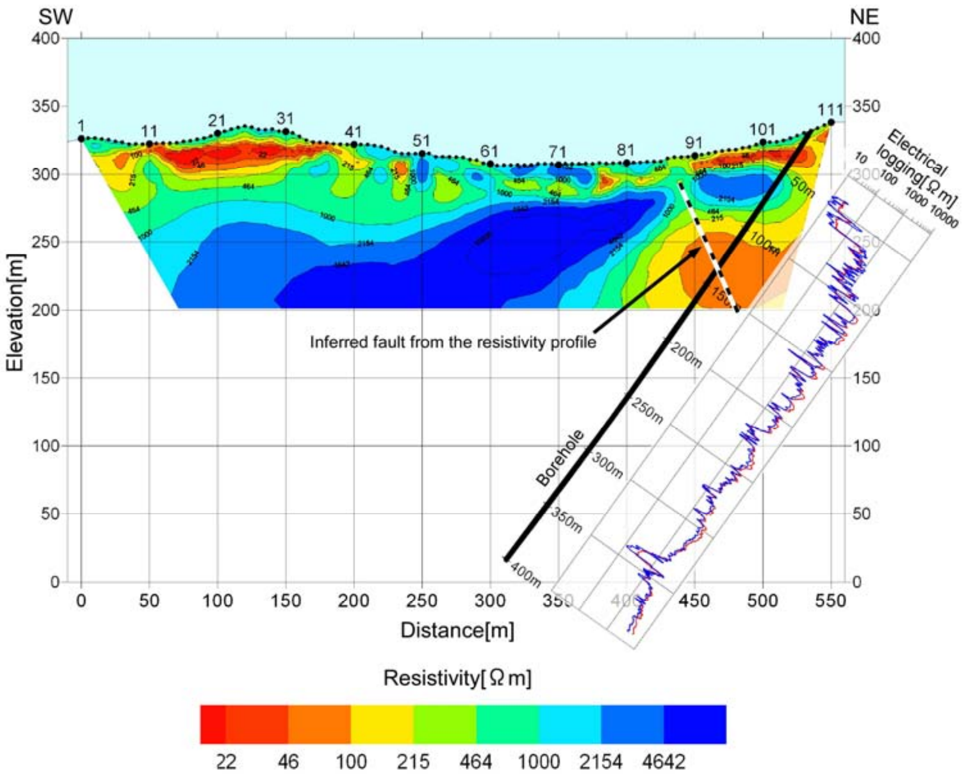


Fig. 4.2-3 Result of electrical survey[6)]

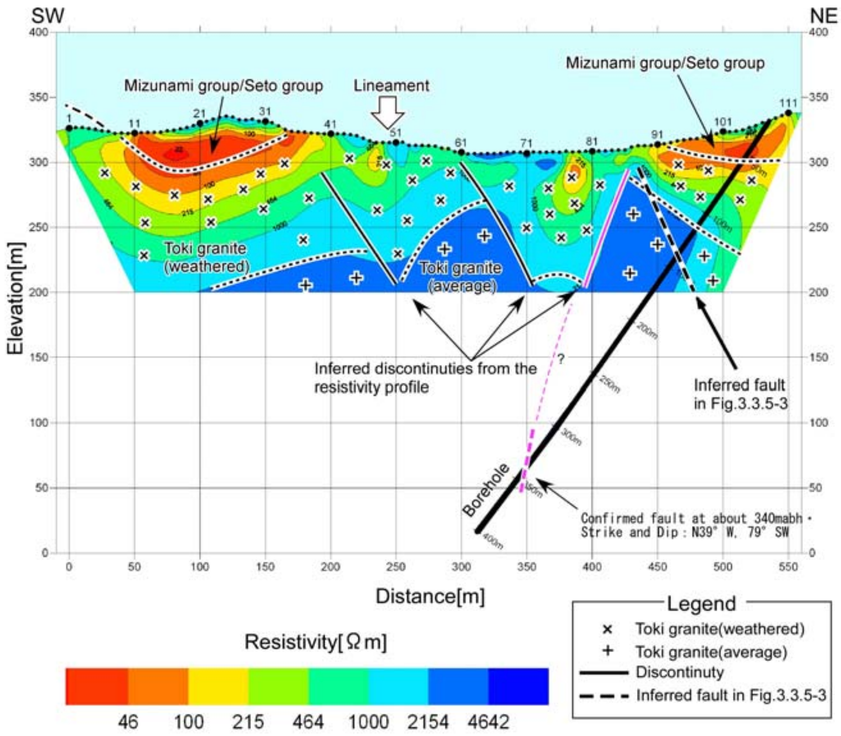


Fig. 4.2-4 Interpretation of resistivity profile[6)]

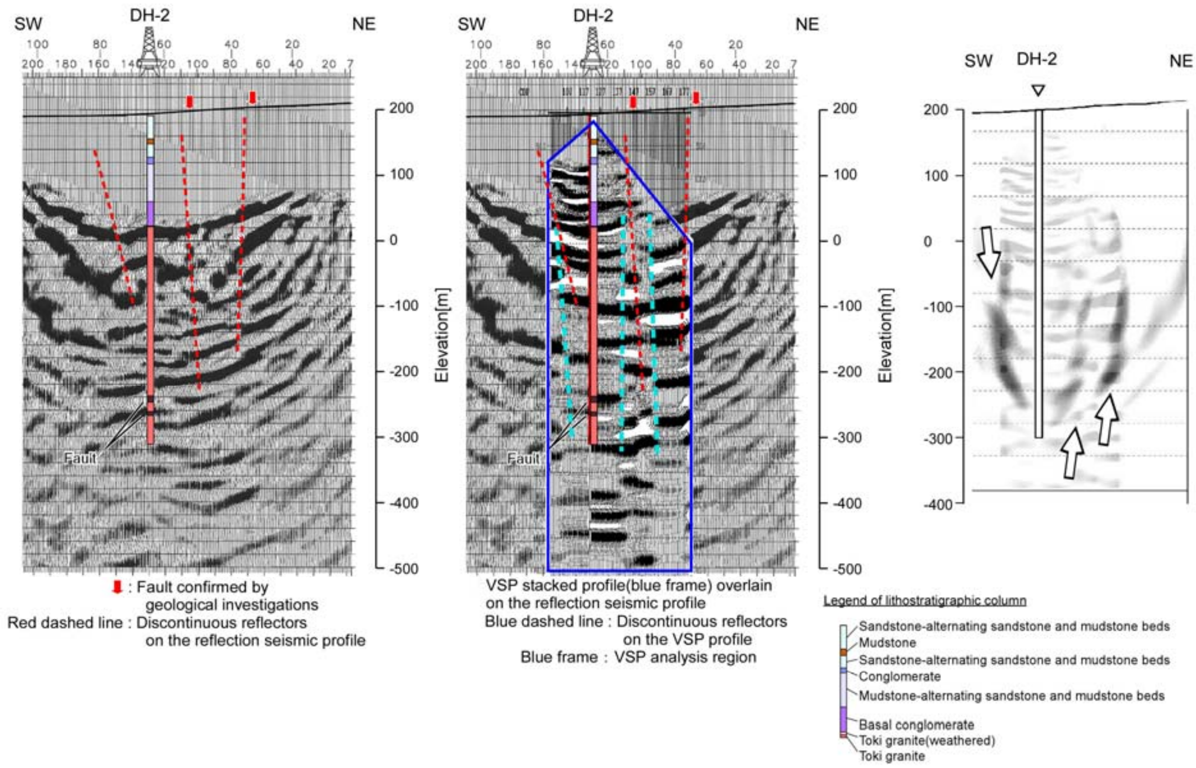


Fig. 4.2-5 VSP Stacked section[9)]
(a) Reflection seismic profile (Right fig.)
(b) VSP stacked section using vertical component of 3-component geophone (Center fig.)
(c) VSP stacked section using horizontal component of 3-component geophones (Left fig.)

4.3 Planning of borehole investigations

Borehole investigations are one of the most effective methods for investigating the geological environment because they allow information on the deep geological environment to be acquired directly from the surface[10]. However, depending on the boundary conditions, various difficulties could occur during the execution of the drilling and testing activities, e.g. borehole collapse. For this purpose, the plans of borehole investigations have to be formulated, with consideration of remedial measures in the case of difficulties, and with the possibility for systematic updates as the investigations progress.

In planning the investigation program, the targets of the investigations should be defined based on the understanding of the geological environment obtained in previous steps. The layout of the boreholes, and the individual investigation items and methods have to be optimized and rationalized based on the results of this understanding as well as restrictions such as time and cost[10]. In particular, drilling procedures must be defined based on predictions of the geological environment, including consideration of the uncertainty in these predictions; they should include the definitions of alternative procedures and techniques in case unexpected occurrences, for example, borehole collapse due to brittle rock conditions, fluid loss due to permeable fractures, etc. It is also important to identify in advance investigation data whose quality may be affected by such countermeasures and to set acceptable limits for data quality level. This information should be agreed among the parties involved in advance, and priorities should be set. In the MIU project, an integrated investigation program was formulated for carrying out investigations in borehole MIU-4 at the Shobasama Site, shallow borehole investigations at the MIU Construction Site (Step 2) and deep borehole investigations (Step 3)[11),12),13]. The appropriate borehole diameter for the expected geological environment, drilling installations such as casing programs and schedules and implementation sections for investigations such as investigations of borehole wall image, fluid logging (see also Section 4.6), hydraulic tests (see also Section 4.7) and groundwater sampling (see also Section 4.8) were coordinated in these comprehensive plans. The results were consolidated in the borehole investigation program as shown in Fig. 4.3-1 for MIZ-1 borehole investigations. Borehole drilling and investigations can be optimized through such a coordination process. Optional measures against troubles such as borehole wall collapse and fluid loss were specified in the program plan in addition to detailed methods for achieving the specific goals of the investigations, such as geophysical logging (see also Section 4.5) and hydraulic tests and quality control measures. It is also extremely important to formulate plans that integrate advice from experts within and outside Japan, because relevant information on troubleshooting during borehole investigations and know-how relating to quality control for data acquisition is seldom readily found.

Borehole investigations provide data on the geological structures, hydraulic characteristic, groundwater chemistry, local stress regime, etc. The costs and time required for drilling activities or stand-by increases as the amount of investigations increases. Investigation requirements in multi-purpose boreholes have therefore to be optimized based on discussions among the parties involved in each investigation. In addition, data and analysis results obtained in different disciplines should be integrated to allow multidisciplinary evaluations to be made for better understanding of the geological environment. For this purpose, an organization structure in the MIU project was established consisting of principal investigators (PI) in charge of coordinating the different disciplines as shown in Fig. 4.3-2, to supervise the various teams and to coordinate investigations. In this way, lateral structures were set up in addition to vertical structures, thereby forming a matrix-type system for implementing the investigations[14].

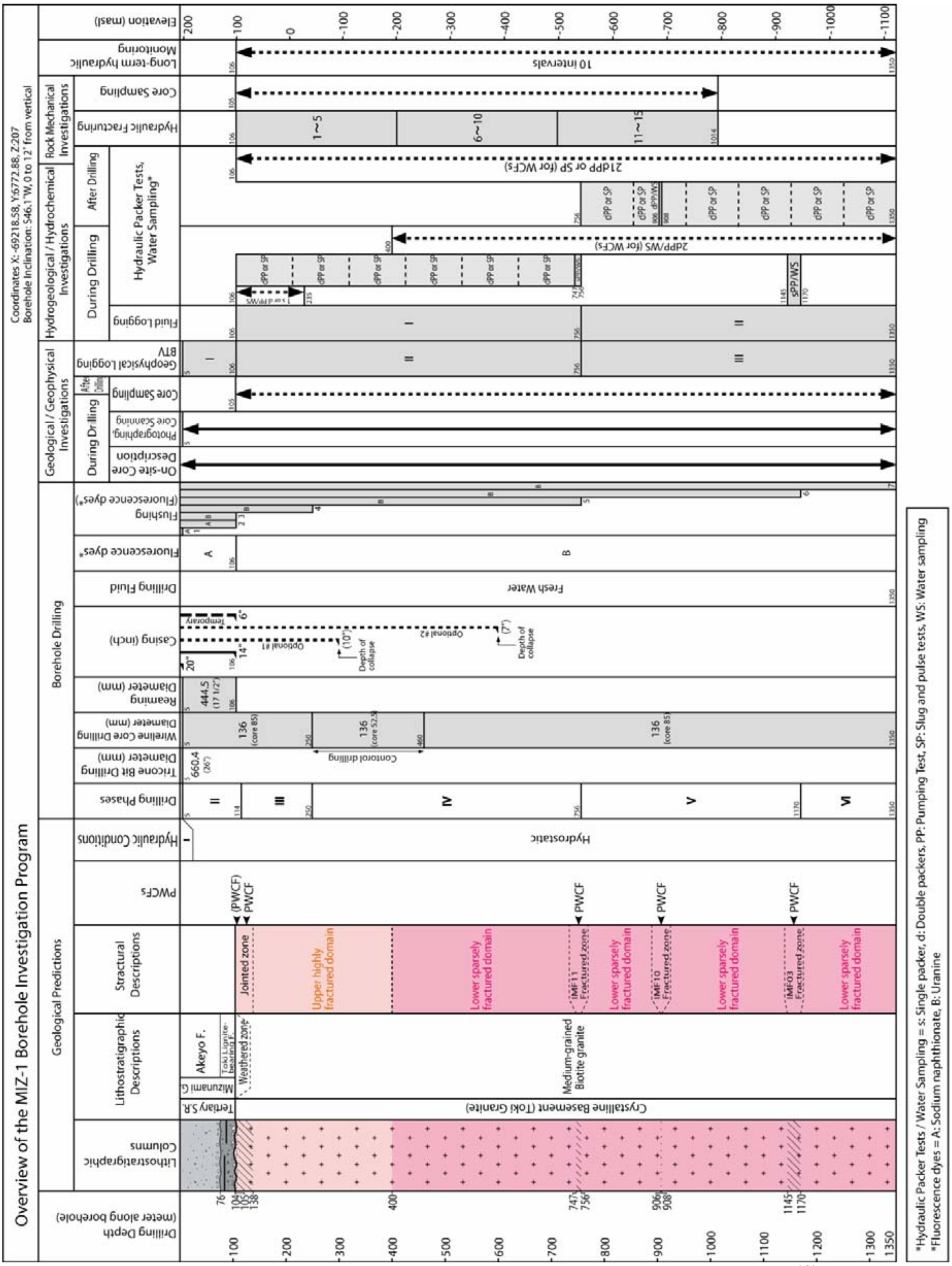


Fig. 4.3-1 Overview of the MIZ-1 borehole investigation program[13)]

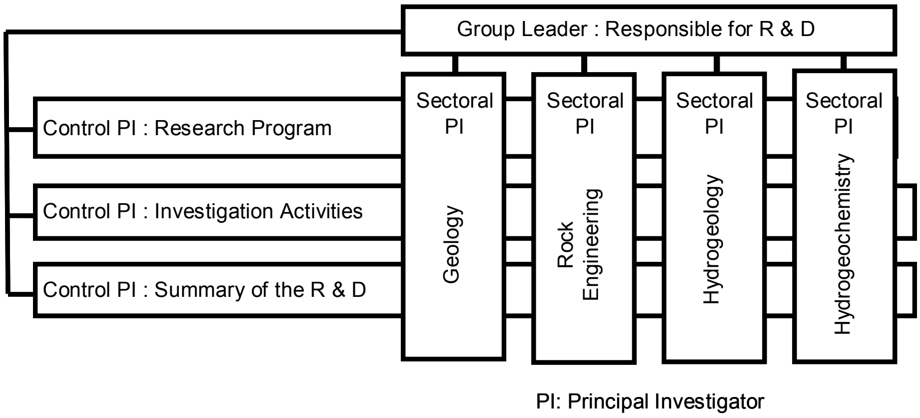


Fig. 4.3-2 Organization control for the promotion of R & D activities in MIU project[14)]

4.4 Borehole drilling

Borehole investigations using drilling fluid involve the introduction of fluids that are different from the groundwater. In the MIU project, investigations have been carried out according to the basic assumption that human-induced impacts should be minimized to avoid disturbance to the geological environment[10)]. Also, based on the experience from the borehole investigations on the Regional Hydrogeological Study and Shobasama Site investigations, it was assumed in the MIU project that difficulties resulting from fluid loss (in which drilling fluid flows out into the rock during drilling) and borehole wall collapse may occur but the scientific borehole investigations e.g. hydraulic testing and geophysical logging can to a certain degree still be conducted even when remediation measures are required. Table 4.4-1 shows the basic specifications of the deep borehole investigations from the surface, mainly covering the Toki Granite.

Borehole diameter

The borehole diameter was set to 5 1/2 inches (approx. 135 mm) or larger. The following describes the technical background[10),15)].

- The rock permeability ranges widely from high to low. Because the degradation of data quality due to pressure loss in the flow lines was of concern, particularly in testing of highly permeable rock, measures such as the use of larger diameter pipes in the test equipment were required. JAEA therefore made improvements such as increasing the pipe diameter in the hydraulic test system (see also Section 4.7). The system was improved based on the assumption that the borehole diameter is 120 mm or larger (equivalent to a drilling pipe of PQ-size or larger) and also considering the need to ensure higher strength of the drilling pipe based on an incident in which a PQ-size drilling pipe broke in the MIU-4 borehole (see also *Strength of the drill-pipe* in this section), resulting in a borehole diameter of 5 1/2 inches (approx. 135 mm) or larger.
- Although sampling of groundwater may be completed in a relatively short period of time when a highly permeable rock domain is present, the infiltration of drilling fluid into rock due to fluid loss or lost circulation can also occur rapidly. Drilling fluid that infiltrates into the rock should be recovered quickly to allow quality-assured hydrochemical data to be obtained. Thus, the diameter of the test system needs to be enlarged to allow installation of submersible pump such as Mohno pump with the capability of flow rate above 40 (liters/min).

- The borehole diameter should be large enough to improve the core recovery rate so that a large amount of geological information (detection of the structure, material for laboratory experiments etc,) can be obtained from the borehole.
- It is possible to have more choice for installation of standard high precision equipments for geophysical logging, fishing operations, if such cases arise etc.
- Consideration should be given to improving borehole stabilization using cement or additional casings, as measures against fluid loss and borehole collapse. Large-scale fluid loss often occurs when discontinuities are encountered. Particularly in the case where drilling becomes difficult when encountering a fault or a similar feature deep underground, it will be necessary to leave open the option of drilling with a slightly smaller diameter from this depth onwards by setting additional casing pipes.

Selection of borehole drilling locations

The optimum locations and layout for borehole drilling should be decided considering logistical and environmental aspects as well as technical and geoscientific reasons based on the goals of the investigations. Investigations using the deep borehole MIZ-1 in Step 3 were intended to characterize the major discontinuities inferred based on existing information and the geological environment in zones in the granite located at a depth of 1,000m or more. Controlled drilling was planned such that the borehole was initially drilled vertically from the surface to a depth of 250 m; in order to encounter the discontinuities of interest (subvertical), it was then planned to incline the borehole from the north-east of the URL site to the south-west in increments of 1.5 degrees for every 30 m to a depth of 460 m, resulting finally in a borehole with a dip angle of 78 degrees from the horizontal (orange drilling trace shown in Fig. 4.4-1)[10),13),14)]. The borehole was drilled by controlled drilling because (1) information on the geological environment covering a wide range needed to be acquired because it was the last borehole investigation in Phase I, (2) of the geometry between the source and receiving boreholes to be used in the cross-hole seismic tomography survey in Step 4 and (3) the limitations that the borehole should not cross the MIU Construction Site or impede the construction of the surface facilities for the excavation of the underground facilities (see also Section 3.5).

Managing the drilling trace

The planned control function did not operate effectively in borehole MIZ-1, resulting in a deviation from the planned drilling trace to a depth of about 500 m by 90 degrees to the east (black drilling trace shown in Fig. 4.4-1). At this point, considering that adjustment and re-alignment would be difficult, the borehole was backfilled with cement in the section from the bottom up to a depth of 350 m. From this depth, sidetrack drilling was conducted in a south-east direction using the wedge method and MWD method (a method for drilling while measuring the direction to be drilled)[16),17)]. As a result, the borehole was successfully curved and adjusted in accordance with the planned direction and dip angle (red drilling trace shown in Fig. 4.4-1). Planned controlled drilling was then resumed (from a depth of 495 m). From then on, fixed-angle drilling (at a fixed dip angle and direction) was conducted using the conventional wireline drilling method. Eventually, the borehole was mostly drilled in accordance with the planned drilling trace (blue drilling trace shown in Fig. 4.4-1)[10),14),17)]. The reason why the drilling trace could not be controlled according to plan in the MIZ-1 borehole was that control procedure of the dip angle and direction was insufficient and the capability of the controlling device used was not sufficient for the strength of the rocks encountered[10),17)].

Measures against borehole collapse

When a collapse occurs during drilling, operation has to be halted and the planned geophysical logging and testing carried out to the depth of the collapse in order to secure the characterization of groundwater and rock formations along this section of the borehole. After completing the investigations, the collapsed area should be protected with cement before continuing the drilling and proceed with the investigations in deeper sections. If a further collapse occurs in the cement-protected zone, a casing pipe should be inserted to the depth of the collapse and the pipe should be firmly fixed with cement before continuing the drilling. If a collapse were to occur in the shallow underground, the borehole should be enlarged using a larger-diameter bit before inserting a casing pipe and protecting the collapsed portion with cement. In this way, drilling can continue in a borehole with a diameter equivalent to that before the collapse. In contrast, if a collapse occurs in a deeper section, the insertion of casing means that drilling can only continue with a reduced drilling diameter. It should be anticipated in advance that an alternative drilling method using drilling mud might have to be applied for cases where further drilling is difficult to carry out. This may be because the collapse of the borehole wall continues due to the presence of faults or because the delay in operations due to the time required to implement countermeasures becomes unacceptable. In the borehole MIZ-1, a collapse occurred in a brittle rock zone due to the influence of a fault over the section 920-980 m (see also Fig. 3.5.1-1). In this case, the borehole was stabilized by cement injections into the unstable fractured zone. The borehole was drilled using mud to avoid compromising performance of the investigations due to delay in drilling and to reduce any difficulties to the drilling activities deeper underground[15)]. When drilling mud is used, the quality of cementation could be affected due to the fact that cleaning the cementation area by the spacer might be insufficient especially in the areas with large breakout. This results in a poor quality cementation due to poor hardening of the cement (gelation)[17)].

Management of drilling fluid

In order to investigate hydraulic characteristic and groundwater chemistry, freshwater drilling was used in the investigations, except when the above-mentioned measures were taken against a collapse. Here, "freshwater" refers to water from rivers or shallow groundwater reservoirs with a low mineralization (EC normally less than 1,000 μ S/cm). In the case of Mizunami, the chemistry of the freshwater drilling fluid is nearly equal to the groundwater encountered in the shallower part of the borehole. This water was used to minimize reactions between the drilling fluid and the groundwater or rock in the investigation area. Drilling with freshwater can cause on one hand difficulties in removing the drilling cuttings out of the borehole, and the other hand is not able to create a mud cake on the borehole wall to stabilize the borehole and/or prevent in- /outflow to the borehole. This may result in the development of borehole breakout as well as major difficulties during drilling e.g. stuck drilling pipe. The removal of cuttings during freshwater drilling was addressed by selecting drill-bit for smaller grain size cuttings in combination with an optimized annulus (between drill-pipe and borehole wall) to enhance the flow velocity of the circulation water[15)]. In addition, a centrifugal separator was used to facilitate the removal of the cuttings from the drilling fluid. Attention should also be paid to the circulation pressure to avoid high flow velocity of the circulating water, which can cause collapse of the borehole.

To quantitatively determine the ratio of residual drilling fluid in the groundwater sampled during the water sampling surveys, a fluorescent dye was added to the drilling fluid and its concentration was controlled periodically to ensure a more or less constant level (see also Section 4.8)and determine any changes in drilling fluid mass balance (in-/outflow).

Strength of the drill-pipe

In borehole MIU-4 (controlled drilling with a length of about 790 m) at the Shobasama Site, the threaded portion of the drill-pipe was broken and the pipe became jammed due to insufficient discharge of drilling cuttings resulting from the collapse of the borehole wall in a fault zone. It took approximately 3 months of activities to recover the jammed pipe and to stabilize the borehole (injection with cement)[18),19)]. The drill-pipe used in the MIU-1 borehole became jammed due to breakage of the temporary stainless steel casing pipe, causing a delay of about 1.5 months in the drilling work[20)]. Therefore, special attention has to be paid to the selection of the strength of the connectors and torque management during drilling and the strength of the pipe itself, in addition to measures for prevention of borehole wall collapse and drilling fluid management.

Recording of drilling parameters

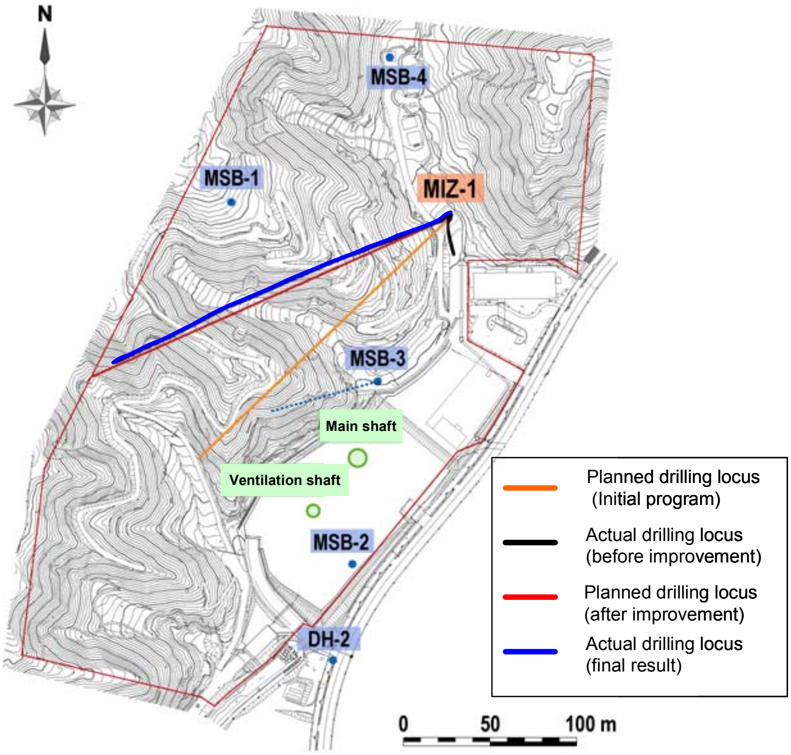
Drilling parameters include the following: drilling efficiency, torque, rotational speed, bit load, circulation pressure; drilling fluid parameters include: drilling fluid balance, temperature, electrical conductivity, pH, viscosity, density etc. These were measured for a control and, as necessary, an optimization of the drilling process. Additionally, they can be used as a first “detection” mechanism for the encountered geological environment during drilling. At the Shobasama Site drilling activities before the MIU-4 operations, only one data set with average or typical values of the above mentioned parameters were recorded by the drilling operators for every single drillcore section (about 3 m). Based on experience with drilling borehole MIU-4 and subsequent boreholes, a monitoring system was introduced to continuously record data on these parameters, allowing the selection of optimal drilling parameters and hardware configuration for avoiding borehole collapse. Changes in parameters such as return fluid volume, water temperature, electrical conductivity and pH were used to determine the depths of important water conducting features. Data should be acquired promptly to allow an immediate reaction, if needed. During the MIZ-1 borehole investigations, a telephone line system was installed connecting the drill site and office of the project team, for constant monitoring of data and a prompt implementation of actions against difficulties; in addition, the information could be used for pre-selection of test intervals[15)].

Sampling of drill-cores

A high core recovery rate is a key issue in borehole drilling. Initially a double core barrel was used; although the core recovery rate was over 90%, this method involved problems with the retrieval of the core from the core barrel, resulting in core damage. In fault zones the recovery rate drops and, most importantly, fault gauge material from these zones can not be recovered for analysis. To improve this situation, the triple-core wireline method was used, which introduces a transparent acrylic liner in the inner core barrel[18)]. By adopting this method, the damage of cores during retrieval and transfer in the core boxes was reduced; full cores could be obtained in an almost undisturbed condition, except for isolated cases in brittle rock zones or some relatively large faults. Even partial cores obtained from the fault zones showed a better recovery rate compared to previous methods[10)].

Table 4.4 -1 Basic specification for the deep borehole investigation[10)]

Borehole diameter	Above 5 ½”	
Casing program	Multistage drilling	
Drilling water	Fresh water tagged with fluorescent dye	
Control for the drilling water	Monitoring for fluorescent dye concentration and loss of drilling fluid during drilling	
Coring	Triple-barrel drilling method with an acrylic inner core barrel	
Borehole protection	Fluid loss	Plugging with LCM (Lost Circulation Material, e.g. cellulose)
	Collapse	Partial cementing
	Large scale collapse	Installation of casing pipes and full hole cementing



Topographic map: 1/1,000 (made by JAEA)

Fig. 4.4-1 Planned and actual drilling locus of MIZ-1 borehole investigation[10)]

4.5 Geophysical logging

Zones with extensive fracturing are expected to affect the groundwater flow characteristics of the deep geological environment[21)], and determining the distribution and geological/hydraulic characteristics of such zones is an important item for investigation. Thus, when conducting borehole investigations, the distribution and characteristics of fractured zones are investigated and evaluated by core logging, investigations of borehole wall image, etc. However, the interval of a fractured zone is difficult to determine accurately because in general, the definition of a fractured zone and its objective criteria for identification have not been clearly specified. In order to develop objective definition and identification criteria, a principal component analysis[22)] was conducted using multiple data obtained by the borehole wall imaging, geophysical logging, etc., which allows continuous quantitative data versus depth to be obtained. The fractured zone and the background fractured rock are then distinguished from one other based on the principal component scores (Fig. 4.5-1). However, the anomalies identified by statistically processing the difference in the scores of the principal components tend to not clearly identify zones such as fractured zones and alteration zones with property values different from those of the background fractured rock (Fig. 4.5-1). Therefore, the level of fracturing in the core and the degree of alteration should be checked to make the final decision regarding the definition of fractured zones. This method is considered to be generally effective to distinguish background fractured rock from fractured/ altered zones because the degree of fracturing or alteration is greater when the principal component score is lower and because no distinct fractures were observed in the zones identified as background fractured rock based on the principal component scores[23)].

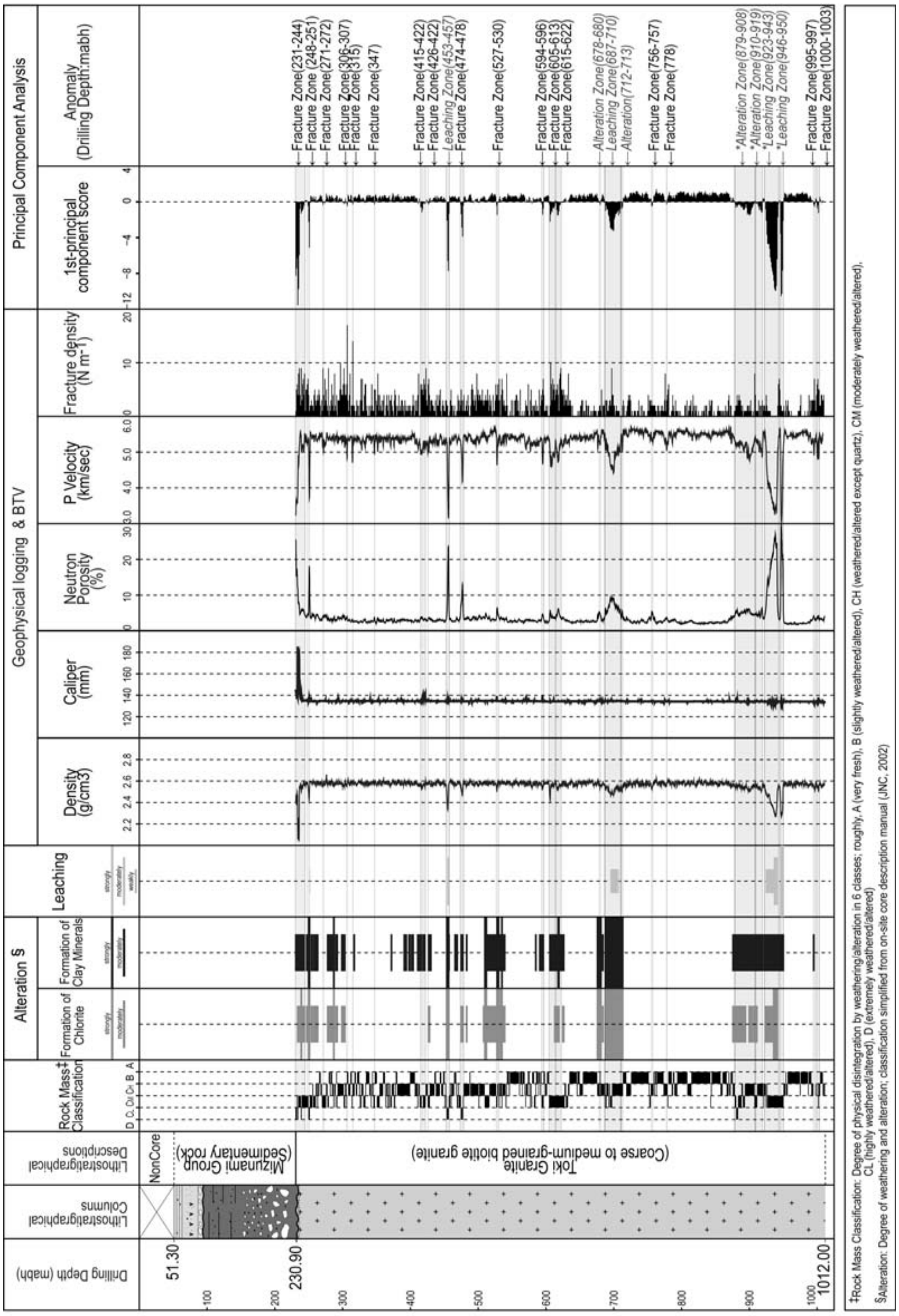


Fig. 4.5-1 Identification of fractured zone intervals using the principal component analysis based on geophysical logging data (DH-15)

4.6 Fluid logging

Since fractures (fractured zones) act as the main conduits for groundwater flow in fractured media such as crystalline rock, determining their locations is important to allow such features to be reflected in the hydrogeological modeling and in analyzing groundwater flow. In the investigations in Steps 2 and 3, fluid electrical conductivity (herein after FEC) logging was conducted to identify water conducting features with a high resolution. In this method, the borehole fluid is replaced by fluid with an electrical conductivity which is different from that of the groundwater (e.g. de-ionized water or saline water). Then electric conductivity logs of the fluid are measured along the borehole before and during a pumping phase periodically. Thus water bearing fractures with an inflow into the borehole create changes in the electric conductivity profile[24].

In the investigations in Steps 2 and 3, borehole fluid was replaced with de-ionized water. This allowed the identification of inflow points of groundwater (Fig. 4.6-1) which has not been detected by the classical flow-meter logging methods, which is generally used for the detection of water conducting features[25),26]. The hydraulic tests with test interval covering the detected inflow points indicated that water conducting features with a transmissivity higher than 10^{-8} m^2 s^{-1} could be detected by the FEC logging. As a result, it was confirmed that this logging method is capable of detecting water conducting features with a transmissivity two orders of magnitude lower than that detected by flow-meter logging method using impeller or electric-magnetic flow-meter etc.

As mentioned above, because the FEC logging determines the position and transmissivity of water conducting features based on the contrast in electric conductivity in groundwater, the measurement results reflect not only the hydraulic characteristic but also the groundwater chemistry. More specifically, if the groundwater has more or less constant electrical conductivity (i.e. similar groundwater chemistry), and if there are no significant variations of the formation hydraulic head along the borehole, the strength of the electrical conductivity signal is proportional to the hydraulic conductivity of the water conducting features. Therefore, a greater volume of groundwater would be assumed to have intruded in an area with a higher electrical conductivity signals. It should be noted that for correct interpretation of fluid logging results, the interaction between hydraulic properties, hydraulic head and salinity of the water conducting features should be always carefully evaluated and considered.

The impact of drilling mud may be an issue for fluid logging in general, including FEC logging. One example of the impact of drilling mud would be clogging of water conducting features caused when the mud extrudes into an otherwise highly water conducting feature during drilling, which may result in the degradation of the hydraulic characteristic around the borehole. In such cases, fluid logging may underestimate the hydraulic characteristic of the water conducting feature because the hydraulic characteristic around the borehole is reduced.

Thus, in order to properly evaluate permeability along a borehole, it is appropriate to conduct fluid logging in combination with hydraulic testing so that the hydraulic characteristic of water conducting features identified by the fluid logging can be verified by the hydraulic test results.

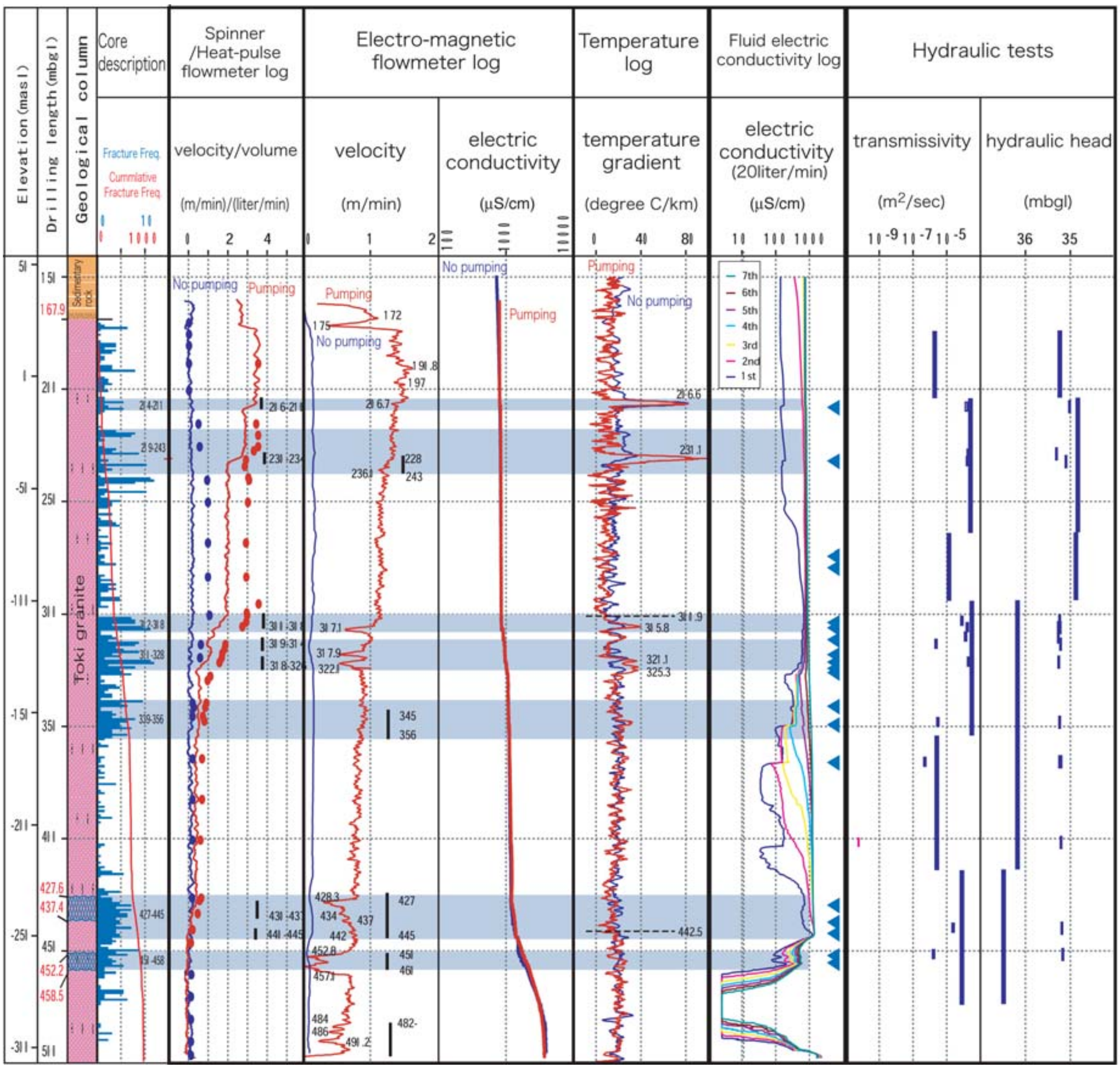


Fig. 4.6-1 Results of fluid logging and hydraulic test in 500m borehole

4.7 Hydraulic testing

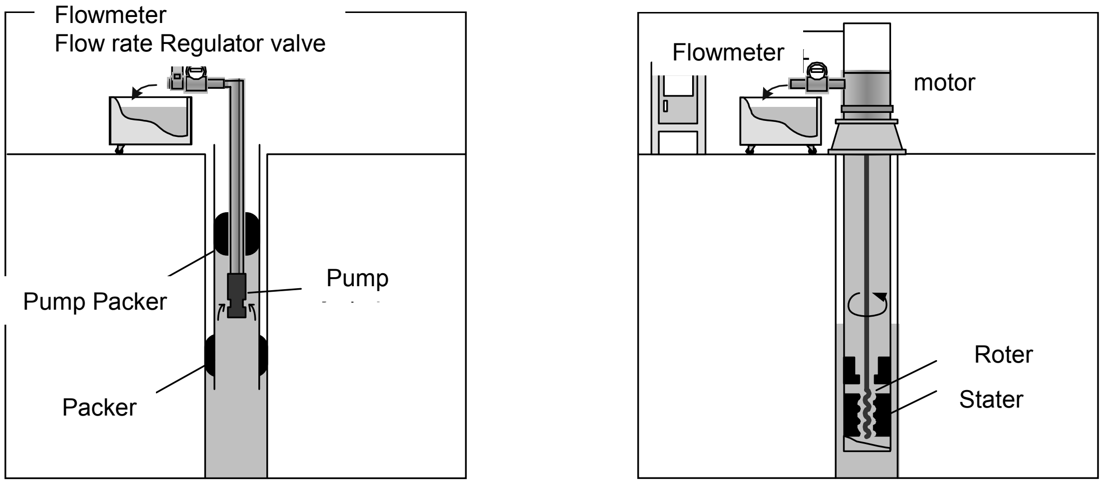
Single-hole hydraulic packer testing is an important method for characterizing the hydraulic properties (e.g. hydraulic conductivity, storativity) of the rock formation of interest, determining the system state (e.g. hydraulic pressure), which are important parameters for developing, testing and improving hydrogeological models. In order to ensure sufficient quality of test data for rocks with a wide range of hydraulic characteristics (hydraulic conductivity in the order of 10^{-12}-10^{-3}m s^{-1} [27),28)]), a series of improvements were successfully undertaken on JAEA's packer test equipment, and testing procedures and data evaluation methods[16)] were further developed during Phase I.

The previously developed hydraulic packer test system for low permeability rocks developed by JAEA[29)] had small diameter lines (only a few millimeters in diameter) because that system focused mainly on pulse and slug tests. Therefore, when the system was used for testing more permeable rocks, it was difficult to ensure the quality of the test data because of pressure loss due to flow resistance in the lines. The test system was improved to include larger diameter lines and to minimize the pressure losses in them. In addition, an improved pump that can deliver large volumes of water (Fig. 4.7-1(a) and Fig. 4.7-1 (b)) was developed to reduce the impact of borehole storage by maximizing the flow to get the test data out of the so-called wellbore storage period as quick as possible. This is one of the problems in evaluating the hydraulic conductivity of rock by means of pumping tests, and to obtain, over a longer period of time, data in the time span in which the proper evaluation of hydraulic properties would be possible.

Standardized hydraulic packer tests conducted in both high and low permeability formations require, as is expected, a longer period of time to be completed in the low permeability formation. The time that can be spent on hydraulic testing may be restricted by the project management to be able to keep the overall borehole investigation schedule. When only one a standardized test sequence is performed, the quality of test results will differ depending on the rock permeability. Thus, a flexible testing procedure (sequential hydraulic test: Fig. 4.7-2) was developed[30)] in which an appropriate set of test types could be objectively selected depending on the expected and continuously derived permeability of the test section, ensuring an increased quality of test results.

The sequential hydraulic test involves, first after the so-called pressure static recovery period (PSR), a pulse withdrawal or injection test (PW/PI) ,which is an effective method for estimating hydraulic conductivity of rocks with low permeability, to roughly estimate the permeability of the rock, and followed by subsequent tests depending on the results of the first pulse test. For evaluation of the test data, a derivative plot of pressure variation was adopted[31)] to identify whether, for example, the data obtained correspond to the representative permeability of the rock away from the borehole and hence whether the test sequence could be stopped. The derivative plot of pressure variation also facilitates identification of any encountered hydraulic boundaries and the appropriate flow model for the test interpretation. This method allows reduction of the scatter of the evaluation results resulting from differences in the experience of different testing/interpreting engineers. Using the derivative plot also helps researchers to decide the appropriate time for completing and terminating the measurement because the plot can also indicate the actual status of the test period (early, mid-time or late-time response) and the time needed for the convergence of the pressure measurement in order to be able to identify or derive a flow model.

Applying the test equipment described above and a series of test methodologies to borehole hydraulic tests allowed hydraulic properties to be determined within the usual limited time available while ensuring data quality. The field applicability of the newly developed method was confirmed repeatedly in the field.



(a) Pump packer (b) Cavity Pump

Fig. 4.7-1 Schematic figure of pump packer and cavity pump

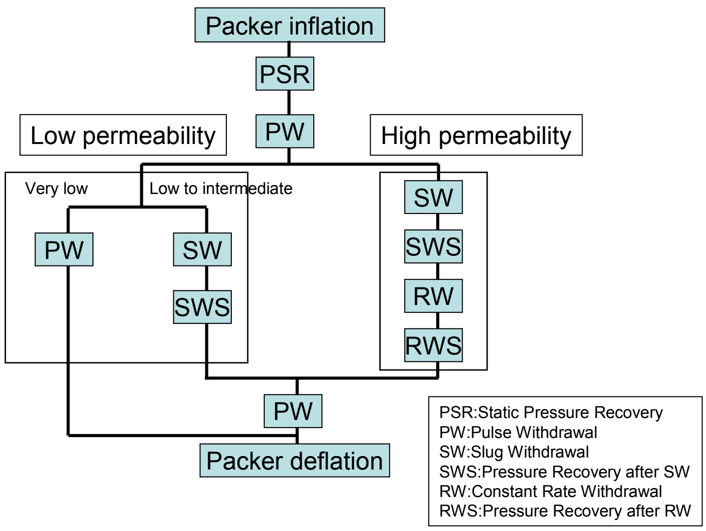


Fig. 4.7-2 Sequential hydraulic test

4.8 Hydrochemical investigations

When sampling groundwater in a borehole drilled in a fractured medium such as crystalline rock, sampling should be conducted where the borehole encounters water conducting features in the formations of interest (as evidenced, for example, by drilling fluid losses or groundwater inflows) through pumping or natural outflow, in case of artesian conditions. The time lapsed between drilling through the water conducting feature and the start of water sampling period can significantly affect the hydrochemical data quality.

In the deep borehole investigations at the Shobasama Site (boreholes MIU-1, 2 and 3), groundwater sampling was scheduled and conducted after the borehole had been drilled to the target depth (1,000 m). During this procedure, however, the borehole encountered a fracture (fractured zone) where drilling fluid was lost and a large volume (several tens to several hundreds of cubic meters) of drilling fluid infiltrated into a fracture (or fractured zone) by the time the sampling started. The water sampling could no longer be conducted within a reasonable duration as the contaminated water had to be removed in order to get more or less “clean” formation water. Under normal conditions, a water sample with less than 10 % of contamination by drilling fluid is aimed at. To achieve this, groundwater sampling in MIU-4 and MIZ-1 boreholes was conducted in combination with a standard hydraulic pumping test for determining the hydraulic properties during the drilling phase. To reduce the volume of drilling fluid infiltrating into the rock, the procedure followed was designed to halt drilling and conduct a pumping test as soon as significant drilling fluid losses occurred. The aim was to get a more or less uncontaminated sample (drilling fluid contamination below 1 %) or at least until a minimum number of good quality samples were recovered, representing a series of samples with different levels of contamination. Normally, this allows the uncontaminated hydrochemical data of the formation to be extrapolated. What is important for the success of the procedure is to be able to determine the exact rate of contamination by the drilling fluid (%) at the start of the sampling period. The method described below was examined and used in the investigations[32),33)]. A basic requirement is to keep the concentration of fluorescent dye, which is added to drilling fluid, at a more or less constant level. The physico-chemical parameters such as pH, electrical conductivity, redox potential and/or oxygen concentration were measured continuously during the entire pumping phase of the water sampling test. The groundwater chemistry (major components) and concentrations of fluorescent dye in the groundwater discharged during the pumping test were analyzed and measured on a regular basis. Additionally, batch samples were taken to determine the development of tracer content and major elements. Groundwater was then sampled when the concentration of the fluorescent dye was sufficiently low (aiming at ≤ 1% drilling fluid contamination) whereby the physico-chemical parameters would no longer change significantly. In cases where the concentration of the fluorescent dye could not be reduced sufficiently, the groundwater chemistry of the formation not contaminated by the drilling fluid could be estimated through extrapolation, based on the relationship between the concentration of the fluorescent dye and the groundwater chemistry. Thus, the real formation groundwater chemistry could be determined based on the results of chemical analysis of the periodic samples taken during the course of the drilling fluid discharge process. However, for isotopes and groundwater species (e.g. aluminum ion) whose concentration is too low or tends to be changed by water-rock interactions (thus cannot be correlated with the concentration of the fluorescent dye), their concentrations cannot be determined by extrapolation. Consequently, the drilling fluid contamination should be lowered as much as possible. In order to use such a method, a binary mixture of drilling fluid and groundwater needs to be assumed and the tracer content and the chemistry of the drilling fluid should be kept constant throughout the entire investigation period. For this purpose, pH and electrical conductivity of the drilling fluid was constantly monitored so that the drilling fluid could be adapted when variations in water chemistry were observed. In extreme cases the drilling fluid can be replaced.

One of the drawbacks of the water sampling method with a normal pumping test on the surface is the possible change in concentration of dissolved gas and physico-chemical parameters due to degassing during pumping. A certain backpressure at the surface could form which can be solved by sampling the groundwater under in-situ pressure conditions using a batch-type sampling bottle inserted directly into the test interval section. If this is not possible, alternatively a water sample should be taken directly above the downhole shut-in tool by using a dedicated sampling system after the pumping test has been completed and the pump equipment has been dismantled.

The real need for groundwater sampling should be considered in terms of the specified investigation goals and duration (and hence cost), because uncontaminated groundwater sampling could take much longer than originally planned and calculated. The time needed for a clean water sample and at least the success of the entire sampling activity depends on the total amount of drilling fluid loss in the test interval section and the permeability and head of the test interval. When sampling is to be carried out, it is important to consider in advance the selection of the appropriate groundwater sampling method and planning of field work to ensure the required data quality.

If the allocated time for groundwater sampling during the entire drilling and testing period of the borehole is not sufficient, formation groundwater can in some cases be sampled using batch-type sampling bottles prior to the installation of the long-term groundwater monitoring system, after drilling has been completed for the entire length of the borehole[32),33)]. Using this method, however, the borehole which acts as a conduit between the different permeable systems, may lead to mixing of waters from different systems, until the installation of the long-term groundwater monitoring system, due to the difference in hydraulic head between the aquifers. In such cases, the monitoring equipment should be installed as soon as possible, but in any case a sampling program that extends over a long period should be designed to confirm that the chemistry of the groundwater sampled from the various water conducting features has not been affected by that of other systems. It should be noted that the installation of casings into the borehole and the cementation of these can make it impossible to get high quality water samples from such long-term monitoring boreholes of specific areas.

Disturbances of the geological environment induced by borehole drilling are also normally experienced during the investigations. In the site-scale borehole investigations, the adhesion to the borehole wall of black iron compounds (mainly iron hydroxide and iron sulphide) assumed to be formed by the reaction of iron in the drilling fluid and hydrogen sulphide gas was observed by borehole wall imaging[34)]. The iron contained in the drill bit was dissolved in the drilling fluid after abrasion and iron compounds were expected to be formed by the reaction of the dissolved iron and sulphides in the groundwater. These iron compounds may alter the redox potential of the groundwater because they could be a major controlling solid phase for the redox reaction. Thus, in order to obtain the redox potential of groundwater, the redox reaction of a redox reactant present in rocks and a human-induced redox reactant formed underground during drilling should be predicted in advance based on thermodynamic calculations. In addition, investigations of borehole wall image should be conducted to check whether there is a human-induced solid phase precipitation due to redox reactions.

4.9 Initial stress measurement

Initial rock stress is one of the most important factors in the design and excavation of the underground tunnels and has a significant effect on the layout and stability of the underground facilities. A large number of initial stress measurement techniques have been proposed thus far, ranging from those in commercial use to those under development[35)]. Initial stress measurement techniques can be roughly classified into two categories: one using boreholes and the other using core samples. Examples of the former include hydraulic fracturing and stress relief techniques. The latter includes the Acoustic Emission (AE) technique, Deformation Rate Analysis (DRA) and Differential Strain Curve Analysis (DSCA) based on the behavior of micro-cracks in the cores. These techniques were used as the investigation methods in Phase I. Note also that estimation of stress states can also be performed with geodetic evaluation methods, such as land-surveying and GPS information, in combination with modeling.

When the underground tunnels to be constructed are large, or when the drifts are designed in three dimensions, the 3-D principal rock stresses data is needed. However, since there is no practical method for measuring 3-D initial stress states with just one deep borehole, the 3-D stress states were evaluated using a combination of results of hydraulic fracturing, AE technique, DRA and DSCA. The stress relief technique was found to be the most reliable and established method of the borehole techniques; it determines the 3-D principal stresses without providing a hypothesis regarding the magnitudes and directions of the principal stresses for the calculation of values[36)]. The stress relief technique evaluates the initial stress in the following manner: first, a pilot hole with a small diameter is drilled at the end of a borehole and a strain gauge is installed in the pilot hole. The pilot hole is then overcored, aligning the axis of the overcoring borehole with that of the pilot hole so that the stress acting on the rock in which the strain gauge is installed is released. The initial stress is then obtained based on the value for elastic recovery measured at the time of stress relief. There are few cases of initial stress measurement using the stress relief technique in deep boreholes, because of difficulties due to water and heat resistance. Thus, a measurement system was developed to solve these difficulties and to enhance the applicability of initial stress measurements based on the existing stress relief technique for deep boreholes.

The initial stress measurement system developed (Fig. 4.9-1) consists of a strain gauge cell and a cementing tool for measuring the strain at stress relief, a data logger for recording the strain at stress relief, a magnetic compass, an inclinometer and a power supply system (lithium battery). The data logger, etc. are contained in the upper cell (pressure container) made of stainless steel, which is capable of withstanding water pressure at a depth of 1,000 m. Although two types of strain gauge cells (embedding type and hole wall attachment type) were used in the investigations, other types of cells can also be used. The embedding type strain gauge cell used in the present system has a structure in which the cementing tool at the tip removes the well water when it is pushed into the bottom of the pilot hole and adhesive cement is applied around the strain gauge cell. The hole wall attachment type strain gauge cell has a structure in which three units of rosette strain gauges are directly attached to the wall of the pilot hole when the cementing tool is pushed into the bottom of hole. With the adoption of a scheme that describes the sequence of processes, starting from the drilling of the pilot hole through the installation of the initial stress measurement system and to the overcoring for the wireline system[37)], the efficiency of the measurement process was significantly improved. The new scheme allowed the initial stress measurement procedure, which otherwise takes several days, to be completed in six hours.

Initial stress measurements using the newly developed system were carried out in a borehole drilled from the ground surface at the Tono mine (Toki City, Gifu Prefecture), when the borehole had reached a depth of 200-250 m. The rock in question was the Toki Granite and the test was conducted at a point in the zone at a depth of 200-250 m where there were no natural fractures. As a result, a continuous change in the strain associated with stress relief was measured (Fig. 4.9-2), demonstrating measurement of the initial stress states in a deep borehole by means of the stress relief technique[38)].

As shown in Fig. 3.5.6-l, the initial stress states may vary significantly depending on the existence of discontinuities such as faults in particular. Therefore, the distribution of major discontinuities should be determined before planning the measurement work.

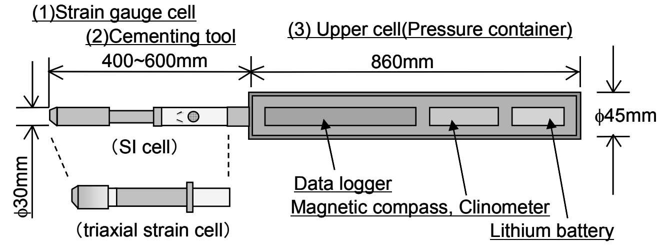


Fig. 4.9-1 Outline of the new stress measurement equipment[38)]

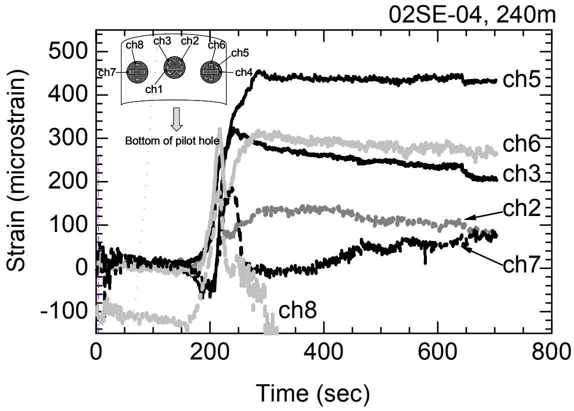


Fig. 4.9-2 Measured stress relief curves[38)]

4.10 Geological and hydrogeological modeling and groundwater flow analysis

For effective characterization of the geological environment, it is important to clarify, in a stepwise manner, the relationship between the number of investigations and the level of understanding or uncertainties regarding the characteristics of the geological environment, as well as to specify key factors to be characterized in subsequent investigations. All models of geological environment (geological model, hydrogeological model, hydrochemical model and rock mechanical model etc) should be developed for this purpose and updated as required based on additional findings[39)]. In addition, investigations using a geological environment model as a tool should be required since the following advantages are envisaged.

- The entire site investigation process can be organized into a chronological order and information that contributes to effectively formulating similar investigation plans may be provided by recording information obtained at each investigation stage.
- Modeling and visualization of various types of technical information would facilitate not only sharing of knowledge among researchers from different disciplines but also providing information to the wider public.

For effective characterization of the geological environment, it is also important to interpret the obtained data and develop models of geological environment as soon as possible after the investigations and to plan subsequent investigations based on the results. To support the rapid development of such models, the Geological Modeling Analysis and Simulation Software (GEOMASS) system that integrates software and analysis codes required for a series of tasks ranging from geological and hydrogeological modeling to groundwater flow analysis was developed[40].

The GEOMASS system consists of EarthVision®, which supports the development of the geological model and visualization of the results of the modeling and groundwater flow analysis, and Frac-Affinity, which is used in hydrogeological modeling and groundwater flow analysis (Fig. 4.10-1). EarthVision® is a commercially available software developed by Dynamic Graphics, Inc. for modeling the geometry of complex geological structures[41]. Frac-Affinity is a groundwater flow analysis code for spatial discretization (grid generation) and numerical analysis based on the geological model developed with EarthVision®[42].

This system has advantages in that the modeling and numerical analysis are integrated and both discontinuities and rock matrix zones can be taken into account simultaneously. The former saves effort, in particular in terms of the time required to revise or reanalyze the model when additional information is obtained. The latter allows more realistic representation of groundwater flow conditions.

(a) EarthVision®

EarthVision® has been applied for modeling the complex geometry of geological structures, areas relating to the investigation and exploitation of oil and natural gas and so on. It is a well established software system that has been used for geological modeling at Sellafield (Nirex), Wellenberg (Nagra), the Äspö HRL (SKB) and Yucca Mountain (USGS, USDOE)[43]. The construction of geological models with EarthVision® involves estimating the geometries of boundaries between formations and discontinuities such as faults and combining these geometries taking into account their relative positions and sequence of geological formation.

A data output function (Frac-Affinity Export) for the groundwater flow analysis code Frac-Affinity has been added to the software, thus facilitating data exchange between EarthVision® and Frac-Affinity.

(b) Frac-Affinity Interface

Frac-Affinity Interface was developed as a module for converting data to be processed between EarthVision® and Frac-Affinity. Based on the geological model created by EarthVision®, Frac-Affinity Interface automatically generates the grid for conducting a numerical analysis with Frac-Affinity. Users can specify several control parameters (e.g. the lower limit of the cell size) for the grid size. Frac-Affinity Interface allows users to specify, as needed, points, lines and surfaces for which results are to be monitored. It also facilitates output of the changes in analysis results at a certain point.

(c) Conversion of analysis result data by Frac-Affinity

A file used to visualize distributions of properties (hydraulic conductivity, porosity, specific storage coefficient, etc.), hydraulic head, flow rate, flux, etc. is output based on the analysis results calculated with Frac-Affinity.

(d) Frac-Affinity

Frac-Affinity is a numerical analysis code for conducting, based on the mass conservation law, a groundwater flow analysis by means of the finite difference method. In Frac-Affinity, porous and fractured media can be simultaneously represented as a hybrid medium (Fig. 4.10-2). The software also has the following advantages: it facilitates the modeling of curved structures such as faults, both deterministic and stochastic fractures can be considered, the property values for the porous medium and deterministic fractures can be set heterogeneously based on a geostatistical method using the fractal law[44),45),46)], hydraulic anisotropy can be assigned to the deterministic and stochastic fractures and tunnel excavation can be taken into account.

With this system, geological/hydrogeological modeling and groundwater flow analyses were conducted for the site-scale area in each of the steps described in section 3 (Fig. 4.10-3). The system made it possible to develop a geological model of an area in which a number of lithofacies (granite, sedimentary rock) and faults are distributed in a complex manner, while checking the visualizations (Fig. 4.10-3). Grid generation for the groundwater flow analysis (discrete model) was done automatically based on the geological model, thereby reducing the effort required for complicated grid generation. The automatic generation function of the discrete model is particularly effective for reducing the effort required for modeling complicated geological structures and conducting groundwater flow analyses based on the model, and 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 analysis results (Fig. 4.10-3).

As described above, adopting a system that integrates the software and the analysis code required for a series of tasks ranging from geological and hydrogeological modeling to groundwater flow analysis, resulted in a significant reduction of the time and effort necessary for such tasks, at the same time allowing revision of the model for integration of additional information. The system also allowed a geological and a hydrogeological model to be constructed immediately after completion of the investigations, whereby the investigations could be functionally combined with modeling of the geological environment.

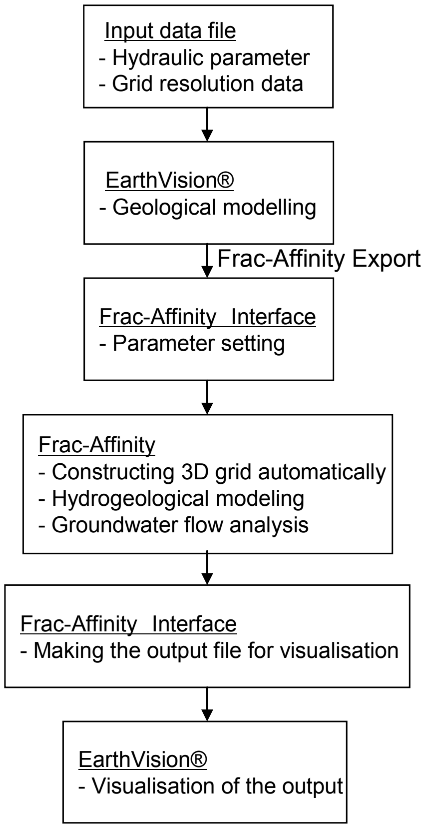


Fig. 4.10-1 GEOMASS system working flow

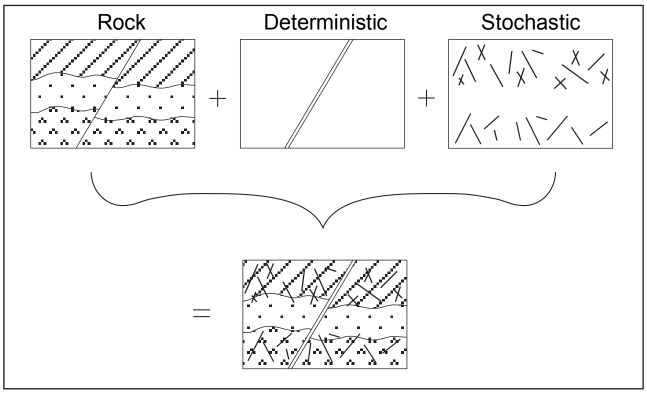
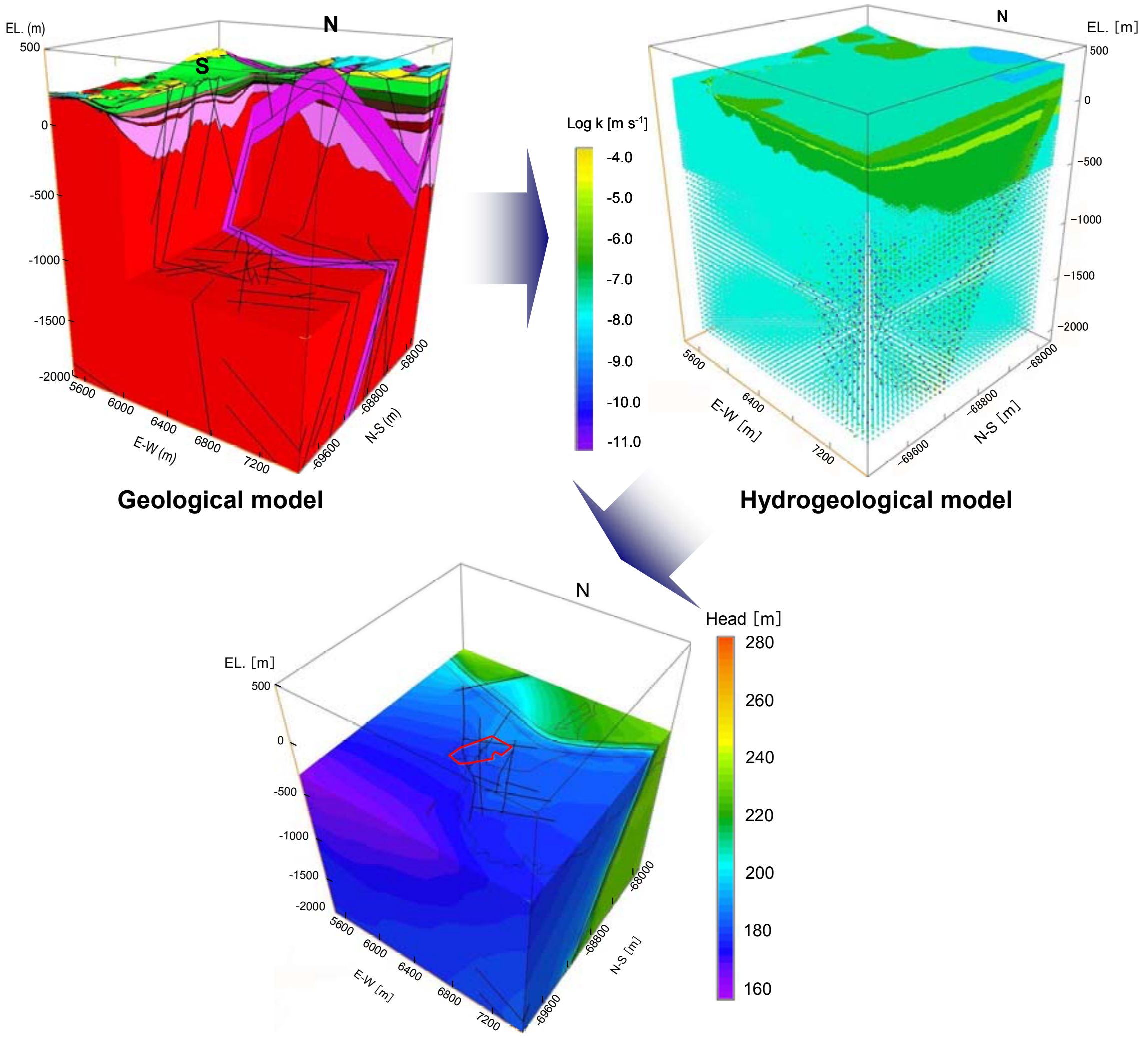


Fig. 4.10-2 Schematic of the constituent components of a hybrid medium



Result of the groundwater flow simulation

Fig. 4.10-3 Geological / hydrogeological modeling and visualization of the groundwater flow analysis result by using GEOMASS system (Step 4)

4.11 Quality control

In order to continually improve the credibility of R&D results on geological disposal techniques and characterization of the geological environment, it is necessary to provide the various stakeholders involved in the different phases of the disposal project with the results of R&D work to allow them to understand the validity of the results; this also applies to the formulation of national safety regulations. Focusing on transparency, traceability, openness and expert review is essential for assuring the quality of R&D results. For this reason, the action program for the MIU project includes clear implementation plans for the various investigations, such as borehole investigations and geophysical surveys[14)]. These plans should include work schedules, organizational structure, investigation/analysis methods to be employed, countermeasures against expected difficulties, and work procedures and checklists for quality control and safety assurance, which require the approval of the person in charge of quality control at the beginning of each investigation. When the investigation is outsourced to a third party, in particular, those involved in the investigations should be thoroughly informed of the goals to be achieved, the data quality to be ensured in the investigations, etc. through the formulation of an implementation plan. Since the work scope will vary for the borehole investigations, quality control plans were prepared for the investigation work according to the investigation program (see also section 4.3), which integrates the implementation plans for the respective investigations. In the deep borehole investigations (borehole MIZ-1) in Step 3, plans were prepared for operations such as drilling, core logging, laboratory examinations on cores, investigations of borehole wall image, geophysical logging, hydraulic tests and analyses of well water, drilling fluid and pumped samples to ensure the quality of the results[15)].

To successfully achieve the investigation goals, it is necessary to plan in advance, for various possibilities, for example borehole wall collapse or fluid loss, and to prepare countermeasures for each of these events. A delay in implementing the required measures will result in increased costs, and, as the situation worsens, the affected area becomes more difficult to restore. From the scientific point of view, there would be an adverse effect on the investigations concerned, a delay in analysis and evaluation, possibility that there will be no opportunity for including the findings in subsequent investigations, or, at the extreme, that the entire investigation plan might have to be postponed due to redirection of the available resources. These situations would be extremely serious for the investigation approach aimed at increasing the understanding of the geological environment based on an iterative approach[10)]. Thus, reviews by experts who have experienced similar situations would be extremely valuable. Finally, the Process Decision Program Chart (PDPC) used in the borehole investigations in the MIZ-1 borehole may also be very useful for future practical applications[15)].

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5. Development of engineering technologies for deep underground application

Two of the goals of the MIU Project are (a) to confirm the reliability and applicability of techniques for investigating the geological environment through their implementation, and (b) to establish the basis for engineering techniques for the construction and maintenance of the shafts and galleries. The aim is to acquire information and demonstrate techniques through designing and constructing the underground facilities based on information on the geological environment. The excavation of the shafts and galleries, one of the major goals, allows the verification of the techniques for the investigation of the deep geological environment and access to the zone to be investigated. The experience acquired and techniques developed when designing, constructing and maintaining the shafts and research galleries will be used as the technical basis for drift excavation in the detailed investigation stage in the actual disposal project.

More specifically, the shafts and galleries constructed deep underground that are required for the investigations will be designed based on information on the geological environment obtained in Phase I of the MIU Project, applying currently available civil engineering and mining technologies. In Phase II, with feedback from the results obtained, the shafts and galleries will be constructed safely and efficiently. By then it will have been demonstrated that research locations for Phase III can be provided and successfully maintained and managed. Establishing methodologies for evaluating the impact on the geological environment caused by the excavation of the shafts and galleries and developing techniques for restoring/minimizing the excavation damaged zone near-field of the underground facility is also an important issue. The latter also contributes to the development of techniques required for the design and construction of the disposal facility and the engineered barrier system.

As a major research facility, the MIU has to provide an environment for implementing geoscientific research as well as for promoting public understanding of the deep geological environment, as indicated in the Framework. This role needs to be taken into account in the design and construction of the facilities.

This section presents an outline of the information on the geological environment relevant for the design of the shafts and galleries acquired in Phase I of the MIU Project for granite (hard rock) and the results of cavity stability analyses. Know-how and experience built up are also presented.

5.1 Study on design and construction of the shafts and research galleries in Phase I

5.1.1 Approach

Detailed design of underground facilities, such as the MIU, should generally be conducted after the conditions of the geological environment at the site have been defined to some extent, i.e. when the Phase I investigations are sufficiently far advanced to allow efficient and economical design processes to be implemented. In the MIU Project, the design of the facility, which was conducted in parallel with the Phase I investigations, was initiated at a time when there were only a small number of investigation boreholes in/around the MIU Construction Site. Therefore, the discussions in this report include information on how the design was updated with the progress of the Phase I investigations.

In particular, no information from boreholes reaching to a depth of 1,000 meters - the planned depth for the shafts and galleries - was available for the initial design phase, which included the layout and size of the facilities and support infrastructure. The only information came from borehole DH-2, with a depth of 500 m, which had been drilled for the regional hydrological study. The initial design was based on this information and data from borehole MIU-1, which did not intersect the Tsukiyoshi Fault. The latter borehole reached a depth of 1,000 meters at the Shobasama Site, where the geological structures are similar to the MIU Construction Site. This allowed to make the necessary assumptions to be made regarding the geological structures and the rock classification at the planned locations for shaft and gallery excavation. This information corresponds to that in Step 0 discussed in Chapter 3.

The design was later revised based on data from the shallow boreholes (MSB-1,2,3,4) approximately 200 meters in depth, which reached the Toki Granite, and the deep borehole MIZ-1, 1,300 meters in depth, drilled at the MIU Construction Site. The revised design is referred to hereafter as the adjusted design. This information corresponds to that in Steps 2 and 3-Discussed in Chapter 3.

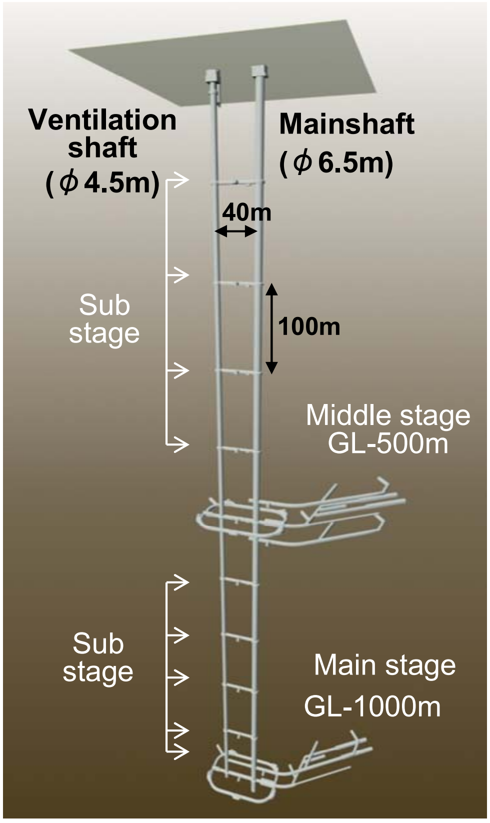
The above design primarily related to the rock mass rating classes, cavity stability and rock support systems. In Phase II, various data on the geological structures and rock conditions will be obtained and application of intelligent construction methods incorporating this information will lead to more appropriate design and construction. The feedback mechanisms for additional data were therefore studied in Phase I.

Compared to other civil engineering structures such as roads, rails and tunnels, the shafts and galleries will extend to a great depth, have a complicated layout and will be visited by various categories of people (scientists, the public, etc.). In this context, important issues to be addressed in the design should include cavity stability during earthquakes, contingency measures for emergencies and disaster prevention based on ventilation network analysis and safety measures. These issues are also discussed in this section.

5.1.2 Layout of shafts and research galleries

Two type of access to the deep underground - shafts and inclined tunnels - were compared and the shaft was adopted based on its advantages in terms of costs, construction period and required construction area. For the investigations in Phase III, it is planned to excavate two shafts (a main shaft and a ventilation shaft) and drifts at various depths (middle stages and deepest stage)[1),2)]. The preliminary layout of the shafts and galleries is shown in Fig. 5.1.2-1 and outlines of the shafts and galleries are described in Table 5.1.2-1 and Table 5.1.2-2 respectively.

According to standard tunnel specifications for mountain construction methods[3] issued by the Japan Society of Civil Engineering, there should be no mechanical interaction between drifts when they are separated by a center-to-center distance of twice (in the case where the rock is a completely elastic body) to five times the tunnel diameter (in the case where the rock is soft). Therefore, the center-to-center distance of the two shafts was set as 40 meters to ensure a separation of 5 times the tunnel diameter (7.3 meters).



Layout of shafts and galleries
- Maximum depth：1,025m
- Main stage：depth of 1,000m
- Middle stage：depth of 500m
- Sub stages：every 100m

Specification of shafts
- Access : Shaft
- The number of access shaft：2 shafts
- The interval of access shaft：40m
- Shapes：Circle
- Inner diameter :
  - Main shaft : Φ6.5m
  - Ventilation shaft : Φ4.5m

Fig. 5.1.2-1 Conceptual Design of Mizunami Underground Research Laboratory

Table 5.1.2-1 Overview of Shafts

		Main Shaft	Ventilation Shaft
Aims		･To reach depth of investigation galleries ･To confirm Phase I geological model ･To confirm the validity of the support plan	
		･Mucking route from galleries to the surface	･Ventilation system for shafts and galleries
		･Transport route for construction and research equipment	･Space for new hoist cage
Depth		1,025 m	1,010 m
Diameter	During excavation	7.3 m	5.3 m
	Final	6.5 m	4.5 m

Table 5.1.2-2 Overview of Galleries

	Main Stage	Middle Stage	Research Galleries	Sub Stage
Aims	・Main investigation stage at GL. -1,000 m depth (MIU target depth)	・Main investigation stage to understand the geological impact depend on the depth at GL. -500 m (Half depth of MIU target depth)	・Measuring station to observe for rock mass behavior around EDZ of Main and Middle Stage	・Connect both shafts ・Space for excavation and investigation equipment ・Additional investigation galleries for depth dependent studies
Depth	1,000 m	500 m	472m, 528m, 970 m	every 100 m
Length	770 m	770 m	240 m	32 m

5.1.3 Rock stability around the underground facilities and supporting infrastructure

(1) Approach of the study

This sub-section describes the results of stability analyses for the shafts and galleries and rock support systems for the initial design. The overall flow diagram for the analyses is shown in Fig. 5.1.3-1. The numerical analyses include defining parameters based on information available at the time of the initial and detailed designs of the MIU, establishing rock support patterns based on the defined parameters and validation of the support pattern based on measured data.

In accordance with the approach used in the H12 Report[4)], for the analyses of the stability of the shafts and galleries and the support system, the rock mass was classified based on information from surface-based investigations and physical properties were assigned to each class. The support system was temporarily established referring to the standard support patterns of the Japan Railway Construction Corporation[5)] and the Japan Highway Public Corporation[6)]. For the temporary system, the mechanical stability of the shafts and galleries was analyzed by 2-D and 3-D finite element analysis methods. The support was designed in such a way to keep induced stress in each support member below allowable limits. The details of the analysis results are described in the following sub-sections.

(2) Prerequisite conditions for the design

1) Rock mass classifications

The locations of the borehole investigations conducted in/around the MIU Construction Site are shown in Fig. 5.1.3-2. The results of the investigations in the following boreholes were considered: borehole DH-2 (approximately 500 meters deep), which was drilled closest to the planned shaft location and extends into the granite; borehole MIU-1 (approximately 1,000 meters deep); one of boreholes drilled at the Shobasama Site, which did not penetrate the Tsukiyoshi Fault.

In the adjusted design, referring to the results from the 3-D structural geological model in Step 3 in/around the MIU Construction Site, as well as the investigation results from borehole MIZ-1 reaching a depth of approximately 1,300 meters at the MIU Construction Site as shown in Section 3.5.1, the rock properties used were updated and parametric studies were conducted for depth and rock classification. The rock classification developed by the Central Research Institute of Electric Power Industry of Japan (CRIEPI)[7] was applied.

2) Rock properties

The parameters for rock properties were set as shown in Table 5.1.3-1 in the initial design, based on the results of the existing investigations as described in Section 3.2.6[8]. The properties of granite that are less dependent on rock classification (unit weight, Poisson's ratio, internal friction angle) were derived directly from average values from laboratory tests using cores, while those dependent on the rock classification (uniaxial compressive strength, elastic coefficient and cohesion) were categorized into three types using a reduction rate ($k=(V_p/v_p)^2$), defined by v_p, the elastic wave velocity measured for cores, and V_p, measured for rocks by geophysical logging, the average values (m) for each item and the standard deviation (σ); Class B (m x k), Class C_H ((m-σ) x k), Class C_M ((m-2σ) x k). For the sedimentary rock, the properties of the C_L class were taken as the average values for the tests conducted when the second shaft was constructed at the Tono mine and those of the D class as the minimum values for the tests conducted in/around the MIU Construction Site using cores. For the adjusted design, the cores from borehole MIZ-1 were classified using the CRIEPI method[7] as described in Section 3.5.6. The properties of granite were set in two ways, one using the average value of the test results in the same rock classification (unit weight, axial compressive strength, Poisson's ratio and internal friction angle) and the other multiplied by the reduction rate based on the above elastic wave velocity (elastic coefficient and cohesion). The results are shown in Table 5.1.3-2.

The initial stress values determined from the hydraulic fracturing tests conducted in boreholes AN-1, MIU-2 and MIU-3 at the Shobasama Site were used for the initial design. As shown in Fig. 5.1.3-3, the minimum principal stress, σ_{min}, of the horizontal stress was comparable to the estimated overburden pressure, σv, calculated from the unit weight of the rocks. The ratio between the minimum principal stress, σ_{min}, and the maximum principal stress, σ_{max}, was approximately two on average at the hanging wall of the Tsukiyoshi Fault. The initial stress used for the analysis (including the sedimentary layer) was set as $\sigma v:\sigma_{min}:\sigma_{max}$ = 1:1:2. For the adjusted design, the results of the hydrofracturing tests in the borehole MIZ-1 were used. As shown in Fig. 5.1.3-4, a different trend for the initial stress was seen around a depth of 600 meters. In the zone shallower than 600 meters, the minimum horizontal principal stress σ_{min} was comparable to the estimated overburden, σv, as in the case of the hanging wall of the Tsukiyoshi Fault at the Shobasama Site. The maximum principal stress σ_{max} is, on average, approximately 1.7 times the minimum principal stress σ_{min}. On the other hand, in the zone deeper than 600 meters, the maximum principal stress σ_{max} was comparable to the estimated overburden σv. The minimum principal stress was an average of approximately 65% of the maximum principal stress. Given this trend, for the adjusted design, different initial stresses were set for zones shallower and deeper than 600 meters, the values at the corresponding depths being obtained by linear regression from each test value. The initial stress used for the analyses is shown in Table 5.1.3-3.

3) Properties of the support system

The properties of rock support materials used in the design are shown in Table 5.1.3-4. The elastic coefficient of shotcrete and lining concrete was obtained using the following formulae (5.1.3-1 and 5.1.3-2). The duration for curing of the concrete from completion of the concrete lining through mucking out the excavated soil as the next step to stripping was determined to be approximately 20 hours using the formulae. The age of support materials was taken as one day.

$$f'_c(t) = \frac{t}{a+bt} d(i) f'_{ck} \tag{5.1.3-1}$$

$$E_e(t) = \Phi(t) \times 4.7 \times 10^3 \times \sqrt{f'_c(t)} \tag{5.1.3-2}$$

Where

$f'c(t)$: compressive strength (N mm^{-2}) of concrete at age t

$f'ck$: design base strength of concrete (N mm^{-2})

t : age (days)

i: reference age (days) for the design base strength, i = 28

a,b: constants to be specified for each type of cement. For early high strength cement, a = 2.9, b= 0.97

d : strength increase of concrete at the 91st day against that at the 28th day. In the case of early high strength cement, d(28) = 1.07

$Ee(t)$: effective Young's modulus (N mm^{-2}) at age t

$\Phi(t)$: correction coefficient of Young's modulus due to a large impact of creep at elevated temperatures up to 3-Days = 0.73

4) Stress release rate

It is planned to use the short-step method for the construction of shafts, whereby one step consists of two blastings (1.3 meters per blasting, total 2.6 m excavation) followed by placing of a concrete lining. This means that the introduction of the support after excavation is delayed compared to excavation with the conventional NATM method, where support is installed after every blasting. Therefore, the stress release rate when the support is installed was set as 80 % in the numerical analysis, which is larger than the value used in the NATM method (usually around 60 %). The 80 % stress release rate was judged to be appropriate based on the result of a separately conducted axisymmetric analysis simulating the excavation process. The stress release rate for the drifts was set as 60 %, because the NATM method was to be used.

(3) Analysis of the mechanical stability of the shafts and galleries

The mechanical stability of the shafts and galleries was analyzed using 2-D and 3-D finite element analysis methods with the property values described above, according to the flow diagram shown in Fig. 5.1.3-5. For zones with cross-sections not affected by the connections and joints to be discussed later in this section (so-called general zones), the stability was analyzed using the 2-D elasto-plastic finite element analysis method. For zones where the shafts and the galleries or two galleries are connected or joined, 3-D behavior needed to be evaluated. The stability in these zones was expected to decrease compared to the zones where 2-D behavior is dominant. Their stability was therefore analyzed by coupling the 2-D and 3-D analyses. The detailed analysis methods for each zone are described below. The evaluation of the rock mass stability around the MIU Construction Site in relation to excavation was based on the comparison of the maximum shear strain (γmax) of the rock around the shafts and galleries that was obtained in the numerical analysis using the critical shear strain (γo) shown in Table 5.1.3-1 and Table 5.1.3-2.

1) Shafts – general zone

For the general zones of the shafts where the short-step method is applied for excavation, the lining concrete was considered to be a permanent structure and the stress induced at the lining was calculated by a 2-D elasto-plastic analysis, which was compared with the allowable stress level ($f'_{ck}/4$) for the horizontal cross-section taking into consideration the initial stress.

2) Galleries – general zone

For the general zone of the galleries where the NATM method is used for excavation, each support measure used was considered to consist of permanent structures and the stress induced for each support measure was calculated with the 2-D elasto-plastic analysis method, which was compared with the allowable stress level for the vertical cross-section taking into consideration the initial stress.

3) Connected/joined sections of the shafts and galleries

The connected/joined parts of the shafts and the galleries were analyzed assuming that the NATM method would be used for the excavation. This assumes that primary supports and secondary lining concrete would be emplaced at the end. A 3-D elastic finite element analysis was conducted at the representative points. The result was normalized with the results of the 2-D elastic analyses of the general zone of the shafts and galleries at the same depth to determine the "influence level". The stability of the shafts and galleries was evaluated by multiplying the results of the 2-D elastic analysis for the general zones of the shafts and the galleries at each depth by the influence level. Here, if the stress in the primary support system is within the range of the allowable stress level, it means that the secondary lining does not have any load. On the contrary, if the stress on the shotcrete of the primary support system is beyond the allowable stress level ($f'_{ck}/4$), the stress in the primary support system was compared with the short-term allowable stress level ($f'_{ck}/1.3$) of the materials for temporary construction and the stress in the secondary lining was analyzed considering the increase in the stress in the case where the primary support system yields.

4) Shape of the cross-section of the shafts and galleries and support system

The locations where the stability of the shafts and galleries were analyzed are shown in Fig. 5.1.3-6 (longitudinal cross-section) and Fig. 5.1.3-7 (top view).

For the analysis of the stability of the support system, the support materials needed to be specified. Analyses were conducted for support patterns based on several construction records for the shaft and the reference support patterns proposed by the Japan Railway Construction Corporation and the Japan Highway Public Corporation to determine the most suitable pattern. The tentative support pattern for the general zone of the shaft used for the analyses is shown in Table 5.1.3-5.

(4) Results of analyses of the mechanical stability of the shafts and galleries

1) General zone

The results of analyses without consideration of the effects of connections between the shafts and galleries in the initial design are shown in Fig. 5.1.3-8. The locations of the longitudinal cross-sections in these analyses correspond to those indicated in the top view of the galleries in Fig. 5.1.3-7 (i.e. A-A). This figure shows the results of the comparison between the strain in the rock or stress in the support and the aforementioned critical strain in the rock or allowable stress in the support.

In the adjusted design, the stability was analyzed for granite at depths from 200 - 1,000 meters (every 200 m) for the shafts and at depths from 200 - 500 meters (every 100 m) for the galleries, considering the combinations of rock class and depth. Two classes for the shaft (C_M and C_L) and three for the galleries (B, C_M, C_L) were selected considering the interrelation with the support patterns. With regard to the cross-section of the galleries for the analyses, taking into consideration the options for the cross-section for a sub stage, three cross-sections were analyzed in addition to the reference size of the auxiliary stage (3.0 x 3.0 m), namely, 4.0 m x 4.0 m, 5.0 m x 5.0 m and 8.0 m x 6.5 m. Similarly to the initial design, a typical example of the analysis results for the strain in the rock and the stress in the support is shown in Fig. 5.1.3-9 for the main shaft and in Fig. 5.1.3-10 for the galleries with a cross section of 3.0 m x 3.0 m.

a) Shafts

For the design of the shafts, OPC (Ordinary Portland Cement) lining concrete (design base strength f'_{ck}=24 MPa) was assumed as the reference material and high strength concrete (design base strength f'_{ck}=40 MPa) was assumed to be used in the case where the stress in the concrete lining is beyond the allowable stress level.

The analysis in the initial design indicated that, since the maximum shear strain might exceed the critical shear strain at the depths

- Depth 63.2 - 175.2 meters
- Depth 826.2 - 1,025.0 meters

The intelligent construction method should be employed in which excavation progresses while monitoring the stability of the shaft wall and galleries as stated in Section 5.1.4.

The analyses for the adjusted design indicated that, since the maximum shear strain of the rocks might exceed the critical shear strain at the following depth in C_L class rock, the intelligent construction method should be employed.

- Depth 450 - 1,000 meters

b) Galleries

For the design of the galleries, OPC shotcrete (design base strength f'_{ck} = 18 MPa) was assumed as the reference shotcrete and high strength shotcrete was assumed in the case where the stress in the shotcrete is beyond the allowable stress level.

The analysis in the initial design indicated that, since the maximum shear strain might exceed the critical shear strain at the depths

- Depth 100 meters
- Depth 900 meters, 970 meters
- Depth 1,000 meters

the intelligent construction method should be employed.

The analyses in the adjusted design indicated the following for each rock class:

- In Class B and Class C_M rocks, the maximum strains in the rock bolts and shotcrete were below the allowable level, implying stability of the support system. However, at a depth of 450 meters and more, the shear strain predicted was beyond the critical shear strain, requiring intelligent construction as described above.
- In Class C_L rocks, the shear strain of the rock was beyond the allowable level at a depth of 200 meters and more; this was also the case for the steel support stress at a depth of 260 meters and more, the rock bolt axial strength at a depth of 380 meters and more and the stress in the shotcrete at a depth of 460 meters and deeper. Measures for keeping the strain or stress within the allowable limit would include changing the pitch of the support system from 100 cm to 90 cm at a depth of 300 meters, increasing the thickness of the support from 10 cm to 12.5 cm (using H125) and decreasing the pitch to 85 cm at a depth of 400 meters and increasing the thickness to 15 cm (using H150) and decreasing the pitch to 80 cm at a depth of 500 meters. However, since the maximum shear strain of the rock might exceed the critical shear strain, the intelligent construction method would be required as previously stated.

2) Connected/joined parts

Key concerns relate to the stability of connected/joined sections of shafts and galleries or those of galleries. Assuming the NATM method as the reference construction method for connected/joined sections, the results of the 2-D elasto-plastic analysis were multiplied by the influence levels obtained by the 3-D analysis.

The result of analyses in the initial design indicated concerns regarding stability at the depth shown below. The adjusted design was not done for the connected/joined parts.

- Depth of 100 meters

Similarly to the general zones, the stress in the shotcrete was beyond the allowable stress level (f'ck/4) in the shafts and galleries (sub stage), but was below the short-term allowable stress level (f'ck/1.3). The results of the stress analysis for the secondary lining concrete taking into consideration the increase in the stress satisfied the allowable stress limit. The range where the stress in the shotcrete exceeded the allowable limit was predicted to be within a few meters of the connected sections. However, the maximum shear strain of the rock largely exceeded the critical shear strain. Also, both the maximum shear strain in the rock and the stress in the shotcrete were above the critical shear strain and the allowable stress at the connecting sections between the sub stage and the evacuation tunnel. Therefore, strict control using intelligent construction as stated previously would be required.

- Depths of 900 meters, 970 meters and 1,000 meters

For the shaft, the stress in the shotcrete was above the allowable stress level (f'ck/4), but below the short-term allowable stress level (f'ck/1.3). When analyzing the stress in the secondary lining concrete, the stress that the secondary lining needed to cover was predicted to be small and the stability of the secondary lining concrete was confirmed. However, since the maximum shear strain of the rock exceeded the critical shear strain, intelligent construction as discussed previously would be required.

(5) Summary of the analyses of the stability of the shafts and galleries and the support system

For the design of the shafts and galleries, their stability and that of the support system were analyzed in two stages - the initial design (corresponding to Step 0) and the adjusted design (corresponding to Step 3). As stated previously, the design of shafts and galleries is preferably carried out at a stage when the geological environment conditions around the MIU Construction Site have been determined. In this study, however, since results for crystalline rock (granite), the major rock type of interest for the analyses, were available for the Shobasama Site, the initial design was conducted in Step 0, when the Phase I investigations had just started, and the adjusted design in Step 3, when the investigations had partly progressed.

For the design of the shafts and galleries, the changes in analysis conditions associated with the transition from the initial design (Step 0) to the adjusted design (Step 3) are summarized as follows. The rock properties and the initial stresses were based on the existing information in Step 0 and were updated based on the information obtained from borehole MIZ-1 at the MIU Construction Site in Step 3. Since it became apparent during the investigations that the geological structure at the MIU Construction Site was complex, it was concluded that analyses based on different rock types at different depths would involve uncertainties and necessitate additional analyses. Therefore, in the adjusted design, analyses were conducted for each depth with the rock type as a parameter. The applicability of each support design is then evaluated with depth. This would eventually contribute to selecting the support design for a given rock type at the time of excavation.

For the design of shafts and galleries in the future, the following points should be noted based on the studies described above:

- The geological environment conditions (e.g. rock properties, initial stress) should be based on data obtained near the planned shaft and gallery locations. The conditions under which the data can be applied should also be defined (e.g. geological structures such as the hanging wall and foot wall of faults, rock type).
- Analyses based on a given rock type would require additional analyses if the type proves to be different from that encountered during the actual excavation. The prediction of rock type would be low accuracy especially when a thick overburden overlies the basement rock, since fault structures could be hidden. Therefore, the stability of the shafts and galleries and the support system should be analyzed using the rock type as a parameter.
- Borehole investigations in/around the excavation site for the shafts and galleries would be desirable in order to reduce uncertainties in the design.

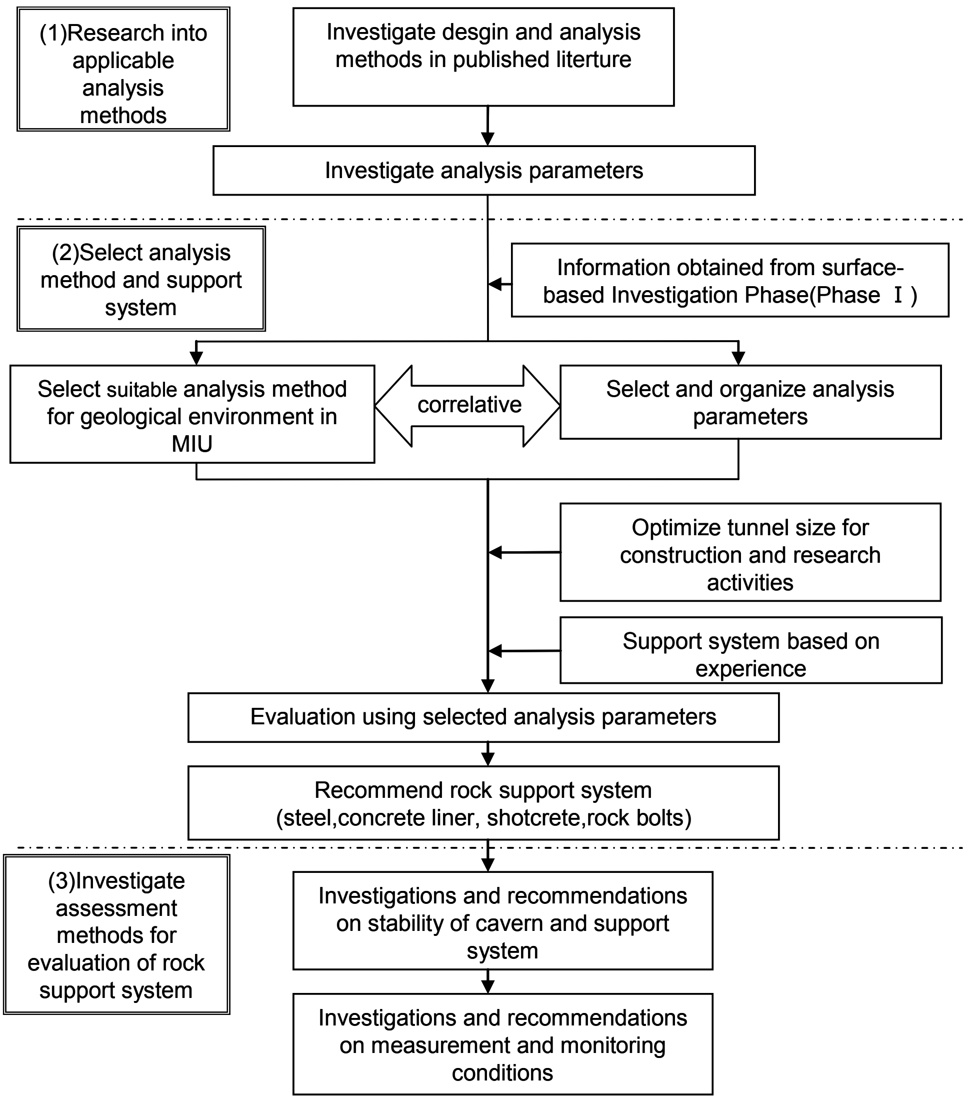


Fig. 5.1.3-1 Flow Chart for Assessment of Rock Support System Stability

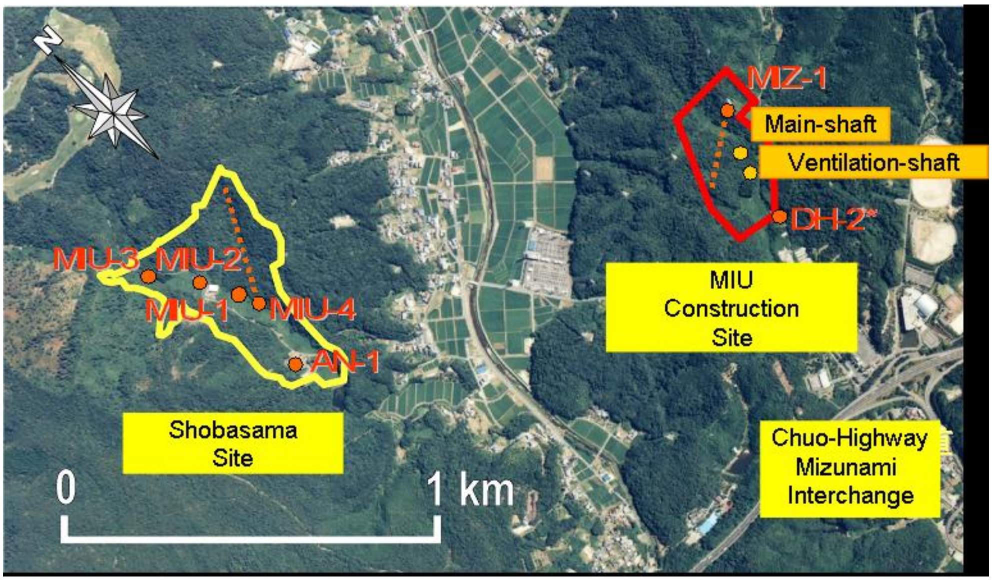


Fig. 5.1.3-2 Location of Boreholes around Mizunami Underground Research Laboratory Site

Table 5.1.3-1 Rock Properties used in Initial Design

Geology	Rock Class [-]	Unit Weight γ_t [kN m^{-3}]	Unconfined Compressive Strength qu [MPa]	Young's Modulus E [GPa]	Poisson's Ratio ν [-]	Cohesion C [MPa]	Internal Friction Angle ϕ [deg]	Critical Strain ε_0 [%]	Critical Shearing Strain γ_0 [%]
Granite	B	26.0	116.36	35.6	0.35	18.9	53.9	0.33	0.44
	C_H	26.0	89.74	30.1	0.35	14.6	53.9	0.30	0.40
	C_M	26.0	63.12	24.5	0.35	10.3	53.9	0.26	0.35
Sedimentary Rock	C_L	18.8	6.40	2.15	0.31	2.10	23.5	0.30	0.39
	D	18.8	1.37	0.628	0.38	0.449	21.5	0.22	0.30

Table 5.1.3-2 Rock Properties used in Revised Design

Geology	Rock Class [-]	Unit Weight γ_t [kN m^{-3}]	Unconfined Compressive Strength qu [MPa]	Young's Modulus E [GPa]	Poisson's Ration ν [-]	Cohesion C [MPa]	Internal Friction Angle ϕ [deg]	Critical Strain ε_0 [%]	Critical Shearing Strain γ_0 [%]
Granite	A	26.3	143.00	50.6	0.29	39.7	51.10	0.28	0.36
	B	26.2	151.11	50.3	0.27	39.2	52.53	0.30	0.38
	C_H	26.3	181.30	49.3	0.27	34.3	52.43	0.37	0.47
	C_M	25.9	174.67	50.5	0.18	37.6	49.30	0.35	0.41
	C_L	23.4	71.83	20.9	0.24	25.2	30.10	0.34	0.43

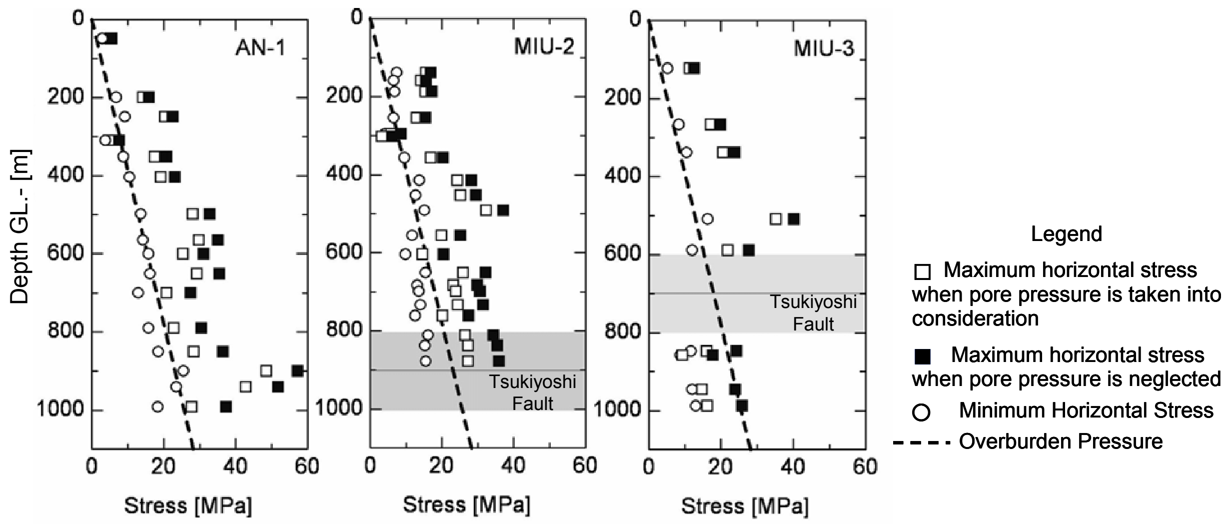


Fig. 5.1.3-3 In Situ Stress Measurements (Shobasama Site)

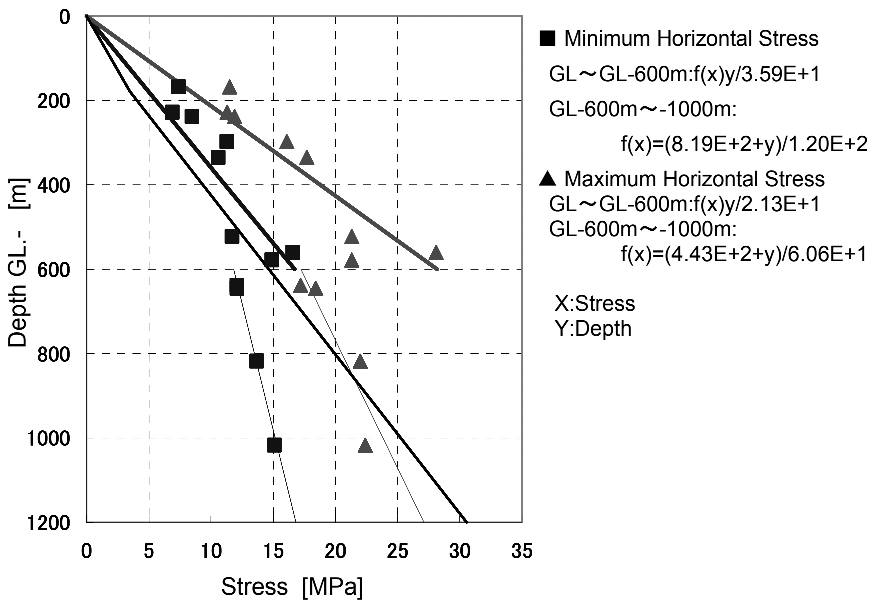


Fig. 5.1.3-4 In Situ Stress Magnitudes used for Revised Design based on MIZ-1 Measurements

Table 5.1.3-3 Initial Stress Condition used in Revised Design

Geology	Depth [m]	Vertical Stress σ_V [MPa]	Minimum Horizontal Stress σ_h [MPa]	Maximum Horizontal Stress σ_H [MPa]
Granite	200	5.20 (1.00)	5.57 (1.07)	9.39 (1.81)
	400	10.40 (1.00)	11.14 (1.07)	18.78 (1.81)
	600 upper	15.60 (1.00)	16.71 (1.07)	28.17 (1.81)
	600 lower	15.60 (1.00)	11.83 (0.76)	17.21 (1.10)
	800	20.80 (1.00)	13.49 (0.65)	20.51 (0.99)
	1000	26.00 (1.00)	15.16 (0.58)	23.81 (0.92)

Table 5.1.3-4 Properties of Support Materials used in Design

Support Member	Design Strength f'_{ck} [MPa]	Allowable Compressive Stress: Short Term $f'_{ck}/1.3$ [MPa]	Allowable Compressive Stress: Long Term $f'_{ck}/4$ [MPa]	Young's Modulus E [GPa]	Poisson's Ratio ν [-]
Concrete Liner	24	-	6.0	8.81	0.20
	40	-	10.0	11.4	0.20
Shotcrete	18	13.8	4.5	3.4	0.20
	36	27.7	9.0	6.0	0.20

Support Member	Material	Allowable Tensile Stress [MPa]	Design Strength of Rock Bolt [kN]	Young's Modulus E [GPa]	Poisson's Ratio ν [-]
Steel Support	SS400	160	-	210	0.30
Rock Bolt	SD345	-	120	210	-

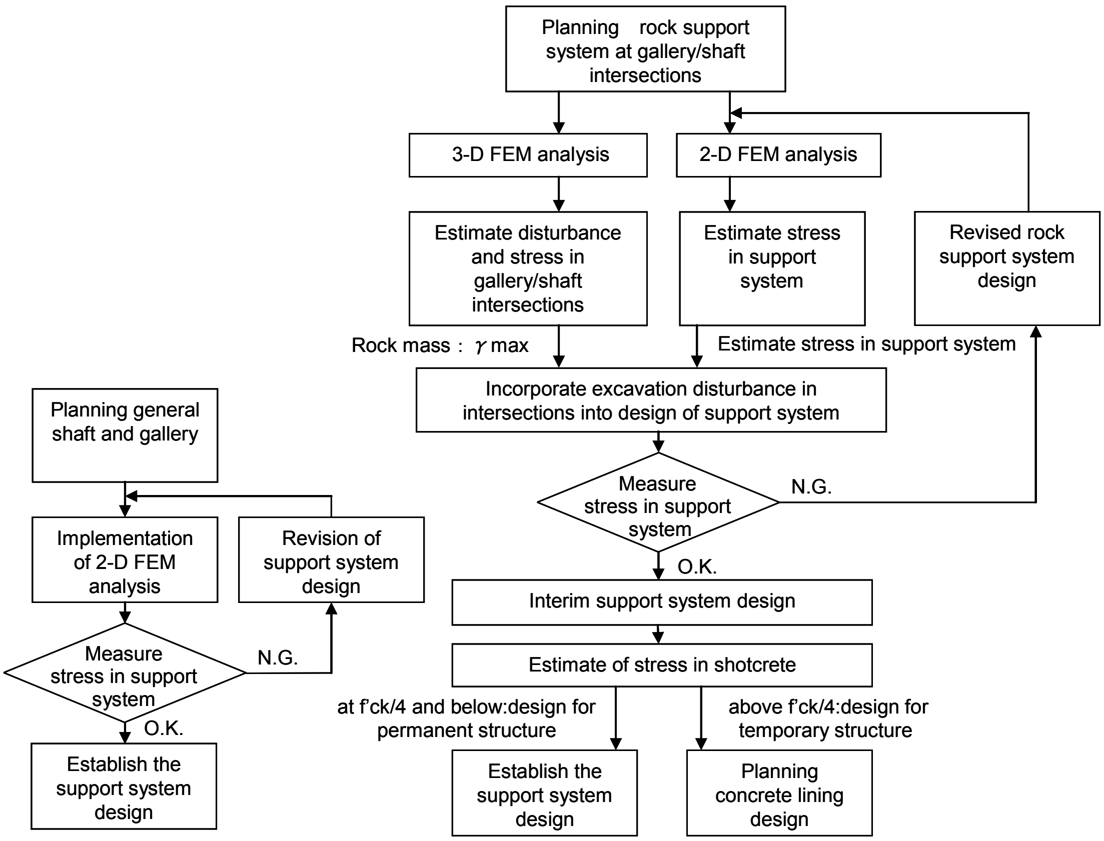


Fig. 5.1.3-5 Flow Chart -Investigation of Gallery Stability

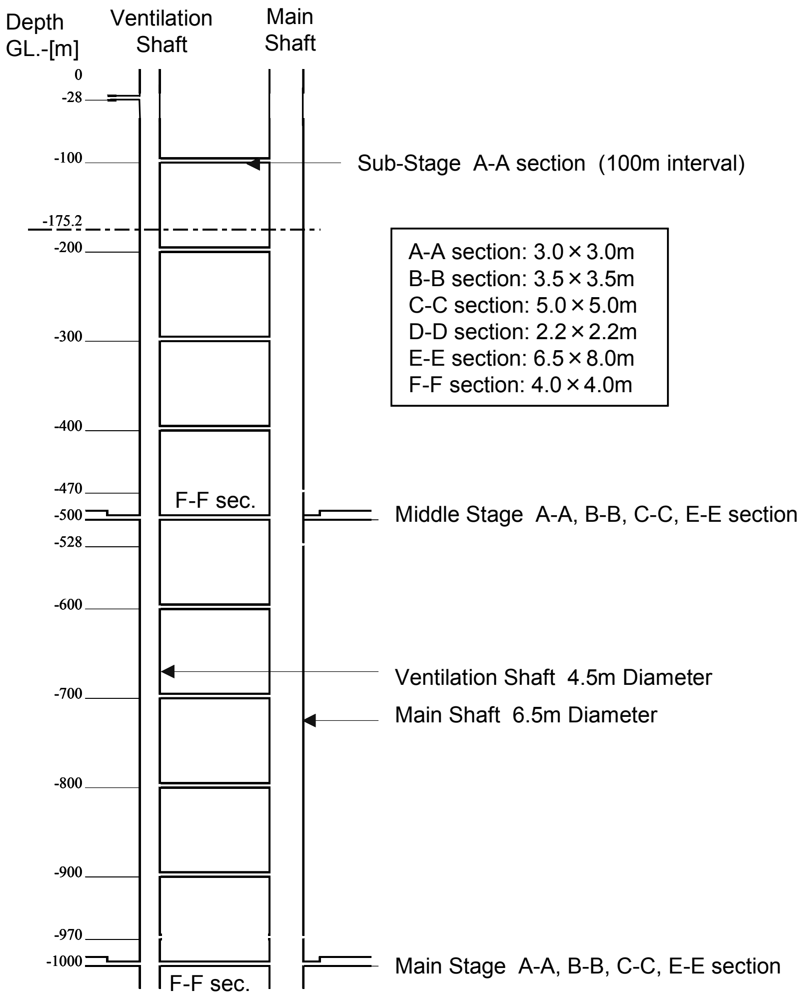


Fig. 5.1.3-6 Investigation Sections for Mechanical Stability in Galleries(vertical X-section)

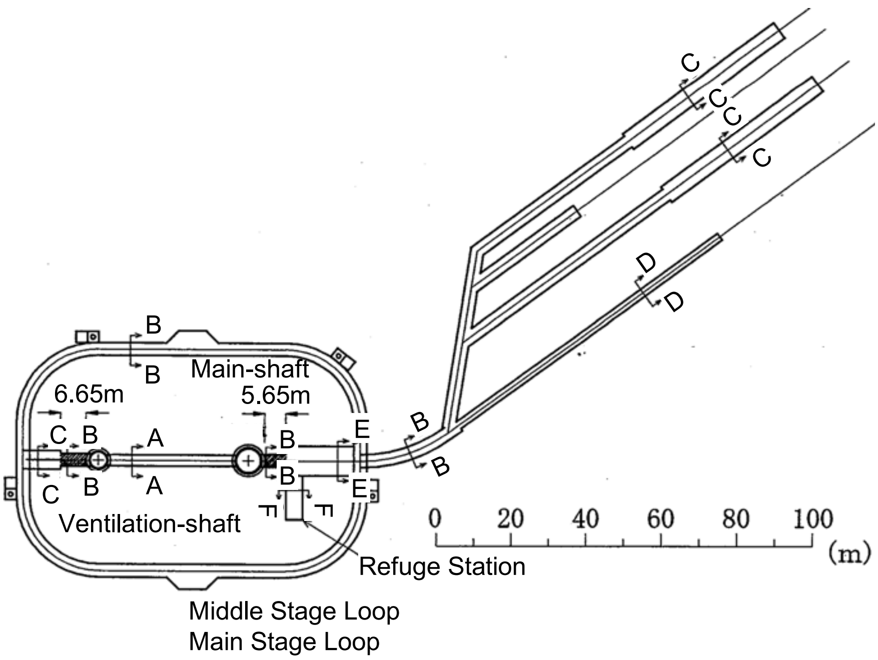
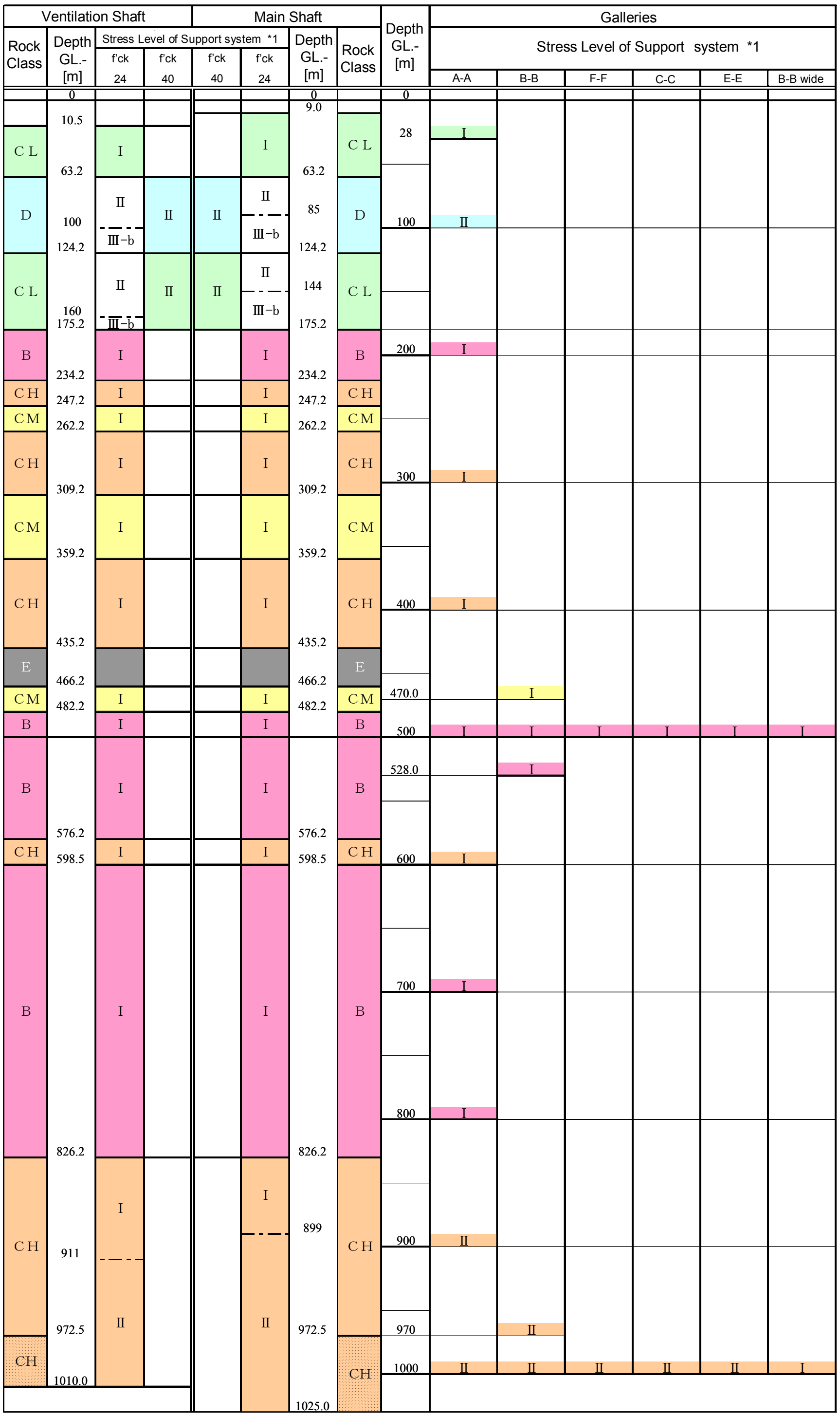


Fig. 5.1.3-7 Investigation Section for Mechanical Stability in Galleries

Table 5.1.3-5 Tentative Support System proposed for Main Part of Shaft

<table>
<tr><th>Geology</th><th>Rock Class</th><th>Concrete Liner Thickness</th><th>Steel Support</th></tr>
<tr><td rowspan="2">Sedimentary Rock</td><td>D</td><td rowspan="5">400 mm</td><td rowspan="2">H-125</td></tr>
<tr><td>C_L</td></tr>
<tr><td rowspan="3">Granite</td><td>C_M</td><td rowspan="3">-</td></tr>
<tr><td>C_H</td></tr>
<tr><td>B</td></tr>
</table>



※1 Stress Level of Support

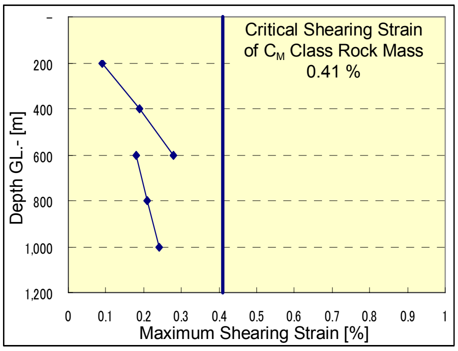
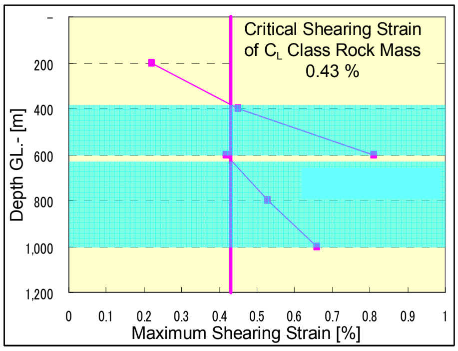
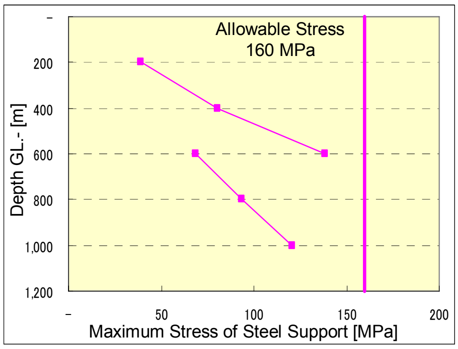
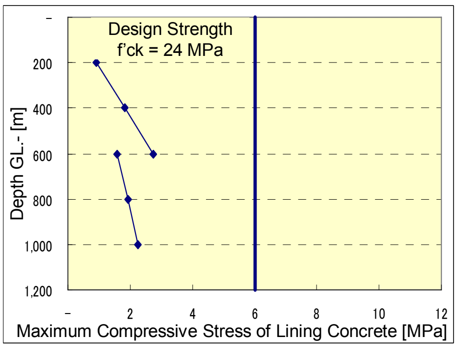
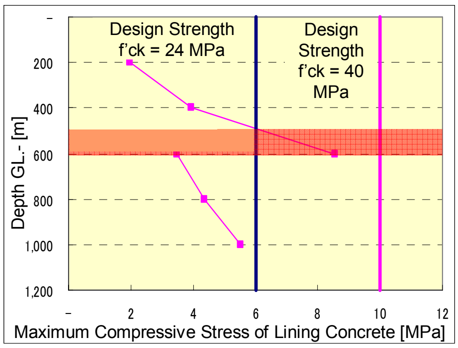
I : Rock Mass-below Critical Shear Strain, Support System Members-below Allowable Stress

II : Rock Mass-above Critical Shear Strain, Support System Members-below Allowable Stress

III-a : Rock Mass-below Critical Shear Strain, Support System Members-above Allowable Stress

III-b : Rock Mass-above Critical Shear Strain, Support System Members-above Allowable Stress

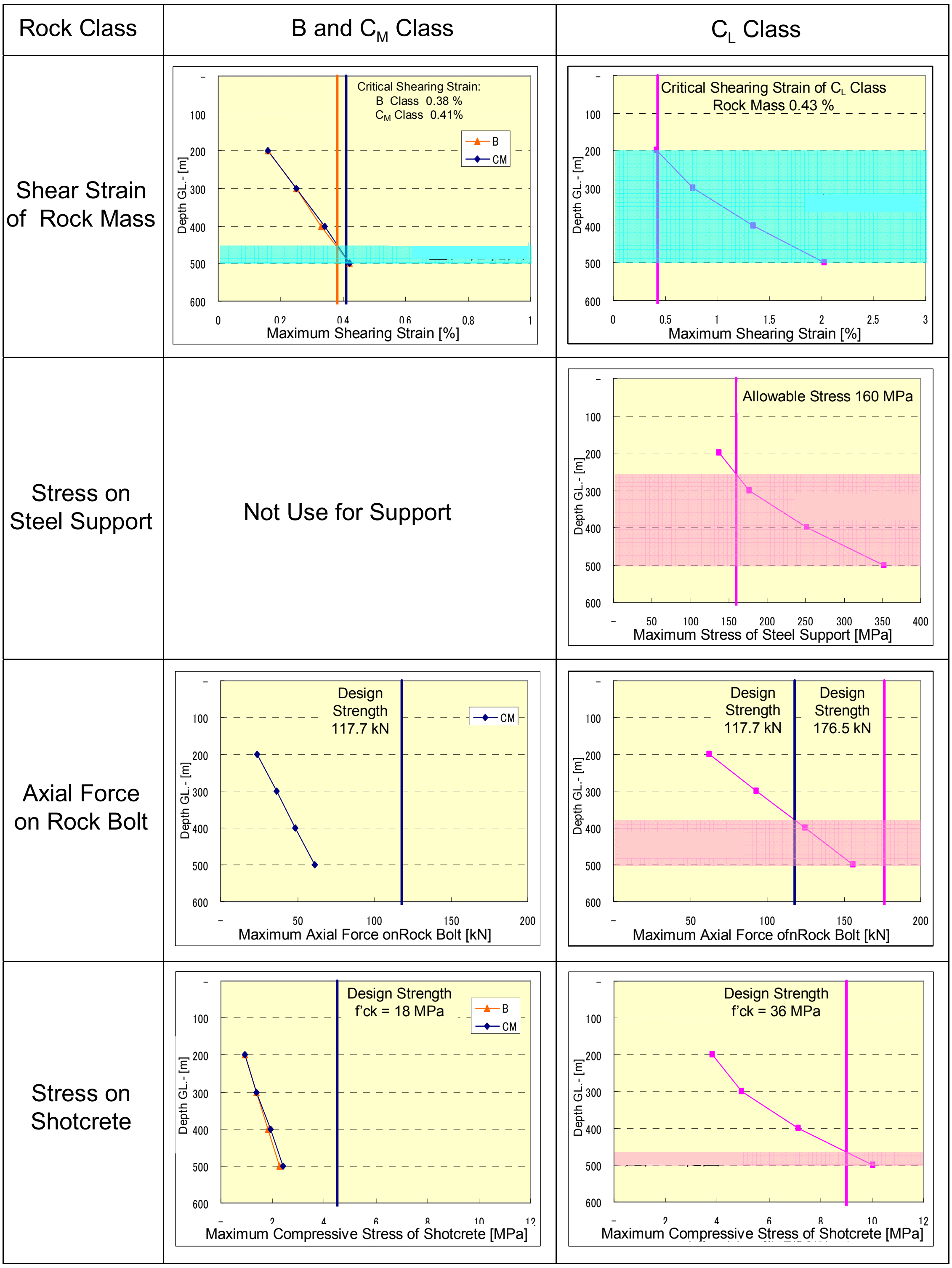
Fig. 5.1.3-8 Summary of Requirements for Shafts and Galleries in the Initial Design

Rock Class	C_M Class	C_L Class
Shear Strain in Rock Mass		
Stress on Steel Support	Not Use for Support	
Stress on Concrete Liner		

Plastic Zone: above critical shear strain

Zone requires High Strength Concrete:above allowable stress in normal concrete

Fig. 5.1.3-9 Revised Stress and Strain in Typical Sections of the Shafts based on Site Specific Data



Plastic Zone: above critical shear strain

Zone requires revised support members:size&spacing of steel support, high strength rock bolt and shotcrete

Fig. 5.1.3-10 Revised Stress and Strain in Typical Sections of the Galleries based on Site Specific Data

5.1.4 Feedback of measured data to design and construction plans

Feedback of various data obtained during the construction of the shafts and galleries in Phase II to the rock mass evaluation, support specifications and construction measures will be essential for establishing appropriate design and construction techniques. In this section, some examples of changes in support specifications and construction measures made based on such feedback are described for preventive measures against three unexpected situations during construction work: the presence of a geological structure that was not predicted, unexpected deformation behavior and unexpected groundwater behavior associated with the excavation of the shafts and galleries.

For the rock mass evaluation, a flow chart was prepared as shown in Fig. 5.1.4-1 describing the provision of feedback from observations of the geology on the tunnel wall and measurements of rock displacement and stresses in the support system in the shafts and galleries, including observations made during the excavation. The flow chart will be applied to the sedimentary rock zone and modified to apply to the granite zone.

For the application of the feedback technique to analyses of the deformation behavior of the rock mass, the elastic modulus and the principal stress ratio of the rock mass were obtained by inverse analysis using measured data for internal displacement during the excavation of the second shaft in the Tono mine. These results were then compared with the actual measurements. Measured and analytical values were 3.3 mm and 3.1 mm respectively for displacement in the N-S direction and 1.8 mm and 0.6 mm for displacement in the E-W direction. These indicated insufficient anisotropy of the displacement, but a generally consistent maximum displacement level. The stress distribution obtained by the direct analysis would allow determination of the local safety factor (proximity to destruction) and could be obtained by defining the cohesion and the angle of internal friction, which would allow evaluation of the distribution of plastic zones. Fig. 5.1.4-2 shows example calculated local safety factors using measured values and measured values multiplied by a factor of 10.

For the application of the feedback technique to the analysis of the volume of water coming from the shaft wall, the estimated hydraulic conductivity was revised based on a comparison between estimates and measurements of water from a specific section. Using the revised hydraulic conductivity, the groundwater inflow rate from subsequent excavation sections in deeper zones was calculated. In the initial design of the shafts and galleries, the hydraulic conductivity $K = 10^{-8}$ m s^{-1}, the average value from the results of in-situ hydraulic tests conducted at the Shobasama Site, was used for calculating the inflow rate using the well hydraulic theory (see Section 3.2.6). Based on the calculations, the capacity of the drainage system was determined for normal use. Another system with the same capacity was also installed for emergencies, ensuring a safety margin of two[9)]. During the excavation of the shafts and galleries, the water from the excavation face and that collected in the catchment ring through the back-drainage materials were drained to the surface using a high-lift pump. The volume of water in the catchment ring could be measured with an electromagnetic flowmeter and total drainage could be measured at the drainage processing facility. Repeated comparison of the estimated volume of water with that actually measured, and the feedback of the results, allowed design of an appropriate drainage system.

As described above, for the feedback of measured data to the design and construction plans (intelligent construction method), a detailed feedback flow chart was prepared incorporating rock mass evaluations based on measurements and analyses. For the geological observations, the most appropriate method for determining the geological conditions of the shaft wall was studied, applying several rock classification methods.

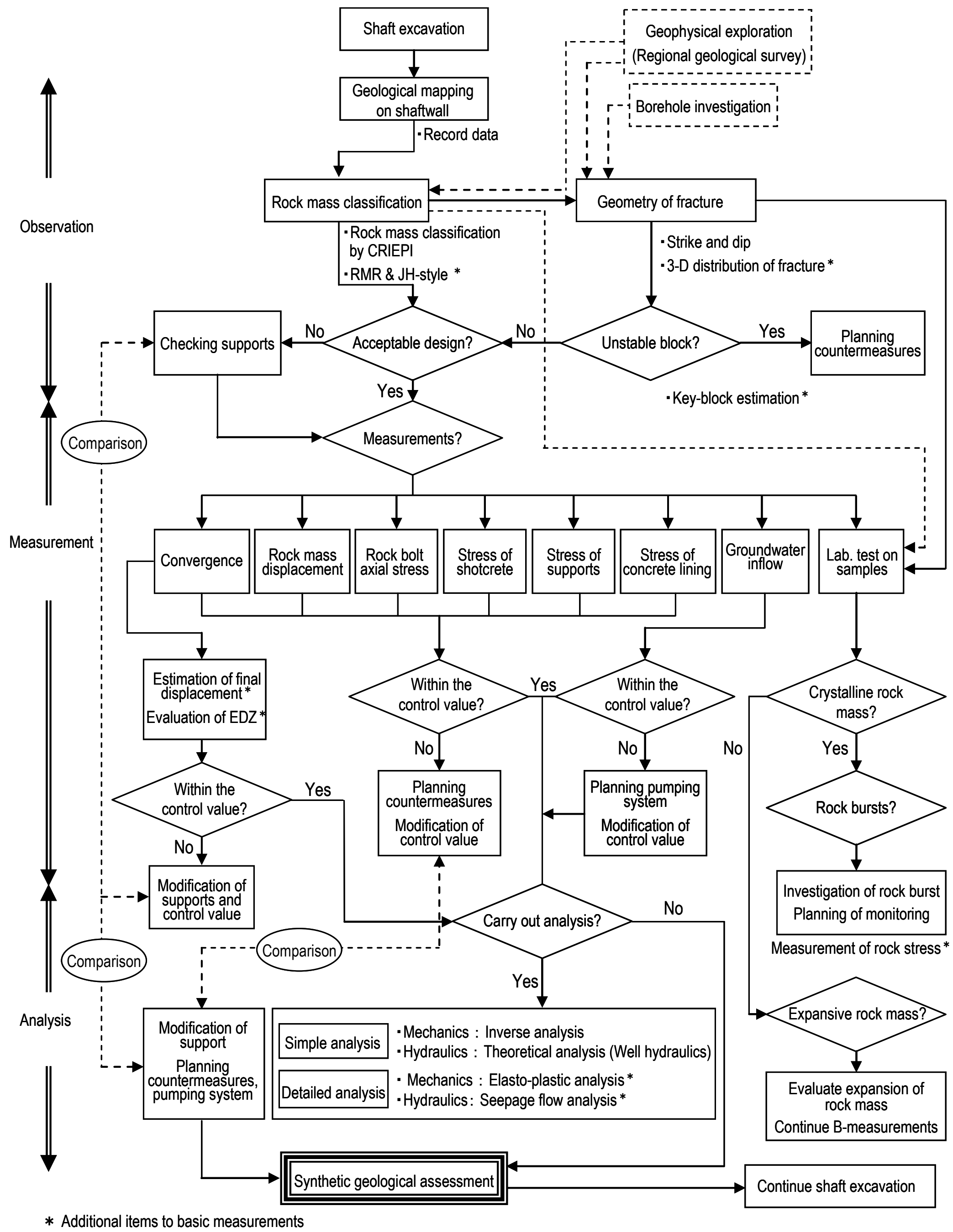


Fig. 5.1.4-1 Flow Chart -Rock Mass Assessment for Shaft Excavation

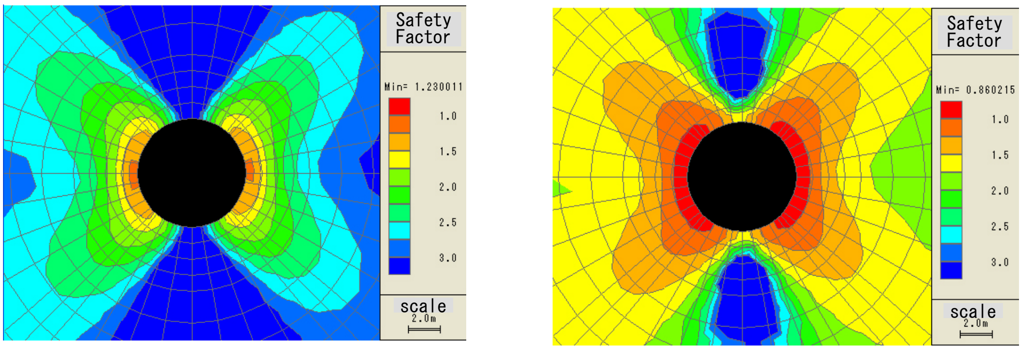


Fig. 5.1.4-2-Distribution of Local Safety Factor

5.1.5 Seismic stability of the shafts and galleries

The MIU Project includes structures extending to a depth of 1,000 meters or more, which is much deeper than conventional underground facilities. To assess the seismic response behavior and evaluation of the integrity of the shafts and galleries during an earthquake, seismic motion in the deep underground environment has to be evaluated.

Seismic analyses were conducted using the static seismic coefficient method used for the stability analysis of tunnels in the H12 Report[4], as well as the FEM dynamic analysis method[10),11]. The analysis boundary conditions, such as the model configuration, rock properties and input seismic motion, were based on the initial design of the MIU.

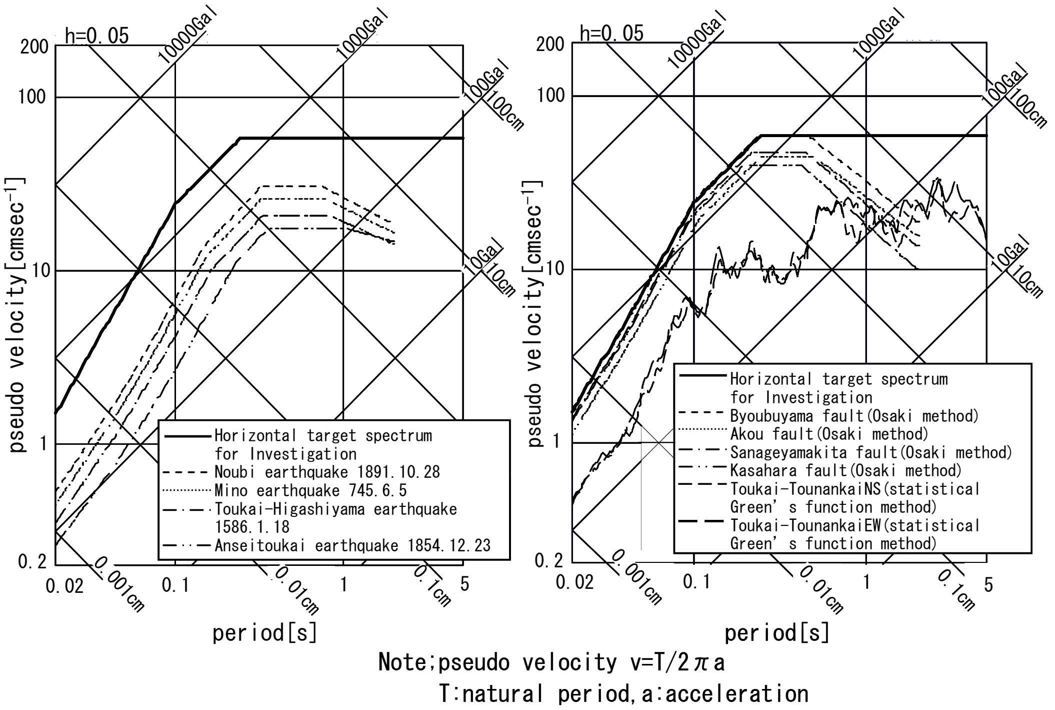
For the input seismic motion, the anticipated Tokai earthquake was assumed in addition to historic earthquakes and the presence active faults nearby, since the area is within the impact zone of the Tokai earthquake. The spectrum of the simulated seismic waves anticipated from the earthquakes is shown in Fig. 5.1.5-1. Earthquakes with the Boybusan Fault as the seismic center are considered to have the largest impact. Therefore, the target spectrum for the horizontal seismic motion for the analysis was set to include the spectrum of the simulated seismic wave as shown in Fig. 5.1.5-2. The spectrum was then analyzed using the sinusoidal synthesis method. As a result, the maximum acceleration was assumed to be 478 gal at the ground surface.

The vertical motion used for the seismic design is generally 1/2 to 2/3 of the horizontal motion. Deep underground, it could be similar to the horizontal motion because of the difference in the amplification environment from that near the surface and the effect of oblique incidence. The characteristics of the vertical seismic motion deep underground were studied using existing seismic records. The ratio of the spectrum of the horizontal motion to that of the vertical motion were compared by calculating the stripped wave at the basement rock surface (outcrop wave) using existing data from the KIK-net observation station of the National Research Institute for Earth Science and Disaster Prevention, data from the Hashima observation station where earthquakes have been recorded at the surface and at a depth of 1,500 meters and data from the Kamaishi mine[12] where earthquakes were recorded at the surface and at a depth of 615 meters. The results of the comparison are shown in Fig. 5.1.5-2. The vertical and horizontal spectra at the two observation stations were, on average, approximately 0.97 and 0.88, respectively. The ratio of the vertical motion was higher (0.66 on average) than that at the ground surface. Referring to the observations recorded at the Kamaishi mine, the target spectrum of vertical seismic motion for the analyses was therefore set as 2/3 (maximum acceleration of 350 gal) that of the horizontal seismic motion. As a result, the ratio of the vertical and horizontal spectra was 0.86 at a depth of 1,500 meters, which is larger than that at ground surface (0.66) and is similar to the observation records from Hashima (0.97 on average) and Kamaishi (0.88 on average)[13].

Seismic analyses to evaluate the integrity of the lining concrete of the shaft in the MIU were conducted by FEM dynamic analysis using the horizontal and vertical seismic motions set as above. The results are as follows:

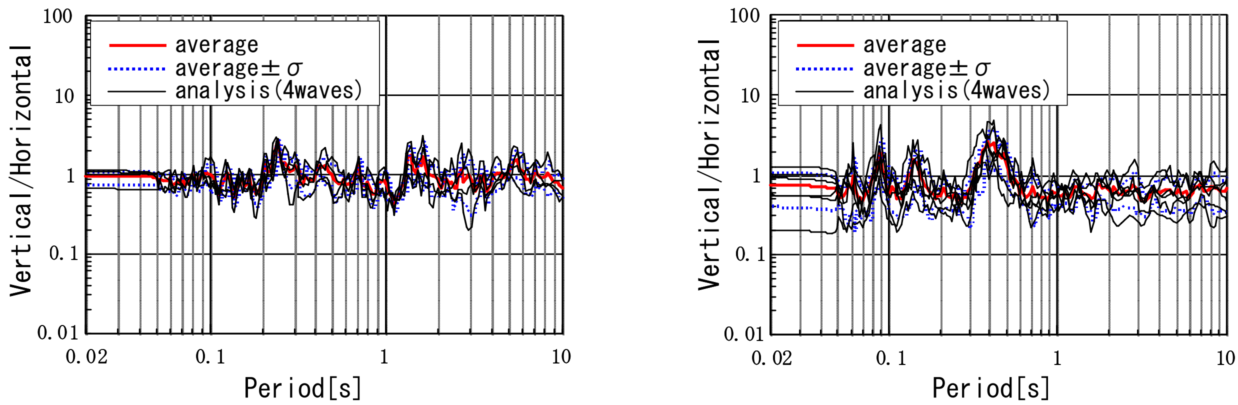
- In-plane shearing force prevails in the lining concrete of the shafts due to horizontal seismic motion, but the increase in the compression stress in the horizontal direction during earthquakes was small. Therefore, the stress level in the shaft lining concrete (stress level during excavation obtained by FEM non-linear analysis carried out for analyzing the stability of the support system + the increase in stress during earthquakes) was judged to be sufficiently lower than the fracture strength.
- Axial force in the horizontal and vertical directions prevailed in the lining concrete of the shaft due to the vertical seismic motion. However, the increase in stress level during earthquakes was approximately half that generated by the horizontal seismic motion. The stress in the shaft lining concrete (sum of that during the excavation and the increase during earthquakes) was judged to be sufficiently lower than the fracture strength.

Horizontal seismic motion was therefore assumed for the seismic design, taking into account the features in the Mizunami region as well as historic earthquakes, nearby active faults and the future Tokai earthquake. Using the seismic motion, the allowable stress in the lining concrete of the shafts was checked using the method employed in the H12 Report. An analysis was also made of the vertical seismic motion considering the features of the very deep shafts. The analysis indicated sufficient seismic resistivity of the shafts.



(a) Historical Earthquake Spectrum (b) Active Fault Spectrum

Fig. 5.1.5-1 Historical Earthquake and Active Fault Spectrum for Investigation[13)]



(a) Hashima Point(depth 1,500m) (b)Kamaishi-Mine Point(depth 615m)

Fig. 5.1.5-2 Vertical/Horizontal Spectrum Ratio[13)]

5.1.6 Measures to limit inflow of groundwater and minimize rock burst

Unexpected high water inflow is a sudden event that should be avoided during the construction of shafts. Studies to establish measures against unexpected high water inflow include, for the presumed geological conditions, predicting the depth where water-conducting features may occur, use of predictive techniques to plan measures against fractures, preparation of grouting guidelines and formulation of other measures. Fig. 5.1.6-1 shows the primary strategy. Planning of measures against sudden unexpected water inflow was based primarily on stopping the water by grouting, bearing in mind that the water in the shafts has to be pumped to the surface and according to the policy that special care has to be taken to avoid impacts on the surrounding environment. Since the time needed for grouting after the occurrence of unexpected high water inflow (post-grouting) is expected to be long and involve considerable cost, pre-grouting is taken as the reference measure.

Two types of measurement techniques of water flow are considered: pilot borehole drilling and indirect geophysical logging. Pilot borehole dilling involves direct investigation of the zone ahead of the face before excavation, allowing detection of conditions that could result in water inflow. Geophysical logging uses differences in properties between intact rock and rock with fractures that may either represent permeable zones, sealing zones or fracture zones. The techniques include reflection seismic surveys and electrical/electromagnetic surveys.

For applying grouting to prevent unexpected high water inflows, the following need to be determined: the anticipated locations where water inflow may occur, the volume of inflowing water and the drainage (i.e. pumping) capacity, criteria for switching from ordinary drainage, procedures for making decisions on the implementation of grouting, reference injection pressure and reference injection conditions. The grouting procedure is shown in Fig. 5.1.6-2.

Pre-grouting was planned for the case where the occurrence of fractures is predicted by investigations of the geological environment and the location of inflowing water is predicted by referring to past examples and existing guidelines. The plan includes injection holes in three lines with a 1.5 meter pitch within the range where the diameter is 3 times larger than the diameter of the excavation. A detailed plan will be formulated by determining the positions of the fractures on the wall of shafts and galleries based on the geological structure model.

Other sudden incidents include rock burst, which may occur in hard rock deep underground, and collapse, where a rock mass slips down primarily along a discontinuous surface in the shaft wall. Specific cases of such incidents were investigated[14] and the possibility of occurrence and appropriate countermeasures were studied.

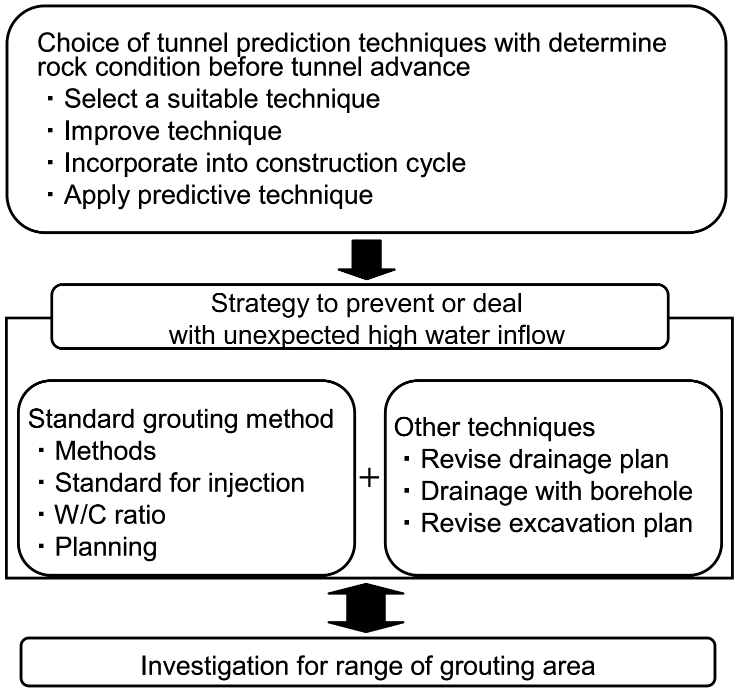


Fig. 5.1.6-1 Countermeasures for Unexpected High Water Inflow

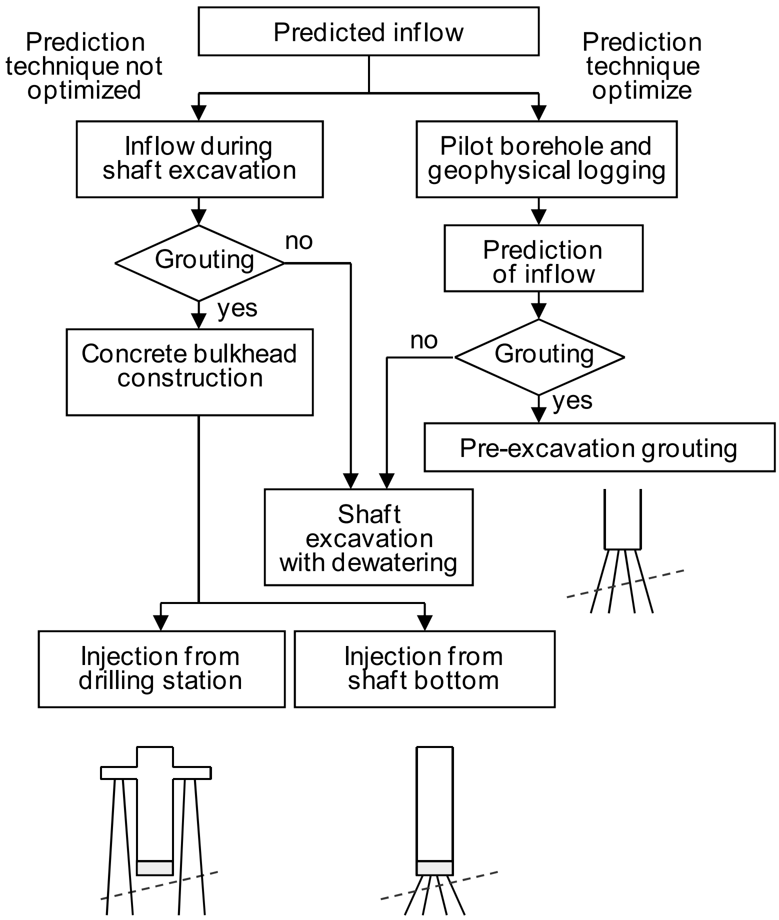


Fig. 5.1.6-2 Grouting Flow Chart

5.1.7 Safety measures

(1) Disaster prevention concepts based on analysis of the ventilation network

a) Ventilation network analysis

Fire is highly likely to lead to a serious disaster in the shafts and galleries and securing evacuation routes and evacuation time is most important. Due to the depth of the MIU, there may be cases where sufficient evacuation time cannot be ensured. In addition to evacuation to the surface, the primary concept for disaster prevention in the event of fire is considered to be evacuation to a safe refuge in the facility. Based on this, the location for safe evacuation (refuge), how to ensure the evacuation time and the space, configuration and conditions required for the refuge were studied. As part of the study, the conditions in the shafts and galleries were estimated based on the 3-D layout and the ventilation conditions were estimated using the ventilation network analysis method that is frequently applied in the field of mining. An analysis was also conducted for the case assuming fire. The ventilation network analysis is a type of computer analysis that is conducted to determine the airflow circulating in the ventilation network (including all tunnels that make up the underground space, ventilation pipes and air leakage circuits). It also determines the temperature and humidity inside the facility and the behavior of gas and smoke during a fire. This is important for designing the shafts and galleries, daily ventilation management and air control at the time of a disaster. The ventilation network analysis method was used because the shafts and tunnels will be connected with each other in the facility, which is different from tunnel excavations in conventional civil engineering. These connections make it difficult to calculate the airflow based on a simple theory.

The prediction of gas behavior during a fire based on the ventilation network analysis is shown in Table 5.1.7-1. In the analysis, the construction stage was divided into small sub-stages and the behavior of gas generated at different locations was analyzed. Based on the result, the locations and specifications of the refuges were examined. As a result, one refuge was located in each gallery and ventilation and fire extinguishing systems were designed.

The outline of the ventilation system on completion of the shafts and galleries is shown in Fig. 5.1.7-1. The system with a local ventilation fan and ventilation pipe will be changed to a total ventilation system that uses the whole shaft once the shaft reaches a depth of 500 meters. For excavation of the shaft below 500 meters, a local ventilation fan will be installed at a depth of 500 meters and ventilation will be achieved by extending the ventilation pipe. When excavation reaches the final depth, the fan and pipe will be removed and replaced by a system using the whole shaft. Ventilation at the middle stage and the main (deepest) stage will be achieved with a local ventilation fan and ventilation pipe.

b) Underground integrated management system

Scientists, visitors and construction workers will be present at various times in the shafts and galleries in the MIU and thorough consideration of ensuring the safety of these persons in the event of a disaster such as fire is required. The system considered for the shafts and

galleries consists of the following independent components:
a) An entry/exit control system
b) An underground condition management system
c) An underground communication management system and
d) An underground fire monitoring system.

These systems can work independently at the time when they are introduced, but will be developed so that they function together, as a single integrated system. For example, if fire occurs at a certain location in a shaft or gallery, the fire monitoring system would immediately identify the location of the fire and the underground communication management system would report the fire to the facility operators. At the same time, a fire analysis would be conducted using data obtained using the underground condition management system as input data and the behavior of gas generated by the fire would be predicted. In order to protect workers in the underground facility from smoke, an optimum ventilation system will be selected and the operation of air doors and the ventilation system will be controlled. Workers will also be informed of safe evacuation routes and the locations of the refuges. Fig. 5.1.7-2 shows the concept of the integrated underground management system as described above. A further explanation is given below.

The integrated system is linked to the individual systems through:

- A fixed data management system (layout of the shafts and galleries and location coordinates)
- A variable data management system (data from sensors installed in the shafts and galleries)
- An information processing/analysis system (anomaly detection and fire-affected zone analysis)

Linking these individual systems to form an overall system with displays and control/indicator functions allows continuous management of the underground environment, prevention of disasters and the spread of any disaster that occurs and ensuring the safety of underground workers. A dedicated program was developed which, in addition to the four systems described above, links the fire analysis for predicting gas behavior using the ventilation network analysis and the thermal environment analysis for predicting the distribution of temperature, humidity and wind speed. A system for supporting decision-making based on the GIS (Geographical Information System), including evacuation route analysis, was also constructed on a trial basis. This system would monitor the location of workers underground and the environment inside and outside the facility at all times. A thermal environment analysis conducted at the same time would compare the results with the underground environment data and, if an anomaly is detected, a fire analysis would be conducted to identify the area over which the fire may extend and to identify routes for evacuation. These analysis results and data would be input to the GIS information management application and stored in the database. The information would also be transmitted to management through the user interface.

The system constructed as above was demonstrated as a model case at the Tono mine, using measured data from the mine. A series of systems - monitoring of different types of sensor and underground environment analyses, identification of underground worker location and display of evacuation route for emergencies - were operated successfully and their effectiveness was confirmed. Fig. 5.1.7-3 shows an example of the evacuation route at the Tono mine. In the future, an underground information management system for the shafts and galleries in the MIU will be developed and improvements will be made using data obtained during excavation of the shafts.

(2) Risk management

Worldwide, the MIU will be a pioneering URL consisting of two shafts to a depth of 1,000 meters and a number of galleries at various depths. This means that there is little experience in the construction of such a facility and various risks are anticipated. Such risks may seriously affect the construction work. Risk management involves identifying and evaluating such risks in advance and formulating and implementing measures for their mitigation. This method was originally developed in the field of finance and has been actively applied in engineering sectors in recent years. Here, risks that may occur at the time of excavation of the shafts and galleries were identified and the correlation between events was evaluated; quantitative evaluations of losses were conducted using statistical data and event trees[1),15)].

The evaluation was conducted for four types of construction area, classified depending on depth, and twelve events were identified based on questionnaires returned from experts. After being classified and reorganized, these events were subjected to quantitative analyses in terms of delay in the construction schedule, loss of construction funding and loss of social trust. Fig. 5.1.7-4 shows the risk correlation among events based on the returned questionnaires. The 12 events identified were reorganized into 7 groups and their correlation is presented in the figure. As an example of the quantitative evaluation of risk based on the classification, the loss of working days (number of days that the construction work is delayed due to the occurrence) in each group is shown in Fig. 5.1.7-5[16)]. Although scattering of data may be largely due to the lack of statistical data, the loss of working days was the highest for Group 5 (falling objects + machine failure + fire) at all depths. At levels shallower than 500 meters, the risk of Group 4 (unexpected high water inflow) was relatively higher than that in the levels deeper than 500 meters. Thus, quantitative comparisons were possible for the number of lost working days by depth and event.

Finally, risk reduction measures were studied. Four types of measures were formulated for each event: advanced measures (risk mitigation), regular management (risk containment), insurance (risk transfer) and post-event measures (risk containment). Examples included improvement of the systems that could have a significant impact on construction processes if they malfunction or improvement of early detection of signs of risks by instrumentation control, intelligent construction, improved periodical inspections and advanced examination of countermeasures. The intelligent construction method, in particular, has been developed in conjunction with the NATM method in the field of tunnel engineering to avoid risks during construction work. It can be both a risk containment technique and a verification technique for design conditions and methods.

As discussed above, with quantitative evaluation of the significance of a risk, the type of measures to be taken can be made clear. The applicability of the methods will be evaluated and the methodology will be improved in the future through inclusion of information obtained during the excavation of the shafts and galleries.

For the safety measures, which are the most important issue in this project, an integrated management system was developed. This couples the systems for entry/exit control, environment management, communication, fire prevention and the ventilation network analysis. Risks were also identified and reflected in the provision of safety measures using the risk management system considering the features of the shafts.

Table 5.1.7-1 Ventilation Network Analysis in Case of Fire

Location of Fire	State of Fire Condition	Means of Escape
Main Stage and Middle Stage	Maintain operational aireflow conditions. Smoke-laden air will exhaust via Vent. Shaft.	Main Shaft and Middle Stage will be safe area. It is possible to escape from the Main Shaft.
Lower Part of Main Shaft and Ventilation Shaft	Smoke-laden air will exhaust via Vent. Shaft. Some back-flow of smoke laden air into sub-stage and into whole MIU may occur. Incremental increase in heat and gas concentration is expected to be low.	Recommended option is to wait in a refuge station but escape via Main Shaft using oxygen mask will be possible.
Shallow Part of Main Shaft	Smoke-laden air will exhaust through the Vent. Shaft via the Middle Stage. Gas flow into the whole MIU will take considerable time.	Same as above.

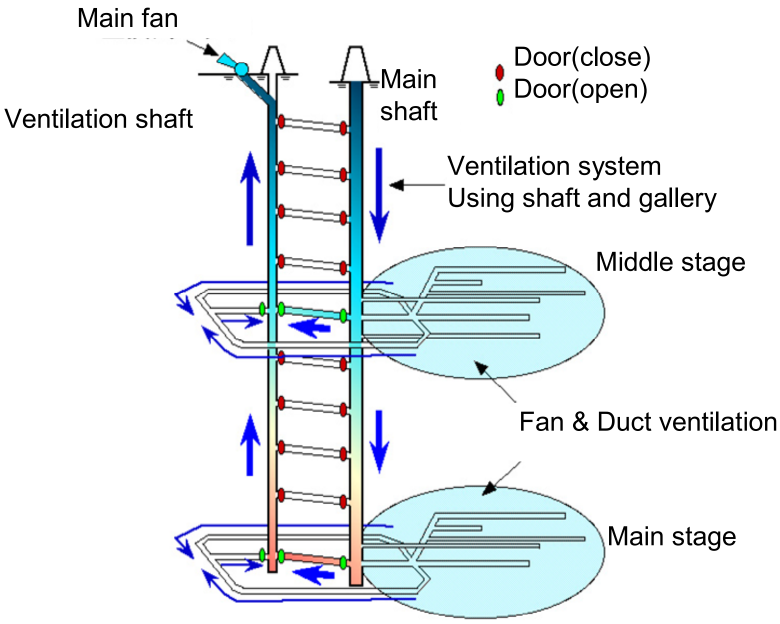


Fig. 5.1.7-1 Ventilation system based on ventilation network analysis

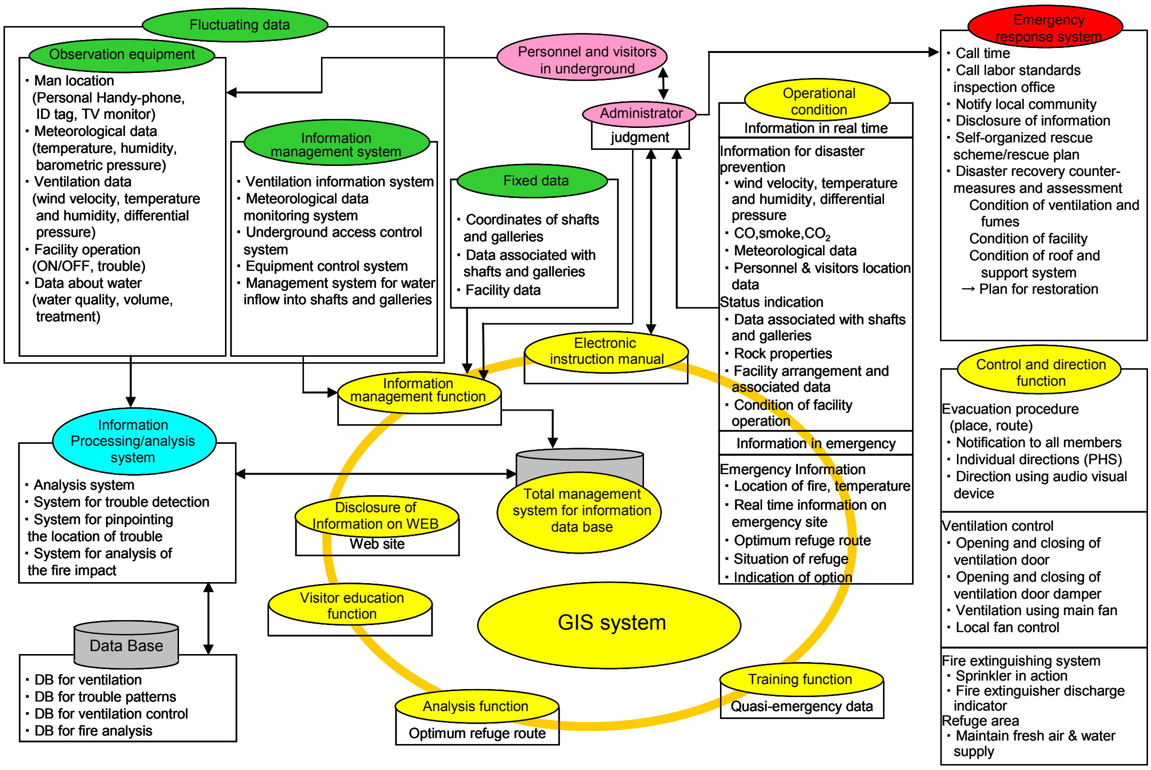


Fig. 5.1.7-2 General Conception of URL Total Control System

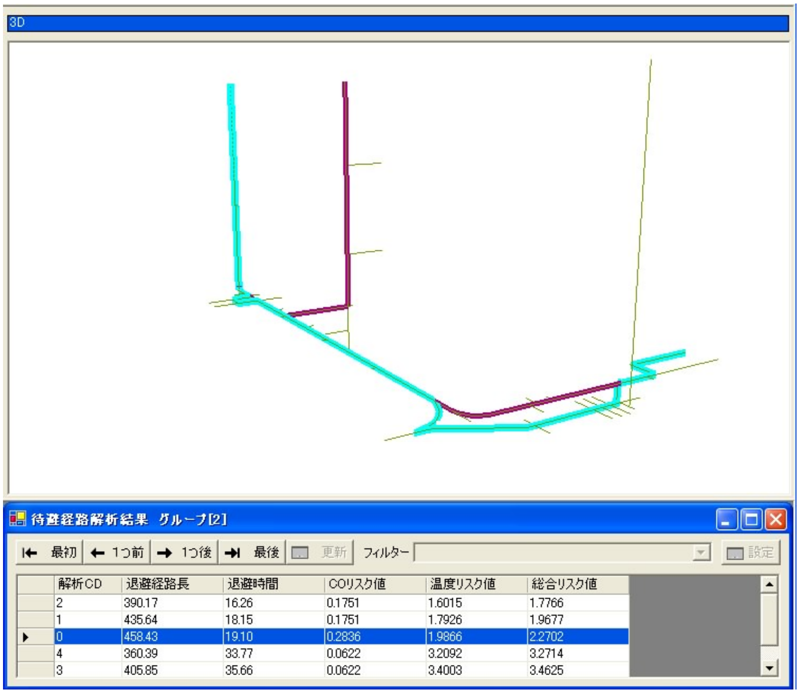


Fig. 5.1.7-3 3-D-Display Sample of Refuge Route in Tono Mine (blue line)

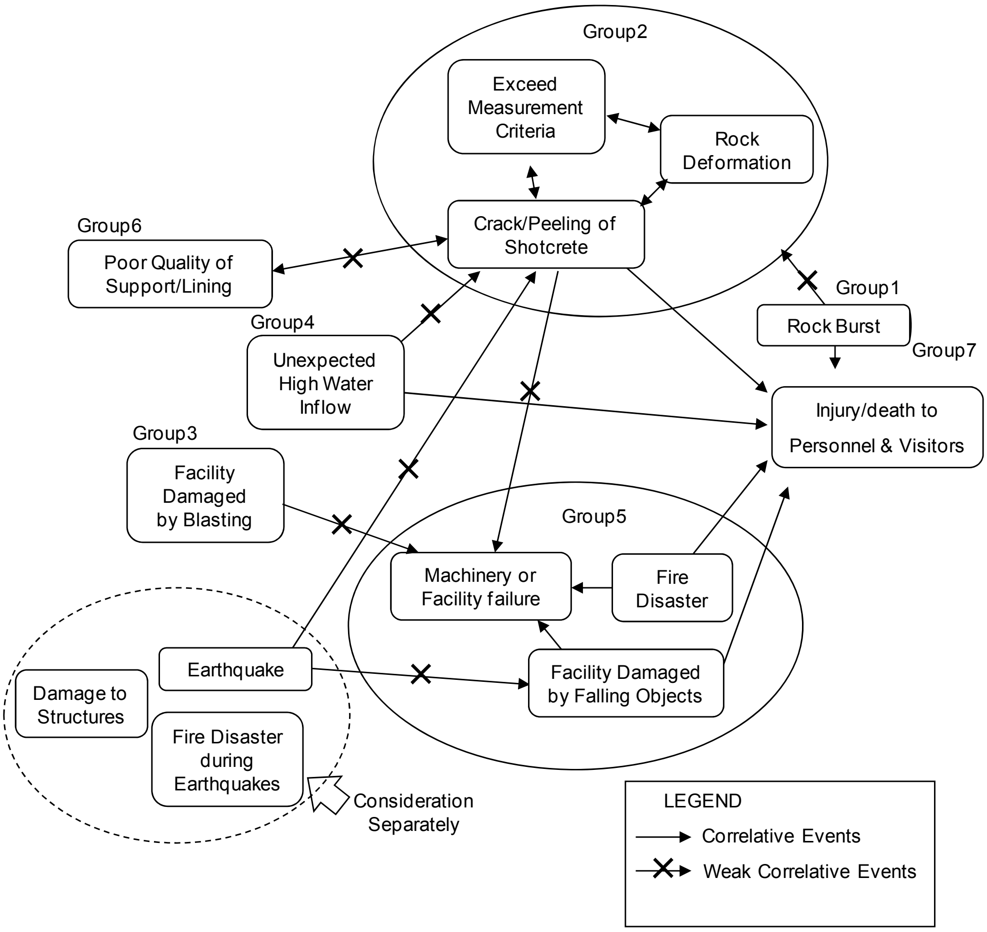
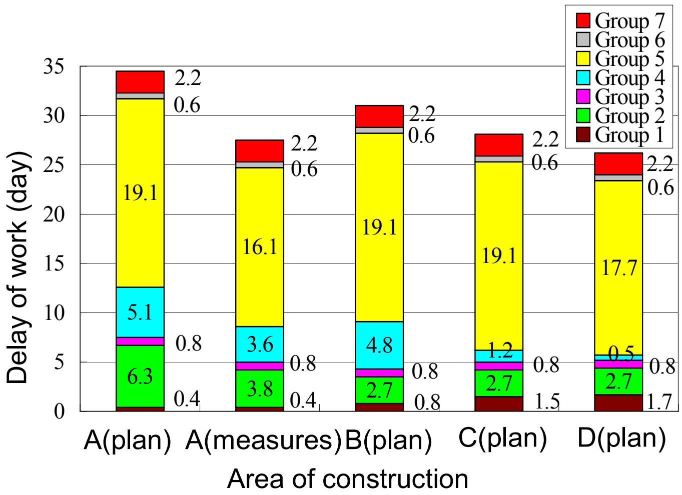


Fig. 5.1.7-4 Risk Correlation



Group1;Rock burst
+ injury/death to personnel or visitors
Group2;Exceed
measurement criteria
+rock deformation
+crack/peeling of shotcrete
+ injury/death to personnel or visitors
Group3;Facility damaged by blasting
Group4;Unexpected high water inflow
+ injury/death to personnel or visitors
Group5;Facility damaged by falling objects
+machine/facility failure
+fire disaster
+ injury/death to personnel or visitors
Group6;Poor quality of support/lining
Group7;Injury/death to personnel or visitors
caused by the other hazards
in Group 1,2,4 and 5

A area; 0 to 300m depth
B area; 300m to 500m depth
and middle stage
C area; 500m to 1000m depth
D area; Middle and Main stage

Fig. 5.1.7-5 The Result of Risk Evaluation (Delay of Work)

5.1.8 Construction plan

(1) Outline of the overall plan

The shafts and galleries of the MIU will be excavated to a depth of 1,000 meters, according to the role of the MIU and considering the following aspects:

- Providing a research area for demonstrating the reliability of techniques for geological disposal as indicated in the H12 Report, assuming a disposal depth in hard rock of 1,000 meters.

- Determining the implications of tunnel excavation deep underground that will require sophisticated techniques to overcome difficulties such as unexpected high water inflow and rock burst, compared to conventional civil engineering practices.

- Economic considerations of shaft sinking, whereby the construction costs are acceptable for a 1,000 m deep shaft, but will suddenly increase for shafts deeper than this.

An outline of the topography and geology at the site and the excavations for the MIU are described below.

(2) Locations of the shafts and galleries

The shafts and galleries of the MIU will be constructed at the MIU Construction Site. The surface facilities for the construction of the shafts and galleries will be located in an area covering approximately 1.2 hectares within the 7.8 hectare MIU Construction Site.

(3) Topography and geology

The topography around the MIU Construction Site is hilly, with an elevation of approximately 200 meters above sea-level. The Hazama River runs across the site. Around the MIU Construction Site, Tertiary sedimentary rocks widely and unconformably overlay the Cretaceous Toki Granite. The Tertiary sedimentary rocks are lithologically divided into the Mizunami Group and the Seto Group. The lower part of the Mizunami Group is mainly composed of tuff, silt/sandstone and conglomerate. The middle and upper parts of the Mizunami Group are mainly composed of mudstone and silt/sandstone alternating with shallow marine facies. The Seto Group consists of unconsolidated clay, sand and gravel.

(4) Schedule

The results of the investigations in the shafts and galleries at the MIU are expected to provide the technical basis for selection of detailed investigation areas in the disposal project to be implemented by the Nuclear Waste Management Organization of Japan (NUMO) and for the safety regulations to be formulated by the Japanese Government. The construction of the shafts started in March 2003 and it is planned to reach a depth of approximately 500 meters by 2009. Construction will then continue to the final depth of 1,000 meters.

(5) Construction systems

The construction systems can be divided into the portal system, excavation equipment and peripheral systems[3),4)]. The layout of the systems at the ground surface is shown in Fig. 5.1.8-1.

(6) Excavation sequence

After land preparation, a three-stage excavation was employed for the shaft construction as shown in Fig. 5.1.8-2.

(a) Construction of the upper portals of the shafts

The foundation concrete for the upper portals of the shafts was applied directly to the rock (stable mudrock of the Mizunami Group in this case) to a depth of 9.0 meters for the main shaft and 10.5 meters for the ventilation shaft. Because of the small site area, excavation was done with soldier beams and breast boards. The foundation concrete was emplaced after completion of this excavation.

(b) Construction of the lower portals of the shafts

The lower portal of the shaft is the section from the excavated base up to the section where the moveable scaffolding is temporarily fixed inside the shaft. The depths of these sections were 42.0 meters for the main shaft (total 51.0 meters depth) and 35.0 meters for the ventilation shaft (total 45.5 meters depth). These are necessary distances for preventing damage to the scaffolding from blast excavation at the base. The short-step method with a sinking length of 1.0 meters/round was adopted in view of safety, duration of construction and economic considerations. After completing the excavation of this section, the surface facilities were constructed.

(c) Excavation of the general zone of the shafts

Shaft construction was implemented after the installation of systems such as the scaffolds had been completed.

Considering the relationship between the excavation cycle and the progress of each blasting round, an irregular short-step method was adopted as the safest and most effective excavation cycle; 1.3 meter blasting and mucking out cycles were repeated twice and lining concrete was then put in place for the 2.6 meter section. However, for the sections where rock conditions were not good, the method was changed to the normal short-step method, placing the lining concrete after a 1.3 meter blast and mucking out. An example of the time cycle at a depth of 500 meters is shown in Table 5.1.8-1, where three hours of observation of the geology of the shaft wall was guaranteed for one cycle.

Since the proportion of the total working time required for mucking out increases with the depth of excavation, for the mucking out to be effective a kibble exchange method was adopted for the deep part of the shafts; this reduces the time of kibble transportation by exchanging two kibble buckets at the scaffolds inside the shafts.

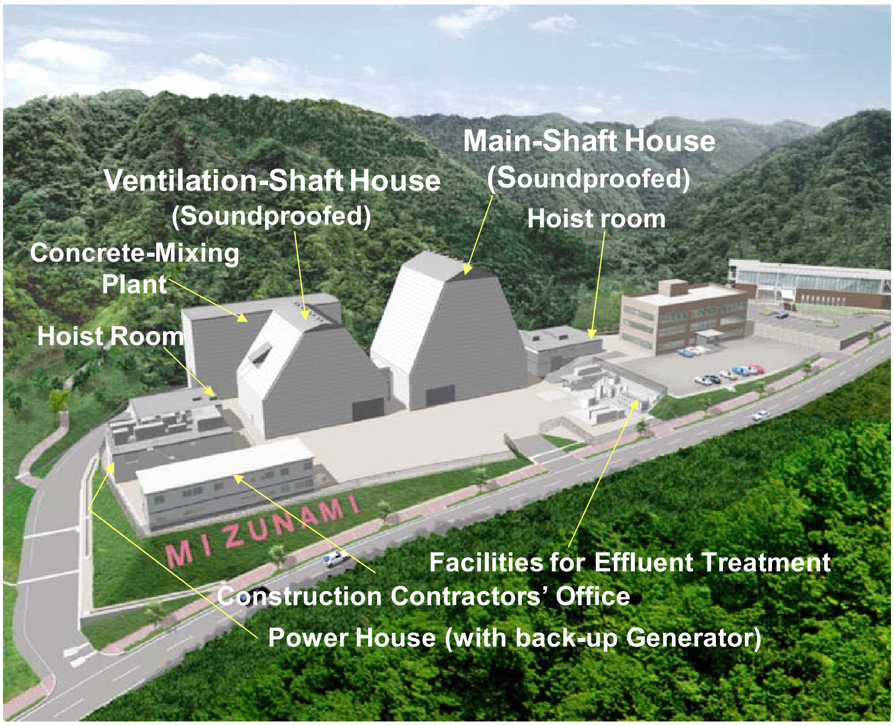


Fig. 5.1.8-1 Layout of Surface Facilities

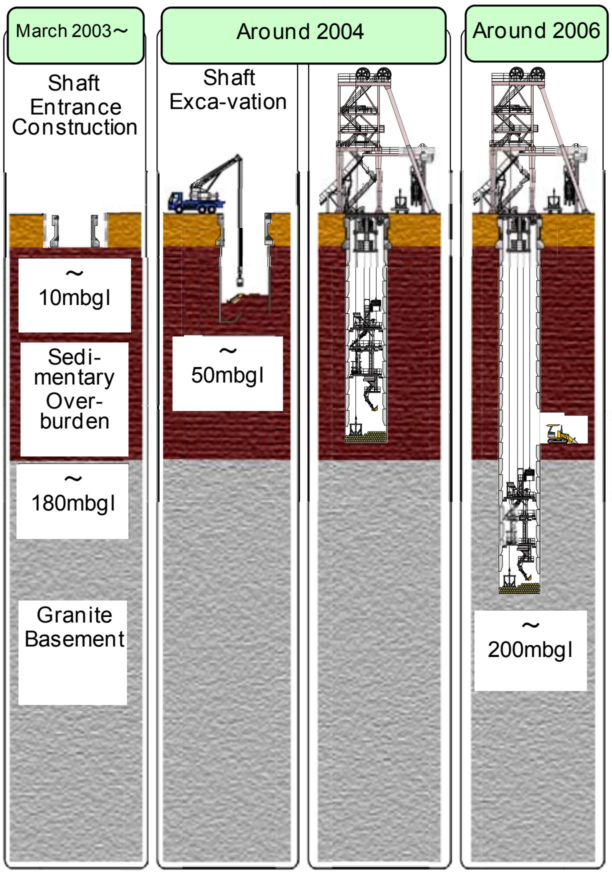
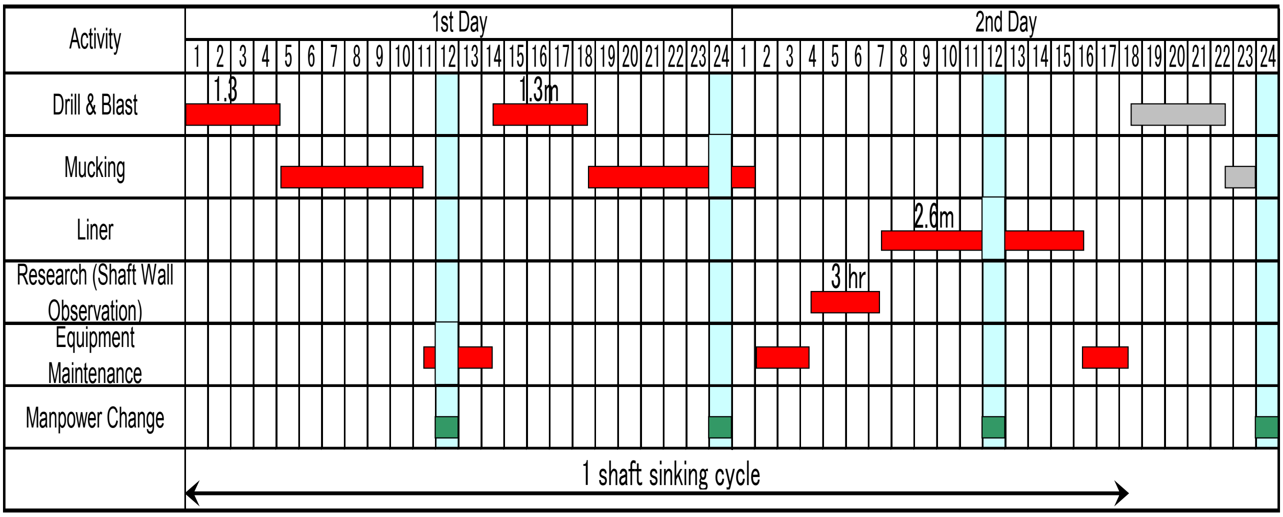


Fig. 5.1.8-2 Construction of Mizunami Underground Research Laboratory

Table 5.1.8-1 Cycle Time for Shaft Sinking (eg., Main Shaft, Granite, Rock class B, GL. -500 m)



5.2 Environmental impact assessment on construction work

Understanding the impact of constructing the shafts and galleries of the MIU on the surrounding environment is critical not only from a research viewpoint, but also in terms of environmental aspects. The principles set out in the Environmental Impact Assessment Law of 1997 can be used as guidelines for the environmental impact assessment. Although this law is not applicable to the construction of the MIU, issues that are of concern in terms of the impact of the excavation of the shafts and galleries were selected from the range of environmental factors in order to assess the environmental impact. The results are shown in Table 5.2-1.

Factors of particular concern in terms of impact on the populated area around the MIU construction site include noise and vibration and the chemistry of river water (surface water), bottom sediments and hydrology (stream flow, near-surface groundwater level). For these factors, data accumulated before implementing the construction of the shafts in Phase I were compared with the data obtained during the progress of the excavation in Phase II and subsequent phases to evaluate the level of the impact. Details will be discussed below for each factor. With regard to topography, landscape and important fauna and flora, monitoring was limited to types of fauna and flora for which monitoring has been conducted at the Shobasama Site. This is because the scale of the MIU construction is significantly smaller that that of projects to which the law applies and the site had already been developed. The degree of impact was therefore judged to be limited.

Table 5.2-1 Range of Factors for Environmental Impact Assessment and Possible Issues due to MIU Construction

Environmmental Factors for the Environmental Impact Assessment			Potential Issues at the MIU Construction Site	
			Expected Condition	Monitoring
Preserve the Natural Environmet	Atmosphere	Air Quality	－	－
		Noise Level	Excessive noise due to blasting and other construction activities	○
		Vibration	Strong vibrations due to blasting and other construction activities	○
		Odor	－	－
		Others	－	－
	Water	Surface Water Quality	Decrease in water quality as water flows into shaft	○
		Sediment Quality	River and stream sediment quality affected by drop in water table and reduced run-off	○
		Groundwater	Drawdown of groundwater from groundwater inflow into the shafts	○
		Others	Decresed river flow due to drawdown of water table	○
	Bedrock & Soil	Topography, Geology	Modification of toporography	－
		Ground	－	－
		Soil	－	－
		Others	－	－
Conservation and Preserve the Biodiversity of the Natural Environment		Vegetation	－	－
		Biological	－	－
		Ecosystem	－	－
Human Interaction		Preserve Natural State of Landscape	Changes of landscape by development of MIU site and surface facilities	－
		Green Space	－	－
Other Environmental Aspects		Waste Materials	Material excavated during underground construction(muck pile)	－
		Greenhouse Gases	－	－

5.2.1 Monitoring of noise and vibration

Monitoring of noise and vibration before starting construction of the shafts in Phase I was conducted at seven observation points located within an approximately 1 km radius of the MIU. The levels of noise and vibration were measured for 10 minutes every hour and the sources of the noise and characteristics of the vibrations were determined at each observation station.

After starting construction of the shafts in Phase II, the noise and vibration will be measured while typical construction work is being carried out. Machinery used for the excavation work will be checked and the effect of using different machinery will also be evaluated.

5.2.2 Investigations of river (surface) water chemistry and river sediments

The water chemistry and bottom sediments of the Hazama River running across the MIU Construction Site were investigated by analyzing samples collected in high and low water seasons, before starting the construction of the shafts in Phase I. There were two sampling points - upstream of the MIU Construction Site (200 meters from the shafts) and downstream of the site (100 meters from the shafts). The analysis items are shown in Table 5.2.2-1. The analyses were based on the method specified in the Japan Industrial Standards (JIS) and guidelines of the Environment Agency of Japan. From these analyses, baseline information was obtained on the water chemistry and the sediments of the Hazama River before starting the construction of the shafts.

After starting the construction of the shafts in Phase II, the impact of the excavation will be evaluated by analyzing samples collected at the same points.

Table 5.2.2-1 Water Quality and Sediment Analysis

Analytical Test Areas			Items to test	Samples needed	Analyses to do
Water Quality		Basic tests	5	2	2
		Biological tests	7	2	2
		Health tests	26	2	1
Sediment Analysis	Content test	Basic tests	11	2	1
		Health tests	23	2	1
	Elution	Health tests	26	2	1

5.2.3 Shallow hydrological investigations

Equipment for measuring the stream flow of the Hazama River running across the MIU Construction Site and the near-surface groundwater level in shallow wells around the site was installed before starting the construction of the shafts. The observations will continue in Phase II and thereafter. After analysis, these data will serve as baseline information before the excavation and will be used as reference values for evaluating any changes after excavation.

(1) Investigation of the stream flow

The investigations were conducted with flowmeters (water gauges) installed at three points along the Hazama River - upstream (approximately 1.3 km from the MIU Construction Site), midstream (around the MIU Construction Site) and downstream (approximately 0.8 km from the MIU Construction Site). The stream flow was calculated based on the relationship between the water level and stream flow at the above locations that had been determined previously (current meter method).

The water level observation data were recorded on a PC card every 10 minutes and compiled every month. The data were compared with data on precipitation. The results indicated that the stream flow is in the order of 0.01 $m^3 s^{-1}$ at the three locations on clear days and that it responds to small precipitation events in the order of a few mm $hour^{-1}$.

(2) Investigations of the near-surface groundwater level

Water gauges were installed at ten locations (one borehole and nine wells), including privately owned shallow wells, around the MIU Construction Site to monitor the groundwater level. The depths of seven wells were less than 10 meters and the depths at the other three locations were greater than 10 meters.

Based on continuous observations, the variation in the groundwater level throughout one year at each location, as well as the correlation between the groundwater level and pumping or precipitation, was determined. Also, the average groundwater level over one year was determined, which serves as reference information for determining the changes associated with the excavation and identifying trends and impacts (i.e. response to precipitation, frequency of use, recovery trend of the water level).

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6. Summary and conclusions

The MIU project is a comprehensive URL project in crystalline rock (granite) that has been ongoing since 1996 as one of the URL projects mentioned in the Framework of AEC. The objectives of the project are to develop the technical basis for investigation, analysis and assessment of the geological environment and to improve understanding of the geological environment through application of various technologies relevant to geological disposal, based on a stepwise investigation approach. In January 2002, the decision was made to construct underground facilities and other related facilities at the MIU Construction Site and the Phase I investigations were initiated. Since July 2003, the construction of the shafts has been proceeding in parallel with the Phase I investigations. In March 2005, the surface-based investigations were completed and the shafts passed through the sedimentary rock formations to reach the top of the granite in 2005 fiscal year.

Goals in Phase I of the MIU project are: 1) to construct models of the geological environment from all surface-based investigation results that describe the geological environment prior to excavation and predict excavation response, 2) to formulate detailed design concepts and a construction plan for the underground facilities, and 3) to establish detailed investigation plans for Phase II.

This report summarizes the results of investigations up to the end of March 2005 focusing on aspects of “geoscientific investigations” and “engineering technologies”, and provides an example of stepwise investigation, analysis and assessment of the geological environment relevant to geological disposal using surface-based investigations of the crystalline rock in the Tono area as a case study. Specifically, for the site-scale area around the MIU Construction Site, strategies employed and lessons learnt during the implementation of the iterative approach as well as during the course of conducting individual investigation and analysis technologies are documented. In addition, know-how that is expected to be useful in implementing the disposal project is described in detail. This can be used as a basis for the design of surface-based investigation on the preliminary and detailed investigations to be conducted for the selection of disposal sites by NUMO and in establishing siting factors for the selection of detailed investigation areas and safety review policies by the government.

The overview of the results of the Phase I investigation is as follows:

1) Geoscientific investigations

For the studies relating to development of a technical basis for investigation, analysis and assessment techniques for the deep geological environment, characteristics and processes of the geological environment that are important for geological disposal were reviewed mainly on the site scale from the viewpoints of long-term safety assessment, design and construction of underground facilities and environmental impact assessment. The specific aims for R&D activities were then set accordingly. To successfully achieve these specific aims, the Phase I investigations were divided into five sequential steps, Step 0 to Step 4. In each subsequent step, the investigations were conducted based on an iterative approach according to the geosynthesis data flow diagram.

More specifically, the relationship between the type and volume of information obtained with the progress of investigations and the level of understanding of the geological environment were evaluated in each step.

At the same time, issues (characteristics, processes, etc.) for investigation in the subsequent step were defined and included in the formulation of investigation plans. As a result, the understanding of the characteristics and processes of the geological environment that are important for geological disposal was improved, as indicated by the evolution of the geological and hydrogeological models. In addition, a logical path leading from investigation to assessment (systematic data flow) was established as a geosynthesis data flow diagram for each investigation step. The geosynthesis data flow diagram illustrates the data that need to be acquired and the subsequent process of interpretation and synthesis of information by different disciplines.

For the geological environment, the characteristics and processes to be investigated should be specified as far as possible. At the same time, investigation plans optimized and rationalized in terms of investigation targets and methods, taking into account restrictions such as time, cost and impact on the environment, should be formulated. The development of a quality control system and establishment of an organizational scheme to facilitate implementation of quality control practices were also shown to be important. The technical know-how and experience with successes and failures, built-up in the course of the investigations were documented as far as possible to form a knowledge base for basic technologies for the disposal project and formulation of safety regulations.

A large part of the investigation/analysis techniques and technical know-how established in the course of investigations for the relevant geological environment (crystalline rock) could be applied to different locations and geological environments based on similar examples in Japan and abroad. Techniques for investigations and analyses and technical findings established or obtained in Phase I could be applied widely with appropriate consideration of the differences in the characteristics of the geological environment of interest and implementation of appropriate modifications.

2) Engineering technologies

The investigations on engineering techniques for the deep geological environment involved determining the detailed layout of the underground facilities, cavity stability analyses, design of support systems and seismic design. In addition, the construction techniques, equipment and systems applicable for the actual work were selected, detailed construction plans formulated and countermeasures against sudden events and safety measures were established. Although these designs will eventually be validated based on information obtained during the excavation of the underground facilities and by in situ tests to be conducted in Phase III, the results of the design activities at the current stage can be summarized as follows:

- Evaluation of cavity stability and support system design: the rock mass classification was based on surface-based investigations using the methods employed in the H12 Report and physical property values were assigned to each rock mass category. The support system was provisionally established taking into account the physical properties and referring to standard tunnel specifications. The rock mechanical stability of tunnels was evaluated for each tunnel support system by 2-D and 3-D finite element method analyses and it was confirmed that the stress in the support system was below the acceptable level. The support system design was then finalized. It should be noted that, since this analysis was conducted in parallel with the Phase I investigations, the layout and size of the tunnels and the support system in the initial design were based on data from Step 0 and the design was updated in the adjusted design based on data from Step 3. As a result, the effectiveness of the design using rock classes as a parameter and the borehole investigations in/around the location of the underground facilities was demonstrated.

- Seismic design: A seismic wave model was developed to test the seismic design. The model took account of the features in the Mizunami region as well as historic earthquakes and nearby active faults and assuming the Tokai earthquake. Based on the seismic wave model, the allowable stress in the lining concrete of the shafts was checked using the method employed in the H12 Report. An analysis was also made of the vertical seismic motion considering the features of very deep shafts. The analysis indicated sufficient seismic stability of the shafts.
- Techniques for providing feedback of measured data to the planning of design/construction (intelligent construction method): a detailed feedback flowchart was developed, coupling the rock mass evaluation to the observations, measurements and respective analyses. For the geological observations, various rock classification methods were applied to identify the optimum methods for evaluating the geological conditions of the shaft wall.
- Measures against unexpected high water inflow: planning of the measures to be taken in the event of sudden unexpected water inflow was based primarily on stopping the water by grouting, considering that the water in the shafts must be drained to the surface and taking into account that the policy for the MIU project is to avoid impacts on the surrounding environment. Since grouting after the occurrence of unexpected high water inflow or a large quantity of water (post-grouting) is expected to require a long period of time and involve high costs, pre-grouting before such incidents was used as a reference countermeasure.
- Safety measures: The concept of an integrated management system coupling systems for controlled entry/exit, fire, environment and communication with ventilation network analysis was developed. Also, risks were identified using the risk management method considering the features of the shafts; these were reflected in the safety measures.

A key issue at the conclusion of Phase I is the further improvement of the reliability of the technologies applicable to the relevant geological environments. It will be important to iterate the application and evaluation of methods for understanding the geological environment with the progress of stepwise investigations in the MIU project. This should be done building on the know-how that has been accumulated as well as experience from failures.

In order to improve the reliability of the technologies applicable to relevant geological environments, the program in Phase II and subsequent phases will include solving identified issues and verification of the investigation results (e.g. geological environment models and prediction of the changes of the geological environment due to construction of underground facilities) and design/construction techniques developed in Phase I, as well as continuing stepwise investigations based on the iterative approach to improve the understanding of the geological environment. Based on the additional knowledge obtained in Phase II and subsequent phases, task flow diagrams that constitute the lower level of the hierarchy of the geosynthesis data flow diagram will be established to complete the detailed hierarchical technology system. Results from other research institutes will also help in developing sophisticated technical bases that support the disposal project and safety regulations more solidly.

The development of engineering technologies in Phase II will include verifying the design of the underground facilities based on measured data obtained during excavation and identification of techniques for construction, construction measures and safety measures. Specifically, data acquisition will continue and advanced design and construction technologies will be developed through iterative validation of the URL design. Impacts on the surrounding environment associated with the excavation will also be monitored.

The detailed investigation program for characterization of the geological environment and development of engineering technologies in Phase II and subsequent phases will be formulated separately based on the examinations including the review of the layout of underground facilities using the results of the Phase I investigations.

The MIU project is in the phase where investigations are being conducted in parallel with the excavation of the underground facilities. As of the end of March 2007, the Main Shaft and Ventilation Shaft had been constructed to a depth of about 200 m and excavation of a Sub Stage at the 200 m level had been initiated. From 2008 onwards, based on the information obtained during excavation, the models of geological environment (geological model, hydrogeological model, hydrochemical model and rock mechanical model etc) constructed based on data from the surface-based investigations are to be tested to validate the surface-based investigation techniques. The design and excavation/lining technologies for the shafts and research galleries are also to be verified in terms of their effectiveness for the relevant rock and seepage conditions. The results of these investigations are expected to be compiled as a knowledge base to support the disposal project and safety regulations, the aim being to contribute to the selection of detailed investigation areas planned for the early 2010s.

As a core organization for the research and development of geological disposal technologies in Japan, JAEA will continue to conduct fundamental R&D using the URLs at Horonobe and Mizunami and laboratory facilities at Tokai (ENTRY, QUALITY, etc.). The results will be published openly, the facilities opened to the public and cooperation with national and international research organizations and universities will be promoted. In this way, JAEA will contribute to developing technologies, fostering researchers and improving acceptance of geological disposal by the public, all of which are required for supporting disposal projects extending over long periods of time.

The progress described in this report was made possible by collaboration between domestic and international researchers and research laboratories. We would like to express our gratitude to all of them and hope for their continuing cooperation and support.

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Appendix 1

Locations of investigations on Regional Hydrogeological Study and the Surface-based investigation phase at the MIU project

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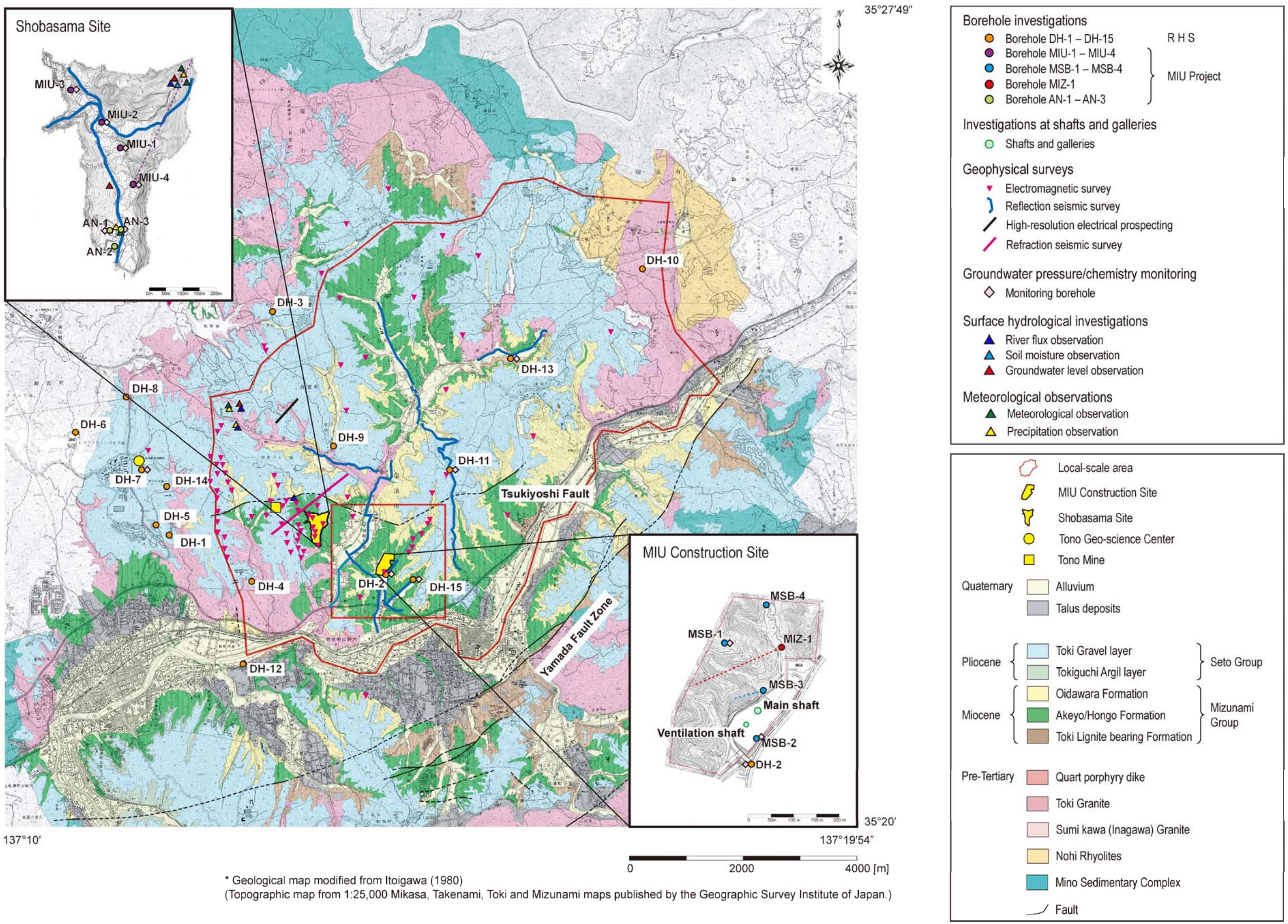
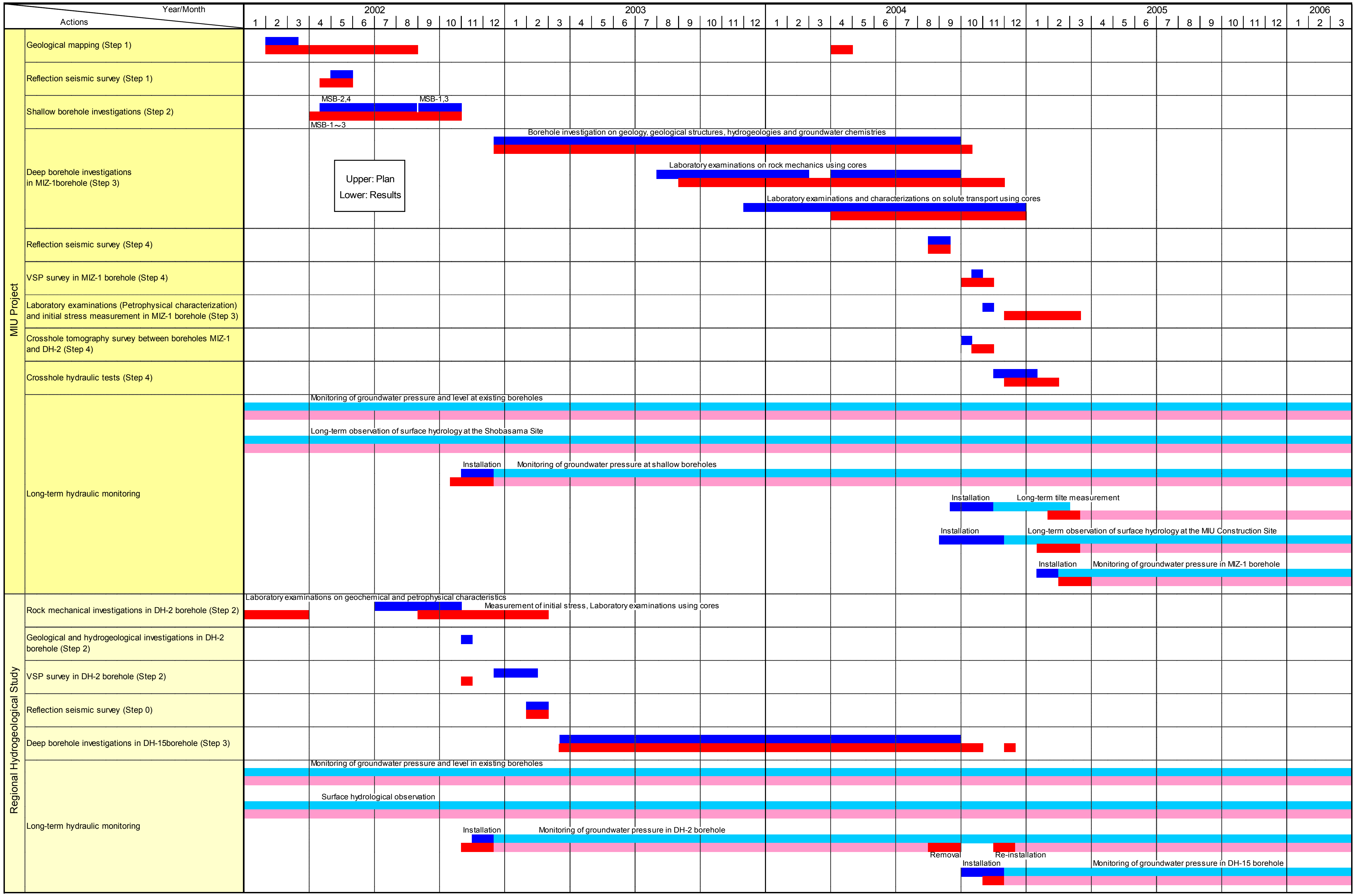


* Geological map modified from Itoigawa (1980)
(Topographic map from 1:25,000 Mikasa, Takenami, Toki and Mizunami maps published by the Geographic Survey Institute of Japan.)

Appendix 2

Schedule of the Surface-based investigation phase at the MIU project

Schedule for the Phase I Investigations



Appendix 3

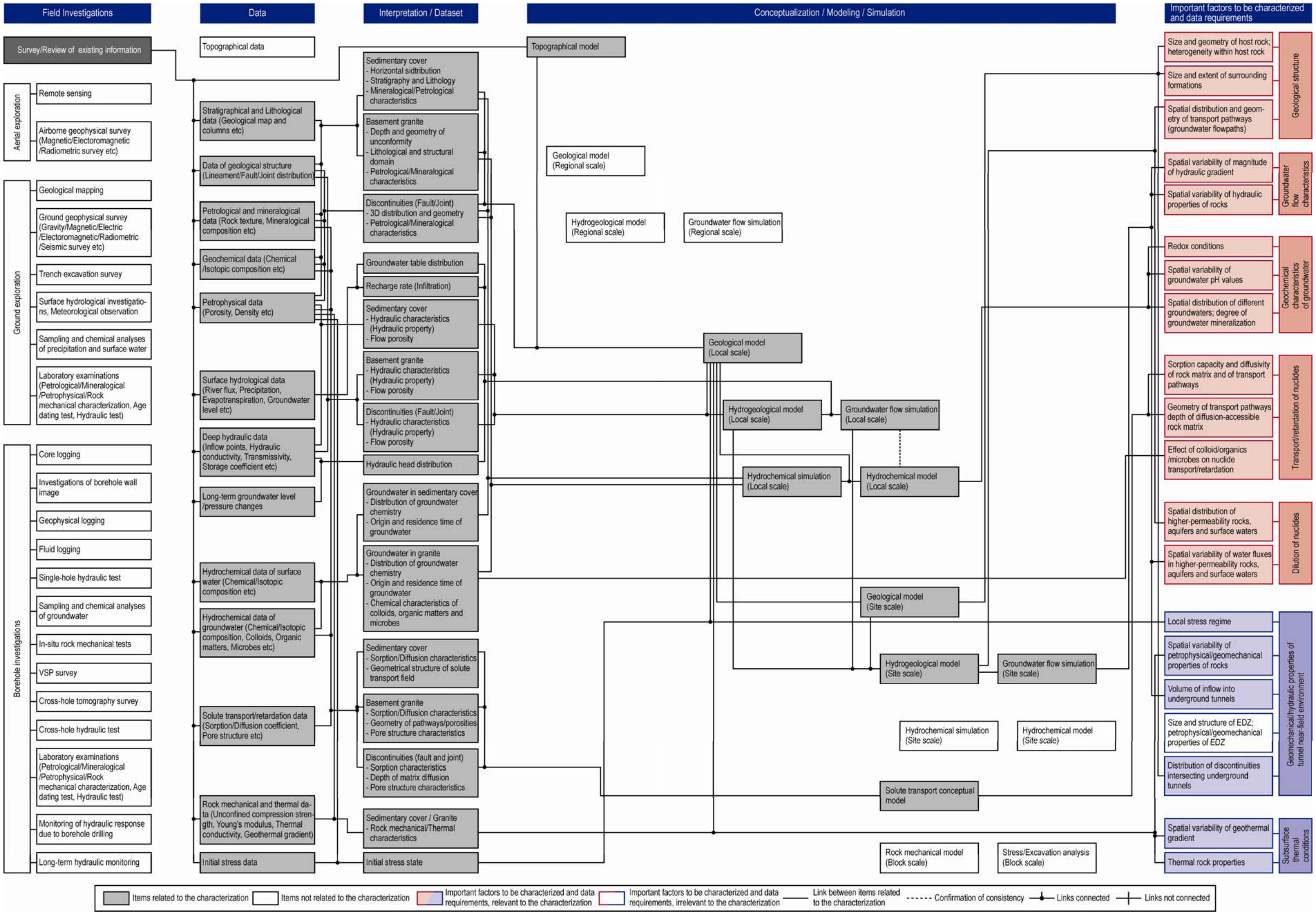
Overview of the borehole investigations

Outline of borehole investigations

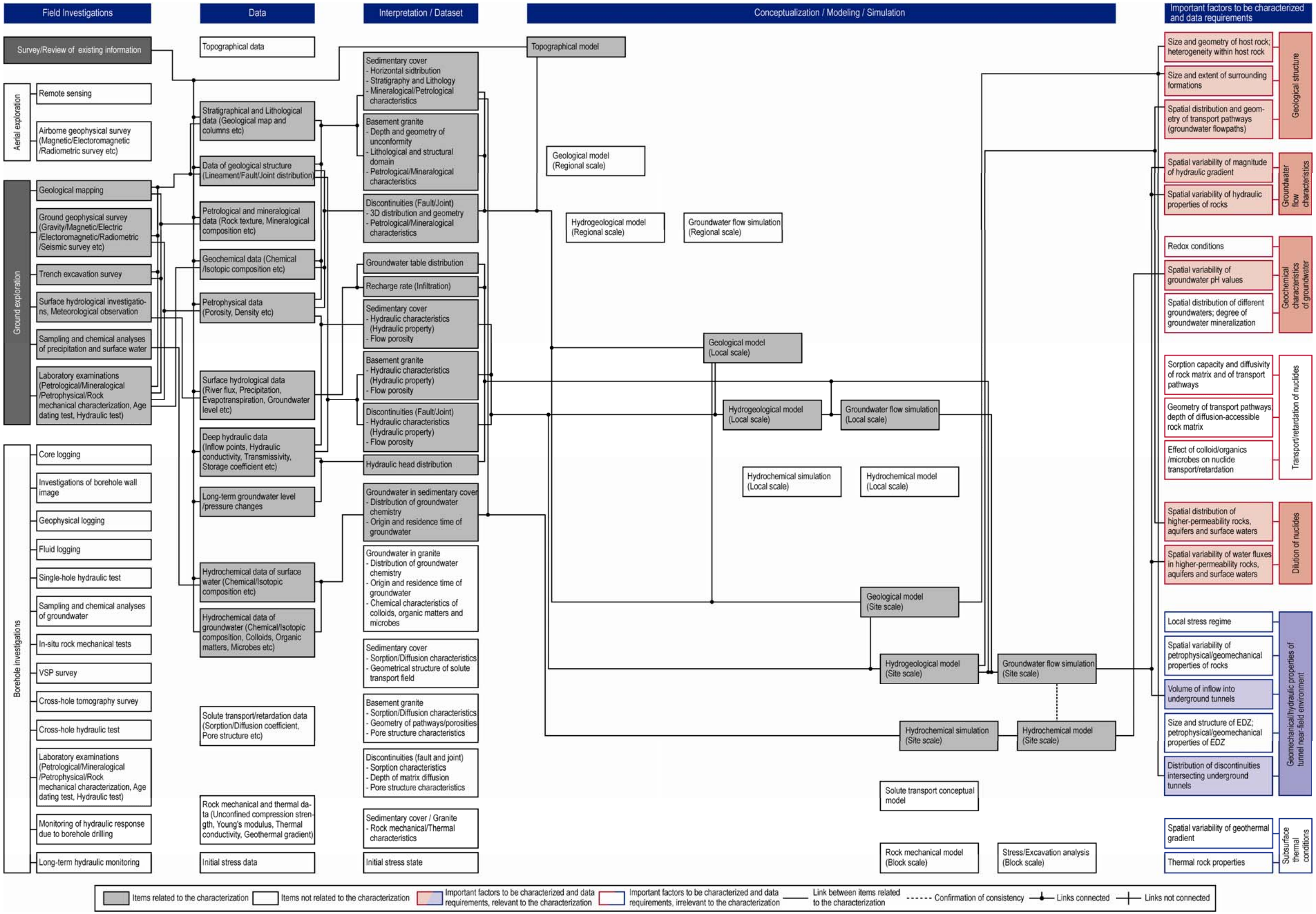
Borehole ID.		Objectives	Drilling points (World geodetic system JGD2000)	Borehole length (m)	Diameter	Drilling fluid	Investigation Items																														Long-term hydraulic monitoring
							Geology/geological structure																	Hydrogeology					Hydrochemistry				Rock mechanics					
									Investigations of borehole wall image																												
							Core logging	Petrological/Mineralogical characterization	Borehole TV (visible image)	Borehole televiewer (reflection image by ultrasonic wave)	Borehole radar	Borehole curvature logging	Borehole diameter logging	Electrical logging	Micro resistivity	Density logging	Neutron logging	Natural γ logging	Spectrum logging	Temperature logging	Acoustic velocity logging	Cement bond logging	Susceptibility/resistivity logging	Electromagnetic flowmeter logging	Flowmeter logging	Electrical conductivity logging	Hydraulic test	Pumping test	Isotope/water chemistry analysis	Organics/microbes analysis	Gas analysis	Physico-chemical parameters	Geomechanical examination	Petrophysical examination	Thermal property examination	Hydrofracturing test	Borehole loading test	
Regional Hydrogeological Study	DH-2	Establishment of techniques for borehole drilling and investigation, and characterization of the geological environment of the Toki Granite	N. latitude 35° 22'36.86378" (-69125.013) E. longitude 137° 14'15.06221" (6437.382) Altitude 193.158 m	501	98.4 mm (HQ)	Fresh water (with Lester thickener)	○	○	○	○		○	○	○	○	○	○	○		○	○				○	○	○	○	○			○	○	○				MP system Continuous monitoring of groundwater pressure
	DH-9	Characterization of the east part of the local-scale area	N. latitude 35° 23'50.46962" (-66857.41) E. longitude 137° 13'38.42126" (5511.229) Altitude 275.42 m	1,030	123 mm (to 1020 m) 98.4 mm (from 1030 m) (PQ Wellman's method)	Fresh water	○		○			○	○	○	○	○	○	○		○	○				○		○	○	○		○	○		○				MP system Monitoring out of service
	DH-10	Characterization of the geological environment on the boundary of local-scale area, particularly hydrogeological and hydrochemical characteristics around the boundary between the Toki River and Kiso River catchments	N. latitude 35° 25'31.3027" (-63745.17) E. longitude 137° 17'13.95187" (10945.735) Altitude 475.562m	1,012	98.4 mm (HQ)	Fresh water	○	○	○			○	○	○	○	○	○	○		○	○		○		○		○	○	○		○	○	○	○	○			
	DH-11	Characterization of the geological environment in the central part of the local-scale area, especially hydrogeological and hydrochemical characteristics of the deep sedimentary rock formations	N. latitude 35° 23'36.53405" (-67285.355) E. longitude 137° 14'59.62225" (7560.463) Altitude 339.883 m	1,012	98.4 mm (HQ)	Fresh water	○	○	○			○	○	○	○	○	○	○		○	○		○		○		○	○	○		○	○	○	○	○			MP system Continuous monitoring of groundwater pressure
	DH-12	Characterization of the geological environment in the discharge area of the groundwater flow system in the local-scale area	N. latitude 35° 21'45.9499" (-70695.4) E. longitude 137° 12'35.88713" (3935.04) Altitude 137.385 m	716	98.4 mm (HQ)	Fresh water	○	○	○			○	○	○	○	○	○	○		○	○				○		○	○	○			○						
	DH-13	Characterization of the geological environment in the recharge area of the groundwater flow system in the local-scale area	N. latitude 35° 24'40.12797" (-65324.696) E. longitude 137° 15'41.91513" (8625.771) Altitude 277.514 m	1,015	98.4 mm (HQ)	Fresh water	○	○	○			○	○	○	○	○	○	○		○	○				○		○	○	○			○						MP system Continuous monitoring of groundwater pressure
	DH-15	Characterization of the E-W trending fault running through the MIU Construction Site	N. latitude 35° 22'33.72832" (-69221.278) E. longitude 137° 14'34.06865" (6917.15) Altitude 213.225 m	1,012	134.5 mm (CHD-134)	Fresh water	○	○	○			○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○		○						SPMP system Continuous monitoring of groundwater pressure
MIU Project	MIZ-1	Characterization of the NNW trending fault and the upper highly fractured domain in the MIU Construction Site	N. latitude 35° 22'45.21313" (-68867.674) E. longitude 137° 14'17.69641" (6503.679) Altitude 206.563 m	1,300	134.5 mm (CHD-134)	Fresh water	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○		SPMP system Continuous monitoring of groundwater pressure
	MSB-1	Characterization of the geological environment in the zone from ground surface to the shallow underground at the MIU Construction Site	N. latitude 35° 22'45.51329" (-68858.514) E. longitude 137° 14'12.74108" (6378.611) Altitude 253.081m	201	123 mm (PQ)	Fresh water	○	○	○			○	○	○	○	○	○	○	○	○	○			○	○		○	○	○		○	○						MP system Continuous monitoring of groundwater pressure
	MSB-2	Characterization of the geological environment in the zone from ground surface to the shallow underground at the MIU Construction Site	N. latitude 35° 22'38.67879" (-69069.074) E. longitude 137° 1415.50737" (6448.577) Altitude 198.488 m	176	123 mm (PQ)	Fresh water	○	○	○			○	○	○	○	○	○	○	○	○	○			○	○		○	○	○	○	○	○						MP system Periodical sampling/groundwater pressure monitoring
	MSB-3	Characterization of the geological environment in the zone from surface to the shallow underground, and the NNW trending fault in the MIU Construction Site	N. latitude 35° 22'42.12533" (-68962.856) E. longitude 137° 14'16.08543" (6463.09) Altitude 204.622 m	182	123 mm (PQ)	Fresh water	○	○	○			○	○	○	○	○	○	○	○	○	○			○	○		○	○	○		○	○						MP system Continuous monitoring of groundwater pressure
	MSB-4	Characterization of the geological environment in the zone from ground surface to the shallow underground at the MIU Construction Site	N. latitude 35° 22'48.24724" (-68774.2) E. longitude 137° 14'16.36972" (6470.129) Altitude 214.448 m	99	123 mm (PQ)	Fresh water	○	○	○			○	○	○	○	○	○	○	○	○	○			○	○		○	○	○	○	○	○						MP system Periodical sampling/groundwater pressure monitoring
	MIU-1	Characterization of the geological environment in the deep underground at the Shobasama Site	N. latitude 35° 23'04.30137" (-68280.295) E. longitude 137° 13'26.74404 "(5217.414) Altitude 220.070 m	1,012	98.4 mm (HQ)	Fresh water	○	○	○		○	○	○	○	○	○	○	○		○	○				○		○	○					○	○	○			MP system Continuous monitoring of groundwater pressure
	MIU-2	Characterization of the geological environment in the deep underground at the Shobasama Site	N. latitude 35° 23'06.8011" (-68203.296) E. longitude 137° 13'24.54537" (5161.884) Altitude 223.280 m	1,012	98.4 mm (HQ)	Fresh water	○	○	○		○	○	○	○	○	○	○	○		○	○		○		○		○	○					○	○	○	○		MP system Continuous monitoring of groundwater pressure
	MIU-3	Characterization of the geological environment in the Tsukiyoshi Fault at the Shobasama Site	N. latitude 35° 23'09.95371" (-68106.199) E. longitude 137° 13'20.85962" (5068.816) Altitude 230.375 m	1,014	98.4 mm (HQ)	Fresh water	○	○	○		○	○	○	○	○	○	○	○		○	○		○		○		○	○					○	○	○	○		MP system Continuous monitoring of groundwater pressure
	MIU-4	Characterization of the geological environment in the Tsukiyoshi Fault at the Shobasama Site	N. latitude 35° 23'00.77324" (-68388.994) E. longitude 137° 13'28.28716" (5256.42) Altitude 216.994 m	780	123 mm (PQ)	Fresh water	○	○	○	○		○	○	○	○	○	○	○		○	○			○	○			○	○	○	○	○	○	○				MP system Continuous monitoring of groundwater pressure

Appendix 4

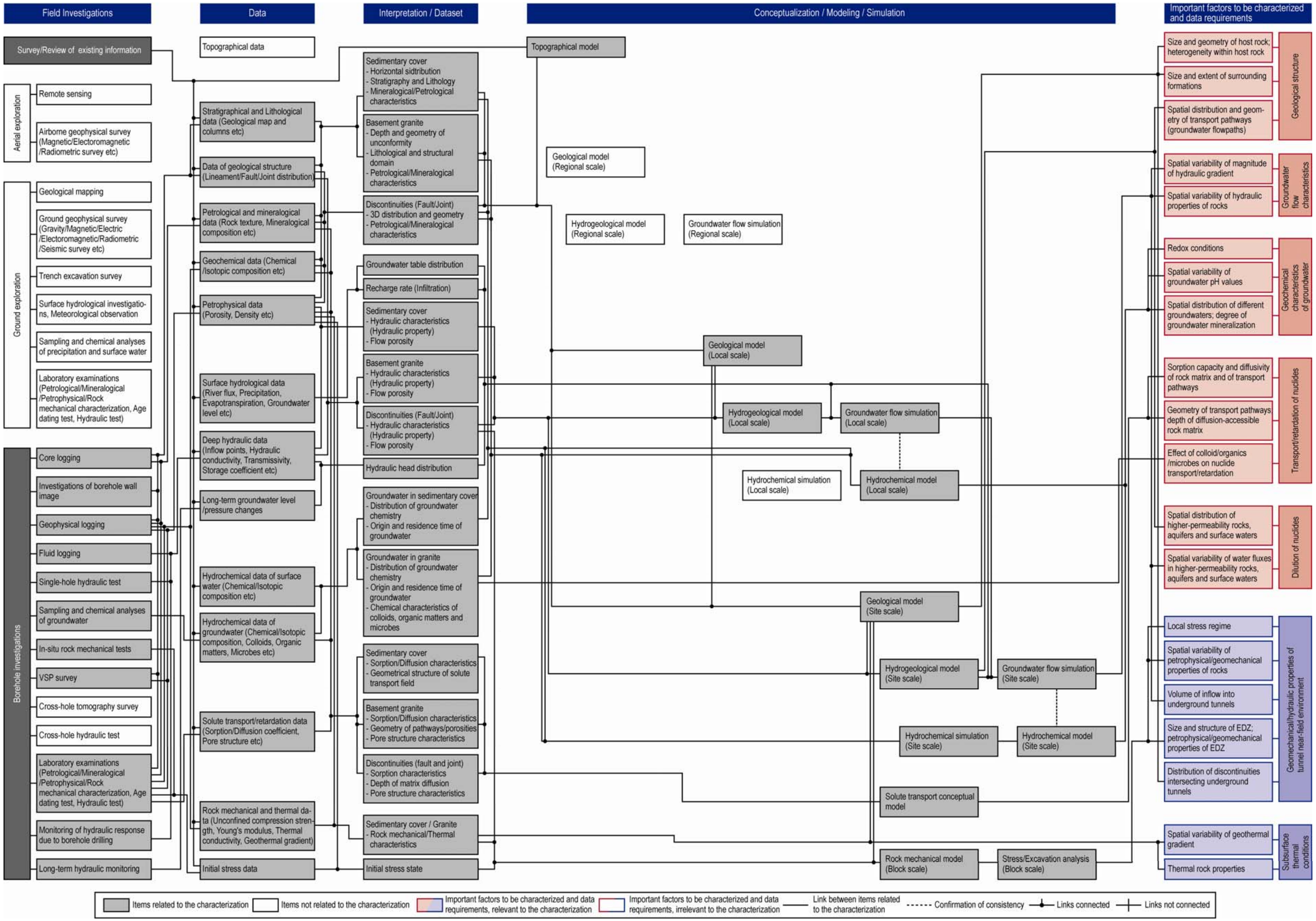
Geosynthesis data flow diagram



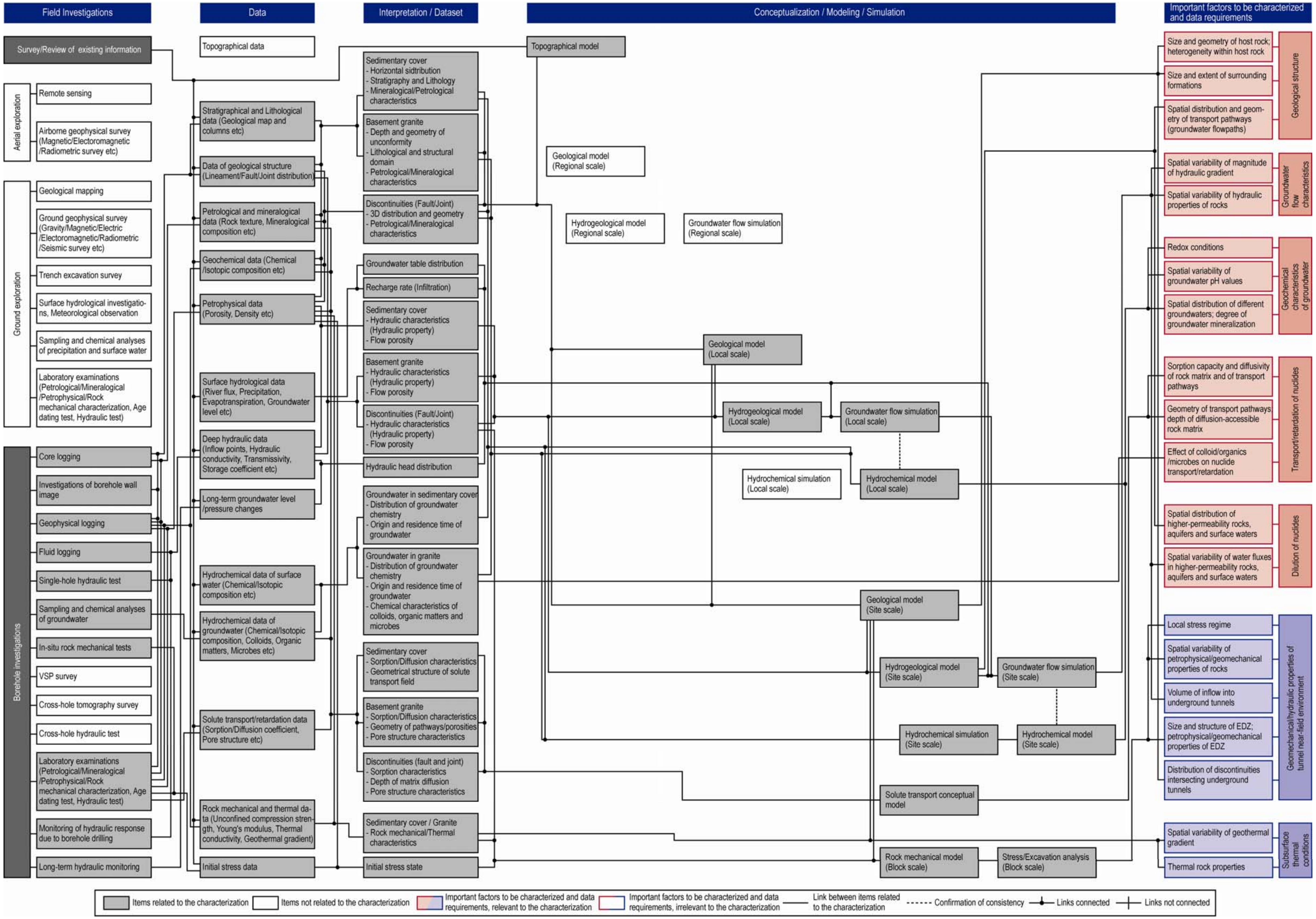
The geosynthesis data flow diagram in Step 0



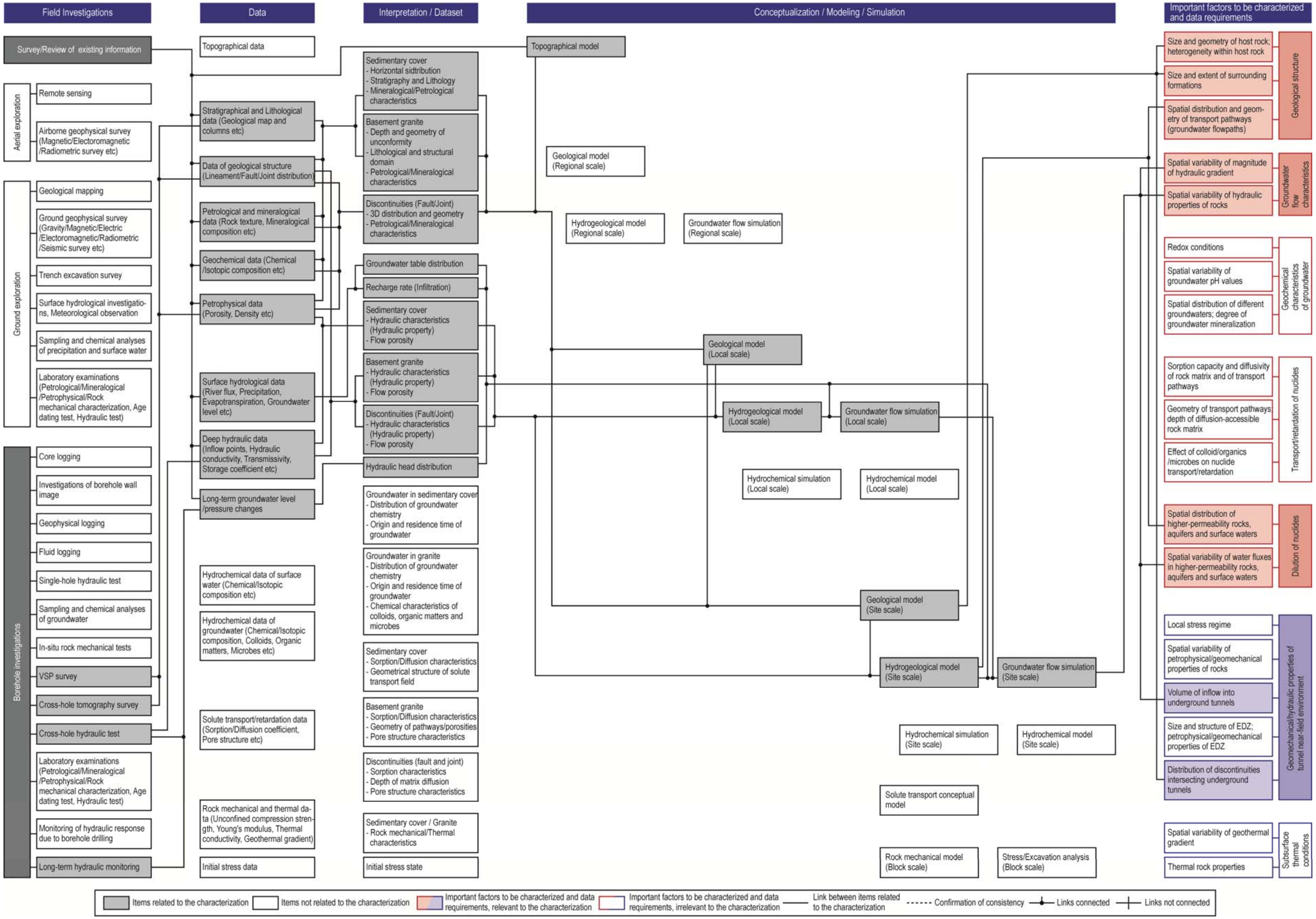
The geosynthesis data flow diagram in Step 1



The geosynthesis data flow diagram in Step 2



The geosynthesis data flow diagram in Step 3

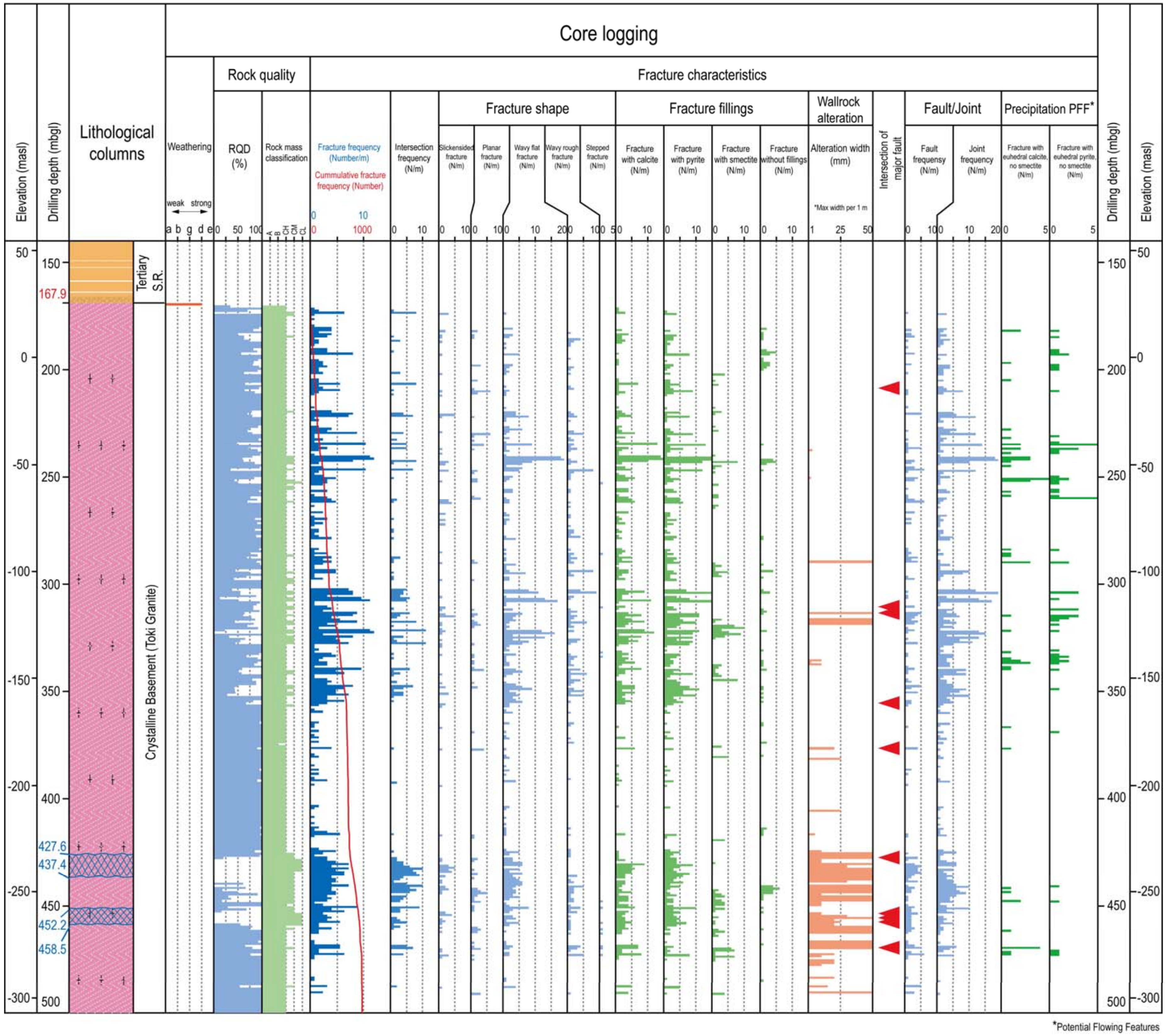


The geosynthesis data flow diagram in Step 4

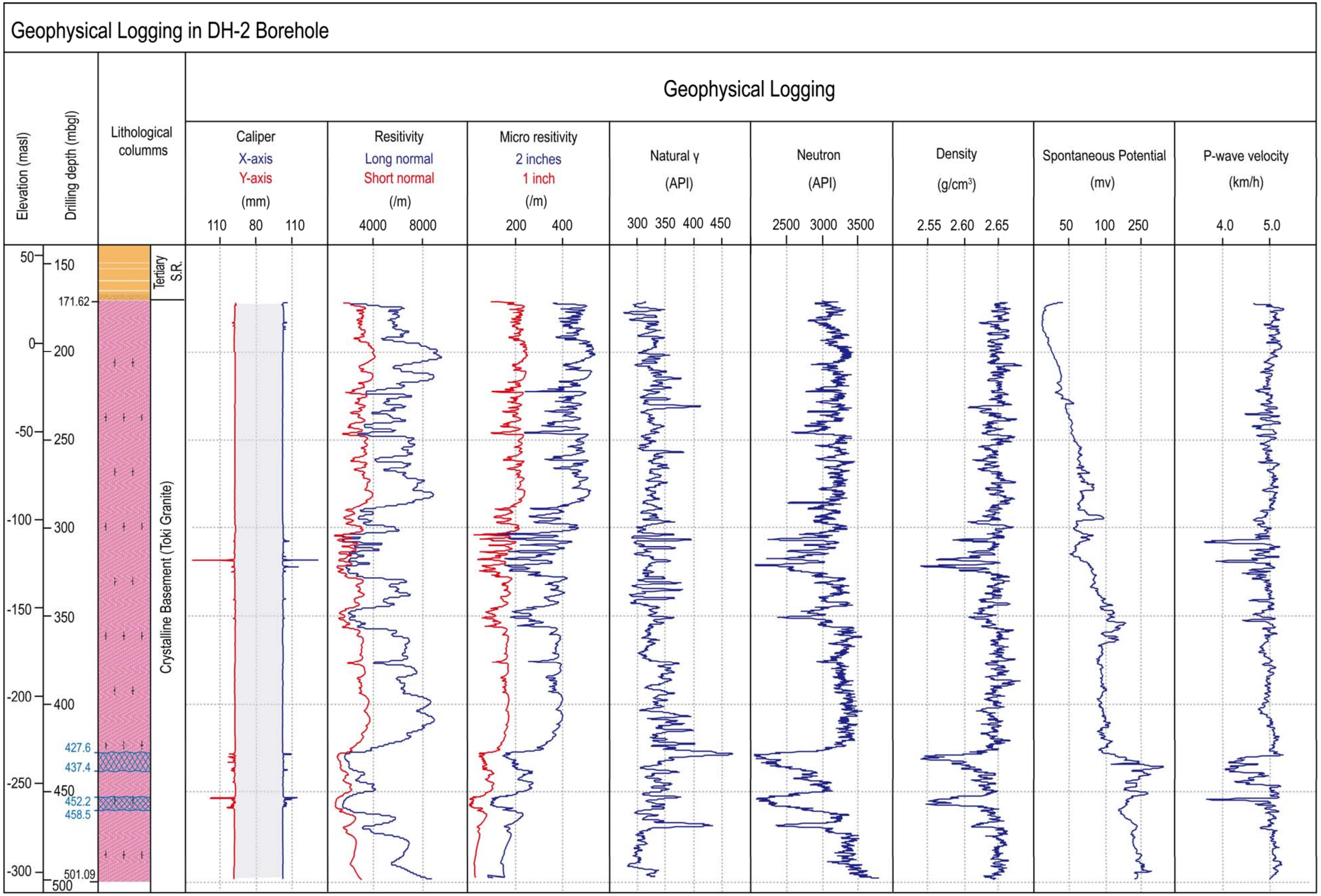
Appendix 5

Overview of the results of borehole investigations in Regional Hydrogeological Study area

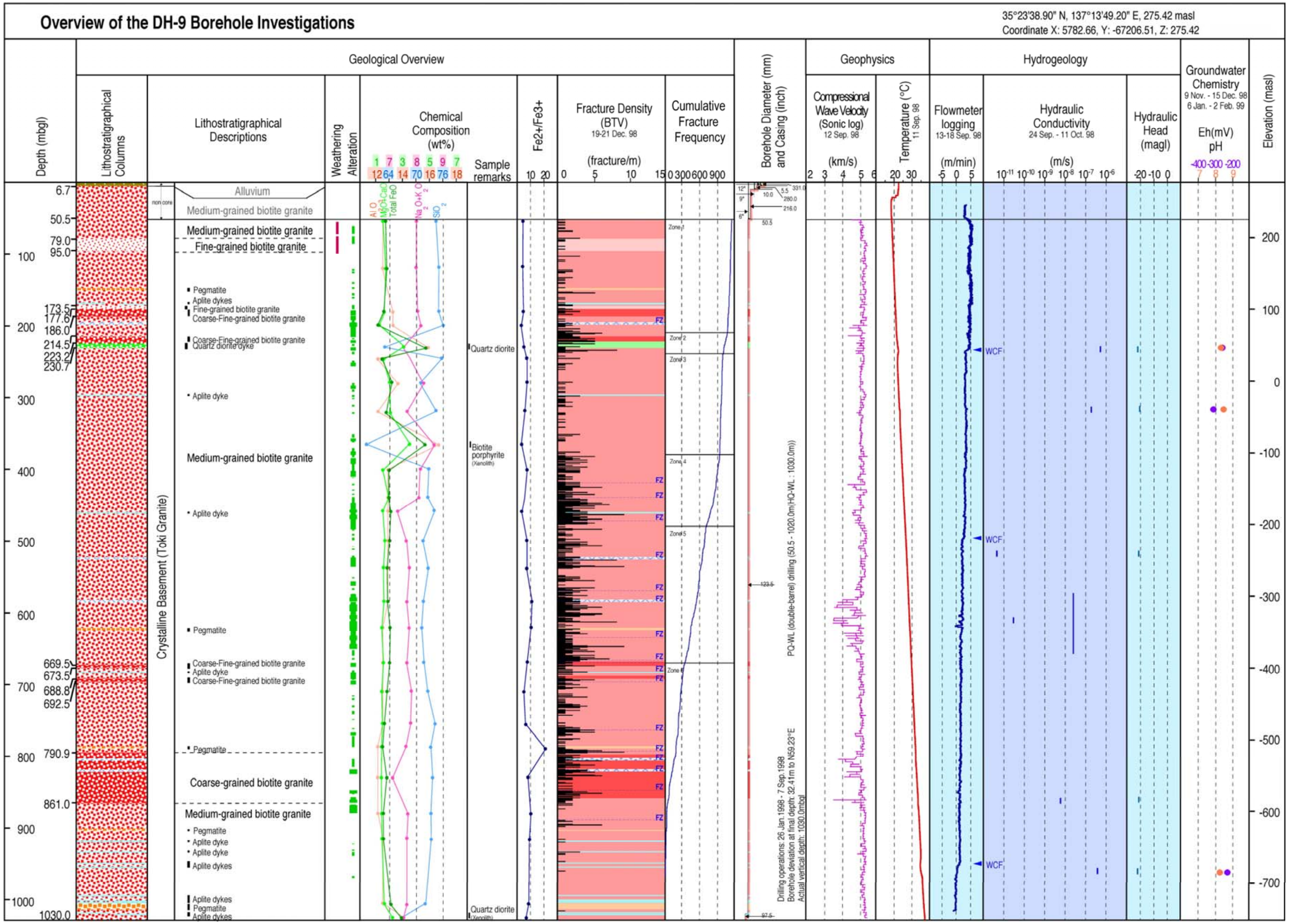
Core Logging in DH-2 Borehole



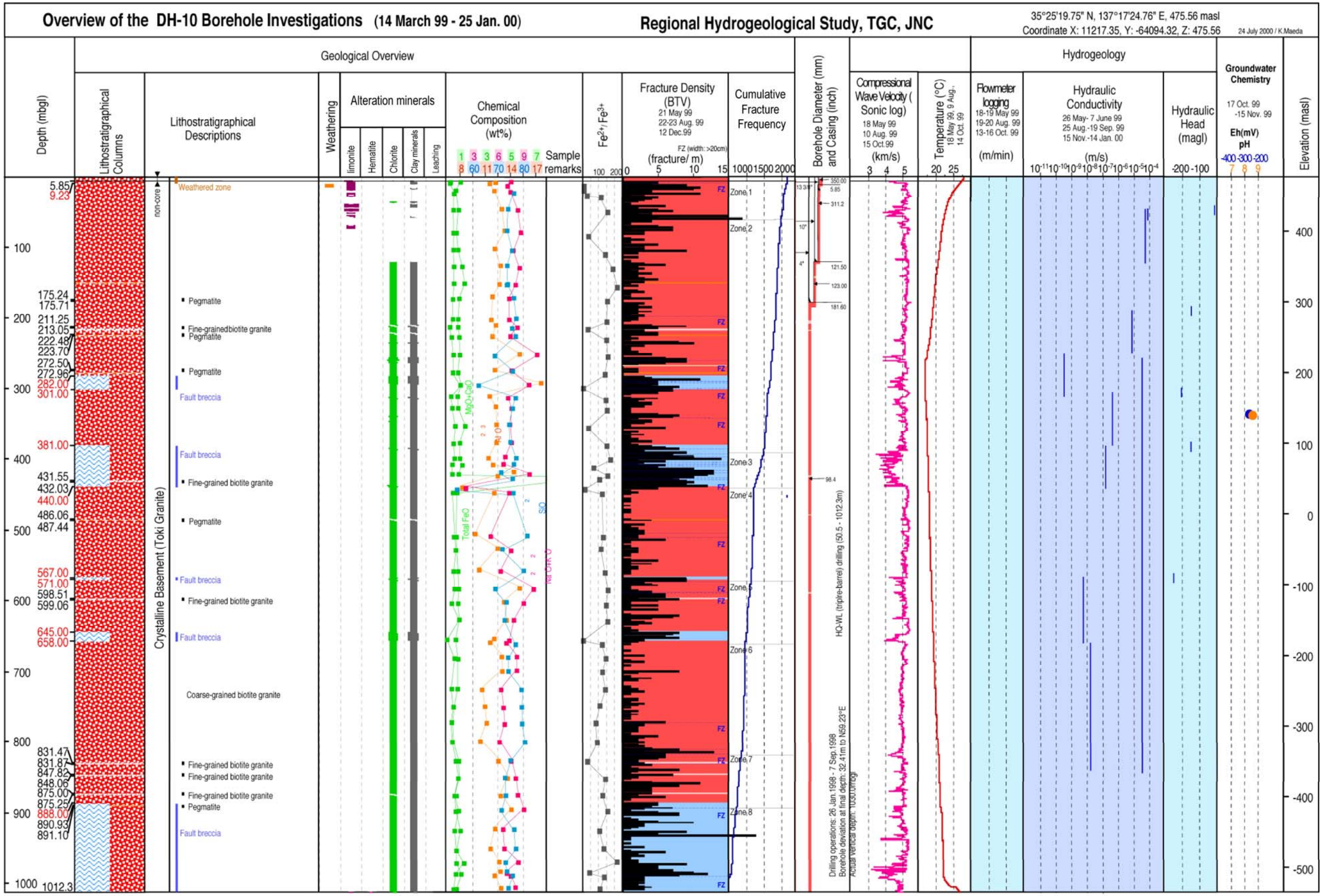
Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-2; Geology)



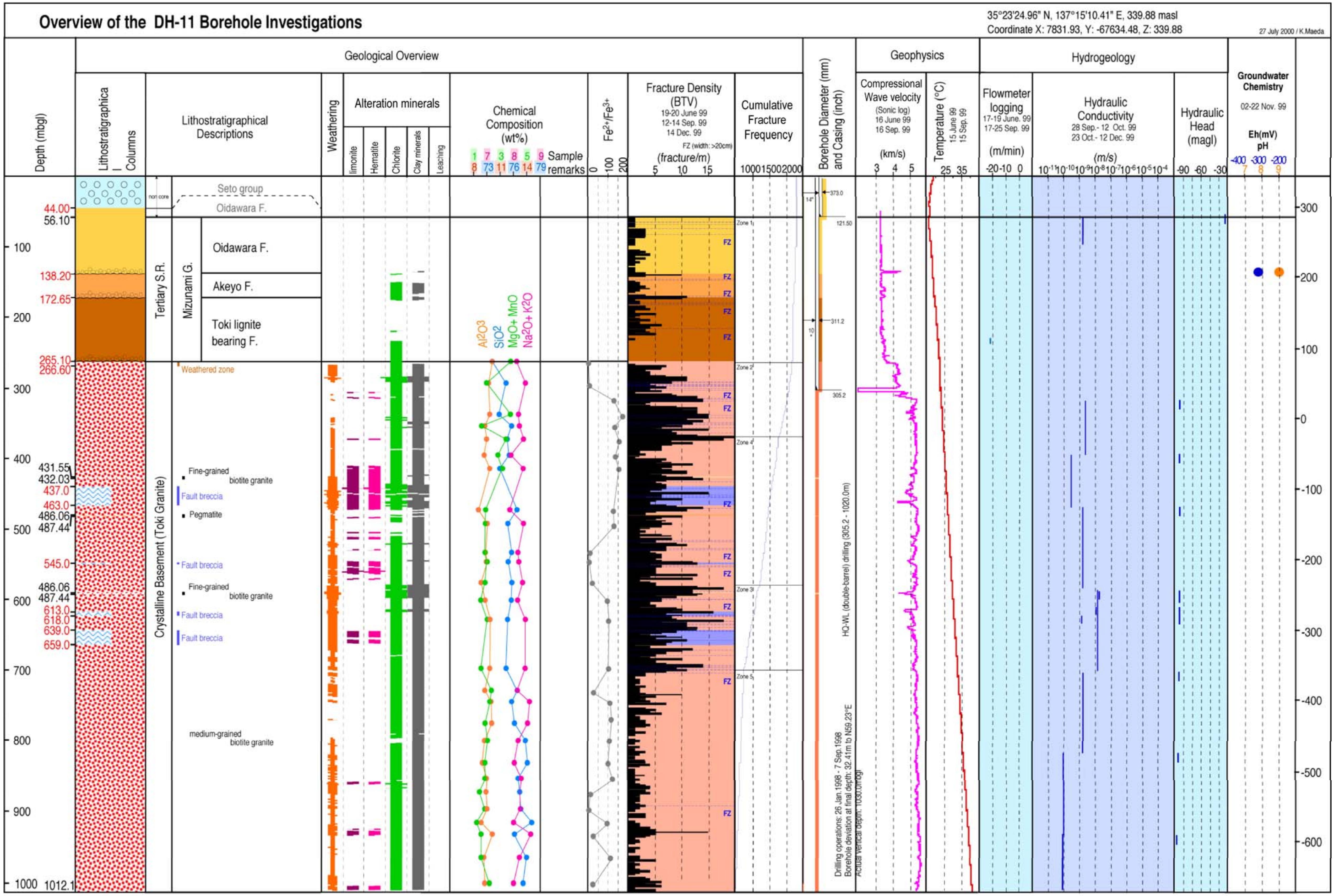
Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-2; Logging)



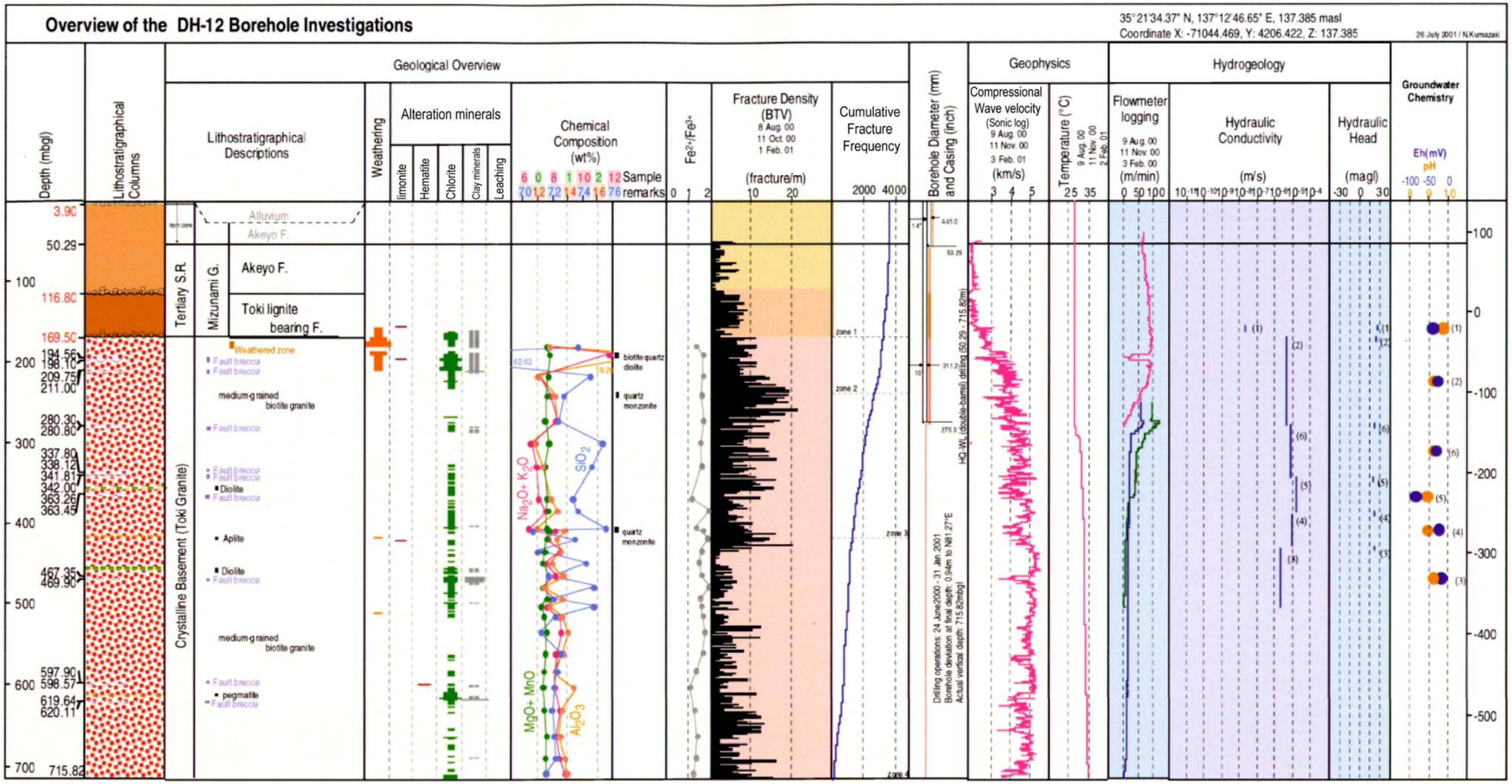
Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-9)



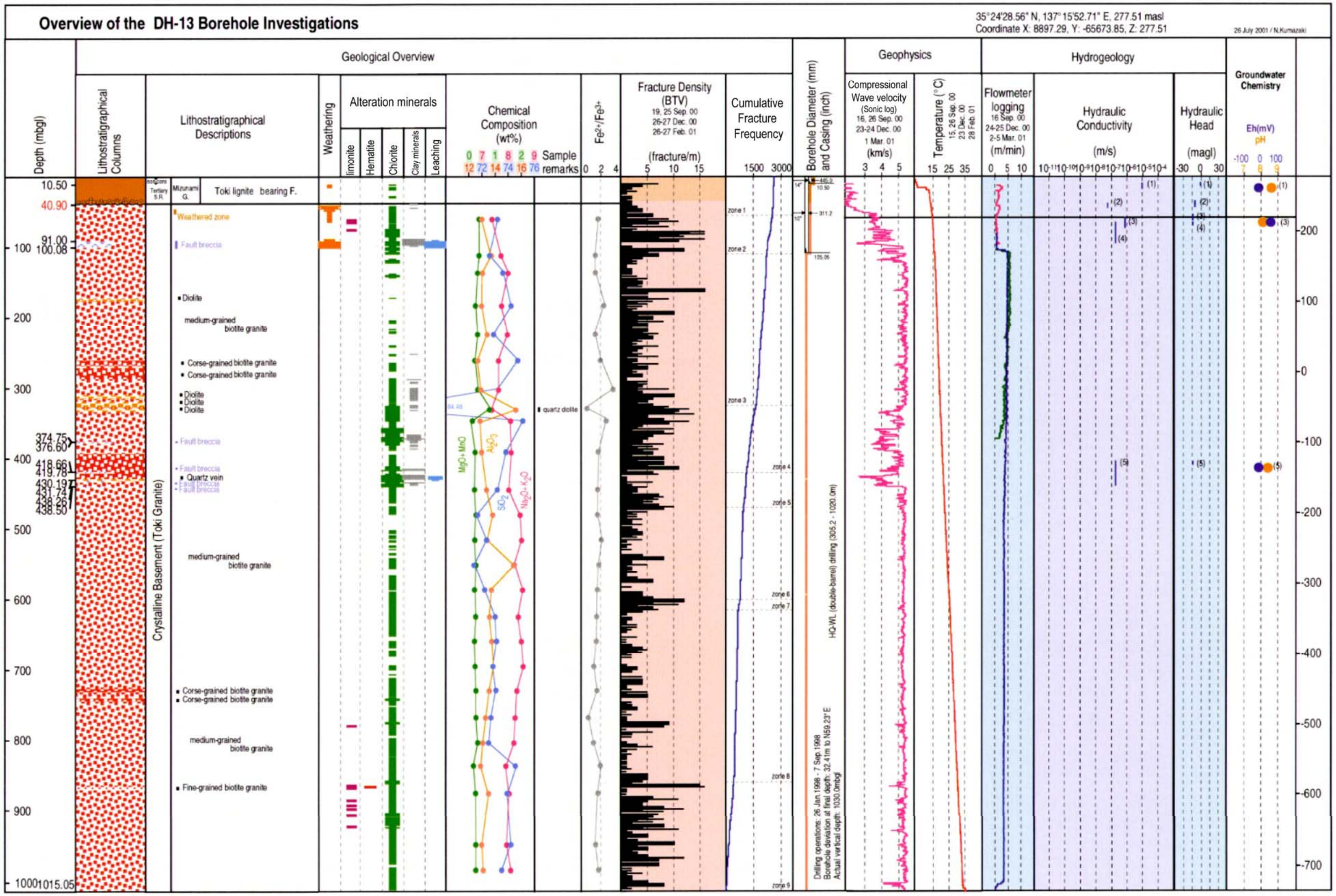
Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-10)



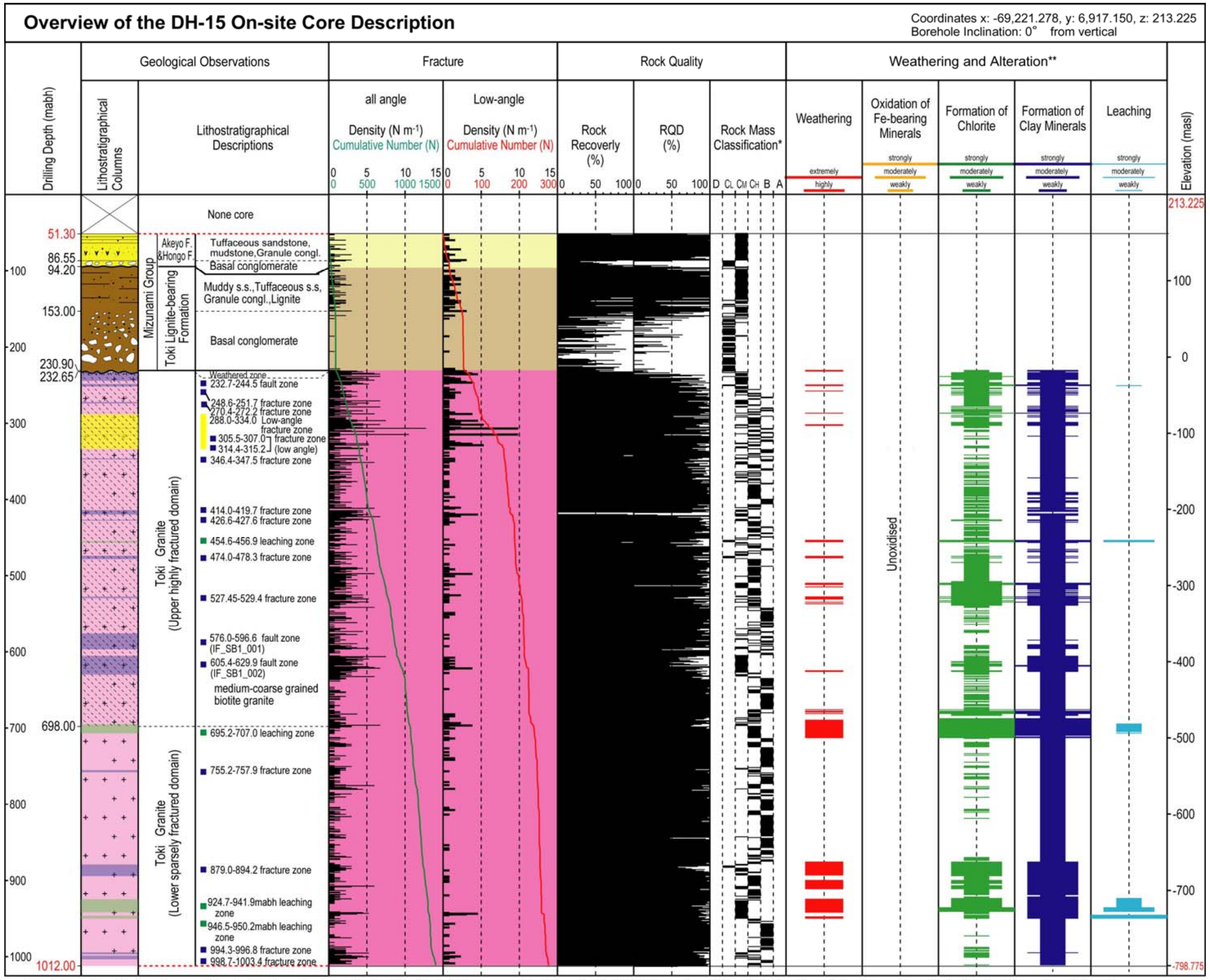
Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-11)



Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-12)



Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-13)



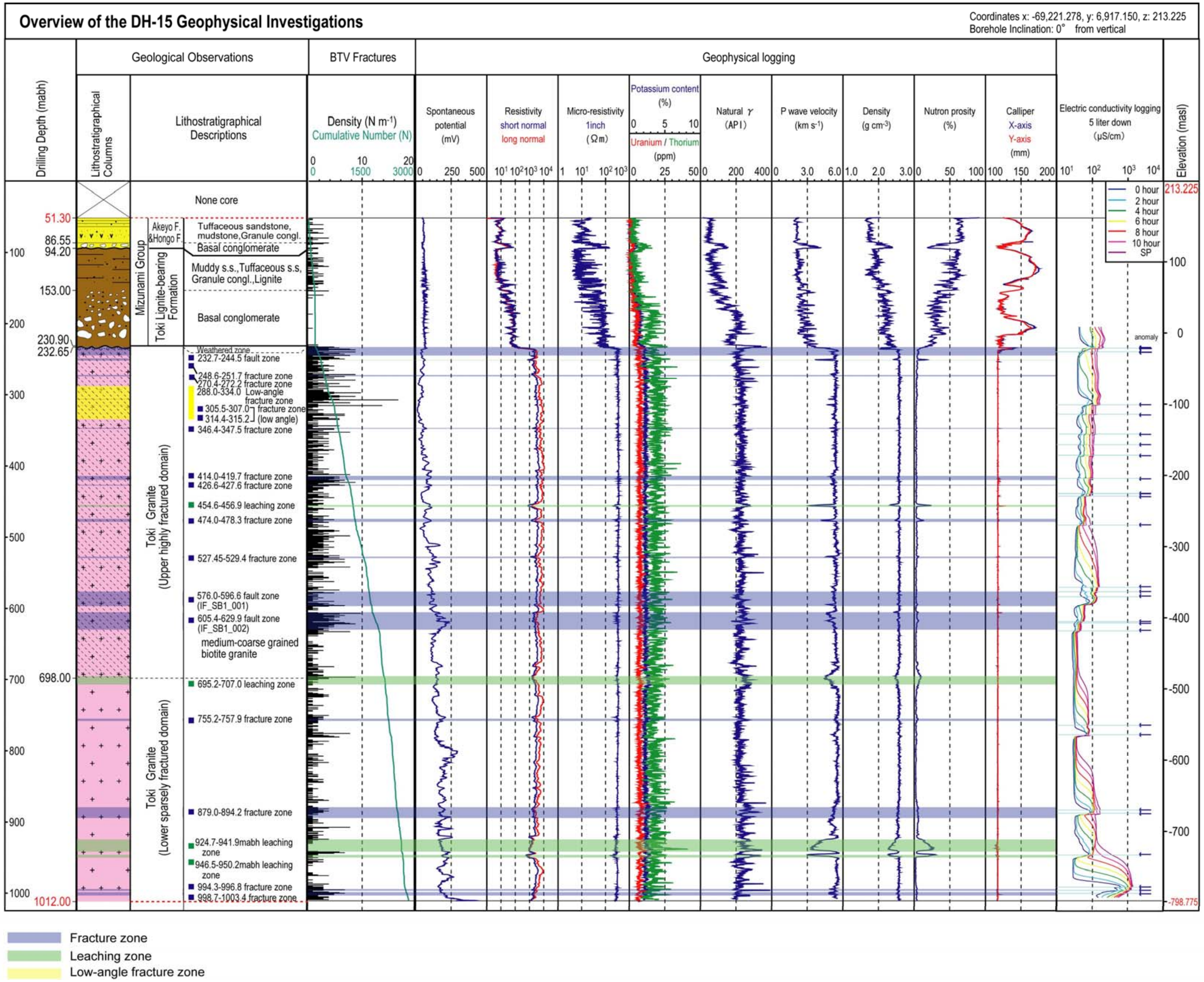
* Rock Mass Classification: Degree of physical disintegration by weathering/alteration in 6 classes; roughly, A (very fresh), B (slightly weathered/altered), CH (weathered/altered except quartz), CM (moderately weathered/altered), CL (highly weathered/altered), D (extremely weathered/altered)

** Weathering and Alteration: Degree of weathering and alteration; classification simplified from on-site core description manual (JNC, 2002)

Fracture zone   Leaching zone

Low-angle fracture zone

Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-15; Geology)



Results from the borehole investigations in the Regional Hydrogeological Study (Borehole DH-15; Logging)

Appendix 6

Overview of the results of borehole investigations in Shobasama site

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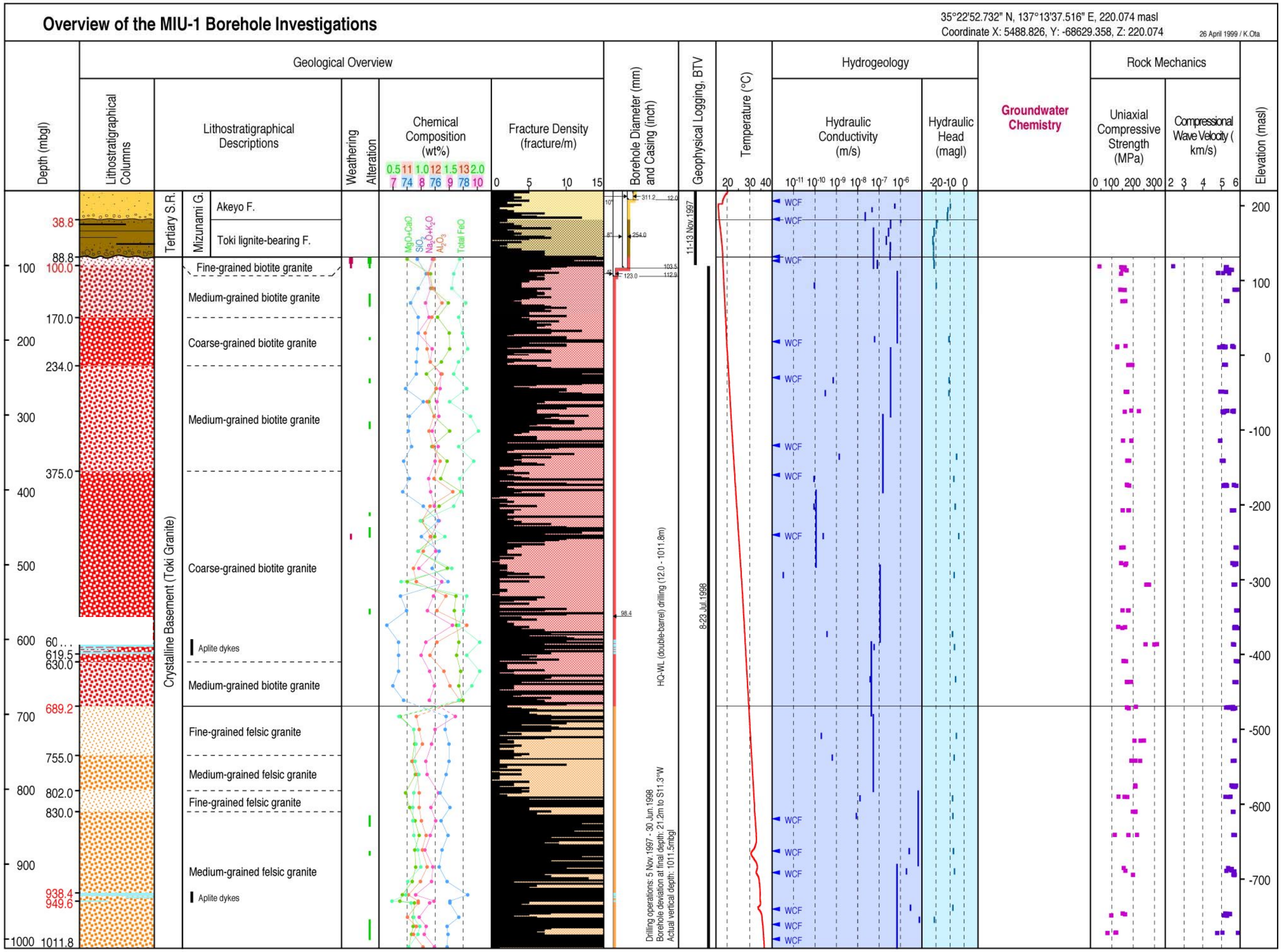
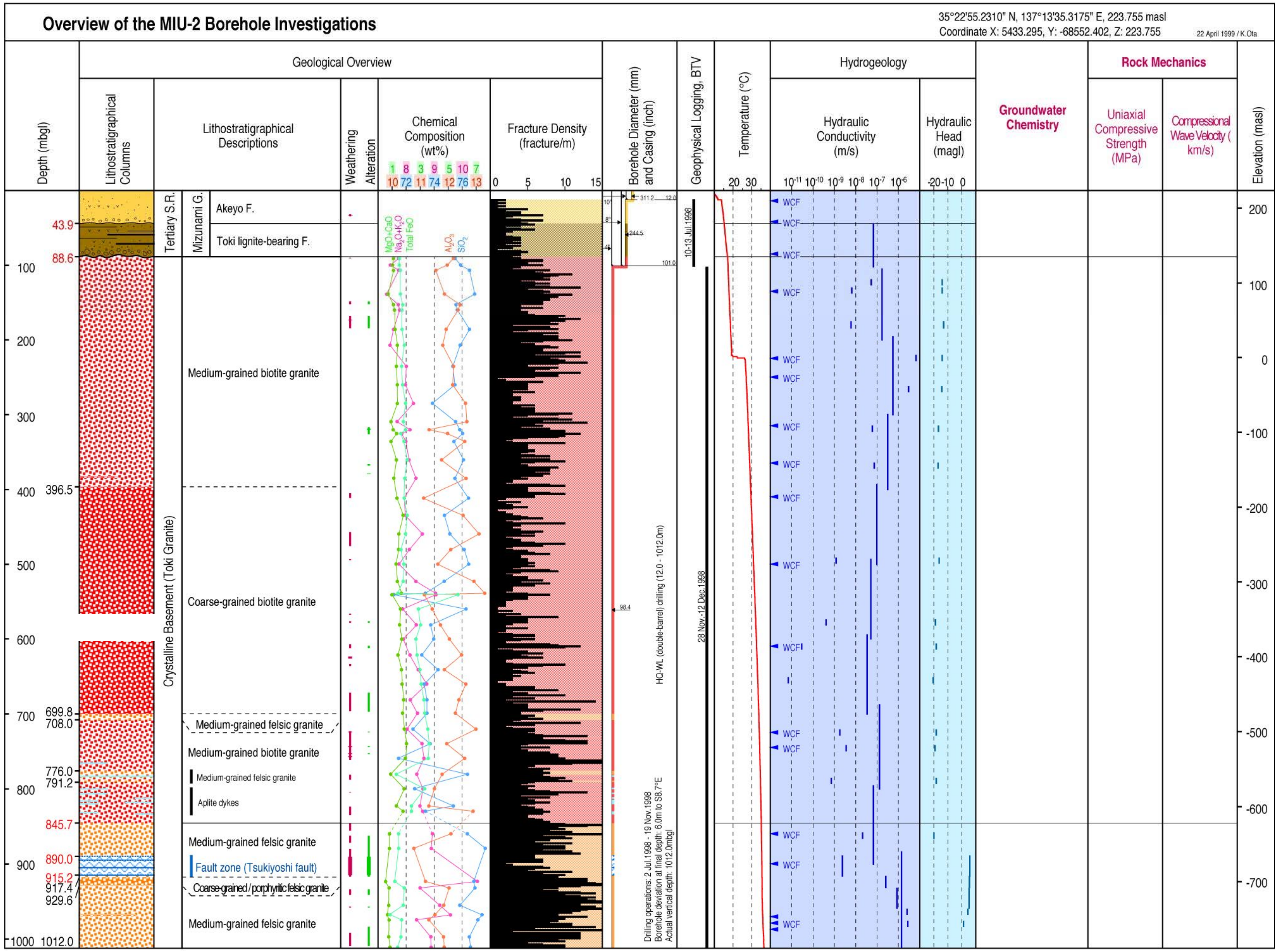
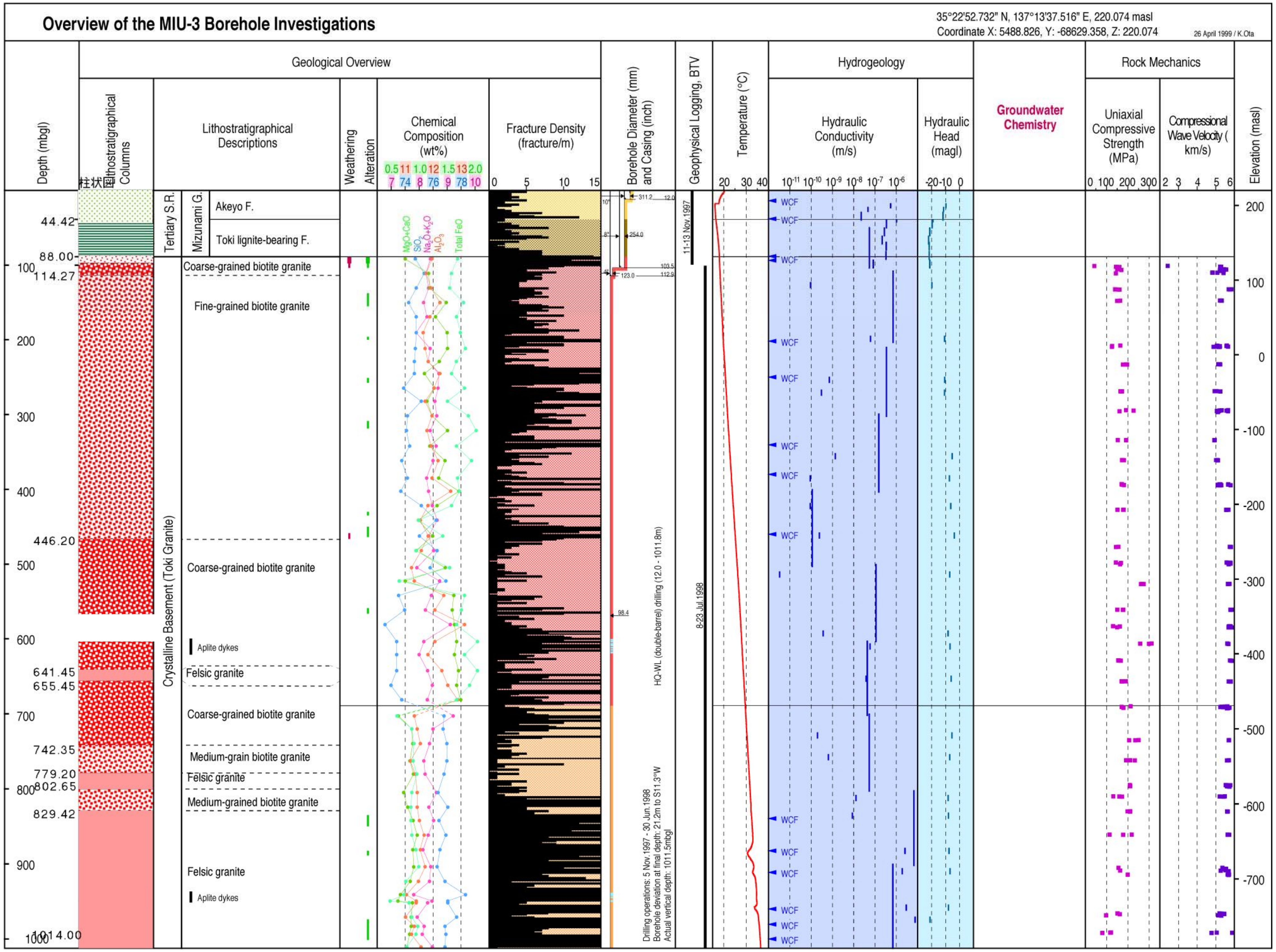


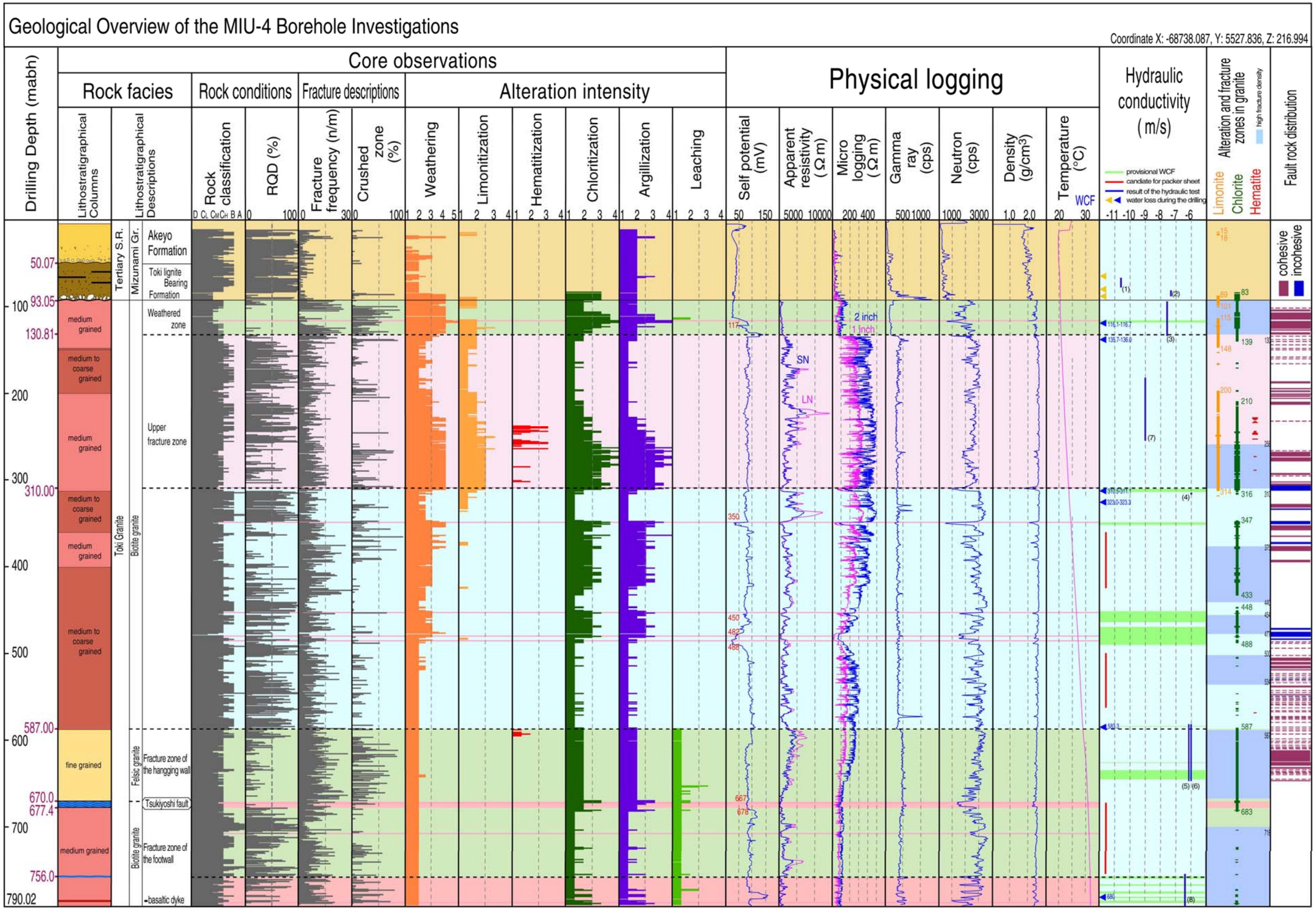
Results from the borehole investigations at the Shobasama Site (Borehole MIU-1)



Results from the borehole investigations at the Shobasama Site (Borehole MIU-2)



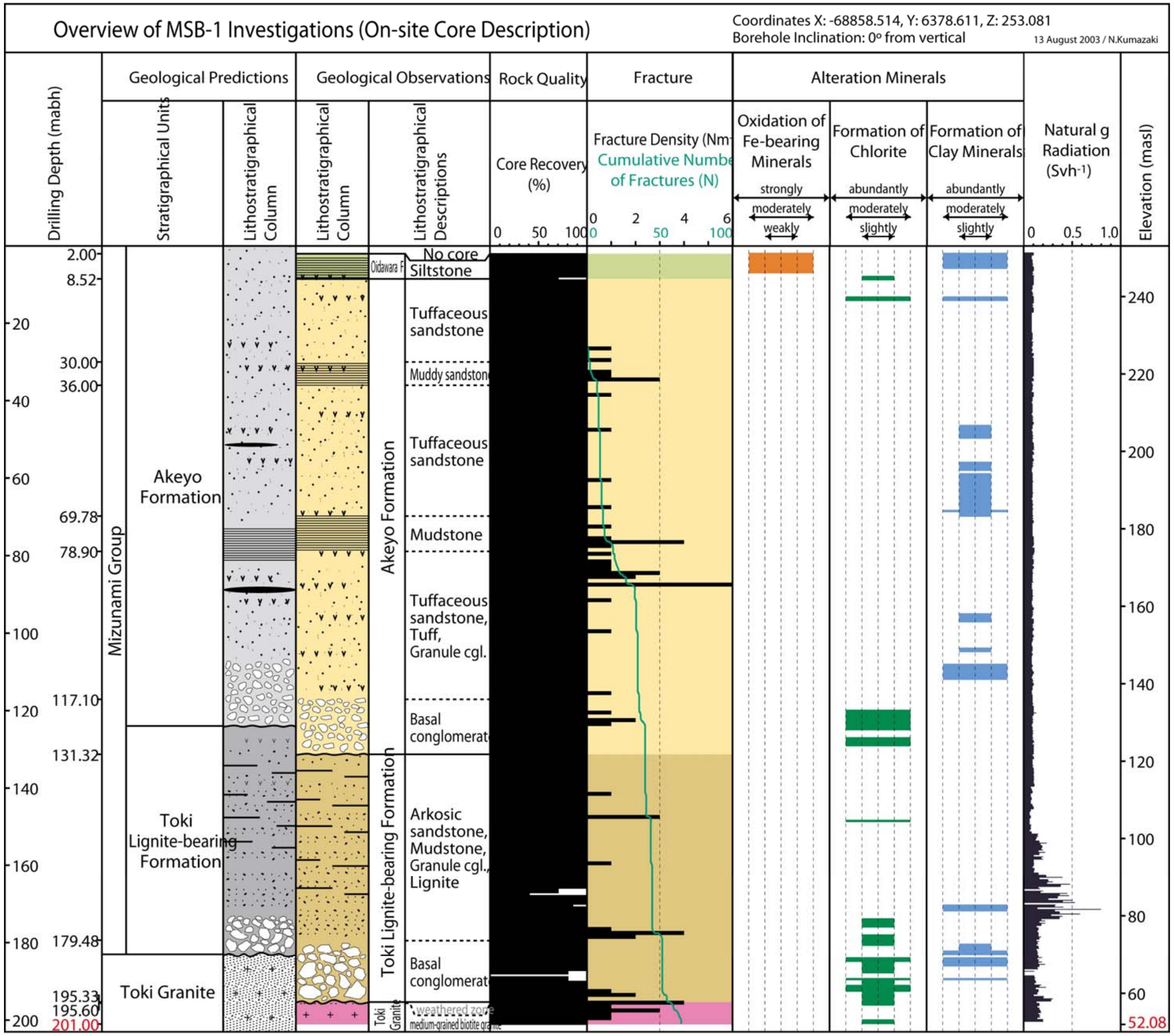
Results from the borehole investigations at the Shobasama Site (Borehole MIU-3)



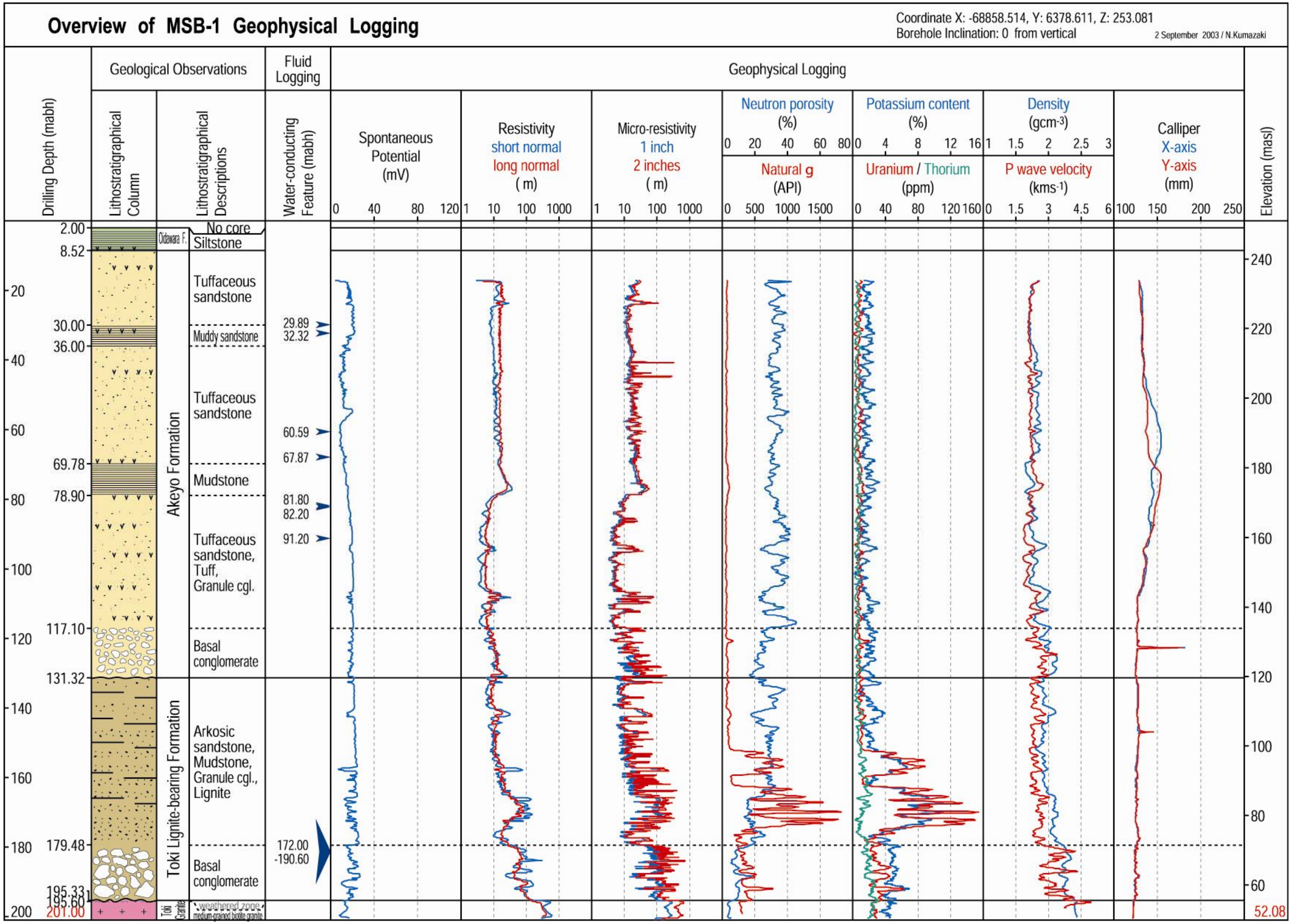
Results from the borehole investigations at the Shobasama Site (Borehole MIU-4)

Appendix 7

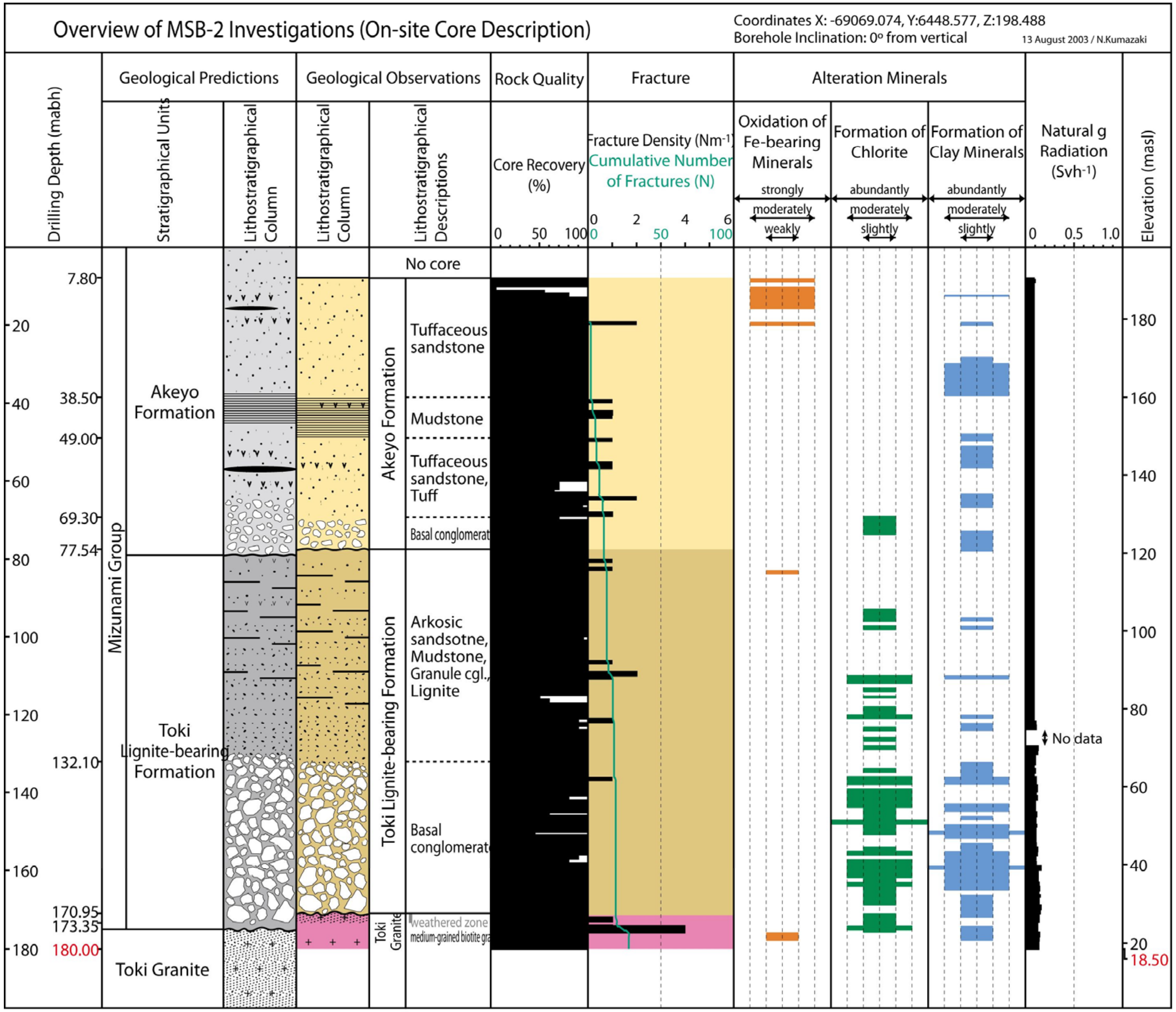
Overview of the results of borehole investigations in the MIU construction site



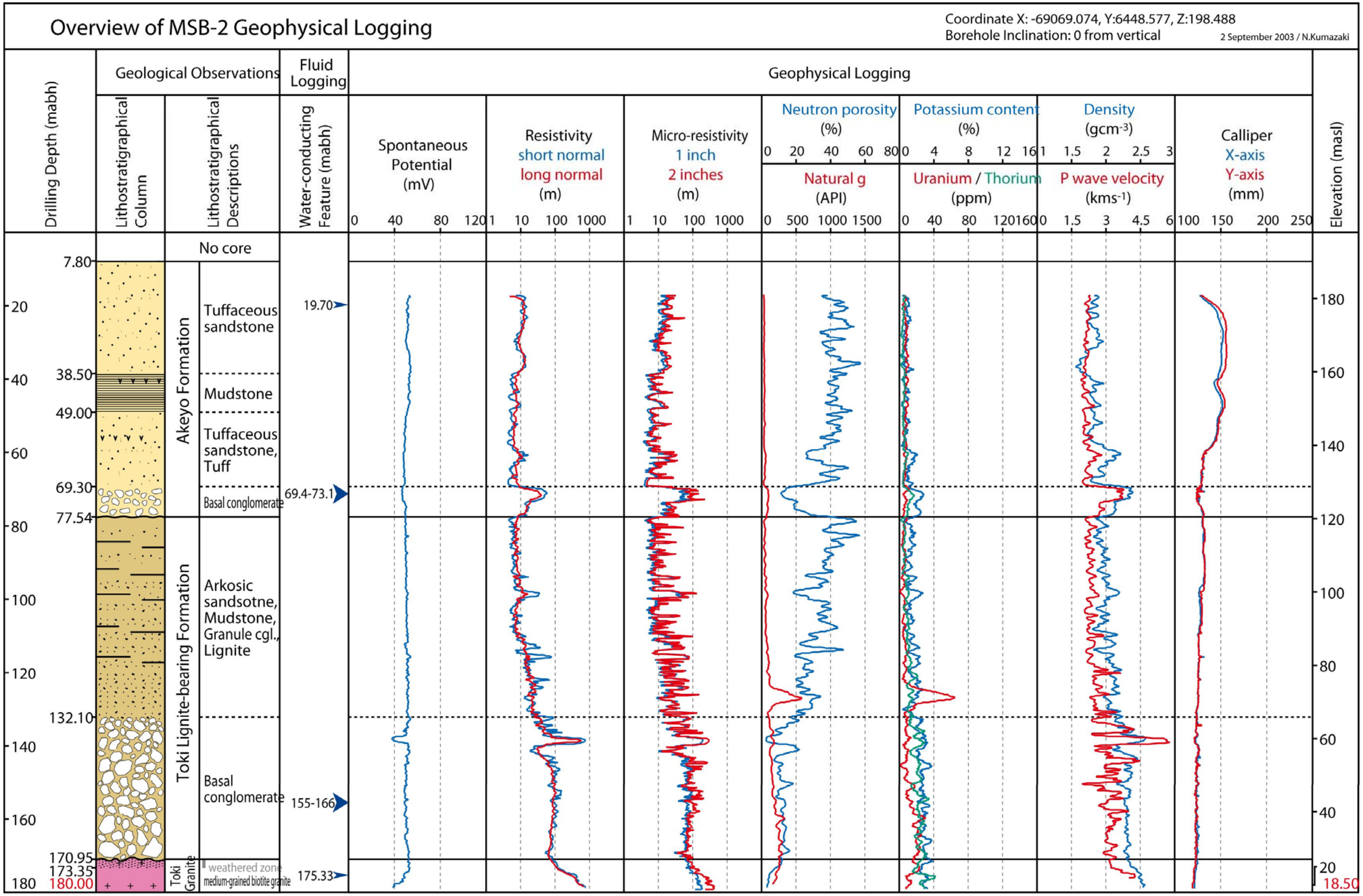
Results from the borehole investigations at the MIU site (Borehole MSB-1; Geology)



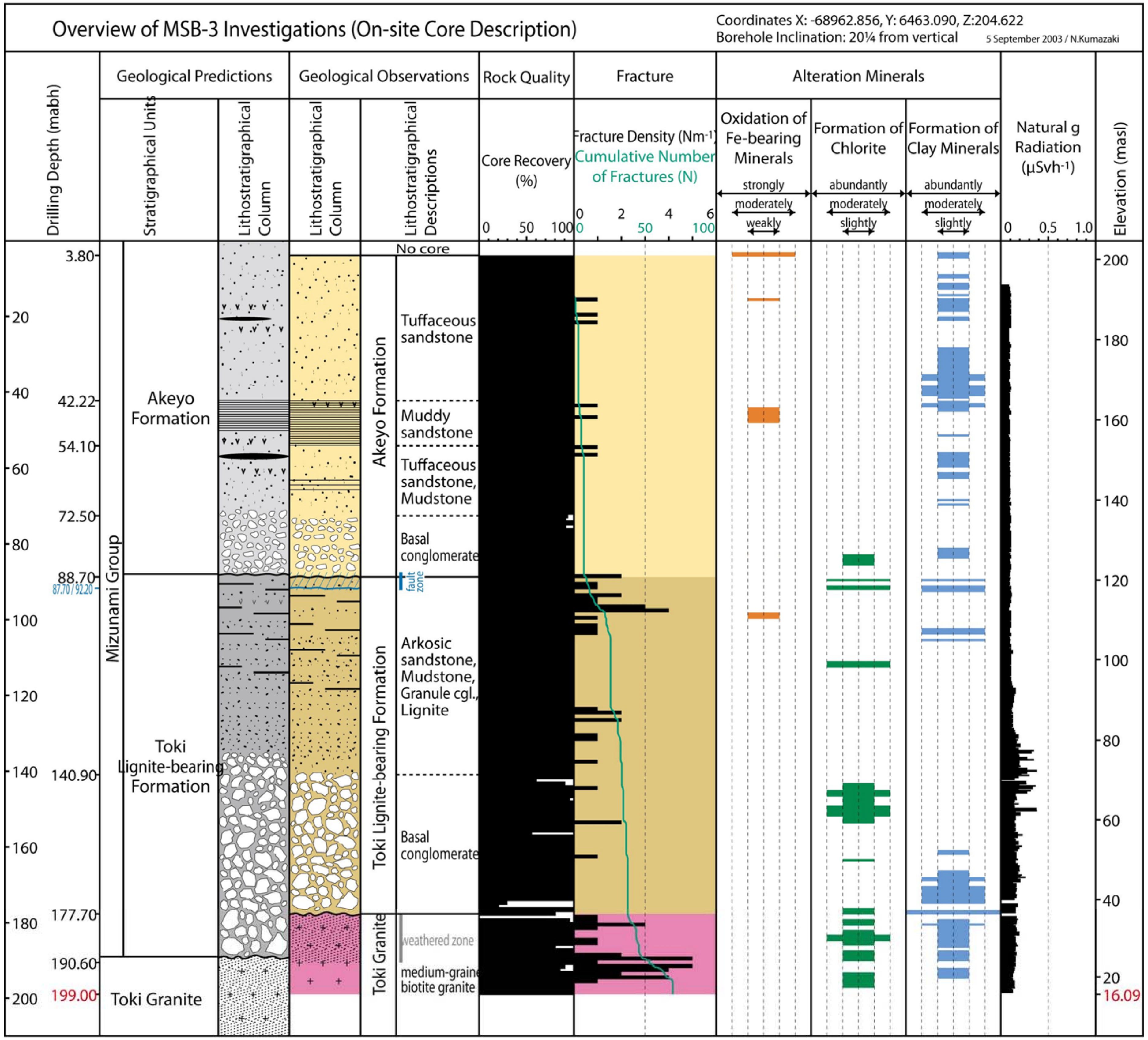
Results from the borehole investigations at the MIU site (Borehole MSB-1; Logging)



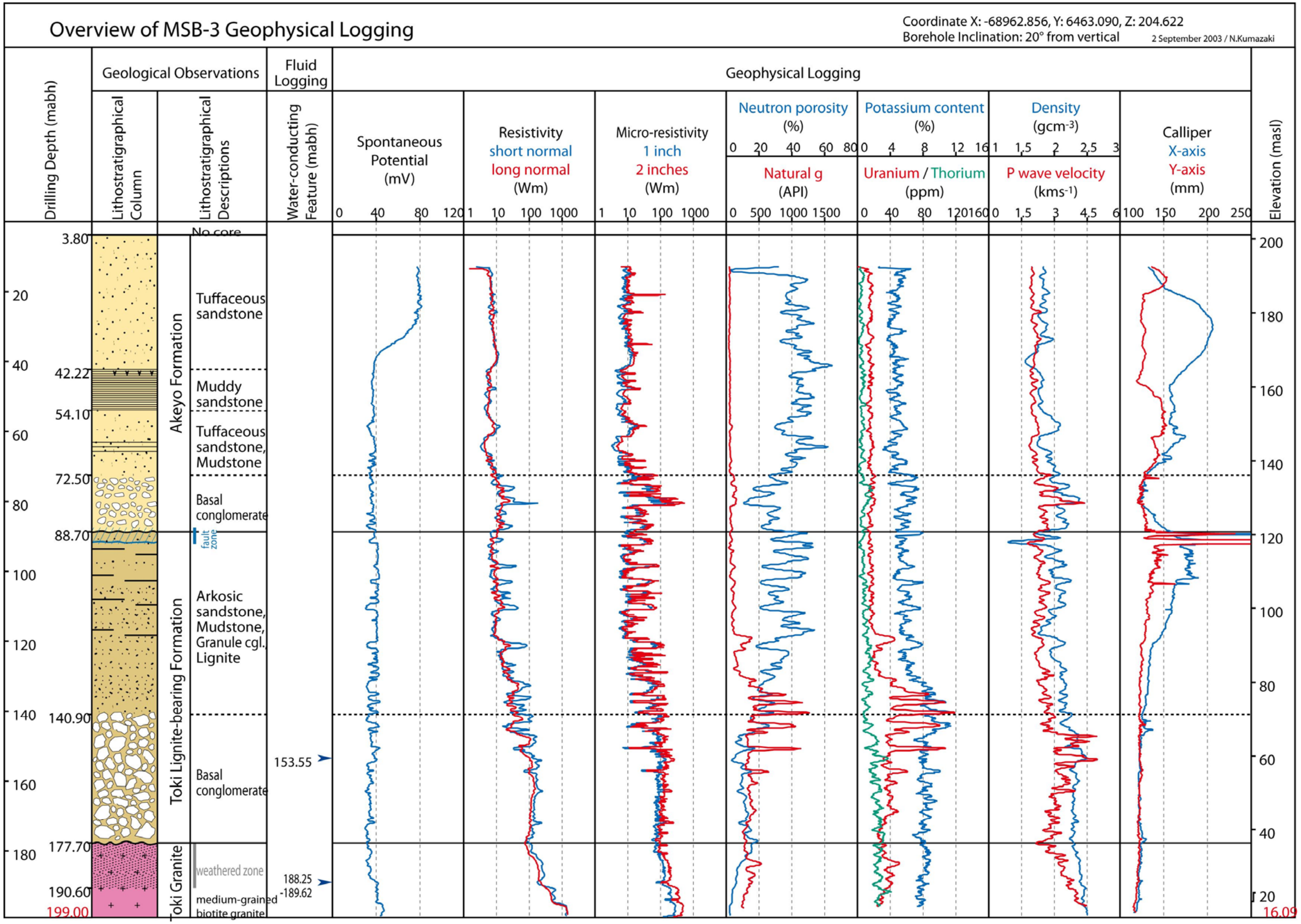
Results from the borehole investigations at the MIU site (Borehole MSB-2; Geology)



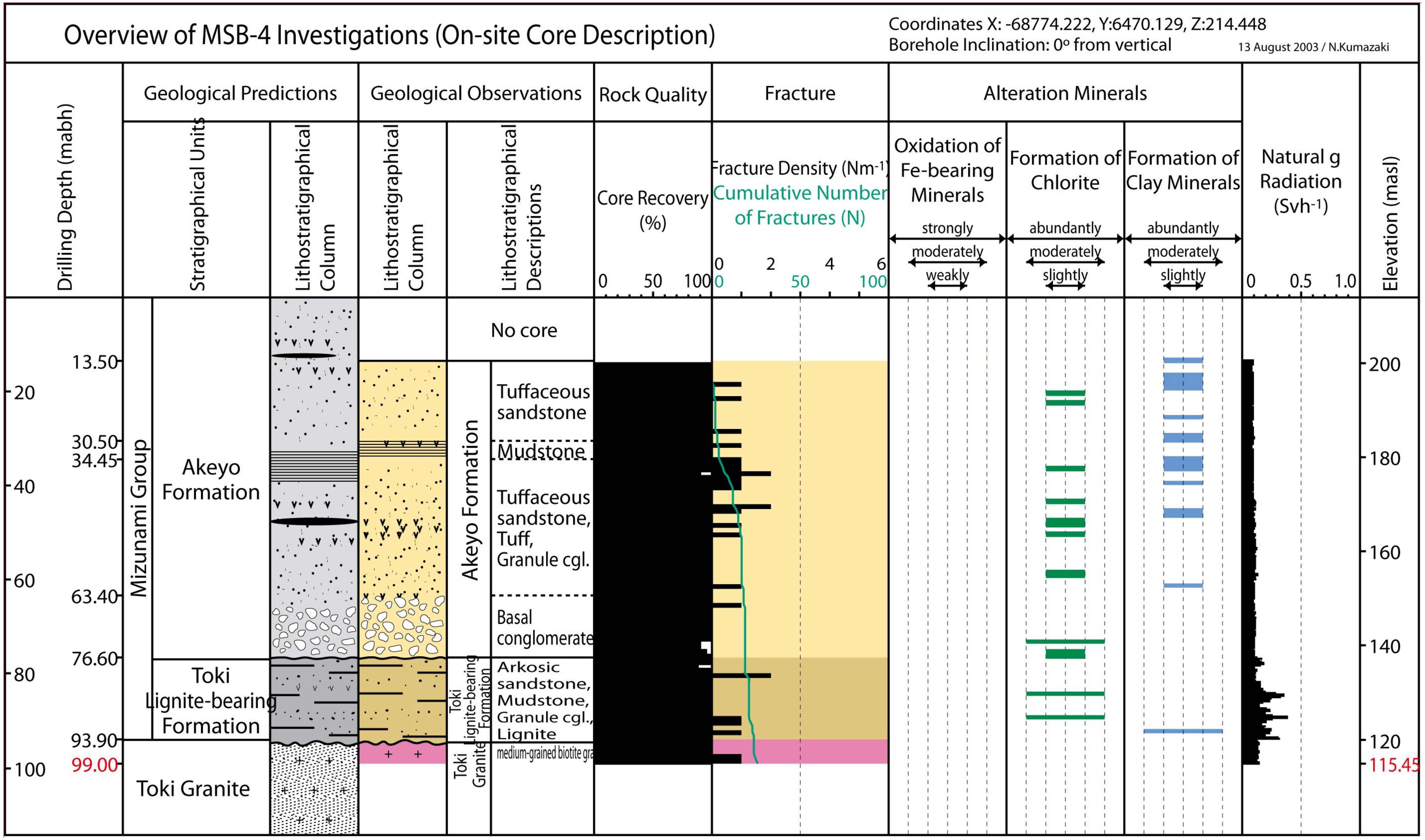
Results from the borehole investigations at the MIU site (Borehole MSB-2; Logging)



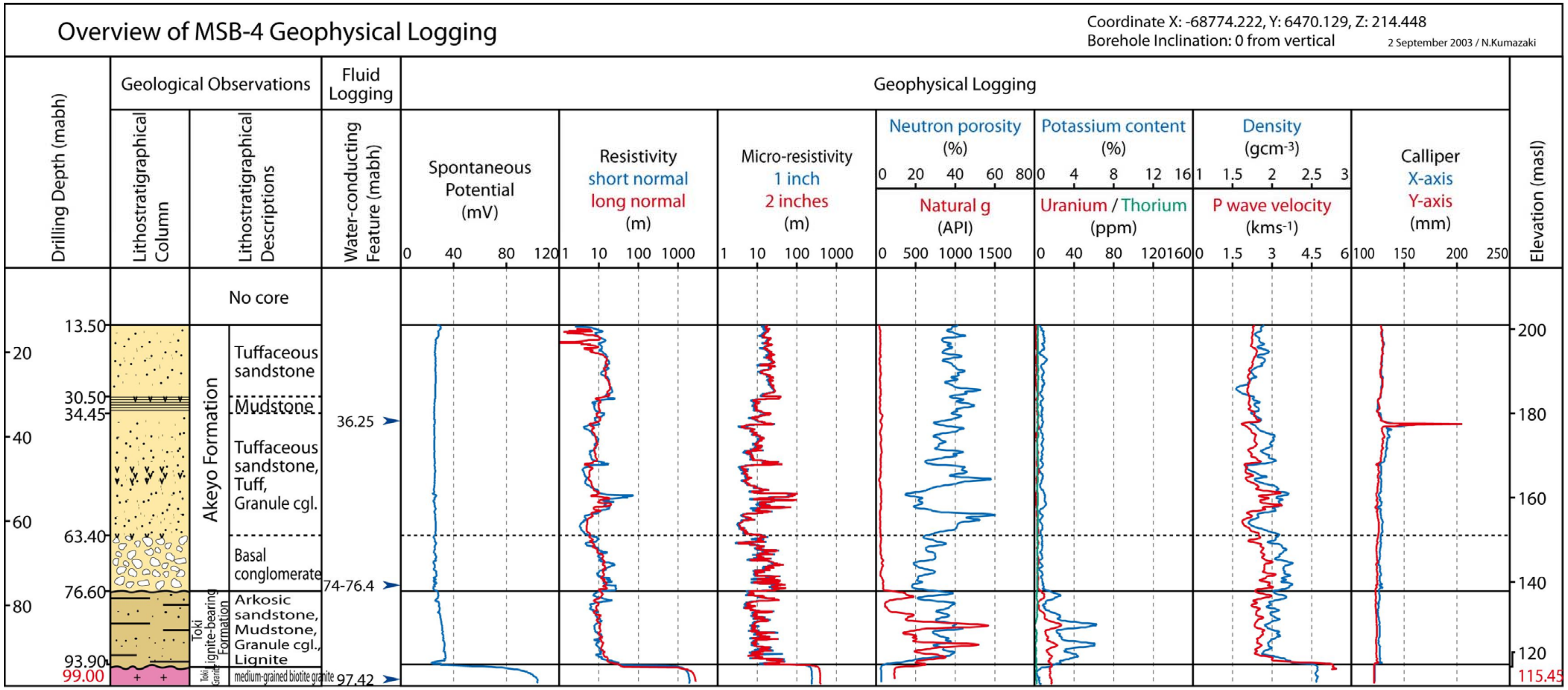
Results from the borehole investigations at the MIU site (Borehole MSB-3; Geology)



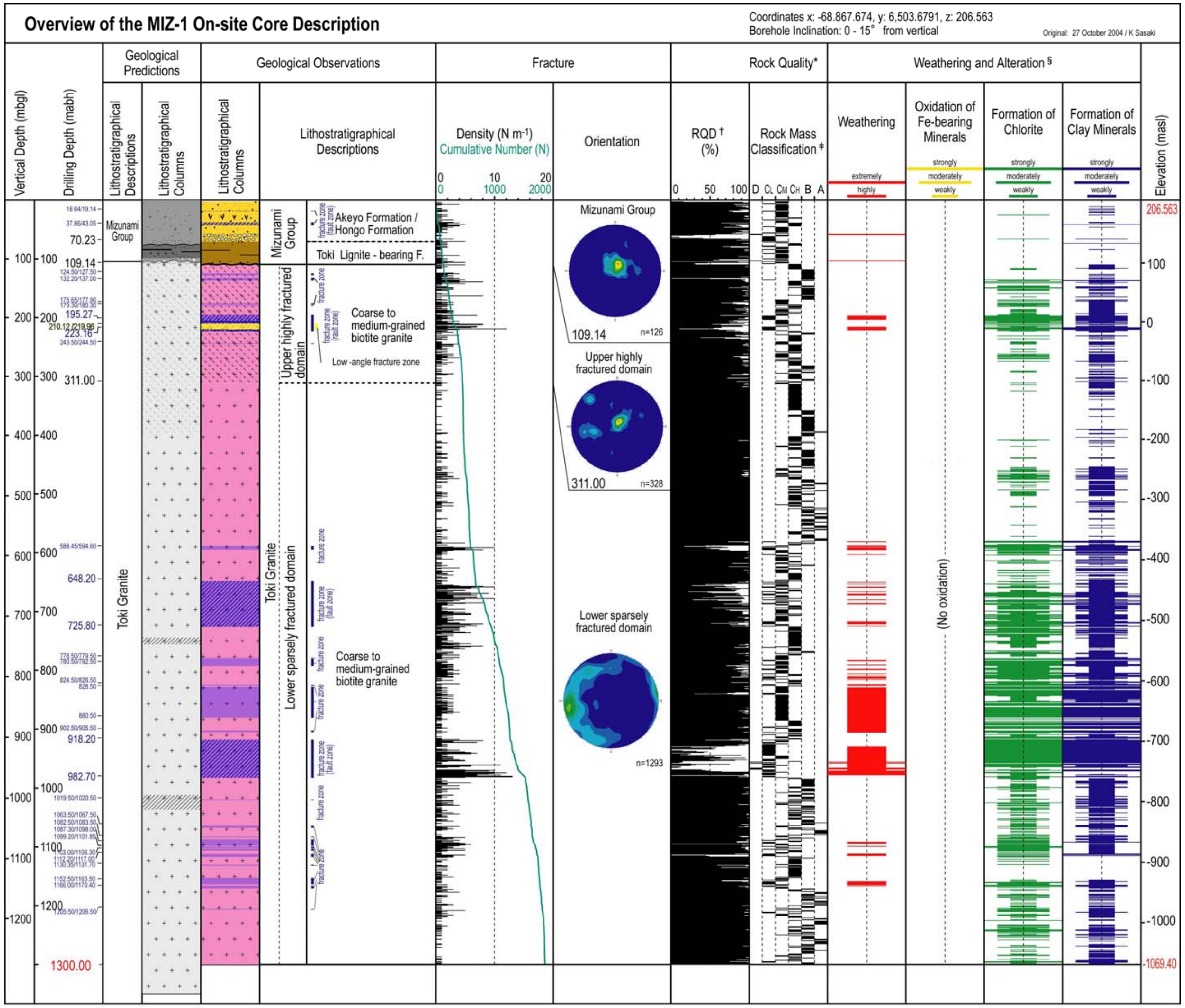
Results from the borehole investigations at the MIU site (Borehole MSB-3; Logging)



Results from the borehole investigations at the MIU site (Borehole MSB-4; Geology)

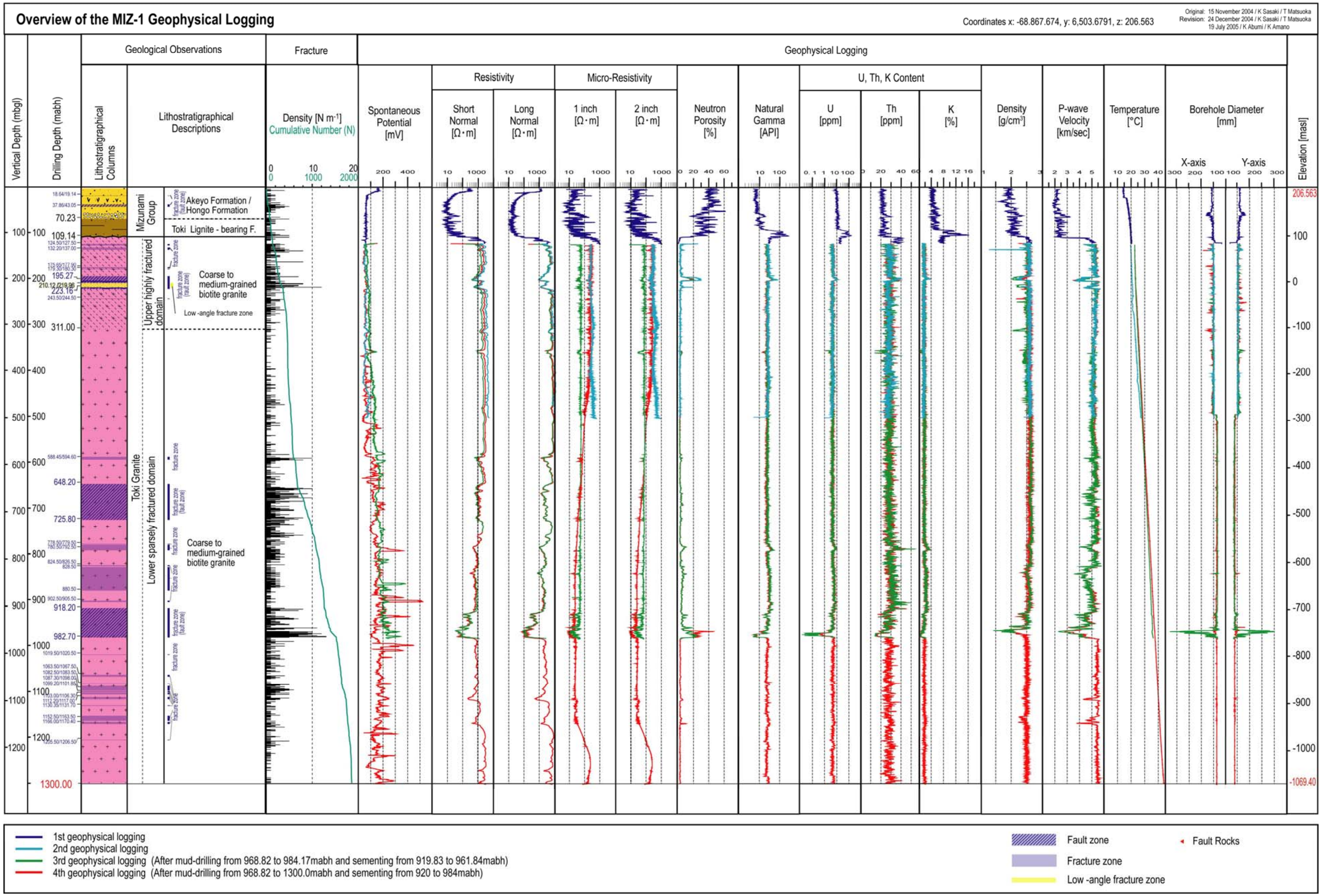


Results from the borehole investigations at the MIU site (Borehole MSB-4; Logging)



Results from the borehole investigations at the MIU site (Borehole MIZ-1; Geology)

* Rock Quality: n (core recovery over 90% in 1m drilling), n (core recovery below 90% in 1m drilling)
† RQD: Rock Quality Designation; defined by the percentage of the sum of lengths of cores over 10cm in the whole core length in 1m drilling
‡ Rock Mass Classification: Degree of physical disintegration by weathering/alteration in 6 classes; roughly, A (very fresh), B (slightly weathered/altered), CH (weathered/altered except quartz), CM (moderately weathered/altered), CL (highly weathered/altered), D (extremely weathered/altered)
§ Weathering and Alteration: Degree of weathering and alteration; classification simplified from on-site core description manual (JNC, 2002)



Results from the borehole investigations at the MIU site (Borehole MIZ-1; Logging)

Appendix 8

Techniques/methods for investigation and assessment of geological environment, applied and developed in the surface-based investigation

Investigation techniques used/developed for the investigations of the geological environment in Phase I (1/7)

Investigation techniques		Objectives, background, problems, etc	Findings, know-how and issues
Lineament surveys		* Determine correlation between small scale lineaments and discontinuities identified by other surveys through interpretation of images with the largest scale used. * Determine what size of lineaments will be effective in estimating discontinuites by examination of the dimension limit and interpretation precision of lineament that could be identified by statistical approach.	* The interpretation limit small scale lineament was 300-400 m in length. * The precision of the location in the interpretation was in the range of 20-60 m. * The results of statistical analyses of fractal properties indicated that the lineaments and fractures observed in bedrock outcrops have similar fractal properties. So, the utilization of these results would allow predicting frequency of fractures over meters to tens of meters in length; these lengths would be difficult to identify by outcrop surveys or lineament surveys. * Acquiring data on fractures with a length of several to several tens of meters would be required during excavation of the underground facilities to evaluate effectiveness of this method and reduce the uncertainty.
Geophysical surveys	Reflection seismic survey	* Evaluate the effectiveness of reflection seismic surveys on granite for which applicability has not been evaluated as well as for sedimentary rocks.	* The NMO (Normal Move Out) correction and deconvolution parameters focused on the granite were applied as a trial processing/analysis aiming at improving S/N ratio of the reflection events and reflection imaging accuracy in granite. Surface wave suppression, surface consistent deconvolution, t relative amplitude preservation and pre-stack time migration were also applied. * In these processing and analyses, reflection events that seem to reflect actual geological structures in the granite can be visualized. Therefore, under the condition where the granite is covered with thick sedimentary rocks, in particular, these processing techniques and methods would be effective for the interpretation of geological structures.
	High density electric survey	* Develop a survey technique for areas where granite outcrops and the reflection seismic survey do not generate clear reflection events such as geological boundaries in the sedimentary rocks in order to identify discontinuities dipping at high angles.	* Information obtained at boreholes such as geophysical logging data would contribute to deduce correct results when used as constrained conditions of inversion. * For the planning of the investigation program, the survey line should be set considering the uncertainty of the geological structure being more complicated than anticipated.
	Multi-offset VSP survey	* Evaluate the effectiveness of the multi-offset VSP survey expected to supplement the result of the reflection seismic survey and to estimate the distributions of discontinuities and fracture zones in greater detail than the reflection seismic survey by setting up several sources around the boreholes.	* From the stacking of each off-set VSP after applied VSP migration, discontinuities of reflection events that are assumed as the extension of the faults dipping at a high angle in the deep granite that are confirmed/inferred by the surface geological mappings and reflection seismic surveys could be identified. * Using the record of two horizontal components of the 3-component geophone in the multi-off-set VSP surveys, the VSP profile that was obtained by data analyzing and stacking in the same way as conventional methods could be used for identifying reflection events that are likely faults dipping at a high angle, and also allow prediction of the distribution of faults dipping at high angles around the borehole.

Investigation techniques used/developed for the investigations of geological environment in Phase I (2/7)

Investigation techniques		Objectives, background, problems, etc	Findings, know-how and issues
Planning of borehole investigations		* Detailed investigation program taking into account potential problems should be formulated and updated with the progress of the investigations, because prompt and appropriate responses should be taken for various problems caused depending on the conditions of the rocks. * In planning the investigation program, the targets of the investigations should be defined based on the understanding of the geological environment obtained in previous steps, and the layout of the boreholes, and the individual investigation items and methods have to be optimized and rationalized based on the results of this understanding as well as restrictions such as time and cost * It would be important to study responses against potential problems anticipated for the geological environment and to identify in advance investigation data whose quality may be affected by such countermeasures and to set acceptable limits for data quality level.. These should be discussed and the results be shared among relevant investigation groups. * Various investigation needs should be optimized. These should be discussed and the results be shared among relevant investigation groups.	* an integrated investigation program was formulated for carrying out investigations in borehole MIU-4 at the Shobasama Site, shallow borehole investigations and deep borehole investigations at the MIU Construction Site. * The appropriate borehole diameter for the expected geological environment, drilling installations such as casing programs and schedules and implementation sections for investigations such as investigations of borehole wall image, fluid logging , hydraulic tests and groundwater sampling were coordinated in the investigation program. * The investigation program included detailed procedures and quality control methods for each investigation objective such as geophysical surveys and hydrological test as well as response options in case of problems such as borehole wall collapse and fluid loss. * Matrix type organization coupling organization by disciplines and cross sectional organization was established for investigations. * Principal investigators (PI) in charge of coordinating the different disciplines were structured on the conventional organization. * Investigation team for supervising investigation common to different disciplines was established.
Drilling techniques	Diameter	* Because the degradation of data quality due to pressure loss in the flow lines was of concern, particularly in testing of highly permeable rock, measures such as the use of larger diameter pipes in the test equipment are required. * Drilling fluid that infiltrates into the rock should be recovered quickly to allow quality-assured hydrochemical data to be obtained. Thus, the diameter of the test system needs to be enlarged to allow installation of submersible pump such as Mohno pump with the capability of flow rate above such as 40 (liters/min). * In the case where drilling becomes difficult when encountering a fault or a similar feature deep underground, it will be necessary to leave open the option of drilling with a slightly smaller diameter from this depth onwards by setting additional casing pipes.	* The diameter of the boreholes were set 5 1/2" (about 135 mm) or larger, in principle.
	Selection of locations	* The locations and layout should be decided considering logistical and environmental aspects as well as technical and geoscientific reasons based on the goals of the investigations..	* The control boring technique was employed in Borehole MIZ-1 considering the restriction on site and system layout and the depth of the geological environment of concern.
	Managing the drilling trace	The planned control function did not operate effectively in borehole MIZ-1 due to: * insufficient control procedure of the dip angle and direction, and * insufficient capability of the controlling device used for the strength of the rocks encountered.	* Borehole was backfilled with cement in the section from the bottom up to intermediate depth, from where sidetrack drilling was conducted using the wedge method and MWD method.

Investigation techniques used/developed for the investigations of geological environment in Phase I (3/7)

Investigation techniques		Objectives, background, problems, etc	Findings, know-how and issues
Drilling techniques (Continued)	Measures against collapse		* When a collapse occurs during drilling, the drilling should be stopped once, and planned logging and testing should be conducted to the depth of collapse in order to secure the characterization of groundwater and rock formations along this section of the borehole. * After completing the investigations, the collapsed area should be protected with cement before continuing the drilling and proceed with the investigations in deeper sections. * If a further collapse occurs in the cement-protected zone, a casing pipe should be inserted to the depth of the collapse and the pipe should be firmly fixed with cement. Then further drilling would be possible. * If a collapse were to occur in the shallow underground, drilling in a borehole with a diameter equivalent to that before the collapse would be possible by reaming the borehole using a larger-diameter bit before inserting a casing pipe and protecting the collapsed portion with cement. * In case of collapse in a deeper section, drilling would be possible by a reduced drilling diameter. * In case where further drilling might be difficult to carried out due to further borehole collapse because of the presence of faults, or the delay in operations due to the time required to implement countermeasures becomes unacceptable, an alternative drilling method using drilling mud should be applied. * When drilling mud is used, the quality of cementation could be affected due to the fact that cleaning the cementation area by the spacer might be insufficient especially in the areas with large breakout. This results in a poor quality cementation due to poor hardening of the cement (gelation)
	Management of drilling fluid	* Drilling with freshwater can cause on one hand difficulties in removing the drilling cuttings out of the borehole, and the other hand is not able to create mud cake on the borehole wall to stabilize the borehole and/or prevented from in- /outflow.	* Removal of the cuttings was improved by selecting drill-bit for smaller grain size cuttings in combination with an optimized annulus (between drill-pipe and borehole wall) to enhance the flow velocity of the circulation water. * The cuttings was actively removed by using a centrifuge separator. * Because high flow velocity of the circulating water may induce collapse of borehole wall, volume of the drilling water circulating at the annulus (between drilling pipe and borehole wall) should be controlled depending on the rock conditions, drilling method, borehole diameter, pumping volume and pumping pressure. * A fluorescent dye was added to the drilling fluid and its concentration is controlled periodically to quantitatively determine the ratio of residual drilling fluid in the groundwater sampled.
	Strength of drilling pipe	* In borehole MIU-4 (controlled drilling with a length of about 790 m) at the Shobasama Site, the threaded portion of the drill-pipe was broken and the pipe became jammed due to insufficient discharge of drilling cuttings resulting from the collapse of the borehole wall in a fault zone. It took approximately 3 months of activities to recover the jammed pipe and to stabilize the borehole (injection with cement). * The drill-pipe used in the MIU-1 borehole became jammed due to breakage of the temporary stainless steel casing pipe, causing a delay of about 1.5 months in the drilling work.	* Special attention has to be paid to the selection of the strength of the connectors and torque management during drilling and the strength of the pipe itself, in addition to measures for prevention of borehole wall collapse and drilling fluid management.

Investigation techniques used/developed for the investigations of geological environment in Phase I (4/7)

<table>
<tr><th colspan="2">Investigation techniques</th><th>Objectives, background, problems, etc</th><th>Findings, know-how and issues</th></tr>
<tr><td rowspan="3">Drilling techniques (Continued)</td><td>Recording of drilling parameters</td><td>* Required for controlling drillings, characterizing geological environment and obtaining information on the conditions in the borehole such as fluid loss.
* Required for taking prompt measures against problems.
* Prompt acquisition would be required, because these data could be utilized as information for estimating the location and scale of the problem and selecting sections for hydraulic tests and/or sampling.</td><td>* Drilling parameters were acquired including drilling efficiency, torque, rotational speed, bit load, circulation pressure, drilling fluid balance, water temperature, electrical conductivity, pH, viscosity, density etc.
*Continuous monitoring and recording of drilling parameters would allow determining borehole conditions and optimum drilling parameters for the drilling in the future. They would be important as signals of borehole collapse such as increase in the drill slime and detection of increase of pumping pressure due to plugging and conductivity, or as a guideline for optimization of drilling bit and parameters.
* The geological environment characteristics utilized in identifying the depth of important water conducting features include parameters such as return water volume, water temperature, electrical conductivity, and pH.
* A monitoring system was introduced after Borehole MIU-4 that could acquire data on parameters continuously.
* Data could be monitored at any time on a personal computer at the office via the telephone line connection from the field.</td></tr>
<tr><td>Sampling of drill-cores</td><td>* A high core recovery rate is a key issue in borehole drilling.
* Although the core recovery rate was over 90%, this method involved problems with the retrieval of the core from the core barrel, resulting in core damage. In fault zones the recovery rate drops and, most importantly, fault gauge material from these zones cannot be recovered for analysis</td><td>* The triple-core wireline method was used, which introduces a transparent acrylic liner in the inner core barrel.
* Drilling parameters including drilling water volume, rotation rate, drilling rate, and optimum drilling sequences based on experiences of the operator need to be established.
* Presently, core sampling relies in many aspects on drilling operator skills, and control of the drilling parameters relies on the sense and experience of the operator. However, since the data on drilling parameters obtained in Phase I are those based on operators' experience, optimum drilling procedures established by quantifying these should be defined in the investigation program or construction procedures.</td></tr>
<tr><td>Basic specification for the deep borehole investigation for Toki Granite in the MIU Project</td><td></td><td><table>
<tr><td>Borehole diameter</td><td colspan="2">Above 5 ½”</td></tr>
<tr><td>Casing program</td><td colspan="2">Multistage drilling</td></tr>
<tr><td>Drilling water</td><td colspan="2">Fresh water tagged with fluorescent dye</td></tr>
<tr><td>Control for the drilling water</td><td colspan="2">Monitoring for fluorescent dye concentration and loss of drilling fluid during drilling</td></tr>
<tr><td>Coring</td><td colspan="2">Triple-barrel drilling method with an acrylic inner core barrel</td></tr>
<tr><td rowspan="3">Borehole protection</td><td>Fluid loss</td><td>Plugging with LCM (Lost Circulation Material, e.g. cellulose)</td></tr>
<tr><td>Collapse</td><td>Partial cementing</td></tr>
<tr><td>Large scale collapse</td><td>Installation of casing pipes and full hole cementing</td></tr>
</table></td></tr>
</table>

Investigation techniques used/developed for the investigations of geological environment in Phase I (5/7)

Investigation techniques		Objectives, background, problems, etc	Findings, know-how and issues
Geophysical logging	Identification of fracture zone	* Formulate an objective definition and identification criteria of fracture zones.	* Principal component analysis22) was conducted using multiple data obtained by the borehole wall imaging, geophysical logging, etc., which allows continuous quantitative data versus depth to be obtained.. * This method is considered to be generally effective to distinguish background fractured rock from fractured/ altered zones because the degree of fracturing or alteration is greater when the principal component score is lower and because no distinct fractures were observed in the zones identified as background fractured rock based on the principal component scores
Fluid logging		* Develop a technique (fluid electrical conductivity (FEC) logging method) to detect water conducting fractures with significant changes in the electrical conductivity by measuring electrical conductivity along boreholes while continuing pumping after replacement of borehole water with water whose conductivity is different from that of the groundwater such as deionized water or saline water.	* Replacement of borehole water with the refined deionized water by circulating borehole water via ion-exchange resin would allow identifying specific inflow points that could not be detected by conventional flow meter logging. * Detection of water conducting features with transmissivity of 10^{-8}m^2 s^{-1} or larger would be possible. * The FEC logging could detect water conducting features with a transmissivity two orders of magnitude lower than that detected by flow-meter logging method using impeller or electric-magnetic flow-meter etc. * In evaluating the results of the fluid electric conductivity logging, differences in the electric conductivity of the groundwater should be taken into account and hydraulic test should also be conducted for water conducting features.
Hydraulic testing		* Improve test system, development of test methods, improvement of data evaluation method to acquire date with a certain quality for rocks with a wide range of hydraulic characteristics (10^{-12}～10^{-3} m^2 s^{-1}).	* Use of larger pipe diameter to reduce pipe line resistance in highly permeable rocks. * Pump modified so that large volume of water could be pumped and borehole storage could be reduced, and a system possible to install the modified pump was manufactured aiming at acquiring data during the time period when hydraulic characteristics could be evaluated appropriate for a long period of time by reducing the effect of borehole storage. * Develop a test sequence that allows effective testing (sequential test) by selecting testing method appropriated for the permeability in the test interval. * For the evaluation of test data, derivative plot of pressure variation was introduced to identify data range for calculating hydraulic conductivity from obtained data.

Investigation techniques used/developed for the investigations of geological environment in Phase I (6/7)

Investigation techniques	Objectives, background, problems, etc	Findings, know-how and issues
Hydrochemical investigations	* Determine contamination rate due to mixing of drilling fluid into in-situ groundwater. * Groundwater could not be sampled from a section with fractures (fracture zone) in the deep borehole investigations at the Shobasama Site (MIU-1, 2 and 3). In these investigations, ground water sampling was planned to occur after completion of drilling to the target depth (1000 m). However during a large volume of drilling fluid (tens to hundreds of cubic meters) were injected to the rock mass and could not be decontaminated the drilling fluid. * To solve this a procedure was developed in which, when fluid loss is found, the drilling is stopped, and groundwater sampling will be conducted simultaneously with the pumping test aiming at reducing drilling fluid contamination. * Overcome the drawbacks of the water sampling method with a normal pumping test on the surface such as change in concentration of dissolved gas and physico-chemical parameters due to degassing during pumping. * To check wether there is disturbance of geological environment associated with borehole drillings.	* Add a tracer (fluorescent dye) in the drilling fluid and manage the concentration in constant during drilling. * Groundwater is then sampled when the concentration of the fluorescent dye is sufficiently low (aiming at $\leq$ 1% drilling fluid contamination) whereby the physico-chemical parameters, like as pH and electric conductivity, would no longer change significantly The groundwater chemistry (major components) and concentrations of fluorescent dye in the groundwater discharged during the pumping test are analyzed and measured on a regular basis.. In cases where the concentration of the fluorescent dye cannot be reduced sufficiently, the groundwater chemistry of the formation not contaminated by the drilling fluid can be estimated through extrapolation, based on the relationship between the concentration of the fluorescent dye and the groundwater chemistry.. * Monitor regularly the pH and electric conductivity of the drilling fluid during drilling. It will be necessary to exchange the drilling water when any sign of change in the fluid chemistry might be detected. * As a measure against changes in the concentration of dissolved gases and physicochemical parameter values, butch-type sampling bottle shall be inserted to the sampling intervals of the pumping test system to sample water under the in-situ pressure condition, or sample groundwater using dedicated sampling system after the pumping tests. * in order to acquire redox potential of the groundwater, it would be required to conduct prediction based on thermodynamic calculation on the redox reaction by redox reaction materials in the rocks and artificial redox reaction materials introduced underground during the borehole drilling, and to check for a redox reaction limiting phase that may have been introduced during drilling, and to check for the redox reaction limiting solid phases artificially introduced during borehole wall image surveys.
Initial stress measurement	* Develop a method that allows determining the magnitude and orientation of the 3D principal rock stresses without any assumption in calculation for borehole investigations. * To overcome water resistance, thermal resistance and handling difficulties. * Modify the conventional initial stress measurement method based on the existing stress relief technique to enhance its applicability for deep boreholes.	* The initial stress measurement system was developed that consists of a strain gauge cell and a cementing tool for measuring the strain at stress relief, a data logger for recording the strain at stress relief, a magnetic compass, an inclinometer and a power supply system (lithium battery). * With the adoption of a scheme that describes the sequence of processes, starting from the drilling of the pilot hole through the installation of the initial stress measurement system and to the overcoring for the wireline system, the efficiency of the measurement process was significantly improved. The applicability of the system to the deep underground was demonstrated at the Tono Mine. * The distribution of major discontinuities should be determined before planning the measurement work, because the initial stress states may vary significantly depending on the existence of discontinuities such as faults such as fault.
Modeling of geology/hydrogeology and groundwater flow simulation	* Develop support tools for the prompt modeling of geological environment.	* Integrated modeling and simulation system, GEOMASS（GEOLOGICAL MODELING ANALYSIS AND SIMULATION SOFTWARE）, was developed, which consists of software and analysis codes that are required for a series of tasks including geological and hydrogeological modeling, and groundwater flow simulation.

Investigation techniques used/developed for the investigations of geological environment in Phase I (7/7)

Investigation techniques	Objectives, background, problems, etc	Findings, know-how and issues
Quality control	* To continually improve the credibility of R&D results on geological disposal techniques and characterization of the geological environment,.	* It is important pay attention to transparency, traceability, openness and peer review for ensuring quality of the research results. * It would be required to anticipate potential events in advance and make provisions of measures against each of the events, to achieve the investigation objectives effectively and appropriately. * Implementation planning documents were formulated for the various investigations, such as borehole investigations and geophysical surveys following the action program. *The implementation planning documents defined work schedules, organizational structure, investigation/analysis methods to be employed, countermeasures against expected difficulties, and work procedures and checklists for quality control and safety assurance and also require the approval of the person in charge of quality control at the beginning of each investigation. * Since the work scope will vary for the borehole investigations, quality control plans were prepared for the investigation work according to the investigation program. * In the deep borehole investigations (borehole MIZ-1), plans were prepared for operations such as drilling, core logging, laboratory examinations on cores, investigations of borehole wall image, geophysical logging, hydraulic tests and analyses of well water, drilling fluid and pumped samples to ensure the quality of the results. * A review was provided by experts with experience in similar cases. * The PDPC（Process Decision Program Chart）was utilized.

Appendix 9

List of collaborative studies

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Cooperation with Universities and other Organizations (1/2)

Organizations and Sections		Title of Research	Outline of activities and results of the cooperation	Period
【University, Organization】				
Saitama University	Graduate School of Science & Engineering	Study on groundwater characterization: Development of comprehensive hydrological investigation and analysis system	As part of the study for development of comprehensive hydrogeological investigation and analysis system, preliminary studies on water balance on the ground surface were conducted, which indicated the effectiveness of the analysis technique based on a artificial neural network model in determining the water balance and evaluating correlations among surface monitoring data.	1996-1999
	Geosphere Research Institute	Study on characterization of groundwater flow: Development of a modeling technique using groundwater monitoring data	For the development of utilization method of groundwater monitoring data for the development of a hydrogeological model, the groundwater monitoring data was analyzed based on an artificail neural network model, which indicated the feasibility of determining correlation among monitoring data and estimation of hydrogeological zone based on the correlation. Artificial effects on the monitoring data can also be quantitatively evaluated.	2000-2002
Kyoto University	Department of Synthetic Chemistry and Biological Chemistry, Faculty of Engineering	Study on the effects of microbial on deep underground environment: (2)Analysis of microbial ecosystem and its material circulation system in the deep underground	To investigate the roles of micobes deep underground in sedimentary rock formation and granite in the Tono area, enzymes produced by the microbial were analyzed based on a DNA analysis technique. As a result, microbe activity involving in the formation of reducing environment could be extracted, and enzymes produced during the course of their metabolism identified.	1998-1999
Hiroshima University	Department of Applied Biological Science, Faculty of Applied Biological Science	Study on the effects of microbial on deep underground environment: (1) diversity of microbial ecosystem and their functions in the deep underground	For the groundwater in the sedimentary rock formation (Mizunami Group), quantity of microbes present in the ground water was measured to determine roles of microbes deep underground. The result indicated that there is a correlation between the presence of particular types of microbial (sulfate-reducing bacteria, and iron-oxidation, reducing bacteria) and hydrochemical characteristics of the groundwater.	1998-1999
	Department of Applied Biological Science, Faculty of Applied Biological Science	Study on the effects of microbial on deep underground environment: Species of underground microbial communities and diversity of metabolism	For the groundwater in the granite (Toki Granite), quantity of microbes present in the ground water was measured to determine roles of microbes in the deep underground environment. The result indicated that there is a correlation between the presence of particular types of microbial (sulfate-reducing bacteria, and iron-oxidation, reducing bacteria) and hydrochemical characteristics of the groundwater. A method for sampling specimens for the studies on microbial using rocks was established for the sedimentary rock formation (Mizunami Group) and granite (Toki Granite).	2000-2002
Tohoku University	School of Engineering	Evaluation of fracturing mechanism in the solidification and fixation processes of magma and permeable fractures	For granitic rock mass formed in different era, anisotropy of joints was investigated based on field surveys and laboratory tests (measurement of elastic wave velocity). The results indicated that the orientation of fractures is consistent with that of joints distributed on the outcrop, the anisotropy of the elastic wave velocity shows a good consistency with that of joint plane and micro cracking, suggesting that joint structures and development level of joint plane could be evaluated based on the anisotropy of the elastic wave velocity.	2000-2002
	Graduate School of Environmental Studies	Development of monitoring technologies based on clinometers	Change in the dip on the ground surface associated with the excavation of tunnels was measured using an inclinometer that could measure minute inclination in the order of nano-radian to develop a technology for estimating hydrogeological structure that could affect on the groundwater flow based on minute inclination data measured on the ground surface. The result of inverse analysis using inclination data obtained to date indicated that obtained zones where the ground water is increased or reduced are consistent with the hydrogeological structure identified/predicted in the studies to date, suggesting the effectiveness of this technique in predicting the hydrogeological structure.	2005-

Cooperation with Universities and other Organizations (1/2)

Organizations and Sections		Title of Research	Outline of activities and results of the cooperation	Period
University of Tokyo	Laboratory for Earthquake Chemistry, Graduate School of Science	Development of geochemical study methodology based on strontium isotopes and rare gases	For sedimentary rock formations and granitic rocks in the Tono area, isotopes of strontium and rare gases were measured to estimate the origin and chemistry formation processes of the groundwater. The result indicated that origin of the ground water was meteoric water in the past and that water-rock interaction was the major process to form the chemistry of the groundwater.	2001-2003
Hokkaido University	Division of Earth Science, Graduate School of Environmental Science	Study on chemical characteristics of organics in the natural environment	A method was developed in which organics in the groundwater were segregated based on their molecular size, and concentration of metal ions were quantitatively analyzed for each segregated solution, to acquire preliminary data on the complexation with metal ions. The result indicated that the analysis of polymer compound based on the 3-D fluorescence spectrum and analysis of low-molecular organics composition based on the fast ion-chromatography would be effective as a method to preliminary determine organics that constitute the humin in the groundwater and their structural features, and that the concentration of solution for each molecular size with reverse osmosis membrane utilizing groundwater pressure would be effective and easy method as a concentration method of natural origin organics.	2002-2004
Waseda University	Graduate school of Education	Preliminary study on analysis of stress field due to micro cracking using a luminoscope: Reconstruction of paelostress field based on quasi-three dimensional analysis of healed microcracks developed in the granite - Case study for Awaji-Nojima Granite	In order to develop technologies to reconstruct paelostress field, healed microcracks were measured three dimensionally and fluid inclusions were measured for the Toki Granite. The result indicated that axis of the principal stress when the healed cracks were formed was oriented in the N-S direction, and that the formation period was 70-60 Ma, which is consistent with the movement direction of the plate at that time considering the revolution of south western Japan due to expansion of the Japan Sea. Thus the method developed in this study would be effective in the reconstruction of the paelostress.	2003-2005
【Other organization】				
New Energy and Industrial Technology Development Organization	Institute fro Geo-Resources and Environment	Study on advanced rock stress evaluation method using cores	For the AE method and DRA method, effect of time period between sampling of cores and measurement of the initial stress on the measurement results were determined quantitatively to develop an advanced rock stress evaluation method using cores. The result indicated that variability of the measured values were larger for larger time period, and the reason for that will need to be investigated in the future.	2004-2006
【Oversea organizations】				
SNL, USA		Development of site characterization techniques	Activities relevant to the development of site characterization techniques include analysis for predicting fracture density distribution based on geostatistical approach aiming at establishing a method to evaluate correlation between quantity of data and prediction results, development of prediction method of the distribution of hydraulic conductivity along the boreholes based on the artificial neural network model, and study on evaluation of uncertainties associated with the hydrogeologicalconceptual model.	1999-2002
NAGRA, Switzerland		Support for planning URL programs	Technical support were provided for the URL projects in terms of formulation of overall program, and planning, implementation and compilation of the results of deep borehole investigations.	2001-
KAERI, Korea		Development of investigation technologies on geological environment	As part of development and utilization of in-situ investigation method and modeling techniques to characterize hydrogeology and hydrochemistry of the groundwater in the granite, general information exchange, technical discussion and staff exchange were made between URLs in both institutes (MIU and Korean URL).	2004-

Appendix 10

Glossary

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Safety assessment

The impacts of the geological disposal system on human health and the environment are analyzed based on predictions of the future behavior of the system and the results are compared with safety criteria defined using appropriate indicators such as dose in order to determine whether the disposal system is acceptable in terms of its safety. The series of analyses conducted as part of the safety assessment is called the safety analysis.

Excavation Disturbed Zone (EDZ)

When excavating a tunnel in rock, the mechanical properties of the rock, the deformation characteristics, hydraulic properties such as hydraulic conductivity and hydrochemical properties such as the redox potential of groundwater could be changed due to the generation and propagation of fractures, changes in stress conditions and changes in pore pressure. The zone where these changes are expected is called the excavation disturbed zone (EDZ). The EDZ consists of three sub-zones: the excavation damaged zone where rock properties are degraded due to microcracks, the unsaturated zone where pore pressure is decreased and hydrochemical conditions may be changed and the stress redistribution zone where stress conditions may be changed and existing fractures may be opened or closed.

Salinity

Quantity of dissolved substance in one kilogram of groundwater or seawater expressed in grams. The salinity of seawater in the open sea is 35 grams on average, which is denoted as 35 $^{0}/_{00}$.

Preliminary investigation areas

Areas selected by NUMO from the volunteer areas (based on literature surveys), where investigations from the ground surface (preliminary investigations) will be conducted. These will include borehole investigations, surface reconnaissance and geophysical surveys.

Lower sparsely fractured domain

A rock zone with sparsely distributed fractures dipping at low angles (0-30 degrees) in the Toki Granite, which is covered by the Mizunami Group; one of geological structural zones defined during the studies of granite by the Tono Geoscience Center.

Redox potential

A quantitative measure for the oxidizing strength of an aqueous solution. Equilibrium electric potential of the redox electrodes.

Sorption

Reaction between solid surfaces and atoms, molecules or particles. Generally, sorption is understood to include both absorption (sorption occurring in the pore of a solid) and adsorption (sorption on the solid surface without pores). Sorption phenomena can be divided into chemical sorption based on forces comparable to those that produce chemical compounds (chemical bonding) and physical sorption based on weak intermolecular forces such as Van der Waals forces.

Upper highly fractured domain

A rock zone with relatively densely distributed fractures dipping at low angles (0-30 degrees) in the Toki Granite which is covered by the Mizunami Group; one of geological structural zones defined during studies of granite by the Tono Geoscience Center.

Hydraulic properties

Properties of groundwater relating to its flow characteristics, such as flow velocity and flow rate.

Detailed investigation areas

Areas selected by NUMO (based on the preliminary investigations), where more intensive geological characterization from the surface and investigations in underground research facilities (detailed investigations) will be conducted for the selection of a final repository site.

Fault

A fracture along which the rocks on both sides have undergone displacement relative to one another parallel to the fracture. The zone where most of the displacement in the fault occurs is called the fault core, which includes, in addition to single slip planes, unconsolidated fault gouge with abundant clay minerals, brecciated alteration zones or significantly hardened cataclastic zones. A zone with a network of geological structures (small faults, veins, fractures, cleavage and folds) formed secondarily along the fault core is called the fault damaged zone.

In this report, faults that have moved periodically within hundreds of thousands of years and are likely to be active in the future are called active faults and those that have moved in the era older than this and are unlikely to be active now and in the future are called geological faults.

Retardation

A phenomenon in which migration of substances such as radionuclides could be delayed due to reaction with rock matrix (e.g. sorption).

Hydrochemical properties

Chemical properties of groundwater, including chemical composition, pH and redox potential.

Geological environment

Underground environment from the perspective of geological disposal, that consists of rocks and associated groundwater.

Geological environment conditions

Conditions of the geological environment from the perspective of geological disposal. Two aspects can be highlighted: characteristics of rocks and groundwater (geological environment characteristics) and their long-term stability (long-term stability of the geological environment). The former includes hydrology and hydrochemistry of groundwater, thermal and mechanical rock properties and mass transport characteristics in the rock. The latter includes the likelihood of potential natural events (earthquakes/fault activity, volcanic/igneous activity, uplift/subsidence/erosion and changes in climate/sea-level) that could affect the properties of rocks and groundwater, and their consequences.

Geological environment model

A model visualizing (conceptualizing) the distribution of geology, groundwater properties and other rocks characteristics from the ground surface to the deep underground based on interpretation of existing information and information acquired from investigations. Depending on the objective of visualization and the information to be described, models are classified into geological models, hydrogeological models, hydrochemical models, rock mechanical models and mass transport models. There are two types: ones representing current conditions in the field at a certain point in time and the other representing the evolution of phenomena with time. These models are updated as information increases and are used as a tool for estimating the level of understanding of the geological environment as well as for predicting future conditions.

Geological model: Model representing the spatial distribution of geology and geological structures.

Hydrogeological model: Model representing the spatial distribution of hydraulic properties (see "hydraulic properties") such as hydraulic conductivity. The hydrogeological model will be used for numerical analyses to predict the evolution of groundwater flow with time (groundwater flow analyses). The hydrogeological model and the groundwater flow analyses are collectively termed the groundwater flow model.

Hydrochemical model: Model representing the spatial distribution of groundwater chemistry and its processes (e.g. mixing of groundwater with different chemistries and water-mineral-organism interactions). There are two types: those expressing the observed hydrogeochemistry on a conceptual basis and those expressing the observed hydrogeochemistry mathematically.

Mass transport model: Model representing mass transport phenomena (see "mass transport") and a simplified structure of the field where the transport phenomena occur. There are two types: those expressing mass transport on a conceptual basis and those expressing it on a mathematical basis,

Rock mechanical model: Model representing the spatial distribution of physical and mechanical properties and initial stress conditions. The rock mechanical model is used for numerical analyses to evaluate the effects of tunnel excavation.

Hydraulic gradient

The change in water pressure (more precisely, total hydraulic head) per unit distance of flow in a groundwater flow direction; one of the factors determining groundwater movement. Since groundwater flows from a point with high pressure to one with low pressure, the direction of the hydraulic gradient would be normal to the contour lines with the same pressure.

Natural analogue

Phenomena occurring in nature that demonstrate long-term evolution of systems in the past that are similar to geological disposal systems, such as the behavior of radionuclides after waste emplacement, corrosion/degradation of the engineered barrier.

Examples include volcanic glass from volcanoes, bronze vessels found in ancient monuments and old cast iron tubes buried in the ground (archeological analogues). Since these are similar to glass or metals to be used in the engineered barriers system, investigation of their long-term changes will allow identification of phenomena that can be expected to occur in the engineered barriers and the validity of their evaluation methods to be checked. In addition, features such as uranium mines that contain natural radionuclides can be used as natural analogue research locations for the geological disposal system as a whole.

Uncertainty

A state whereby the results of models developed based on data and knowledge are not determined conclusively. It can be represented as objective probability evaluated statistically or as subjective probability based on uncertain knowledge evaluated using other approaches.

Mass transport

Movement (or transport) of substances in the environment. It includes natural phenomena such as advection (transport of substances associated with the movement of fluid such as groundwater and air), diffusion (transport of substances from the point with high concentration of the substances concerned to points with low concentration) and sorption (see “sorption”), but not intentional movement by humans (e.g. transport of radioactive wastes).

Discontinuity

Generic expression for structural fractures in rock, which includes fractures, joints, planes of weakness and faults (zones). It may also include depositional surfaces and erosional surfaces. In this report, it is taken to mean mainly faults, joints and fractures. Faults and joints are distinguished based on the displacement parallel to the plane; features with displacement are termed faults, while those without displacement are termed joints. The term fracture is used as a generic term for faults and joints, or in cases where there is no clear distinction between faults and joints.

Water conduit

A water flow path when the groundwater flow is considered as a flow of water molecules connecting pore in the rock. In this report, it means water-conducting features as defined in the report by Mazurek (2000) as a strip-shaped zone with significantly higher transmistivity in rocks.

Rock burst

A phenomenon in which a portion of rock around a tunnel breaks open abruptly with a loud noise during tunnel excavation. It is considered to be caused by the release of elastic deformation energy excessively accumulated in the rocks mass being triggered by the tunnel excavation. It tends to occur when the rock is hard and massive with relatively low fracturing and with a large overburden or under high ground pressure.

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 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	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	キログラム毎立法メートル	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	$m^{-3}\ sA$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ sA$
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	$kg^{-1}\ sA$
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	接頭語	記号	乗数	接頭語	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=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=1l=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3\ kg$

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	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

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	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=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	
デジベル	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	$1\ sb=1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal=1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	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[(c)]	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) 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	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R=2.58\times10^{-4}C/kg$
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=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
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	1cal=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	$1\ \mu=1\mu m=10^{-6}m$

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