# Geosphere Stability Project (1) Development of Geological-Evolutionary Model in the Tono area

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## Introduction

Geosphere stability project is being carried out by Japan Atomic Energy Agency (JAEA) in order to establish techniques for investigation, analysis and assessment of the long-term stability of geological environments, taking into account long-term geological phenomena such as volcanism, faulting, uplift, denudation, climate change, and sea-level change.

In this study, FEP (Features, Events and Processes) analysis and scenario development for geological-evolutionary modeling of mountain area and plain area have been carried out. Paleo-hydrogeological models were constructed in consideration for long-term geological environment such as topographic change and climatic perturbations, and spatial distribution of long-term stability of groundwater flow conditions were numerically assessed.

This paper summarizes the current status of R&D activities with development of geological-evolutionary model in the Tono area, Central Japan.

## Overview of R&D progress

This study has been carried out in the Toki River basin, approx. 20km square. Four stages, 3Ma (million years ago), 1Ma, 0.45Ma and 0.14Ma were selected for geological modeling based on geological history of the last millions of years in and around the study area. 3D steady-state groundwater flow simulations and sensitivity analysis focused on topographic change, recharge rate perturbation and conductivity of faults were carried out using these paleo-geological models. Recharge rates of glacial and interglacial periods in each stages due to climatic perturbation were estimated using the water balance method based on paleo-surface hydrological conditions. In this study, long-term evolution of groundwater flow conditions caused by long-term geological phenomena was assessed using statistical analysis based on the result of sensitivity analysis and then estimation of spatial distribution of long-term stability of groundwater flow conditions and extraction of important factor for assessment of long-term evolution of groundwater flow conditions in the study area have been carried out. In addition, the result of groundwater flow simulation were analyzed from the viewpoint of geochemical environment within the groundwater. Results of this study are summarized as follows;

- Practical approach of mountain area for reconstruction of paleo-topography, geological modeling and assessment of long-term evolution of groundwater flow conditions from several hundreds of thousands of years in the past to the present are shown.
- Statistical analysis using groundwater travel time is effective in order to estimate spatial distribution of long-term stability of groundwater flow conditions quantitatively.
- Topographic change is the most important factor for assessment of long-term evolution of groundwater flow conditions in mountain area.
- Long-term stability area of groundwater flow conditions could be estimated qualitatively by comparison between the result of groundwater flow simulation and groundwater chemistry, pH and redox potential within the groundwater.

## Future studies

In future work, technical know-how and uncertainties of geological-evolutionary modeling will be analyzed. In addition, methodology of investigation, modeling and assessment in the mountain area

 

for understanding of long-term evolution of geological environments will be systematized.

This study was carried out under a contract with Agency of Natural Resources and Energy (ANRE), part of Ministry of Economy, Trade and Industry (METI) of Japan, as part of its R&D supporting program for developing technology of geological disposal of high-level radioactive waste.

Keywords: Long-term stability of the geological environments, Geological-Evolutionary Model, High-level radioactive waste, Geological disposal, Tono area, Mountain area

 

# Geosphere Stability Project
# (2) Development of Geological-Evolutionary Model in the Horonobe area

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## Introduction

Geosphere stability project is being carried out by Japan Atomic Energy Agency (JAEA) in order to establish techniques for investigation, analysis and assessment of the long-term stability of geological environments, taking into account long-term geological phenomena such as volcanism, faulting, uplift, denudation, subsidence, climate change, sea-level change.

In this study, FEP (Features, Events and Processes) analysis and scenario development for geological-evolutionary modeling of mountain area and plain area have been carried out. Paleo-hydrogeological models were constructed in consideration for long-term geological environment such as topographic and climatic change, and spatial distribution of long-term stability of groundwater flow conditions were numerically assessed.

This paper summarizes the current status of R&D activities with development of geological-evolutionary model in the Horonobe area, northern Hokkaido Japan.

## Overview of R&D progress

This study has been carried out in the area of approx. 90 km (east-west) and 30 km (north-south) including outer shelf, plain and hill taking into account sea-level changes and the development of land area. Two stages, approx. 1Ma and 0.33Ma were selected for paleo-geological modeling based on geological history of several millions of years in and around the study area. 3D steady-state groundwater flow simulations and sensitivity analysis using these models were carried out focused on topographic change, climate change (recharge rate and sea-level change), conductivity of faults and strata, and the formation of discontinuous permafrost.

In this study, long-term evolution of groundwater flow conditions caused by long-term geological phenomena was assessed using statistical analysis based on the result of sensitivity analysis. From the results of statistical analysis, the spatial distribution of long-term stability of groundwater flow conditions was estimated and then important factors for assessment of long-term evolution of groundwater flow conditions in the study area were extracted. In addition, the results of groundwater flow simulation were analyzed from the viewpoint of geochemical environment within the groundwater. Results of this study are summarized as follows;

- Practical approach of plain area for the restoration of paleo-topography and geological structure, modeling of geological evolution and assessment of long-term evolution of groundwater flow conditions during past one million years were shown.
- Statistical analysis using groundwater travel time is effective in order to estimate spatial distribution of long-term stability of groundwater flow conditions quantitatively.
- Topographic change and climate change are the most important factors for assessment of long-term evolution of groundwater flow conditions in plain area.
- Long-term evolution of groundwater flow conditions in plain area is slow compared with that in mountain area, while a plain area is sensitive to changes of geological phenomena compared with a mountain area.
- Long-term stability area of groundwater flow conditions could be estimated qualitatively by comparison between the result of groundwater flow simulation and groundwater chemistry, pH and

 

redox potential within the groundwater.

Future studies

In future work, technical know-how and uncertainties of geological-evolutionary modeling will be analyzed. In addition, methodology of investigation, modeling and assessment in the plain area for understanding of long-term evolution of geological environments will be systematized.

This study was carried out under a contract with Agency of Natural Resources and Energy (ANRE), part of Ministry of Economy, Trade and Industry (METI) of Japan, as part of its R&D supporting program for developing technology of geological disposal of high-level radioactive waste.

Keywords: Geosphere stability, Geological-evolutionary model, High-level radioactive waste, Geological disposal, Horonobe area, Plain area

 

# Geosphere Stability Project (3) Provenance analysis techniques

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An uplift rate of mountains attains to a dynamic equilibrium with an erosion rate in the later stage of mountain-building, then the uplift does not cause the change of groundwater flow. However, the uplift can influence the groundwater flow in the early stage of mountain-building that the dynamic equilibrium is not established. Understanding the stage of mountain building is crucial to the stability assessment of geological environments in geological disposal system. In this context, we have carried out the research and development of provenance analysis techniques to elucidate the mountain-building stage. This study presents the results focusing on the R&D using the Electron Spin Resonance (ESR) signals from quartz in sediments.
The R&D was carried out using the Miocene to Pleistocene Tokai Formation distributed over the Tono area, Central Japan. The Tokai Formation is composed of the Tokiguchi-Toudo Formation and the Toki Sand and Gravel Formation. In the northern part of the area, bedrocks consist of Mesozoic sedimentary rocks, the Nohi Rhyolite and the Sanyo Granite, whereas consist of the Ryoke Granites in the southern part. Many studies were performed in the area to clarify the landform developing process (e.g., Moriyama, 1990).
Samples of sediments were taken from the quarry located between the Tsukechi River, a tributary of the Kiso, and the Atera fault. Samples of basement rocks were also taken in and around the quarry. Sediments have a thickness of about 30m, overlying the Nohi Rhyolite. The lower part of sediments contains gravels derived from the Nohi Rhyolite, whereas the upper part contains several different kinds of gravels originated from the Nohi Rhyolite, granites and basalts. The lithology of gravels indicates that the provenance of sediments are different in the lower and upper parts.
ESR signals of quartz grains extracted from the samples were measured. As a result of the measurements, ESR signal intensities of the lower part of the sediments are similar to that of the Nohi Rhyolite, and the intensities of the upper part are similar to the granitic rocks of the Sanyo granite. On the basis of the results and previous studies, the Sanyo granite were not exposed to the drainage basin during the deposition of the lower part between 3.9 and 2.0 Ma, then the granitic rocks were exposed during the deposition of upper part after about 2.0 Ma. We conclude that the ESR properties are effective to estimate the sediment provenance.
This study was conducted under a contract with METI (Ministry of Economy, Trade and Industry) as part of its R&D supporting program for developing geological disposal technology.

Keywords: Geosphere stability, Provenance analysis techniques, Electron Spin Resonance method, High-level radioactive waste, Geological disposal

 

# Geosphere Stability Project (4) Numerical modeling techniques for crustal movement

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The basic framework for assessment of deep geological repository of high-level radioactive waste is extrapolation of the crustal deformation over the past a few hundred-thousand years. However, the quantity and reliability of information for crustal deformation vary from era to era and from area and area. The crustal deformation predicted by extrapolation includes a certain level of uncertainty. Japanese islands have received crustal shortening due to the subduction of oceanic plates for a long time, which is characterized by complicated topography and crustal deformation as a result. In this study, we try to establish the method to estimate the crustal deformation for a long period, using the crustal strain rate in geological time scale (geological strain rate) and numerical simulation considering visco-elastic or elasto-viscoplastic behavior of the crust and upper mantle. At first, we report geological strain rate estimated from active fault database of Japan which is collected by National Institute of *Advanced Industrial Science and Technology.* Next, we report the result of numerical simulation to account for the anomalous crustal deformation around the source region of earthquake swarms by introducing visco-elastic material.
This study was carried out under a contract with Agency of Natural Resources and Energy (ANRE), part of Ministry of Economy, Trade and Industry (METI) of Japan as part of its R&D supporting program for developing technology of geological disposal of high-level radioactive waste.

Keywords: deep geological repository of high-level radioactive waste, plate interaction for a long time, geological strain rate, simulation of crustal deformation, visco-elastic heterogeneity

 

# Geosphere Stability Project (5) Estimation of Groundwater Recharge Rate in Consideration of long-term Changes in Surface Hydrological Environment

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In geological disposal for high-level radioactive waste, a time scale for assessment of long-term stabilities of geological environments is more than several hundreds of thousand years. In the time scale, surface hydrological environment changes by climate changes and by landform changes (e.g. uplift, erosion). Especially, groundwater recharge rate (GRR), which plays upper boundary condition of groundwater flow for deep underground, changes by precipitation, evapotranspiration and runoff-volume. Thus, it is important to estimate GRR in consideration of change of surface hydrological environment. This study shows the estimation method of GRR in consideration of climatic changes and landform changes.
GRR can be estimated by the water-balance method. In the method, estimations of precipitation, evapotranspiration and runoff volume are needed. As a result of observation data based on the previous studies, it has been confirmed that precipitation and evapotranspiration show a positive correlation with temperature. Thus, precipitation and evapotranspiration are calculated by the correlation equation of temperature.
For runoff volume, a method to calculate Runoff-Ratio (RR), which is a ratio of runoff volume against precipitation, is applied. RR is calculated by runoff volume, precipitation and Runoff-Index (RI) decided by landform characteristics.
To confirm the applicability of this method, GRR under the paleo surface hydrogeological condition is estimated in the Toki-River basin. The basin is located on the southern part of Central Japan. The basin is also located on the small undulating mountainous or hilly areas in the relatively low elevation field. The area of the basin is about 340 $km^2$.
The climate of last 0.3 Ma in the study area has been estimated by Sasaki et al (2006). As a result, the temperature difference in the interglacial period and glacial period is approximately 8-10 degrees Celsius. Based on this result, the temperatures of the interglacial period and the glacial period are calculated.
The precipitation and evapotranspiration are estimated by the correlation equation of estimated temperature. The equation for precipitation is decided by the data measured in the Pacific coast of Japan, North Asian, North Europe and North America. The equation for evapotranspiration is decided by the data obtained at high latitude area including this study area.
For runoff volume, at first, the RI which is common to "the current landform and the paleo landform" is calculated. Next, the correlation equation between RI and RR under the current surface conditions are decided. Finally the runoff volume is calculated by the correlation equation using the paleo surface condition.
In the estimation results, the GRR of 0.45 Ma are estimated to be 118% to 237% and the GRR of 0.14 Ma are estimated to be 81% to 196% against the current GRR (118mm/year). In the result of current landform in the glacial period, the GRR is estimated to be 58% to 72%.
Under the glacial periods in the paleo surface environmental conditions, precipitation and runoff volume are estimated to be smaller than the current them. However the GRR under the paleo conditions is larger than the current GRR. This result shows a possibility that the change of runoff volume caused by the change of landform gives a large influence on the change of GRR.
On the other hand, the runoff volume based on the landform of 1.0 Ma couldn’t be estimated. It might cause that the estimated landform is poor undulations and flat terrains. The future issues

 

are an improvement of the runoff estimation method and a confirmation of applicability of the method to poor undulation of landform.
This study is carried out under a contract with METI (Ministry of Economy, Trade and Industry) as part of its R&D supporting program for developing geological disposal technology.

Keywords: High-level radioactive waste, Geological disposal, Groundwater recharge rate, Change of climate in long-term, Change of landform in long-term

 

# Geosphere stability project (6) Chronological and chemical analyses of carbonate minerals

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Chronological and geochemical studies of fracture filling calcite in rocks provide the information for changes in geochemical condition, such as redox potential and pH in deep geological environments [1,2]. Because the calcite can be found as common filling minerals in the natural samples, age zoning and spatial distribution of chemical composition in the calcite could be a wide-use indicator to estimate the past environmental changes [3,4]. Radiometric ages of bulk calcite samples have been reported [5]. On the other hand, U-Pb dating in a micro scale area (less than 10 micrometer) on the filling mineral surface by laser ablation-inductively coupled plasm mass spectrometry system (LA-ICPMS) has been applied to geological samples (zircon, apatite and other minerals) [1]. Additionally, Fe, U, rare earth elements, and other chemical composition in the calcite have proven to be a useful means for the estimation of past geochemical changes. Past redox potential has been estimated by Fe contents in the carbonates, which is based on the distribution coefficient of Fe between calcite deposit and groundwater [3,4]. In this study, we evaluated the possibility of in-situ radiometric dating for the filling minerals by LA-ICPMS and past redox potential by the theoretical calculation using the distribution coefficient. Our new results are shown as follows.

(1) Radiometric dating by LA-ICPMS

In order to develop high spatial resolution dating of the filling minerals, we should make clear the trace element fractionation (U and Pb) on a sample surface during LA-ICPMS measurements and establish the high precision measurements of Pb isotope ratios based on the authentic carbonate standard materials. Therefore, we made efforts to find natural carbonates as possible standard materials with homogeneous U and Pb contents as well as Pb isotope ratios. Imaging analyses (two-dimensional mapping) of the trace element contents and the isotope ratios were adopted to decide the suitable sample analysis points by laser ablation for the radiometric dating of carbonates [1]. Besides, we performed high precise and sensitive measurements in Pb isotope ratios by the LA-ICPMS using the multiple ion counters and the multiple Faraday collectors with high gain amplifiers [1].

(2) Redox potential by the theoretical calculation

For the inorganic geochemical analyses, drilling core samples (DH5, 6, 7, 8, 12) from southeastern Gifu in the middle Japan, and modern carbonate deposits from Shimane and Yamanashi in Japan were analyzed by ICP-MS. For the DH6, 7, 8, calculated redox potential values by the Fe contents were coincident with the observed values of ground water. However, those of other samples showed disagreement with the observed values, which could be caused by secondary mixing with oxic surface water. Therefore, applicable methods and condition (e.g. range of the redox potential values, ground water source and/or their matrices) should be cleared for the theoretical calculation of redox potential by Fe contents in carbonates.

This study was carried out under a contract with METI (Ministry of Economy, Trade and Industry) as part of its R&D supporting program for developing geological disposal technology.

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Keywords: carbonate minerals, radiometric dating, redox potential, LA-ICPMS, geosphere stability, geological disposal

 

# Estimation of hydraulic conditions of groundwater using carbon isotope

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Groundwater flow is an indispensable information to estimate the material cycle in underground environment. Hydraulic simulation referring chemical index of groundwater enables to realize the evaluation of groundwater flow. Japan Atomic Energy Agency (JAEA) has been carried out the hydrochemical and hydraulic monitoring in sedimentary rocks and granite at Mizunami underground research laboratory (MIU) to evaluate an environmental influence around the large-scale underground facility. We studied the relationships between isotopic / chemical composition of groundwater and hydrogeological structure to infer the hydraulic condition.
The $\delta^{13}C$ value of groundwater increase with decreasing 14C activity at depths between 200 - 400 m. The saturation index of minerals indicates that calcite may not dissolve in this domain. The $\delta^{13}C$ value of groundwater is probably changed by mixing of isotopically distinct groundwaters. 14C activity ranges 4 to 31 pMC in relatively highly fractured domain at depths between 200 - 400 m, and ranges 2 to 16 pMC in sparsely fractured domain at the depth of 500 m of granite. It depends on difference of permeability of rock formation.

Keywords: carbon isotope, groundwater, hydraulic condition

 

# Development of centrifuge model test for evaluation of long term geomechanical behavior in HLW near field

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Studies of a prototype test and a numerical simulation relevant to evaluation of the long term behavior between the engineered barrier and host rock surrounding the high radioactive waste disposal repository (called the "near-field") are being conducted. In order to verify the results of the numerical analysis, it is one of the effective method for the accuracy of the numerical model to compare the results of prototype test with the numerical analytic results. However, the period that can be carried out prototype test in practice is about a dozen years at the longest, and it is extremely difficult to verify the numerical analytic results in units of several hundred years.
Based on centrifugal scaling laws for thermal-hydraulic-mechanical (T-H-M) behavior, any two investigations of the same conditions using a centrifuge model test and a prototype are similar and related. And, the centrifuge model test has the advantage that it can greatly shorten the long time needed to see behavior resulting from the typically slow flow of groundwater that satisfies Darcy’s law. Therefore, it is possible to estimate in part the long-term mechanical behavior in practice. Focusing on the point in CRIEPI, we developed the geotechnical centrifuge which can be operated up to 6 months continuously and mounted a model of maximum payload of 1.5 ton, and are developing a method of the long-term geomechanical behavior evaluation experiment of the near-field using the centrifuge. In this development, our target is the geomechanical interaction between the buffer material and the surrounding rock, and we carried out the long term centrifuge model test in order to measure the behavior in the near-felid.
First, we made the reduced model of the near-field consisting of a single model-overpack, ring- and cylinder-shaped buffers, and a cylindrical rock mass. The model-overpack is a stainless steel adjusted to a predetermined weight, the buffer is a compacted Na-bentonite (Kunigel-V1 of 100%), and the rock mass is a Tage tuff. Tests were conducted with a centrifugal force field of 30 G under isotropic stress-constrain conditions with confining pressures of 5 to 10 MPa and injection of pore water up through a time period equivalent to about 165 yr in the field. The temperature condition of the model and boundary is constantly 25 °C (called the "normal temperature test"). We measured the vertical displacement of the overpack, the bentonite pressure, and the strain of the rock mass. Our results showed that the measured values and the temporal changes in the displacement of the overpack, the bentonite pressure, and the strain of the rock mass were clearly dependent on the confining pressure. These data were not convergent during the test. Our data experimentally revealed that long-term behavior in the near-field was changed by the geomechanical interaction between the deformation stress of the bedrock/disposal hole and the swelling behavior of the bentonite buffer.
Next, we developed the “heating-type overpack” enclosing a compact electrical heater in a stainless steel. Using the equivalent rock mass, compacted bentonite and the heating-type overpack, the tests were conducted under isotropic stress-constrain conditions. The temperature of the overpack was constantly 95°C. As the result, the values showed similar behaviors to that of the normal temperature tests partially. However, the different behaviors were measured compared with normal temperature tests. In addition, the flow rate of the injection pore water suddenly changed after hundreds of hours. Furthermore, the density of the buffer was lower than that of the normal temperature tests by X-ray CT imaging in the post-tests. We infer that the high temperature

 

overpack influenced the stiffness and the pore water distribution of the buffer, and the density and the soil pressure of the buffer decreased.

Keywords: Geological disposal , Long term behavior evaluation , Centrifuge model test , Geomechanical interaction

 

# An example of activity evaluation of a minor crush zone including subparallel clay veins in granite near the Monju site

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Introduction: Diverse situation of outcropping crush zones around important building constructions need upgrading of activity evaluation method without the use of overlying sediments. The method using the cross-cutting relations among geologic features in basement rocks is promising. However, minor crush zones without cross-cutting relation from intrinsic or extrinsic (restricted outcrop) properties are frequently observed. An activity evaluation of such minor crush zone was carried out in one outcrop. Outline of the crush zone: A crush zone in granite strikes ca. 030 deg. and dips ca. 60 deg. to E, is observed both side of small stream at the outcrop located in SW from the Monju site, Tsuruga Pen., Fukui prefecture, southwest Japan. The width of the zone is a few decimeter and the length of exposure is about 20 m. Sheared clay veins (b1 - b4) of a few centimeters in width run subparallel in the crush zone showing right step arrangement without cross-cutting relations. The b1 is the longest and soft one running through the left (southern) bank of the stream, b2 is the second long one at hanging wall side of the b1, b3 is the third long one at foot wall side of the b1, only b4 is on the right (northern) bank and partly soft. Continuity between the longest b1 on the left bank and the b4 on the right cannot be checked because of the stream and talus covers. Strikes of the b1 change considerably from NNE in the south to NNW in the north. A strike of the b4 is again NNE. The b2 seems straight near the bend of the b1, and pinch-out to the south. The b3 constitutes partly a level difference (eastern side is high) of granite. The level difference and the b1 are covered thick sediments and showing an nonconformity. The hanging wall of the crush zone is hard and constitutes an overhang rock wall, whereas, the foot wall is fragile due to brecciation with irregular crack. Method and result: 1; Geographic and geologic identification of continuation of the crush zone. There is no tectonic relief. There is no crush zone in granite at observed outcrops at the north of the crush zone. 2; A selection of a clay vein to be evaluated and age estimation of the sediment by means of tephlochronology. We select the b1 clay vein based on the longest continuity. Sediments overlying the b1 and b3 is not deformed by shear along the b1 and contain particles of the AT tephra. 3; Kinematic analyses. Normal (east side down) sense of shear is observed in the b1, b2 and b4 accompanied with sinistral or dextral component. In the b3, shear sense indicators are not observed but structures showing sinistral sense of shear with normal component is observed between the b3 and sediments. 4; Search for similar examples of the level difference of the basement rocks. At an outcrop along other stream, a projected clay-rich crush zone and eroded brecciated zone by present differential erosion is observed. 5; Clay size measurement. Clay size (mode) of the crush zone is 3.91 micron and that of an active Shiraki-Nyu fault (high angle reverse fault of N-S strike with dipping to E) near the crush zone is 0.584 micron. The activity of the crush zone (interpretation): The crush zone is minor structure with no tectonic relief. The sediments deposited since 30000 years ago, and the b1 is not active sympathetically at the latest slip of the active Shiraki-Nyu fault (9000 years ago). The crush zone sheared at multiple stage of deformation but inconsistent with the stage of the active fault, and the level difference seems to be shaped by differential erosion of brecciated zone and buried by sediments. The interpretation that the crush zone is small structure is reinforced by the lesser pulverized clay in the b1 indicating lesser cumulative displacement. These lines of evidence suggest that the crush zone is not an active fault as an expression of a seismogenic fault, or a

 

weak zone which slips accompanied with the active zone.

Keywords: crush zone, fast breeder reactor “Monju”, granite

 

# Estimate of variation of radioactive cesium sedimentation in a soil saving dam with the 3D laser scanner

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We investigate a soil saving dam to estimate amount of radioactive cesium flowing out from forest. A target soil saving dam is located in Abukuma mountain area. We measured amount of sediment with 3D laser scanner and calculated change of amount of sediment. As a result, variation of sediment are 0.5 $m^3$ form Aug. 9, 2013 to Dec. 3, 2014, 0.1 $m^3$ from Dec. 3, 2014 to Sep. 2, 2015 and 1.8 $m^3$ from Sep. 2, 2015 to Dec. 1, 2015. Amount of cesium sedimentation is estimated 720 MBq.

Keywords: accident at the Fukushima Daiichi Nuclear Power Station, 3D laser scanner

 