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Preface

This technical report provides a comprehensive presentation of the "Geoscientific Studies" performed since 1986, and new work for the "Earthquake Frontier Research for Terrestrial Subsurface" programme performed since 1995 in and around the Tono Mine, Gifu Prefecture.

This technical report also provides fieldstop descriptions for visits to the Tono Mine. The descriptions are attached at the end of this report.

1. Introduction

The Tono area, in Gifu Prefecture, contains Japan's largest uranium deposits. The Tono deposits are hosted by Neogene sedimentary rocks. A gallery has been constructed at a depth of 130m in the Tsukiyoshi deposit, the largest ore body in the Tono area. The deposit has not been exploited commercially, hence, the gallery enables observation of the ore body in a relatively undisturbed state.

The main objectives of the geoscientific studies in the Tono area are to provide sufficient information on the deep underground geological environment as a basis for performance assessment studies and development of methods for site characterization. To date, the measurements and experiments have been conducted in the main gallery, shallow boreholes (100m to 200m), deeper boreholes (200m to 1,000m) and shaft No.2, specifically designed and excavated for geoscientific study purposes. Besides these studies, instruments for hydraulic and geochemical measurements in the deep underground have been developed (PNC,1996).

Major geoscientific studies are under way in various fields such as;

(1) Hydrogeology
(2) Hydrogeochemistry
(3) Isotope chemistry of groundwater
(4) Nuclide retardation
(5) Mine-by experiments, and
(6) Development of instruments

The Tono Mine is also used for "Earthquake Frontier Research for Terrestrial Subsurface", performed by JNC. The "Earthquake Frontier Research for Terrestrial Subsurface" is one of the "Comprehensive Frontier Research for Earthquake", which was established in 1995 by the Science and Technology Agency (STA) for promotion of research on earthquakes, and which has been performed by several relevant institutes affiliated with STA. The "Earthquake Frontier Research for Terrestrial Subsurface" is divided into 3 categories. Two of them, namely, "Development of the ACROSS (Accurately Controlled Routinely Operated Signal System) for detecting microscale crustal movements" and "Studies of precursory and co-seismic changes in rock stress, water level and groundwater chemistry", have been performed at the Tono Mine.

2. Geology

The Tono area is situated in the eastern part of the "Inner Zone of Southwest Japan". It lies within the Cretaceous Ryoke granite complex near its boundary with Paleozoic and Mesozoic sedimentary rocks. A Series of Neogene to Quaternary basins were formed on this pre-Tertiary basement. Filling these basins are Neogene to Quaternary sedimentary rocks, which are stratigraphically divided into two groups, the Mizunami Group of Miocene age and the Seto Group of Pliocene age. The Tsukiyoshi fault intersects the Mizunami Group and is covered by the Seto Group (Fig.1). In this area, geological investigations, initially relating to uranium exploration, have been active since the 1960's and there is substantial information relevant to the geoscientific studies.

2. 1 Basement

The basement in the Tono area consists mostly of granitic rock and partly of the Mesozoic sedimentary formations. The age of granitic rock is considered to be about 68 Ma (Suzuki and Adachi, 1998). The granite lithologically consists of medium- to coarse-grained biotite granite and medium-grained hornblende-biotite granodiorite porphyry. Dyke rocks of quartz porphyry and aplite are found in the granitic body.

2. 2 Mizunami Group

The Mizunami group is divided into three formations. These are the Toki Lignite-Bearing Formation, the Akeyo Formation, and the Oidawara Formation, in ascending order.

2. 2. 1 Toki Lignite-Bearing Formation

The Toki Lignite-Bearing Formation unconformably overlies the basement and is partly unconformably overlain by the Akeyo Formation. This formation is extensively distributed over most of the Tono area. The basal part is a conglomerate mainly consisting of granitic clasts. The upper part of this formation consists mostly of sandstone and mudstone interbedded with lignite-bearing facies. The Tono uranium deposits are located in the lower part of this formation.

2. 2. 2 Akeyo Formation

The Akeyo Formation is mostly of volcanic derived sediments. The basal part of this formation generally consists of conglomerate, sandstone and muddy, fine-grained sandstone. Tuff beds are occasionally found and serve as key beds. The middle part is tuffaceous sandstone with abundant marine fossils. The upper portions of the formation consist of fine-grained to medium-grained sandstone and mudstone interbedded with several tuff beds.

2．2．3 Oidawara Formation

The Oidawara Formation, which is distributed mainly in the northern part of the Tono area, unconformably overlies the Akeyo Formation. The formation consists of siltstone and mudstone with some conglomerate in the basal part. The formation is considered to have originated from sediments deposited at greater depth compared with the Akeyo Formation. The characteristics of the Oidawara Formation reflect a rapid Miocene subsidence followed by an extensive marine transgression.

2．3 Seto Group

The Pliocene Seto Group unconformably overlies the Mizunami Group and the basement, and is distributed over the whole area. It consists of clay, siltstone, and conglomerate containing rhyolite and chert clastics. The clay is an important resource for the ceramics industry in the Tono area.

2．4 Ore deposit

The ore deposits in the Tono area are stratiform deposits hosted by the Toki Lignite-Bearing Formation. The thickness of the ore body ranges from 1 to 3m. The uranium mineralization occurs in coarse- to medium-grained sandstone and lignite-bearing tuffaceous sandstone. Uranium exists within a matrix consisting of pyrite, ilmenite, biotite, calcite, montmorillonite, and zeolite. Coffinite has been identified in some cases. The mineralization is considered to be related to the absorption effects of minerals such as biotite and iron-bearing minerals under a reducing environment (PNC, 1995). The age of mineralization, estimated by the Fission Track Method, is about 10 million years ago (Ochiai et al.,1989).

3. Geoscientific studies

3. 1 Hydrogeology

A comprehensive hydrogeological study programme in and around the Tono Mine is being carried out to understand the mechanism of groundwater flow from the ground surface to the deep underground and to develop hydrogeological investigation methodologies for characterization of groundwater flow.

As a part of this programme, the Shaft Excavation Effect project (SEE project) has been conducted at the Tono Mine. The objectives of the SEE project are to verify a numerical model for estimation of groundwater flow in sedimentary sequences cut by a fault, the Tsukiyoshi fault, and to develop a methodology for the characterization of groundwater flow through the prediction of shaft excavation effects. A new shaft (the No.2 shaft) with a diameter of 6m and a depth of 150m was excavated for the SEE project from January 1990 to May 1991.

The programme set up in this project to verify the characterization methods of groundwater flow is composed of the following four steps.

(1) The first step : data acquisition for understanding hydrological and hydrogeological conditions.

(2) The second step : development of a hydrogeological model.

(3) The third step : prediction of the shaft excavation effects.

(4) The fourth step : validation of the model by comparing predicted and measured results.

Some modification of the model might be required to make an acceptable agreement between the results of the simulation and measurement in the final step.

In the first step, subsurface and borehole investigations have been conducted to understand the hydrological and hydrogeological conditions in the study area, 300m by 300m around the No.2 shaft. The subsurface hydrological investigations consist of observations of meteorological parameters, soil moisture contents, discharge rates and water table levels. The recharge rate into the rock mass from the unconsolidated layer near the ground surface was estimated to be 0.57 mm/day from the results of the subsurface hydrological investigations, May 1989 to April 1990. The borehole hydrogeological investigations include piezometric head measurements and hydraulic tests to determine hydraulic conductivity. Piezometric head monitoring systems, the MP system, were installed in 10 boreholes around the No.2 shaft (Fig.2). Piezometric head distributions imply that the Tsukiyoshi Fault has low conductivity and acts as a hydraulic barrier. Hydraulic conductivity of the sedimentary rocks and the granitic basement ranges from 10^{-5} to 10^{-8} cm/sec and from 10^{-6} to 10^{-9}cm/sec, respectively. The subsurface hydrological investigations has been continued for about 10 years (started on September 13th, 1989).

In the second step, a hydrogeological model has been developed based on the data from field investigations conducted in the first step. The model is composed of 12 horizontal hydrogeological units (Fig.3).

In the third step, computer simulation has been conducted to predict the shaft excavation effects on groundwater flow using a finite element method (FEM) code, TAGSAC, that can handle steady state and non-steady state flow for both saturated and unsaturated conditions. The equations employed in this code are based on a combination of Darcy's law and the continuity equation. Boundary conditions chosen were based on the measured piezometric head distribution. The recharge rate is set as 0.57 mm/day. A free seepage surface condition is also set for the upper surface of the model. The initial conditions were determined based on preliminary calculations of the groundwater flow around the existing shaft and gallery. The piezometric drawdown caused by the shaft excavation and the inflows into the No.2 shaft, the existing shaft and gallery was predicted during and after the shaft excavation.

The predicted results are as follows:

(1) The extent of the piezometric drawdown by the No.2 shaft excavation is within approximately 100m from the No.2 shaft, 1,000 days after shaft excavation .

(2) The maximum inflow into the No.2 shaft is approximately 15 liters per minute at the final excavation stage.

In the fourth step, comparison between simulated and measured results has been conducted to validate the hydrogeological model. Fig.4(a) and (b) indicate that the decrease in the piezometric head becomes smaller with increasing distance from the No.2 shaft and that the simulated results show good agreement with the measured values. Fig.5 shows that the transient behaviors of predicted and measured inflow into the No.2 shaft and the existing shaft and gallery are of similar magnitude and trend (Yanagizawa et al, 1992). From these comparisons, the predicted result is considered to be correct.

Through the SEE project, the applicability and validity of the investigation, modeling and simulation methods used in this project were confirmed, and it was demonstrated that the programme set up for the validation of characterization methods of groundwater flow was very useful.

3. 2 **Hydrogeochemistry** (Ota and Seo, 1991 ; Hama et al., 1992)

Groundwater samples were collected from boreholes in the Mizunami Group and the Toki granitic basement (Fig.6). The physico-chemical characteristics of groundwater, such as pH, Eh, electric conductivity and temperature, were measured immediately, under an argon atmosphere, prior to the chemical analyses.

The chemical properties of the surface water and groundwater from the Seto Group are evidently different from deeper groundwater. Groundwater in the Seto Group has a relatively low concentration of dissolved ions, electric conductivity (30-50 μ s/cm) and pH ranges from 6 to 6.5. Groundwater in the Mizunami Group and the Toki granitic basement shows relatively high concentration of dissolved ions and high electric conductivity (120-280 μ s/cm) with a pH ranges from 7 to 9.5 (Fig.7). The geochemical composition of groundwater also changes with depth from Na^{+}-Ca^{2+} HCO_3 type to Na^{+}-HCO_3 type.

The geochemical conditions within the ore body zone have also been investigated. Groundwater samples from this zone in the Toki Lignite-Bearing Formation were collected and physico-chemical parameters of the groundwater were measured continuously under in-situ conditions in a gallery. Measured values show that the Eh value is –300mV and that the uranium content ranges from 0.06 to 0.10 ppb.

In order to understand the chemical evolution of the groundwater, thermodynamic calculation and the water-rock interaction experiment have been carried out. The chemical composition of groundwater in the sedimentary rocks is within the Ca-montmorillonite stability field. Using an average value of $\log[H_4SiO_4]$:-3.05, the activity ratios are also plotted. The boundary between Na- and Ca-montmorillonite stability field on a $2pH+\log[Ca^{2+}]$ vs, $pH+\log[Na^{+}]$diagram, has a slope of 2:1.

An experiment to study a water-rock interaction with crushed. rock samples from the Toki Lignite-Bearing Formation and groundwater sample from the Akeyo formation (Na-Ca-HCO_3 type) was conducted. The results indicate that the Na concentration in the solution increased while Ca concentration decreased and these concentrations reached a steady state within the time frame of the experiment. The total cation equivalence of the solution in the experiment was almost equal to that of the initial groundwater sample.

The results from the thermodynamic calculation and the water-rock interaction experiment indicate that ion exchange reactions between clay minerals and groundwater and dissolution of feldspar are dominant reactions in the chemical evolution of groundwater in the Tono area.

3. 3 Isotope chemistry of groundwater

Measurements of isotopes in the groundwater have been conducted to investigate the origin, movement and residence time of groundwater. Some groundwater samples were collected from the surface and other samples from wells drilled into the uranium ore zone and the granitic basement.

3. 3. 1 Stable isotope

$\delta^{18}O$ and δD (deuterium) values for all water samples plot between the local meteoric water line of the central part of Japan ($\delta D = 8\delta^{18}O+20$, Waseda and Nakai,1983) and the global meteoric water line ($\delta D = 8\delta^{18}O+10$, Crag,1961) as shown in Fig.8. This indicates that all of groundwater at the Tono area is of meteoric origin. The $\delta^{18}O$ and δD values of groundwater in the Seto group are similar to those of present day rainwater. On the other hand, these values of groundwater in Mizunami Group are lower than those of present day rain water. The low $\delta^{18}O$ value of the groundwater in the lower part of the Mizunami Group indicates that the groundwater was derived from higher elevations, or the then average air temperature ranged from 11°C to 12°C, whereas the present day average temperature of the Tono area is about 14°C (Yurtsever, 1975).

3. 3. 2 Tritium

^{3}H (tritium) contents in groundwater from the Mizunami Group are less than 1 Tritium Unit (Fig.9) indicating that groundwater in the sedimentary rocks has been isolated from the surface water for at least 40 years (Waseda and Nakai, 1983). The groundwater in the Seto Group shows similar ^{3}H contents as present day rain water.

3. 3. 3 Carbon-14

Dissolution of carbonate minerals or oxidation of organic matter within the aquifer increase “dead” (no detectable ^{14}C) carbon in the groundwater, giving an erroneous age. In the case of the Tono area, raw ^{14}C age of groundwater was corrected in terms of $\delta^{13}C$ value and total dissolved carbonate content. The corrected ^{14}C ages of groundwater in the lower part of the Mizunami Group range from 13,000 to 15,000 years. These ages correspond to the late Würm glacial stage, at which time the air temperature was lower than that of the present (Seo et al., 1992).

3. 4 Nuclide retardation

The retardation of ^{238}U-decay series (^{238}U, ^{234}U and ^{230}Th) has been studied at the Tono Mine. Microscopic pore-space geometry and chemical retardation have been characterized in detail to understand nuclide retardation in the sedimentary rocks under reducing conditions.

In order to characterize pathways for ^{238}U-decay series retardation in the sedimentary rocks, microscopic examinations combined with resin impregnation of the rock specimen have been made. In addition, observations using cathodoluminescence have been made to confirm whether minerals were contributing to uranium retardation.

The detailed microscopic examination revealed that a three-dimensionally interconnected network made up of three types of pore-spaces is present in the sedimentary rocks.

(1) microfractures in detrital grains (Fig.10a)

(2) cleavages of sheet silicates (Fig.10b)

(3) micropores in the matrix (Fig.10c)

These types of pore spaces have diameters between 0.1 and 10 μm (Yoshida, 1994; Yoshida et al, 1994a). Since idiomorphic calcite has been crystallized in the microfractures and in the matrix pores and pore-spaces have been also impregnated with the resin, pore-spaces of type (1) to type (3) are thought to have functioned as pathways for solute transport. Uranium is distributed along the pathways mentioned above (Fig.10a,b,c). In addition, a zone showing luminescence under UV light was recognized along the microfractures within quartz grains and at the margins of the grains in the matrix, indicating that the above three types of pore-spaces were accessible to uranium retardation (Yoshida, 1994; Yoshida et al., 1994b).

In order to assess chemical retardation processes in the microscopic pore-spaces described above, detailed petrological and radiochemical investigations with batch sorption experiments have been carried out on rock/mineral samples.

Batch sorption experiments using ^{233}U as a tracer show that the uranium-sorbing ability of rocks with low uranium concentrations is 2 orders of magnitude greater than that of rocks rich with high uranium concentrations (Yoshida et al, 1994a). There may be a large volume of uranium sorption sites still remaining in rocks with low uranium concentrations while rocks with high uranium concentrations may no longer have the ability to sorb uranium, probably due to the saturation of their uranium sorption sites. Uranium concentration is associated with common rock-forming minerals : along the cleavages of biotite (Fig.11a), around framboidal pyrite (Fig.11b), inside altered ilmenite (Fig. 11c), in sericitized plagioclase and on the surface of lignite (Yoshida et al., 1994a,c). Such sedimentary rocks have, however, the higher ability to take up uranium, which has been experimentally defined. Heterogeneity in uranium concentration may be due to differences in their hydraulic properties. Hydraulic conductivity of the high uranium-concentrated zone is actually 2 to 3 orders of magnitude higher than that of the low uranium-concentrated zone, suggesting that natural uranium has concentrated preferentially in permeable zones (Yoshida et al., 1994a).

In addition, studies on ^{238}U-decay series disequilibrium show that the whole rock is in a chemical equilibrium state (Fig.12), indicating that the rock has not suffered uranium accumulation/leaching processes. In the sedimentary rocks, reducing conditions might have been maintained for, at least, the past several hundred thousand years (Yoshida et al., 1994a,b).

In summary, in the Tono uranium deposit, since very slow groundwater movement and reducing conditions have governed chemical retardation of ^{238}U-decay series (Yusa et al., 1993; Yoshida, 1994), uranium has been well preserved for, at least, the past several hundred thousand years, in spite of tectonic disturbances such as faulting and uplift. This suggests that rock formations could retain redox-sensitive radionuclides for geologically long periods of time, so long as the ambient hydrogeological and geochemical environments are maintained (Yusa et al., 1993).

3. 5 **Mine-by experiments** (Sugihara et al.,1999)

The objectives of the in-situ experiments on excavation disturbance in the Tono mines are to characterize the excavation disturbed zone (EDZ) and to develop investigation methods for characterizing the EDZ.

Here, the EDZ is defined as the rock zone where rock properties and conditions are changed due to excavation. Fig.13 shows the conceptual model of the EDZ developed for the study. The EDZ is assumed to be an overlapping combination of three zones, namely, excavation damaged zone, unsaturated zone and stress-redistributed zone.

In the NATM drift, the first drift was excavated with the drill and blast method in 1989 while the second drift was excavated with mechanical excavation with a boom header in 1995 (Fig.14). The No.2 shaft was excavated with the drill and blast method from 1990 to 1991. During these excavations, experiments on excavation disturbance were carried out, so two types of excavation disturbance have been studied in the Tono mine. (The study of hydrological disturbance due to shaft excavation is described in 3.1).

3. 5. 1 **Experiment in the NATM drift** (Sugihara et al., 1998 ; Hirahara et al., 1999)

New drifts (test drifts) were excavated using blasting and an excavation machine called a boom header, to estimate the effects of different excavation methods on excavation quality. The test drifts have a horseshoe shaped cross-section and were supported by the shot concrete and rock bolts.

The following research activities were carried out for the experiments in the NATM drift.

(1) Before the excavation
   Rock stress measurement

(2) During the excavation
   Geological observation of the excavation face, convergence measurements, rock mass displacement measurements, excavation vibration monitoring and rock strain monitoring

(3) Before and after the test drift excavation
   Borehole expansion test, hydraulic test and seismic tomography survey

(4) After the excavation
   Seismic refraction survey, fracture observation on niche surface, numerical simulation considering the extent and rock property in EDZ with two-dimensional finite element method (2-D FEM)

Fig.15 and Fig.16 show the layouts of drifts and boreholes in blasting and mechanical excavation experiments, respectively. The tests and survey before and after the test drift excavation were performed in precisely the same locations in the boreholes for measuring changes in rock properties. The seismic refraction survey was performed along the wall of test drifts after the excavation. Fracture observations in the excavation damaged zone were performed on the face of two triangular niches excavated from the walls of Test Drift-2M and Test Drift-1.

Table 1 summarizes the rock properties and spatial extent of the EDZ detected in the NATM drift. The results of the experiments on excavation disturbance in the NATM drift are summarized as follows:

(1) The EDZ induced by blasting excavation had a width of about 0.8m and a P-wave velocity of 50 ~ 60% of that of the intact rock. Hydraulic conductivity increased over one order of magnitude within 1.4m from the drift wall.

(2) The EDZ induced by mechanical excavation had a width of about 0.3m and a P-wave velocity of 65 ~ 70% of that of the intact rock. Hydraulic conductivity did not change in the rock mass within 0.3 ~ 0.5m from the wall of Test Drift-2M.

(3) Maximum particle velocity induced by mechanical excavation is one order of magnitude smaller, compared to that induced by blasting excavation.

(4) The rock displacements around the Test Drifts calculated by elastic-plastic analysis with 2-D FEM correspond 'with the measured rock displacements. It suggested that the quantitative estimation of in-situ rock stress condition and the EDZ were important for accurate simulation of rock mass displacements around drift.

3．5．2 Experiment in the No.2 shaft (Sugihara et al., 1993)

The No.2 shaft has a diameter of 6m and a depth of about 150m. The shaft was excavated by the drill and blast method and was lined with a 40cm thick concrete wall. The shaft penetrates the Tsukiyoshi fault at about 120m below the ground surface.

Three categories of measurement were made: displacement, stress and rock properties. Fig.17 shows the layout of measurement sections and boreholes for this study.

As examples of the results, Fig.18 and Fig.19 show the rock property changes at the B section and the measured and simulated variations in strain at the C section, respectively. The results of the experiment in the No.2 shaft are summarized as follows:

(1) The pattern of displacement was not uniform and was strongly influenced by the presence of discontinuities such as a fault and fractures.

(2) Variations in rock properties were detected in rocks within about 1m of the shaft wall.

(3) The strain variation during the shaft excavation in the vicinity of the Tsukiyoshi fault was measured. The numerical analysis with 2-D FEM could simulate the strain variation in the foot wall of the Tsukiyoshi fault qualitatively, but could not simulate the strain

variation in the hanging wall of the Tsukiyoshi fault. The reason was considered to be a difference of the fracture frequency in hanging wall and foot wall of the Tsukiyoshi fault (Yoshioka et al., 1993).

(4) Seismic tomography roughly detected natural stratified structure at a large scale and the low velocity zone induced by excavation around drift, but failed to detect the fault (Sugihara et al., 1992).

4. Earthquake Frontier Research for Terrestrial Subsurface

4. 1 Development of the ACROSS for detecting microscale crustal movements

In order to clarify the mechanisms of large-scale earthquakes, which occur at plate boundaries, a new geophysical prospecting system has been developed. It is called ACROSS (Accurately Controlled Routinely Operated Signal System), which is aimed to monitor crustal movements and also investigate accurate structures in the solid Earth (JNC, 1998).

The ACROSS system consists of three essential factors; (a) transmitter, (b) receiver and (c) data analysis method. The hardware is composed of mutually synchronized source and receivers. The transmitting signal is generated with rotating eccentric mass, and make it possible to radiate the controlled and coherent sinusoidal signal. The receiver repeatedly stacks seismic data in every constant time length. This stacking technique makes it possible to analyze the signals in limited frequency bands with high signal-to-noise ratio. The GPS clock used for the synchronization enables us to obtain an accurate transfer function between the transmitter and receiver in frequency domain. A transmitting station is located at the Tono Mine (Fig.20).

This system is capable of continuous operation for various purposes. One of the most interesting targets is to detect the temporal variation of elastic wave velocity in the seismic region. By continuous monitoring of microscale crustal movements, it is possible to investigate the crustal structures along the plate boundary below the Tono mine, and examine precursory phenomena and earthquake mechanisms' activity. Basic concepts and several achievements by this system are summarized in JNC Report 1998.

4. 2 Studies of precursory and co-seismic changes in rock stress, water level and groundwater chemistry

Earthquake-related changes in groundwater-levels and pore pressures have been observed in some wells around the Tono Mine (King et al., 1999). Groundwater conditions in the Tono area, and particularly the Toki granitic basement are sensitive to large earthquakes (e.g., Fig.21). Some characteristics of these changes are as follows.

(1) Co-seismic drops of groundwater-levels were often observed in Toki Granite, Mizunami Group and Seto Group.

(2) Post-seismic rises of groundwater-levels and pore pressures were sometimes observed for about a week to a month in Toki Granite and in the lower part of the Mizunami Group. The change in the Mizunami Group was later and smaller than the one in the Toki Granite.

(3) There was a difference in the post-seismic rise between the north side and the south side of the Tsukiyoshi fault. The rise on the south side was smaller than that on the north side. On the other hand, there was no remarkable difference in steady tidal change between either sides.

Co-seismic drops of groundwater-levels seen in the Toki Granite (at SN-3) and in sedimentary rocks overlying the Toki Granite (at SN-1) appear to be correlated with earthquake magnitude and epicentral distance, as observed in some previous studies (e.g., Roeloffs, 1998). That suggests the drops might relate to the change of the corresponding co-seismic strain. However, the amplitude of the drops is too large to be caused by the strain change. Furthermore, all the piezometric level-changes were reductions, in spite of strain changes due to tension or compression. Thus, the drops might be caused mainly by local changes of permeability only around observation wells.

Post-seismic rises of groundwater-levels and pore pressures were larger in amplitude and longer in term than the co-seismic drops. Earthquake-related strain changes were too small and short to explain the post-seismic changes. The rises spread from the Toki Granite to the overlying sedimantary rocks. One hypothesis to explain this spread is that post- or co-seismic pore-pressures rise like a step function and might originate at depth in the crust, and then might spread to upper formations along some interconnected water passage, to the Tono region. It is necessary to monitor pore pressures at deeper region in order to prove this hypothesis.

TGC's previous studies clarified that the Tsukiyoshi fault divided the groundwater system into two (north and south) sides under the Tono area. This characteristic might cause the different response to earthquakes between the north side (SN-1, SN-3 and TH-8) and the south side (TH-7) (PNC, 1996).

To accumulate the basic knowledge of mechanisms and relationships among earthquakes, the above mentioned groundwater behavior, crustal strains, and emitted gases such as radon and hydrogen, some instruments were set-up in the gallery of the Tono Mine. Borehole instruments, namely strainmeters, tiltmeters and accelerometers, were set into a borehole for observations of crustal activity. A monitoring instrument on water-chemistry (pH, Eh, temperature, electrical conductivity) was set-up in a borehole across the Tsukiyoshi fault. Eight instruments to monitor radon gas emitted from the gallerywalls and groundwater, were set-up in the gallery. A quadropole mass spectrometer (QMS) was set-up in the gallery for continuous observations of the atmosphere in the Tono Mine.

5. Description of fieldstops (Fig.22,23)

Stop 1: Monitoring room

To monitor the steady state and earthquake-related changes, observations of water-quality, radon gas, atmospheric gas, crustal stress, etc. has been ongoing in the gallery. Water-quality from the unconformity on the north side of the Tsukiyoshi fault is measured in the vicinity of the ventilation shaft. Radon gas emitted from the gallerywall and groundwater is measured in the vicinity of the monitoring room, on upper and lower measurement drifts, in the vicinity of the ventilation shaft and so on. Atmospheric gases are continuously sampled from the main ventilation fan of the Tono Mine, and measured by QMS in the monitoring room. Stress, tilt and earthquakes are measured by the borehole instrument in a borehole in the vicinity of the monitoring room. All the data are continuously monitored and logged in personal computers or data loggers in this room.

Stop 2: Unconformity

At the unconformity between granite and the sediments, an exposure of highly-weathered, medium-grained biotite granite can be observed. The age of the granite is estimated to be approximately 68 million years (Suzuki and Adachi, 1998). Above the unconformity lies a Neogene lacustrine conglomerate consisting of pebbles and boulders of granite and lesser amounts of quartz porphyry and chert.

Stop 3: Measurement of redox potential (Iwatsuki and Yoshida, 1998)

Groundwater samples from the Toki-Lignite Bearing Formation and Toki Granite were taken and physico-chemical parameters of the groundwater were measured continuously under in-situ condition.

The results of these measurements are as follows.

(1) Toki Lignite-Bearing Formation :

pH : 9.6 ± 0.1, Eh : -300 ± 10mV, type : $Na\text{-}HCO_3$

(2) Toki Granite

pH : 8.2 ± 0.1, Eh : 0 ± 10mV, type : $Na\text{-}Ca\text{-}HCO_3$

Stop 4: Seismic data station

Eight seismographs are located along the gallery in the Tono mine. At this station we collect data from these seismographs, which are synchronized with a GPS clock, accurate to 1 micro-sec of UTC. The data is processed to detect coherent signals and directivity of the in-coming waves. This system works continuously and collects ground motions caused by the ACROSS source and natural earthquakes. The analyzed data are used to study crustal activity in Tono area in real time.

Stop 5: Uranium showing

The uranium minerals are hosted by sandstone and conglomerate. The uranium is concentrated by sorption on clay minerals, lignite and iron-containing minerals such as biotite, ilmenite and pyrite. The ore grade reaches up to 0.1% U_3O_8 in this showing, while average grade of the entire deposit is 0.05% U_3O_8. Secondary minerals such as andersonite and zippeite are also formed on the drift wall due to oxidation reactions with the air. Uranium-series (^{238}U, ^{234}U and ^{230}Th) disequilibrium study suggests that uranium-series nuclides have not migrated significantly on a scale of a few meters.

Stop 6: In-situ experiment of excavation disturbance around a drift

New drifts (test drifts) were excavated from an existing drift about 139m below the surface using blasting or mechanical excavation to estimate the effects of these different excavation methods on excavation disturbance. The average uniaxial compressive strength of the rock is about 8MPa. The boreholes for the measurements were basically drilled into each test drift before the excavation. The measurements for the rock properties changes were carried out at the same locations in these boreholes, before and after excavation, to avoid the effect of inhomogeneousness of rock.

Stop 7: Fault

The Tsukiyoshi Fault strikes E-W and dips about 60° to 70° S. It is a reverse fault with a vertical displacement of 30m. The Mizunami Group is faulted, but the Seto Group which unconformably overlies the Mizunami Group shows no displacement.

Stop 8: In-situ experiment on excavation disturbance around a shaft (Shaft Excavation Effect Project)

The No.2 shaft has a diameter of 6m and depth of 150m. The shaft was excavated by drill and blast method, and has a 40cm wide concrete linear. The shaft intersects the Tsukiyoshi fault at 120m below the surface. The procedure for in-situ experiments in the shaft is the same as the in-situ experiments in a drift. The results basically correspond. The Tsukiyoshi fault, a major discontinuity, can influence rock deformation around the shaft. Rock displacement around the shaft was simulated qualitatively by 3-D FEM analysis. The space in shaft is also used for the micro gravity experiment.

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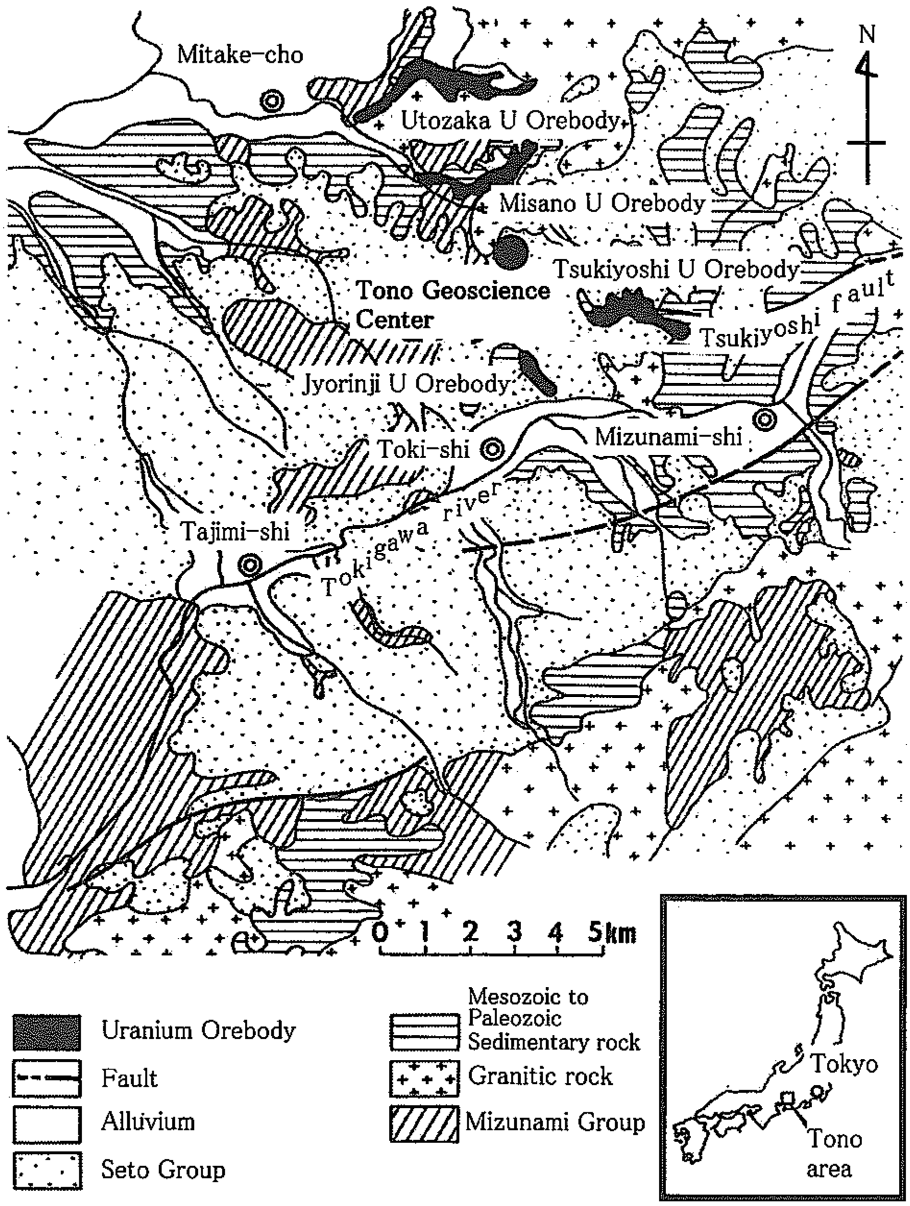


Fig. 1 Geological map of the Tono area

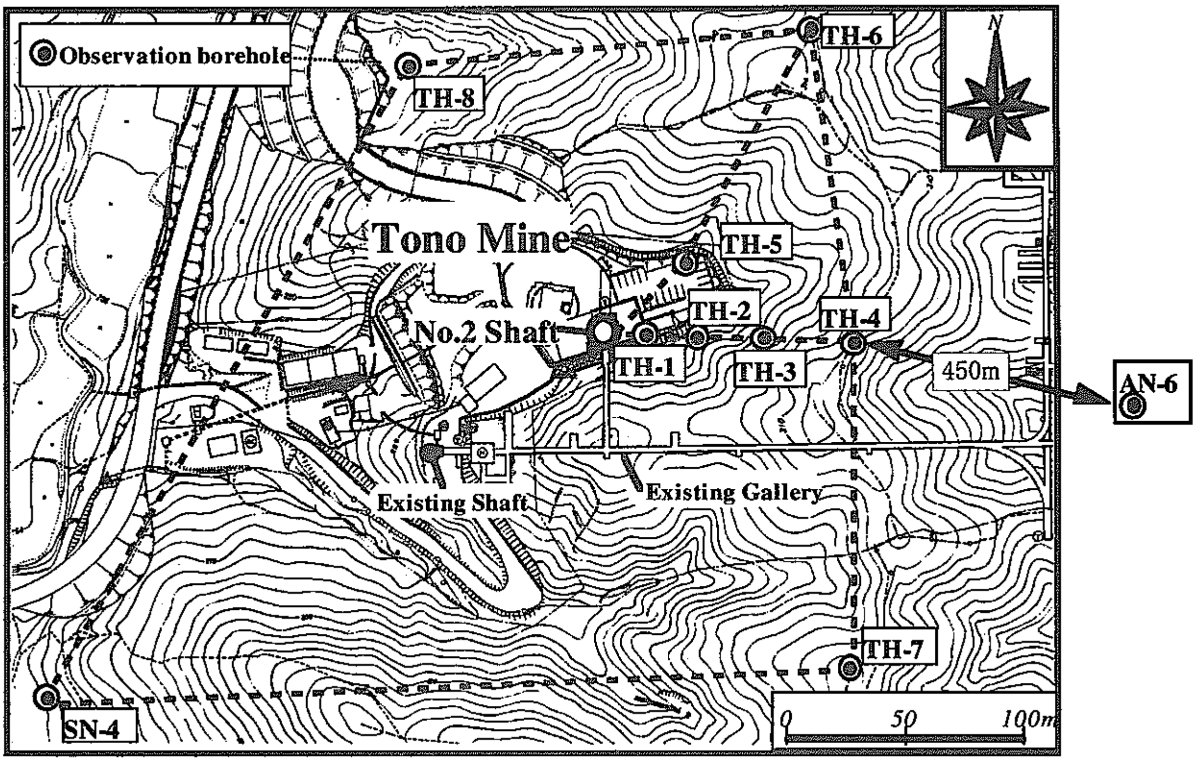


Fig. 2 Location map of boreholes for long-term piezometric head observation.

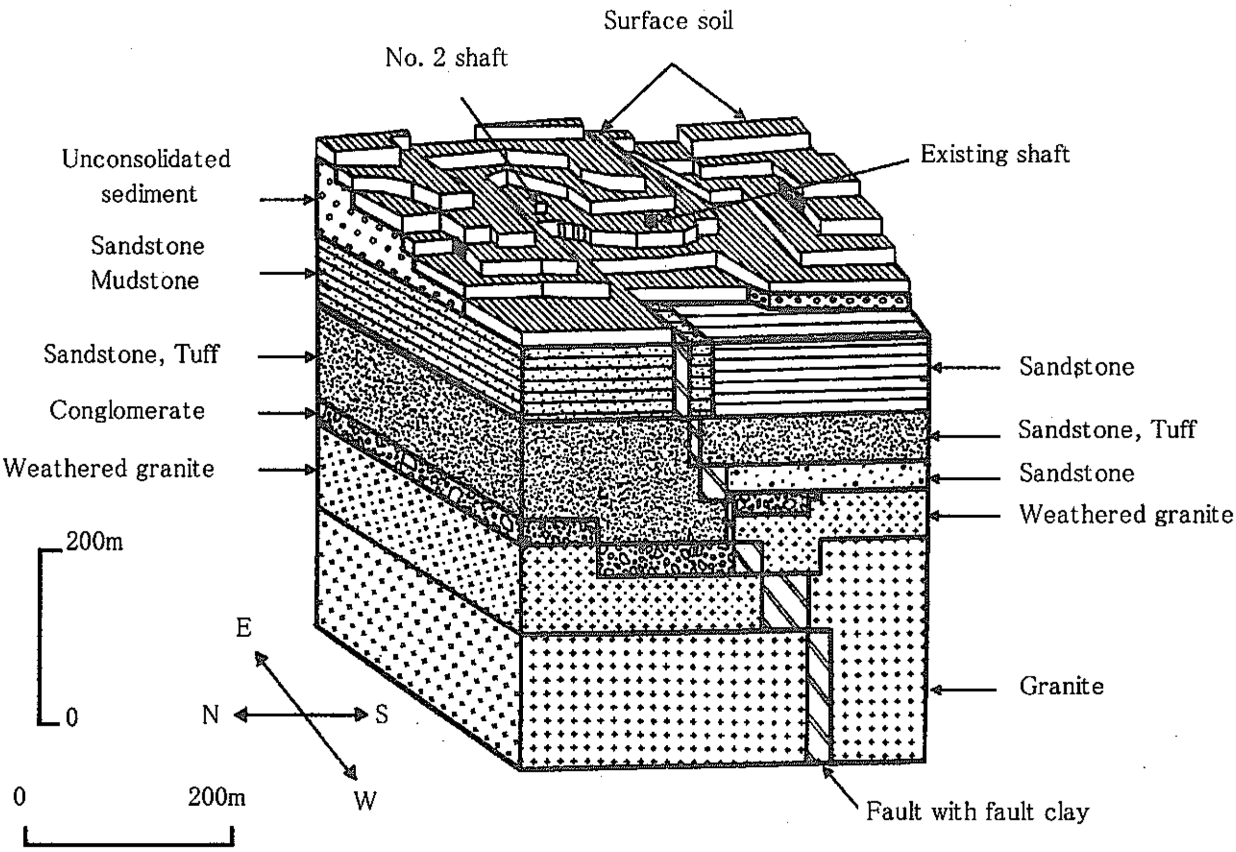


Fig. 3 Hydrogeological model

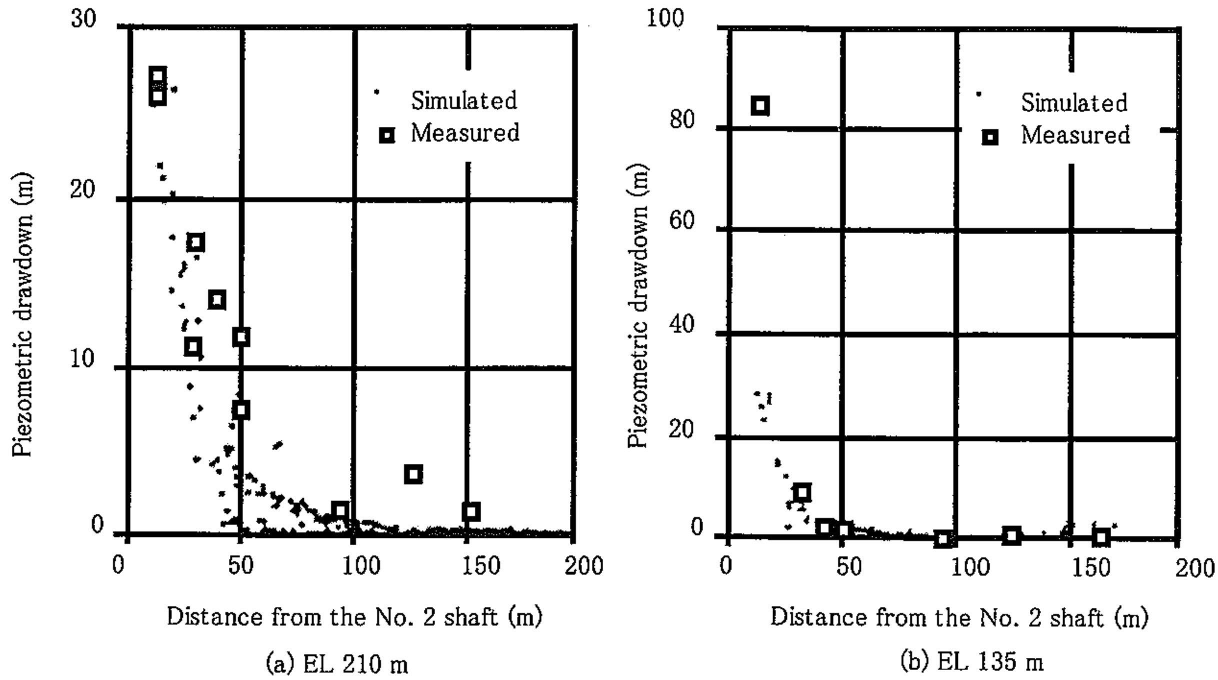


Fig. 4 Comparison of simulated and measured relation between piezometric drawdown and distance from the No. 2 shaft.

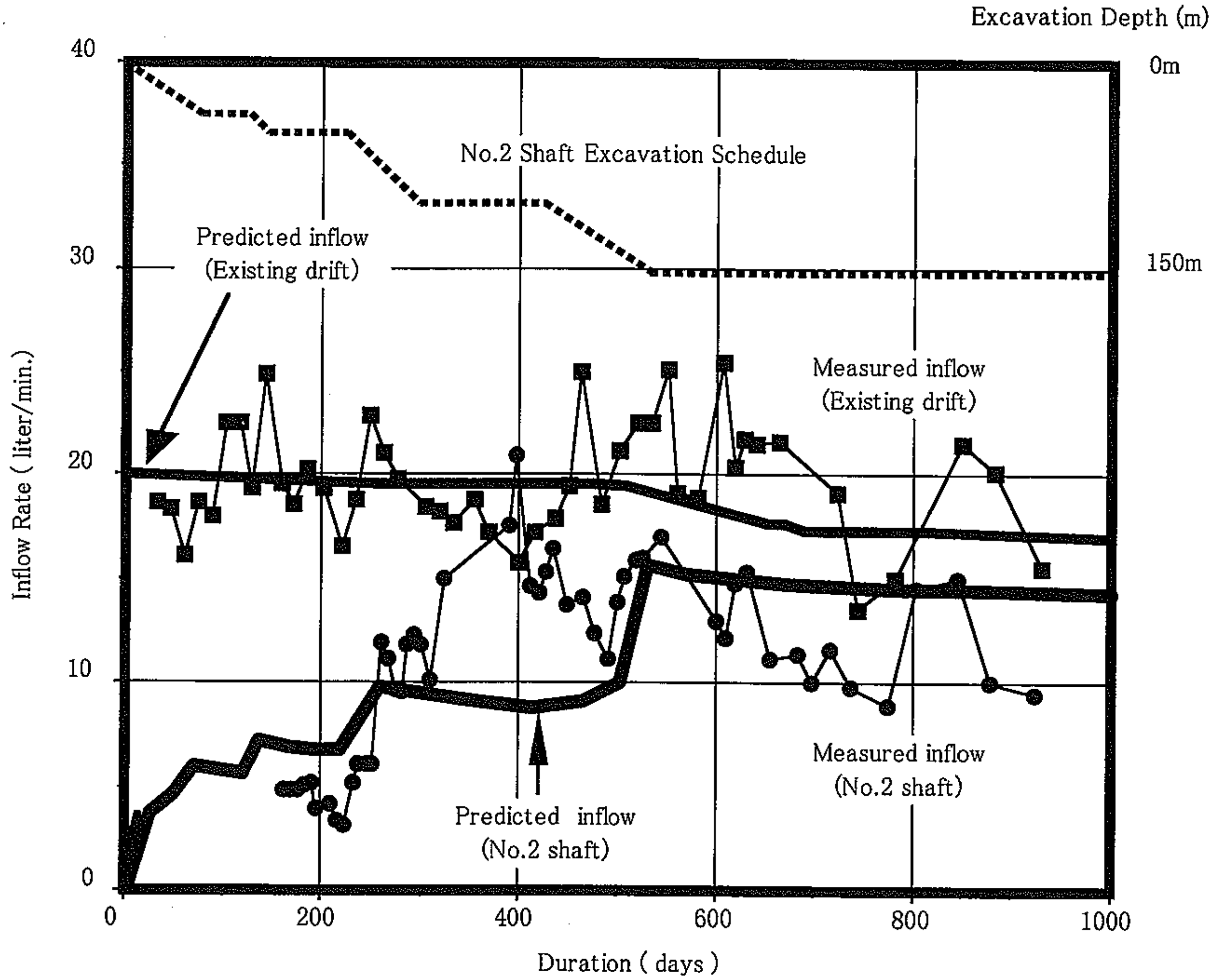


Fig. 5 Comparison of simulated and measured transient behavior of inflow.

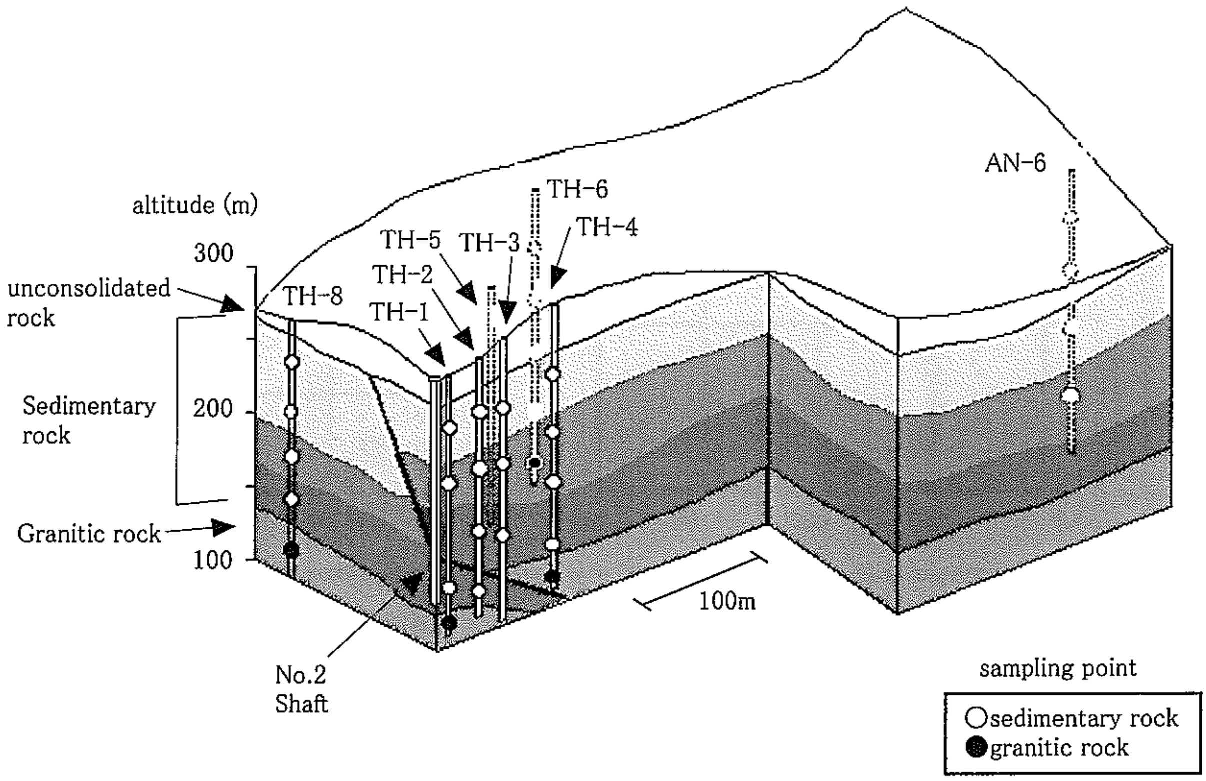


Fig.6 location map of groundwater sampling points

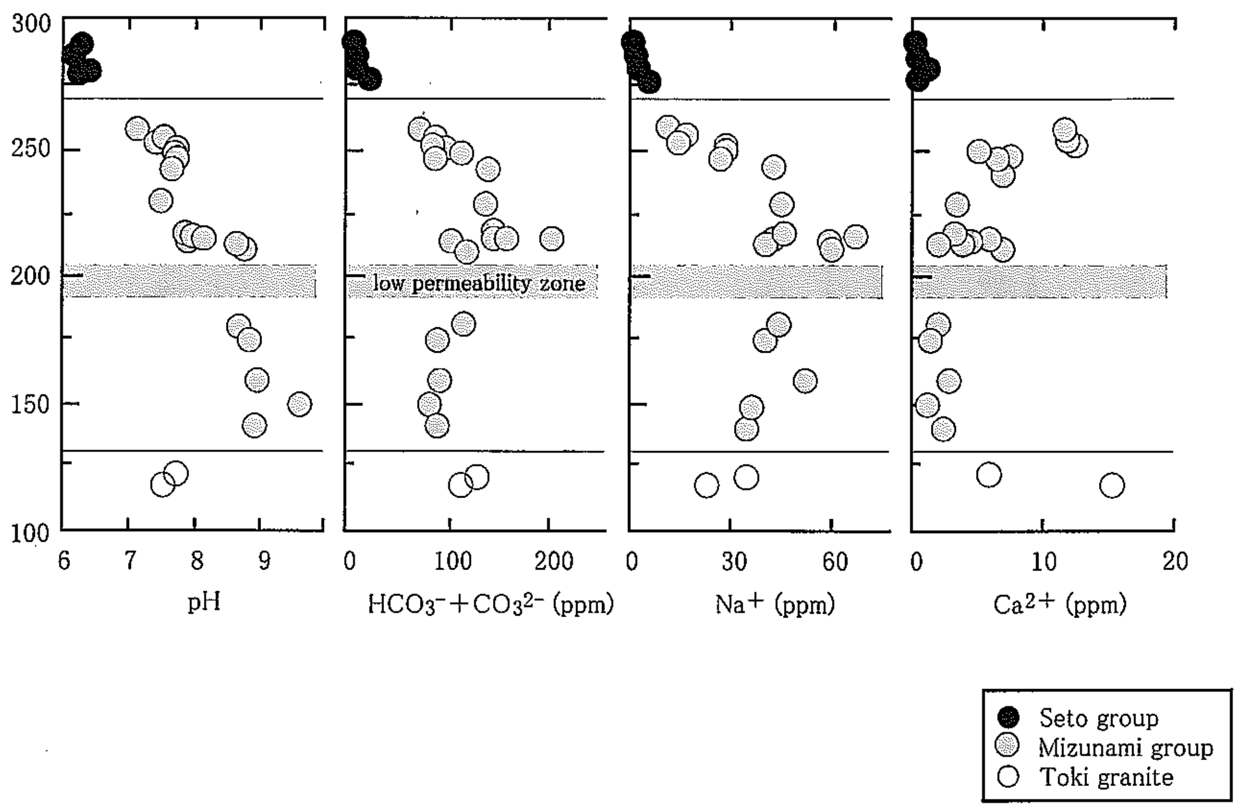


Fig.7 Changes in groundwater chemistry in the Tono area

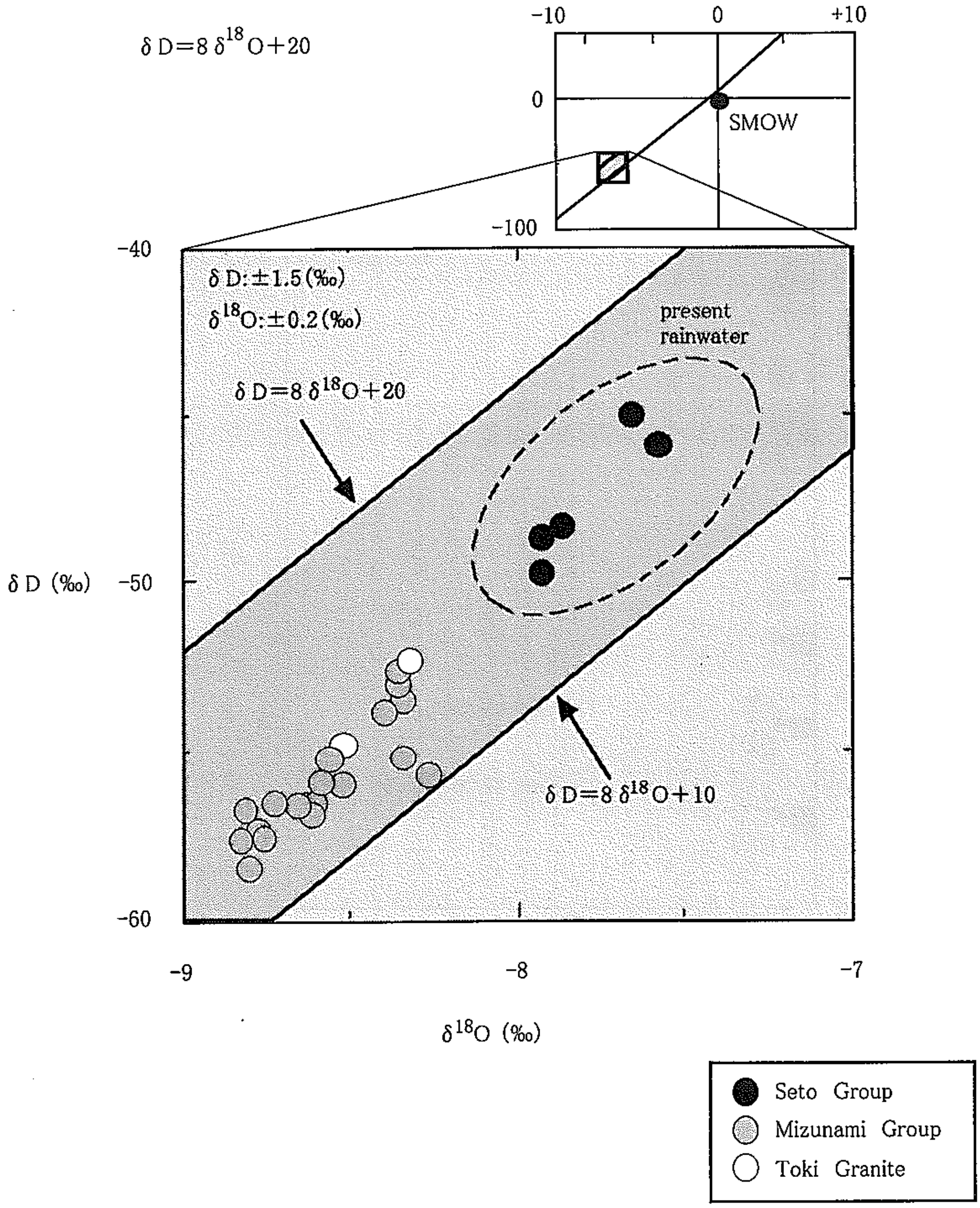


Fig. 8 Relationship between δD and δ^{18}O of groundwater in the Tono area

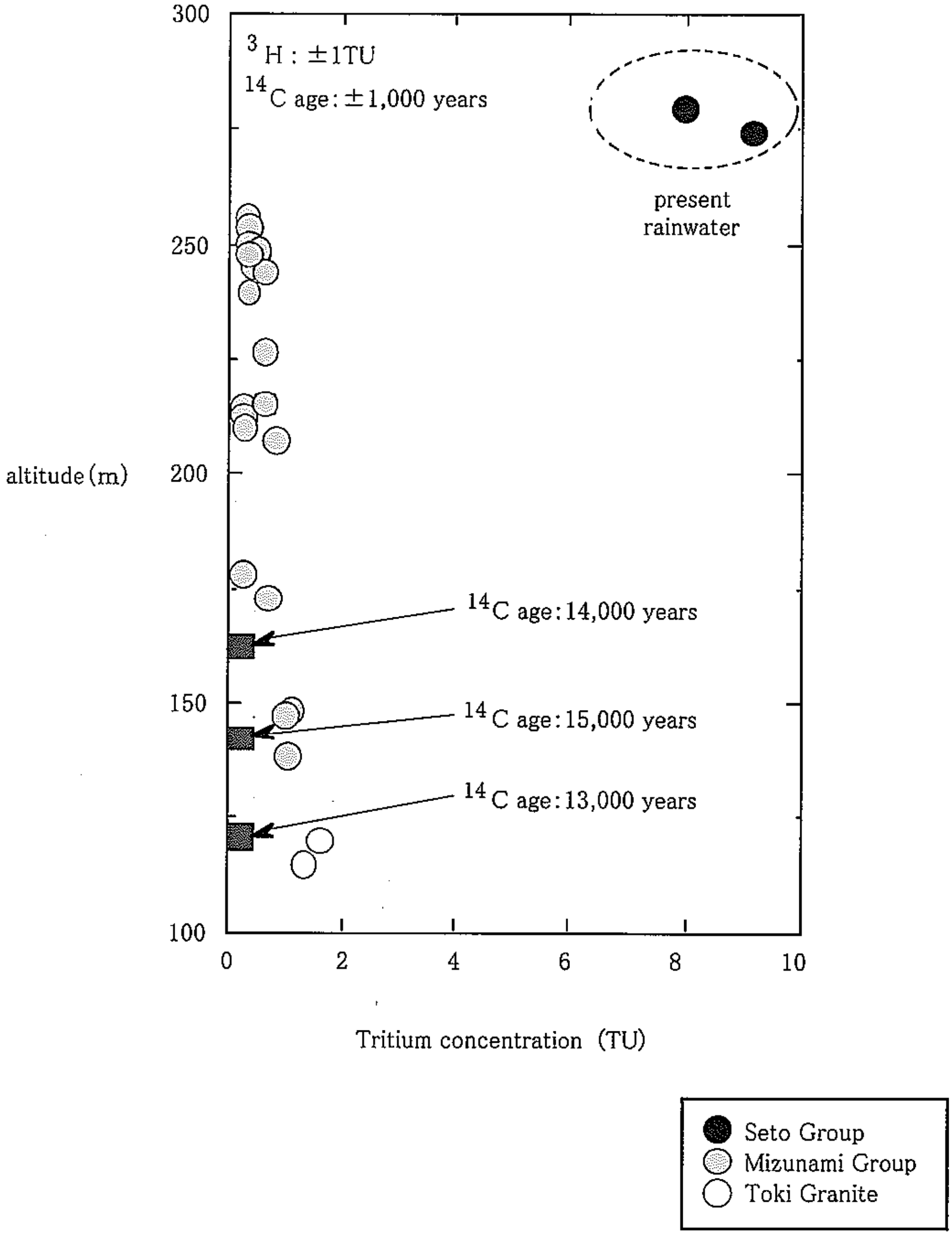
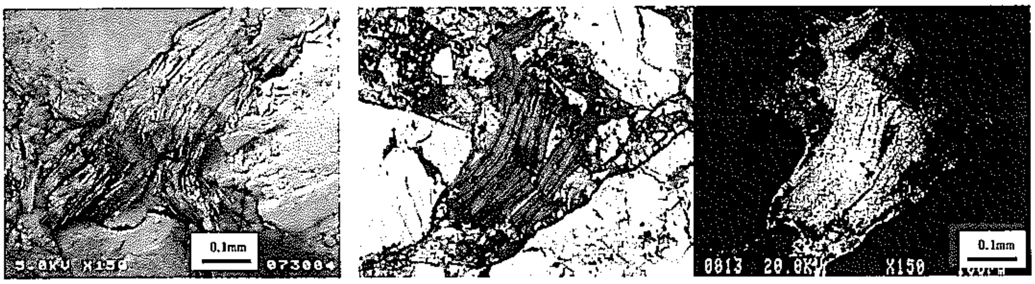
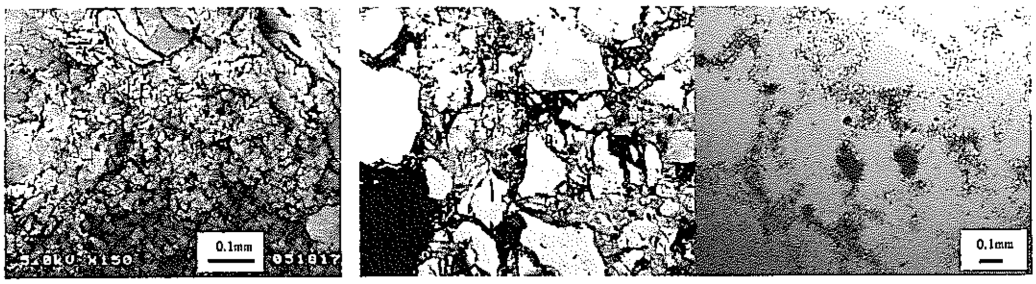


Fig. 9 Tritium density and ^{14}C age of groundwater in the Tono area

a: Microfracture within detrital grains



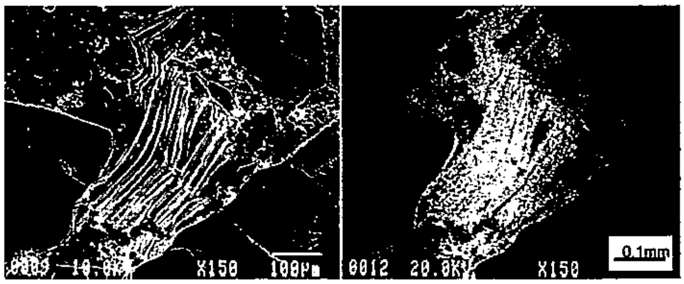
b: Cleavage of sheet silicate



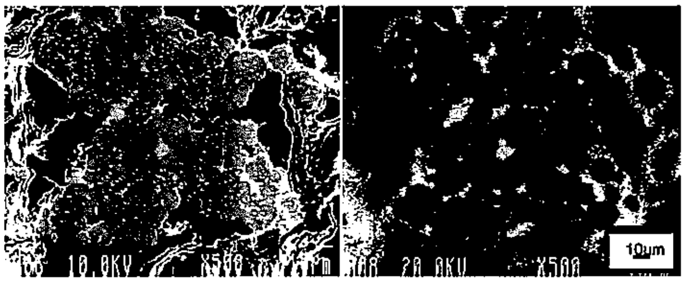
c: Micropores within clayey matrix

Fig.10 Pathways for nuclide migration in sedimentary rocks

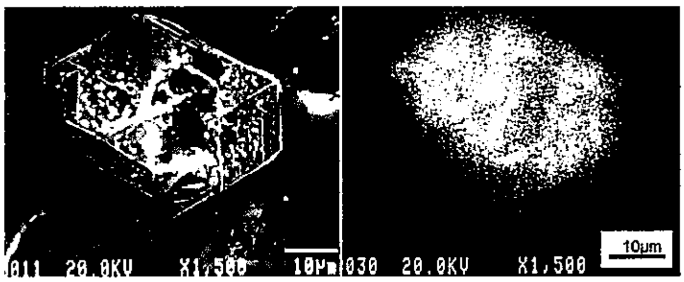
Left: SEM images of pore-spaces, *Middle*: Photomicrographs (plane-polarized light), *Right*: (a, c) a-track images and (b) U-Ma characteristic X-ray photograph



a: Cleavage of biotite



b: Framboidal pyrite



c: Altered ilmenites

Fig.11 Natural uranium retardation associated with iron-containing minerals in sedimentary rocks from Tono mine

Left: BSE images, *Right*: U-Ma characteristic X-ray photographs

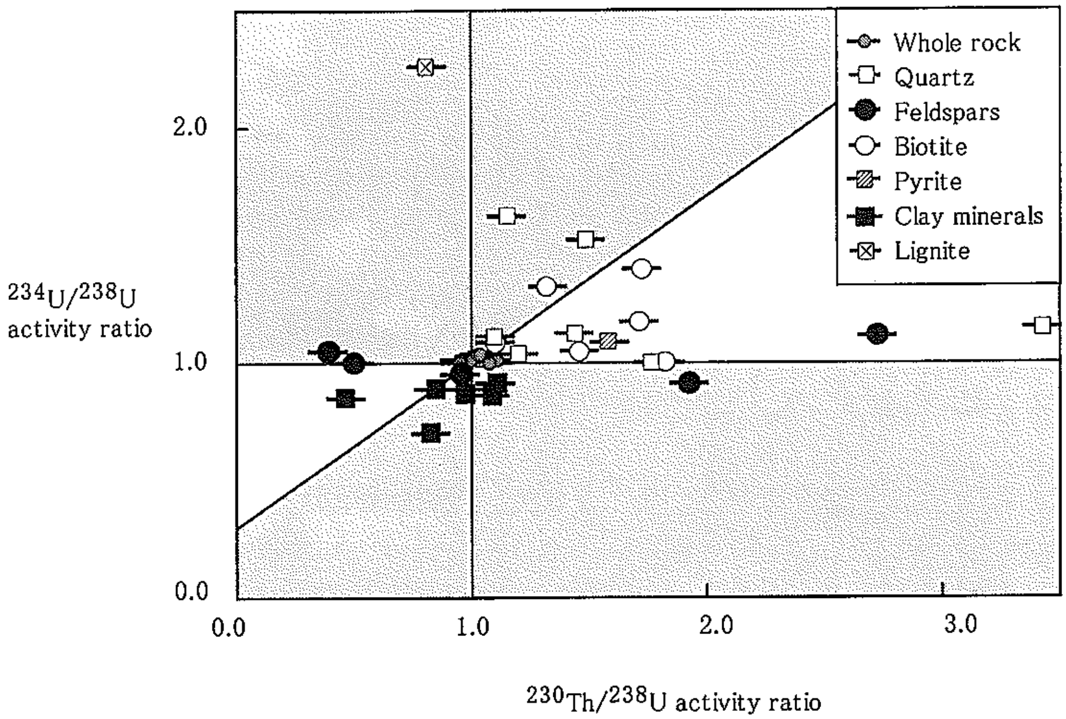


Fig.12 Result of studies on ^{238}U–decay series disequilibrium in sedimentary rocks from the Tono Mine

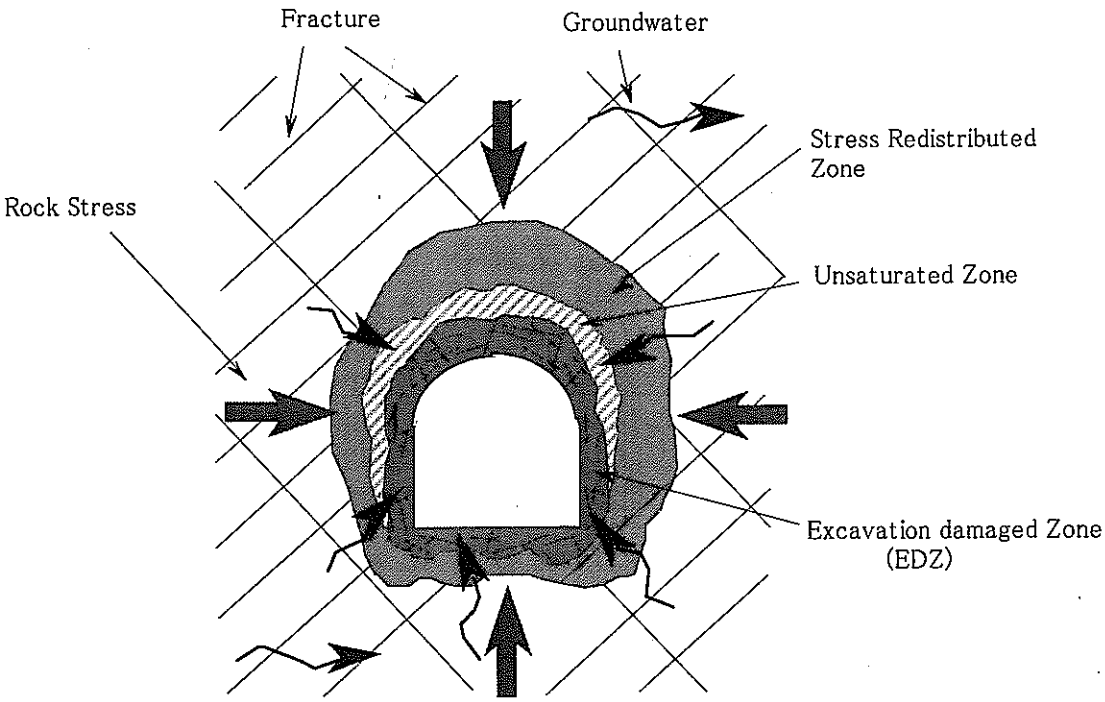


Fig.13 Conceptual model on EDZ

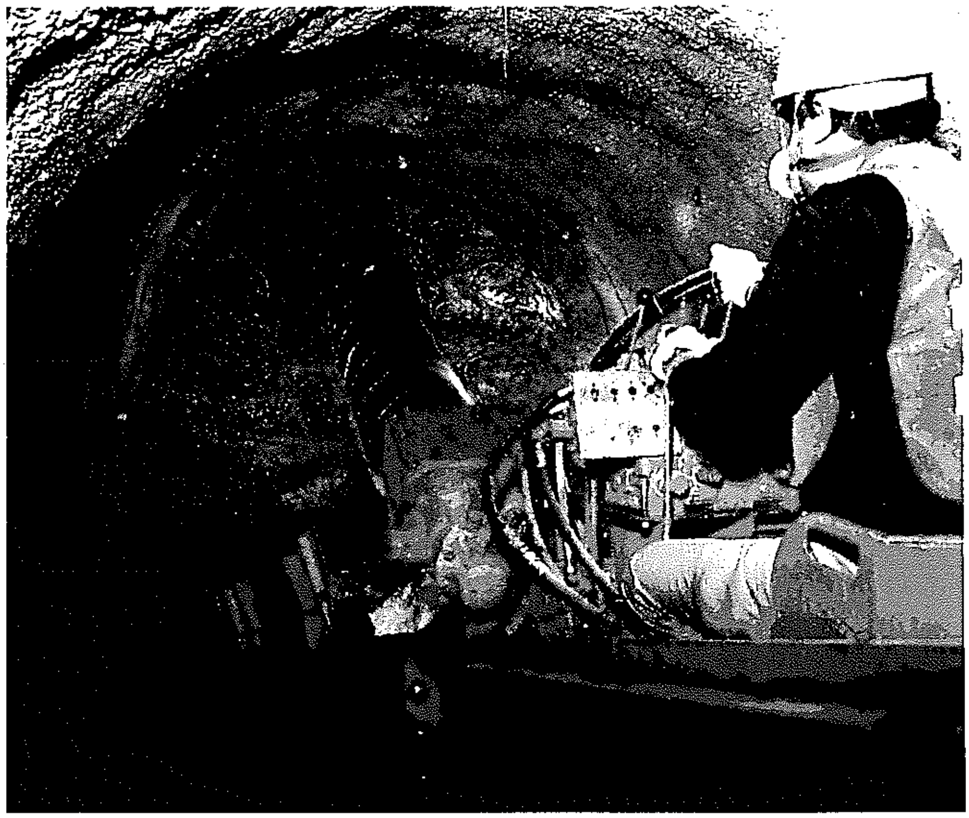


Fig.14 Boomheader

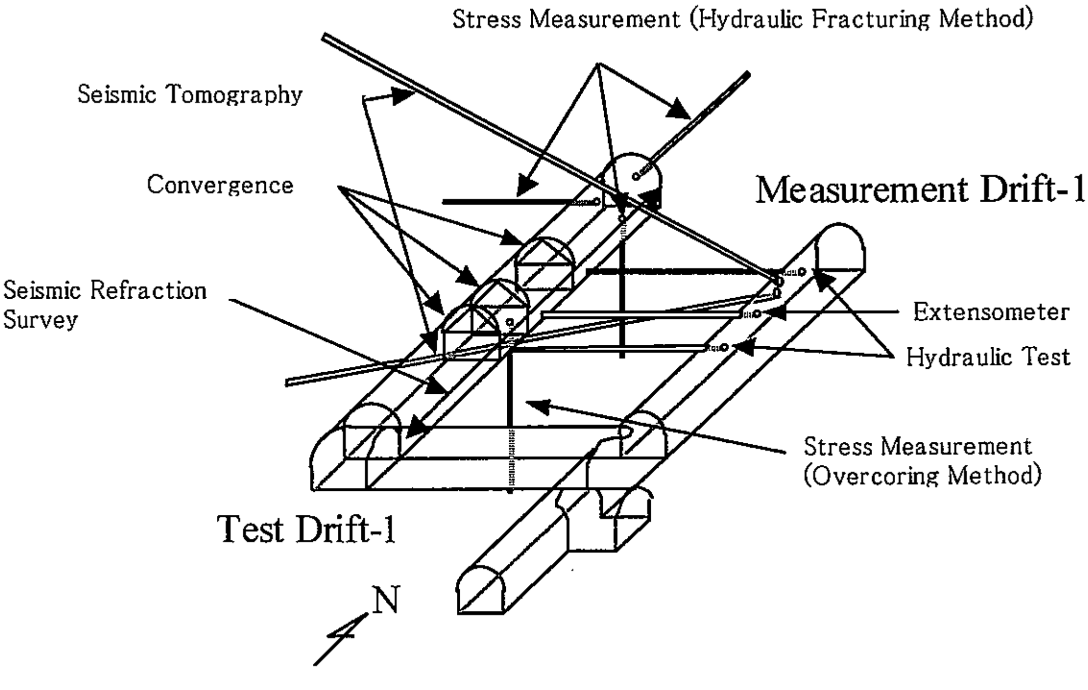


Fig.15 Configuration of drifts and boreholes in blasting excavation

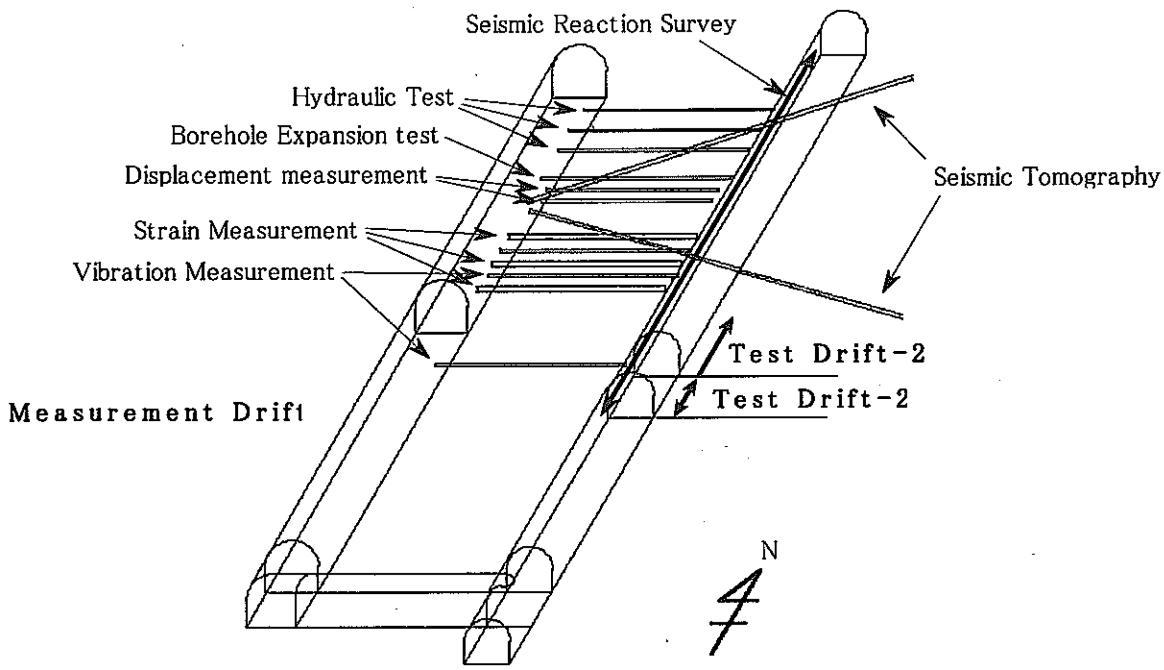


Fig.16 Configuration of drifts and boreholes in mechanical excavation experiment

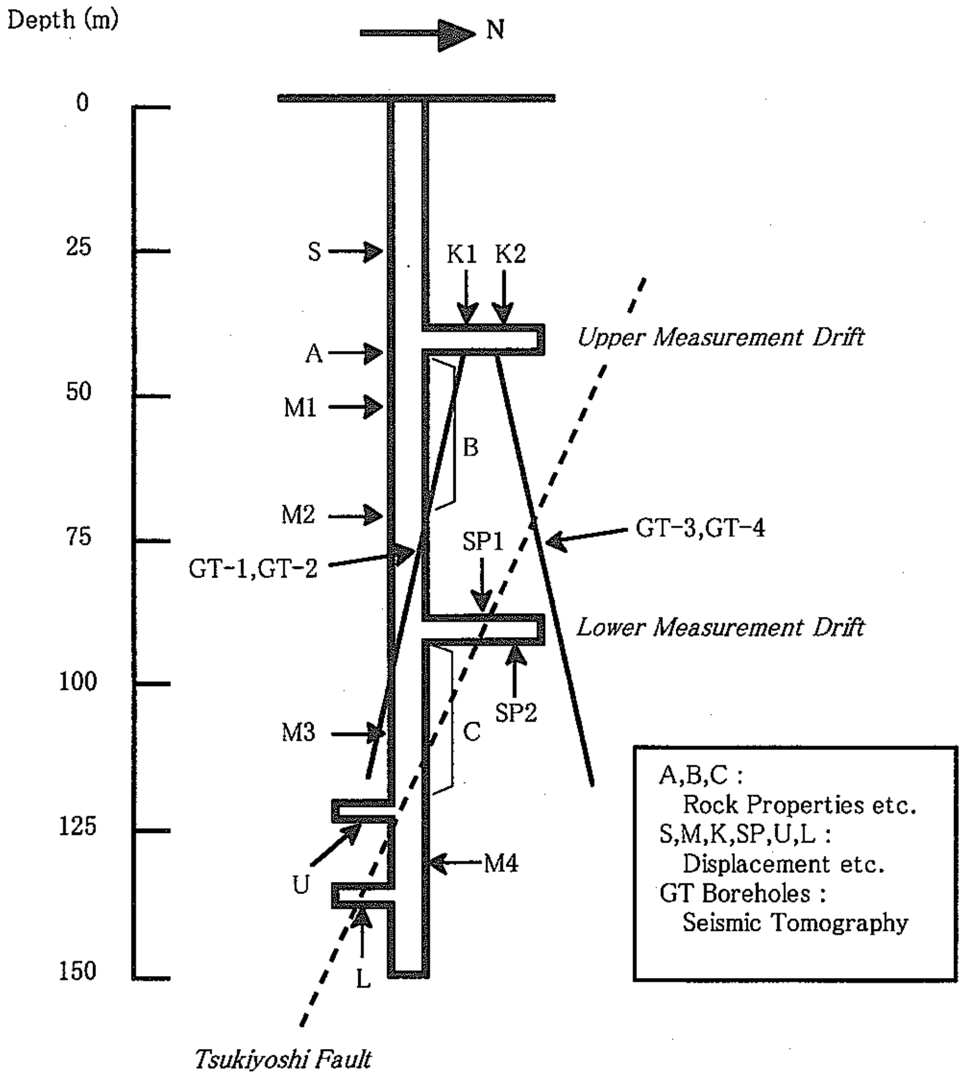


Fig.17 Layout of measurement sections and boreholes in the No.2 shaft

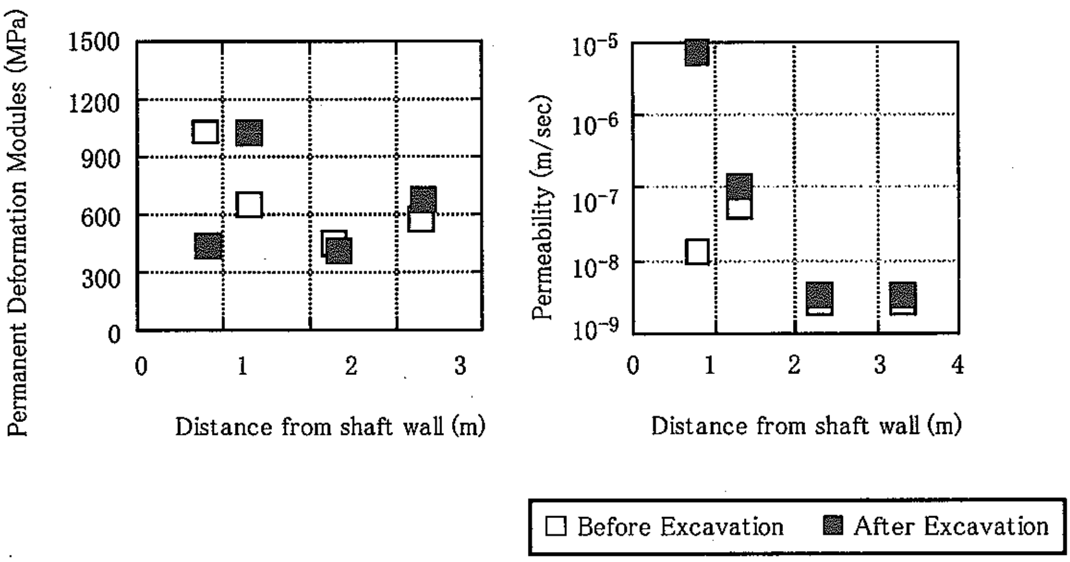


Fig.18 Changes in permeability and deformability at section B

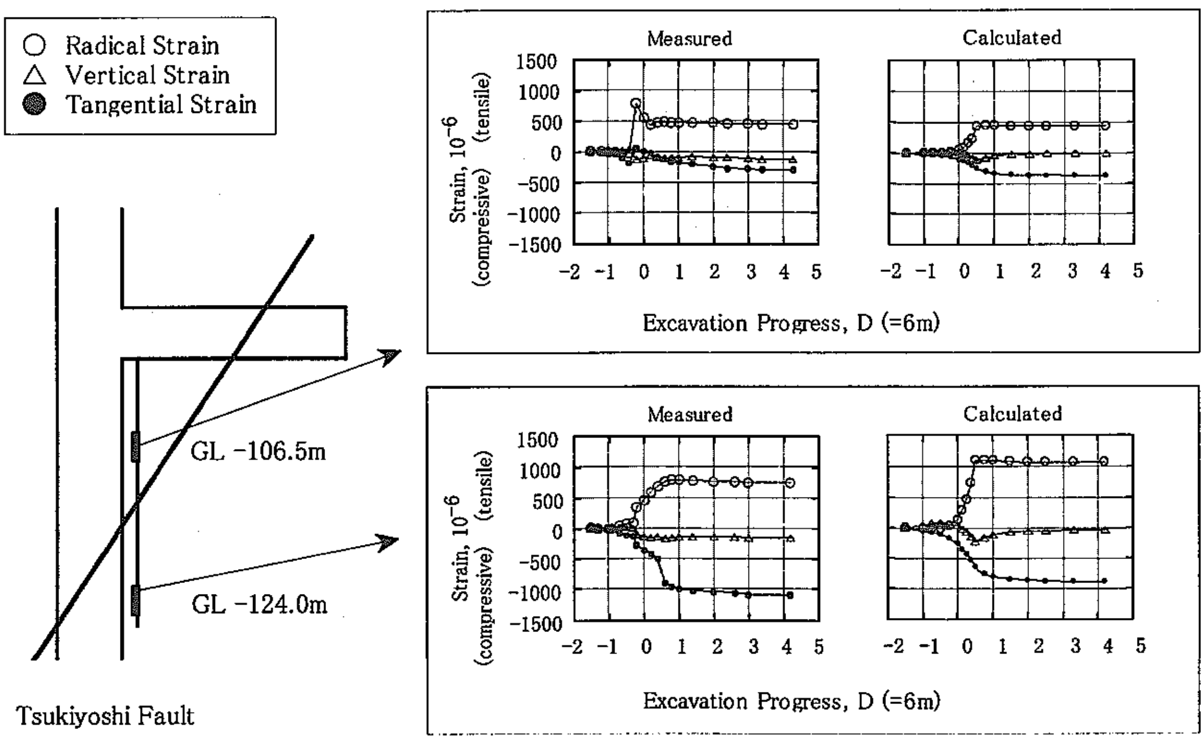


Fig.19 Measured and calculated strain variations in the No.2 Shaft

	Blasting Excavation		Mechanical Excavation	
	Extent	Property Change (ratio to intact rock)	Extent	Property Change (ratio to intact rock)
Excavation Vibration	1～2m	-	0.5～0.8m	-
Elastic Modulus (used in numerical analysis)	0.8m	30%	0.3m	40%
P-wave Velocity (Seismic refraction survey)	～0.8m	50～60%	～0.3m	65～70%
Permeability	～1.4m	increased by at least one order of magnitude	not detected	-
New Fractures	0.6m	-	not detected	-

Tab.1 Extent and properties of the EDZ detected in the Tono Mine

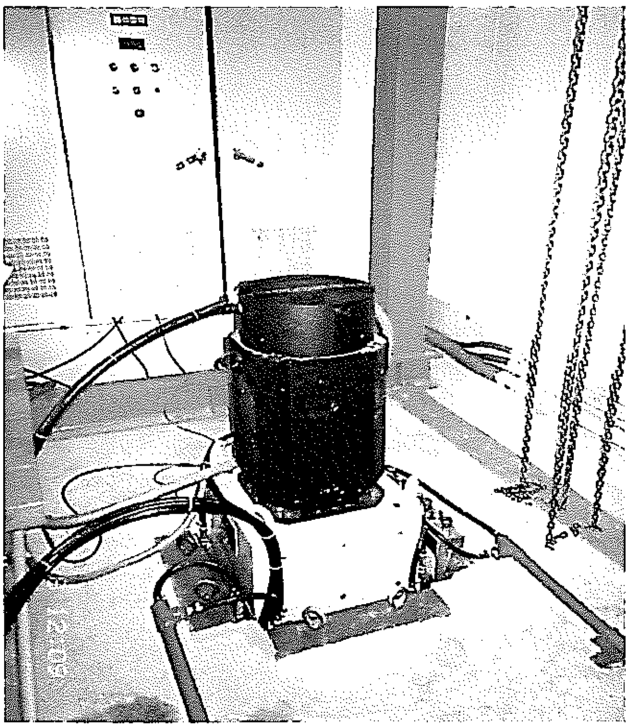
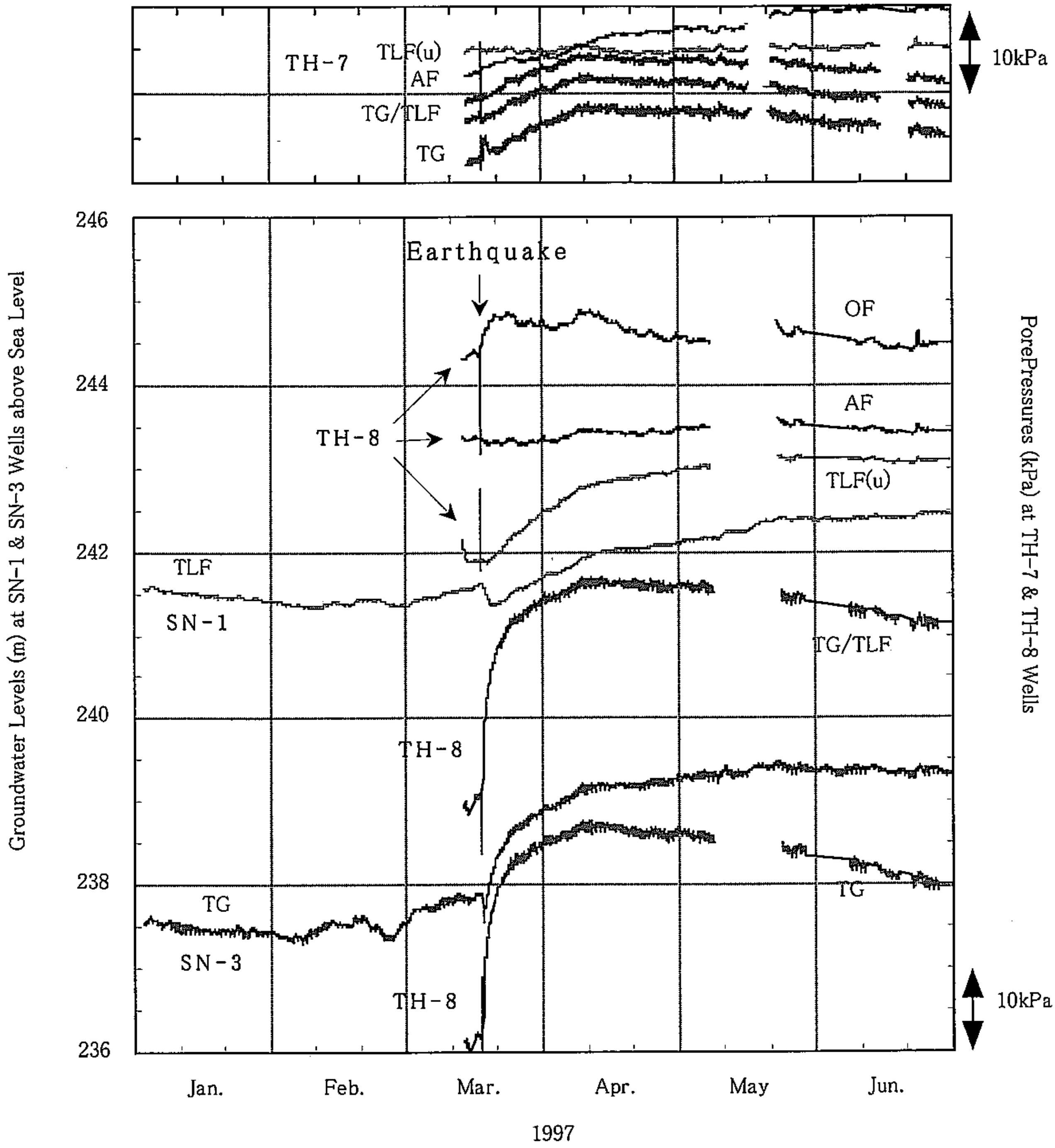


Fig.20 Signal (Seismic) source



OF : Oidawara Formation
AF : Akeyo Formation
TLF: Toki Lignite-Bearing Formation
TLF(u): TLF (upper part)
TG : Toki Granite

Fig.21 Groundwater responses at boreholes in the Tono area to large earthquakes

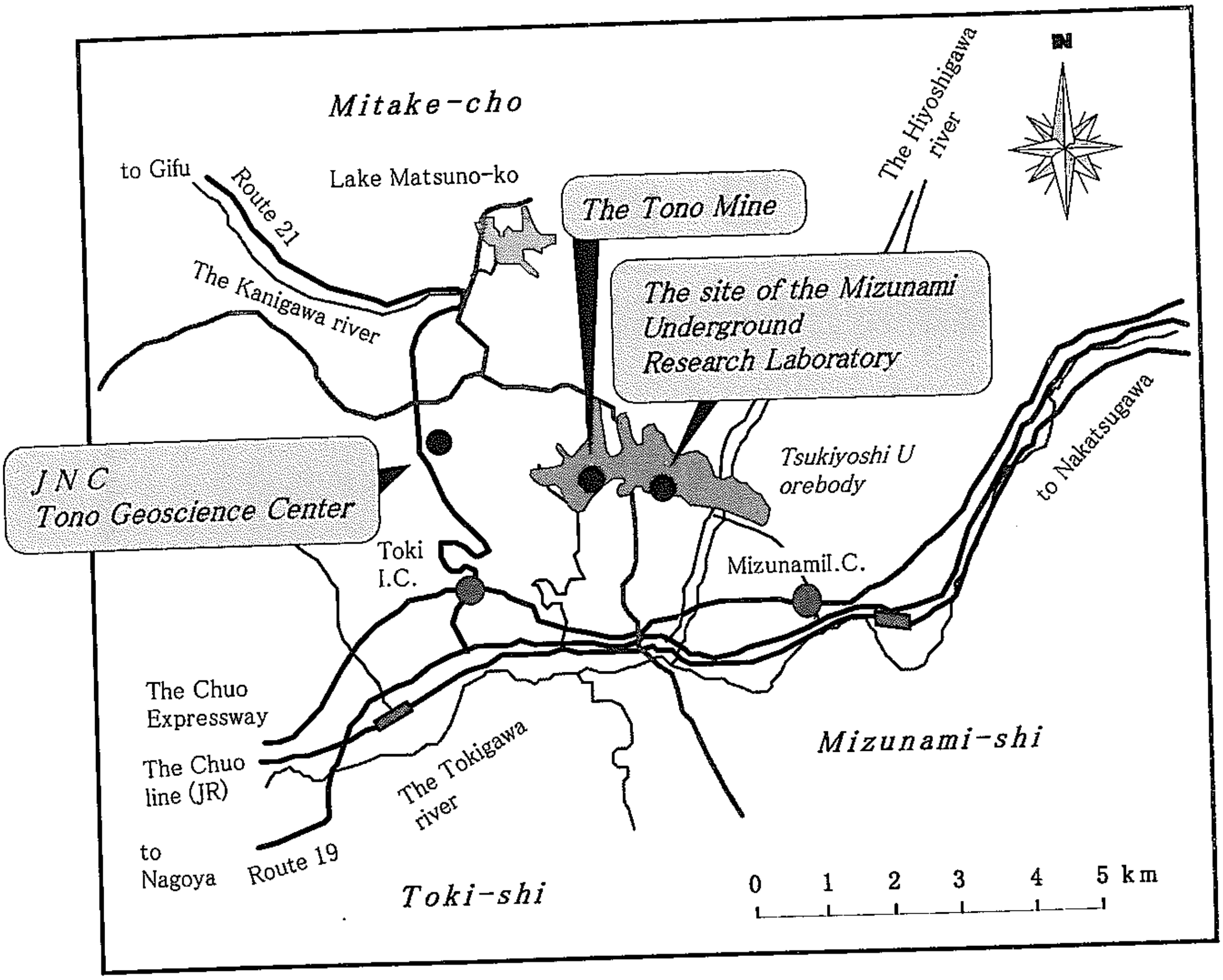


Fig.22 Index map of the Tono Mine and Tono area

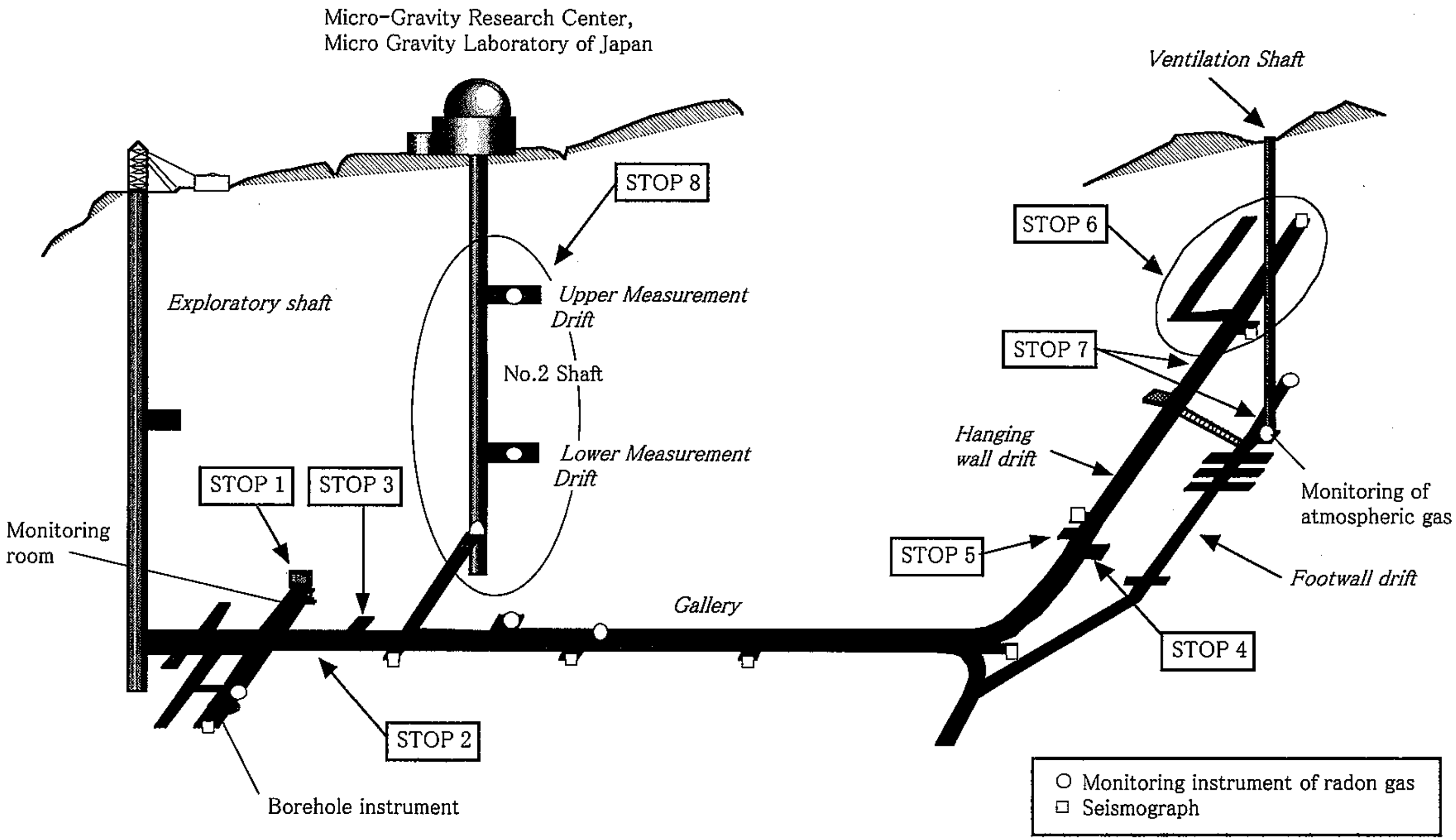


Fig.23 Location map of the facilities in the Tono Mine