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Retardation capacity of altered granitic rock distributed along fractured and faulted zones in the orogenic belt of Japan

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A B S T R A C T

There are wide areas of granitic rocks in the Japanese orogenic belt. These granitic bodies inherently contain fracture and fault systems associated with alteration zones. However, relatively little attention has been given to the possible influence of such widely distributed alteration zones on the migration of radionuclides from any radioactive waste repository that might in future be sited within granitic rock. In particular, the influences of alteration products and micro-fractures, due to chemical sorption and/or physical retardation require further consideration. In order to understand the retardation capacity of the altered deep granitic rocks, detailed geometrical characterization of pores, geochemical analysis, and batch sorption and flow-through experiments have been carried out. These results show that the altered granite has a large volume of accessible pores, particularly in potassium-feldspar grains, which would influence nuclide retardation more than the accessible porosity in other minerals present, such as biotite. The distribution coefficients, Kd estimated from batch sorption tests and flow-through experiments suggest that altered granite has a high capability to retard the migration of nuclides. The retardation would probably be due to sorption on altered minerals such as sericite and iron hydroxides formed along grain boundaries and in pores created by dissolution, in addition to sorption on primary sorptive minerals. These results provide confidence that even altered and fractured parts of any granitic rock that might be encountered in a site for the disposal of high level radioactive waste may still retard radionuclide migration and thereby help the geosphere to function as a barrier.

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1. Introduction

Most of the Mesozoic granitic rocks of Japan were intruded after the early Mesozoic accretionary complex, referred to as ‘mélange’, was formed as the basement of the Japanese archipelago (e.g. Isozaki, 1996). After the intrusion, the stress regime caused by the subduction of the Pacific Plate and Philippine Plate, continued and generated several fault and fracture systems in each granitic body (e.g. Yoshida et al., 2000, 2005). During the development of these fault and fracture systems, groundwater penetrated into the granitic bodies. The water circulated through these pathway structures, resulting in water–rock interactions. These secondary geochemical interactions are considered to be the major processes responsible for the alteration along the fractured and faulted zones. The alteration zones are often pervasive throughout the entire host rock. For example, Mesozoic granitic rock such as the Toki granite (Cretaceous) of central Japan (Yoshida et al., 1989; Nishimoto et al., 2008) and the Kamaishi granodiorite (Jurassic) of northern Japan (Suzuki et al., 1996; JNC, 1999) also include frequent altered zones accounting for about 30% and 25% of the respective rock masses to depths of about 1000 m (Osawa et al., 1993). Mesozoic granite distributed in the Chugoku area of western Japan is also similarly altered (Yoshida et al., 2008). These observations suggest that altered zones would be inevitably encountered in and around a repository sited in granitic rock in Japan. To build confidence that there would be no detrimental effects on long-term safety in this case, it is necessary to evaluate how such altered zones might influence the barrier function against the migration of radionuclides (Fig. 1).

Most evaluations of the contaminant retardation processes in granitic rocks likely to be important in geological disposal of high level radioactive waste (HLW) usually consider the present characteristics of relatively unaltered host rocks (e.g. Nagra, 1994; SKB, 1999; JNC, 2000). In the orogenic belt that is formed by accretionary complex, there are wide areas underlain by Mesozoic to Tertiary granitic rocks. The rocks in each area are distinctive bodies that are partly distinguished by the characteristics of the fractures and fault systems and the hydrothermal alteration zones (Yoshida et al., 2000, 2008). However, relatively little attention has been given to the potential influence of such alteration zones on the barrier function of the geosphere that would form part of any future radioactive waste repository system. In particular, these alteration characteristics imply that groundwater and solutes can be conducted through fractures and faults or crushed zones (e.g. Nishimoto et al., 2008). The alteration also readily illustrates that certain contaminants might react and be...
retarded by the secondary alteration products and open pore geometry, due to chemical sorption and/or physical retardation. However, the detailed characteristics of altered granitic rocks and minerals and their influences on nuclide migration and retardation are not well understood. Thus, these processes are insufficiently taken into account in safety case development (OECD/NEA, 2004), particularly that considered in Japan. The influence of the interaction between altered rock/minerals and nuclides is therefore important in understanding the long-term barrier function of host rocks as well as the behavior of elemental migration in a geological environment.

2. Studied materials and methodology

In order to evaluate the retardation capacity of altered deep granitic rocks, 700 m long drill core taken from Mesozoic granitic rock (Horikawa et al., 2003) in the Chugoku area of Japan has been investigated. The rock is characterized by coarse grains of potassium-feldspar, quartz and biotite (Fig. 2; a-1, b-1). The borehole logging and core observations show that there are several fractured and faulted zones, and almost all these structural features are associated with alteration by water–rock interaction (Nishimoto et al., 2008). The widest alteration zone identified within the drilled cores extends for about 10 m on each side of a fractured zone at a depth of 230 m. Flowmeter logging suggests that the fractured zone is a groundwater-conducting pathway (Horikawa et al., 2003). For almost 20% of the total drilled length, the cored rocks have been altered by water/rock reactions characterized by chloritization of biotite and oxidized precipitation at the mineral grain boundaries. The alteration has been progressed due to geothermal activity during granitic body uplifting (Yoshida et al., 2008).

The philosophy was to examine the detailed characteristics of a small number of samples, rather than attempt to obtain data from a large number of samples, which in any case would yield little additional non-site-specific data. Accordingly, two samples (altered Granites 1 and 2) from the altered zone from the depths below 230.10 m from the ground surface and one sample of fresh granite from a depth of 81.50 m below the ground surface were collected for detailed analysis. Detailed analysis of pore geometry, geochemical analyses and mineralogical observations were carried out in order to reveal the changes in morphological and geochemical characteristics due to alteration. After the mineralogical and geochemical characterizations, batch sorption and flow-through migration experiments were conducted to estimate the retardation properties and/or sorption capacities of the altered rocks.

2.1. Porosity measurement and characterization

The analysis of pore structure involved, firstly, measurement of the effective porosities of rock specimens (\( \phi \approx 1.5 \text{ cm} > 2.0 \text{ cm length} \)) by the water saturation method. Specific surface areas and pore diameters were also measured by means of a nitrogen gas adsorption method. Adsorption/desorption isotherms were obtained for the crushed granite samples by step-wise nitrogen sorption at 77 K for 40 relative nitrogen pressures; \( P/P_0 \) (\( P \) and \( P_0 \) are respectively the equilibrium and saturation pressures of nitrogen at the temperature of adsorption), after heat treating the samples at 423 K for 5 h under a vacuum. The specific surface area and average pore size were calculated by the BET (Brunauer–Emmett–Teller) and BJH (Barrett–Joyner–Halenda) methods respectively to characterize the micro-size porosity that is accessible to nuclides. The measured specific surface areas are given in Table 2. The BET method calculates the specific surface area from the isotherm for adsorption of a nitrogen monolayer (\( P/P_0 = 0.05-0.35 \)), calculated using the cross-sectional area of a nitrogen molecule. The BJH method calculates the radius of mesopores (2–50 nm) from the desorption isotherm by assuming that the desorption process proceeds by capillary evaporation of nitrogen from the interior of the pores, governed by the Kelvin equation (Suzuki, 1990).

2.2. Geochemical analysis

After the determination of their porosities, the rock samples were air-dried and embedded in epoxy resin (Epoxy-154); they were then polished and thin-sectioned. The micro-textures and mineralogies of the resulting sections were observed by optical microscopy. Subsequent chemical mapping and quantitative analyses were also carried out to determine the spatial variations in geochemical characteristics using an X-ray analytical microscope (SXAM, XGT-2000V Horiba Japan). This is a type of X-ray fluorescence analyzer, which shows the distribution of elements across the surface of a sample (Hosokawa et al., 1997). A high-intensity continuous X-ray beam (Rh anode 50 kV 1 mA) 100 µm in diameter is focused with a guide tube and directed onto the surface of the sample on a PC-controlled X-Y stage. X-ray fluorescence from the sample surface is detected with the hp-Si detector of an energy-dispersion spectrometer. X-ray fluorescence maps for the major elements can be produced simultaneously with a transmitted X-ray image.

2.3. Sorption and flow-through experiments

The capability of the rock to retard migrating elements was investigated by means of batch sorption and flow-through experiments. These experiments were conducted using synthetic groundwater under atmospheric conditions and Cs to represent a radionuclide, as shown in Table 1. Cs is a key element in the HLW inventory and therefore has a high priority for investigation (JNC, 2000).

Batch sorption experiments using each three powdered rock samples (\( \phi \approx 100 \mu \text{m} \)) were carried out first. The configuration of these batch sorption experiments, was such that the adsorbate could easily access sorption sites owing to the solid being dispersed homogeneously and the solution/rock volume ratio being large (10 cm\(^3\)/g) relative to the intact system. In each experiment the distribution coefficient, \( K_d \) as shown below, of Cs was obtained from the concentration of Cs in the solution at equilibrium and the quantity of sorbed Cs obtained from mass balance.

\[
K_d = q (\text{the amount of Cs sorbed on the rock} \left[ \text{mol} / \text{g} \right]) / C (\text{the concentration of Cs in the solution} \left[ \text{mol} / \text{l} \right]).
\]

The flow-through experiments were performed to observe sorption/migration behaviors in the intact rock. Instead of a diffusion experiment which needs longer time because of its low diffusivity, to
determine the retardation function of the intact rock within a feasible time frame, an accelerated fluid transport technique, of which configuration will be described later, was employed. This technique accelerates the transport of water through the open porosity of the low-permeability intact rock by centrifugation. A centrifuge produces a constant saturated flow (steady state flow) in an intact core sample up to a few cm in length, within a relatively short period of time (several hours) while avoiding development of a large pressure gradient. Consequently, this method allows the retardation behavior (breakthrough curve) of the core samples to be evaluated much more rapidly than is possible by the conventional through-diffusion technique (Conca and Wright, 1998).

The instrument consists of an ultracentrifuge with sample buckets consisting of both microdispersal cells and effluent collection chambers attached symmetrically to the rotor as shown in Fig. 3. A granite core ($\varphi 1.5 \times 2.0$ cm) sample mounted in a leak free resin capsule was placed in each sample chamber and the upper cell was filled with a test solution ($C_0: 1 \times 10^{-5}$ mol L$^{-1}$ Cs). The sample was centrifuged at 3000 rpm to introduce and accelerate the test solution into the rock. The Cs concentration in the effluent, $C$, was analyzed by
The electrical conductivity of a rock measured by the electrical bridge method reported elsewhere (Conca and Wright, 1990) using rock samples saturated with 0.1 M KCl aqueous solution.

Diffusivities of the rock samples were measured separately by an electrical bridge method reported elsewhere (Conca and Wright, 1990) using rock samples saturated with 0.1 M KCl aqueous solution. The electrical conductivity of a rock measured by the electrical bridge method is related to the diffusion coefficient of solute ion, $K_+^c$, in the rock, based on the following Nernst–Einstein relation.

$$D = \frac{RT \Lambda}{F^2 z^2}$$

where $D$, $R$, $T$, $F$, $\Lambda$ and $z$ are respectively the diffusion coefficient of the ion, the gas constant, absolute temperature, Faraday’s constant, the equivalent conductance of the ion and the absolute value of the charge on the ion. The conductance is related to the rock/cell system by the following equation.

$$\Lambda = \frac{Kt}{C_i} = \frac{Gt}{C_i}$$

where $K$, $t$, $C_i$, $\theta$, and $G$ are respectively the specific conductance, the transference number of the ion, the cell constant for the conductivity cell and the measured conductance of the conductivity bridge. Comparisons between diffusion coefficients calculated from the electrical conductivity measurements, and self-diffusion coefficients obtained by the conventional diffusion method have yielded a good agreement for soil and gravel (McDuff and Ellis, 1979; Conca and Wright, 1990). Diffusion coefficients of the $K^+$ ion in the rocks were obtained from the electrical conductivity measurement for the series of granite samples.

2.5. Accessibility of pores in the intact rock

The accessibility of sorption sites in the rock depends on the migration paths in the intact system. The accessibility of pores in the each one granite core sample used in the flow-through experiments was deduced from observations by Electron Probe Micro Analyzer (EPMA, Shimazu co. ltd.). The rock sample impregnated by a contrast medium ($3Na_2WO_4 \cdot 9WO_3$; sodium metatungstate) using the centrifuge system was prepared. Rock samples were removed from the centrifuge system, sectioned and dried in an electric oven. The sections were then examined by EPMA to characterize the flow paths in orientations perpendicular to the flow direction. The spatial resolution of EPMA is around 1 µm.

3. Results

3.1. Altered granite characteristics

Microscopic observations and geochemical analysis by SXAM show that the alteration of granite was characterized by the formation of secondary micro-fractures and elemental dissolution or precipitation due...
to water–rock interaction. The typical features of alteration identified by optical microscopy and SXAM mapping are shown in Fig. 2 (a–2–5, b–2–5).

Microscopic investigations show that the altered granite is characterized by a network of micro-fractures (Fig. 2; b–2). These micro-fractures are sometimes filled by calcite and Fe-oxides (Fig. 2; b–2, b–1b–5). Along the micro-fractures, most of the biotite is altered to chlorite, and potassium-feldspar grains also contain sericite microcrystals, which were probably formed by relatively high temperature fluid penetration through the micro-fracture network (Yoshida et al., 2008).

The optical microscope observations and the SXAM mapping show that during potassium-feldspar and plagioclase alteration, most of the altered rocks also suggest that Fe was dispersed in the rock matrix. Morphological features of Fe-bearing phases in both unaltered and altered rocks are characterized by a network of micro-fractures (Fig. 2; b–2–5). The porosity of the altered rock has been increased to almost twice that of the unaltered rock. The estimates by the nitrogen adsorption isotherms with the BET method, are shown in Table 3. This result indicates that the interconnected porosities of the altered samples are higher than those of the unaltered samples. Thus, the increased interconnected porosities, and consequently higher specific surface area in the altered samples. However, the diffusion coefficients of the K+ ion in each rock, obtained by the electrical bridge method, are shown in Table 3. This result indicates that the interconnected porosities of the altered samples are higher than those of the unaltered samples. The increase of specific surface area in the altered samples. However, the diffusion coefficients of the K+ ion in each rock, obtained by the electrical bridge method, are shown in Table 3. This result indicates that the interconnected porosities of the altered samples are higher than those of the unaltered samples.

Table 3 Diffusion coefficients of K+ measured by the electrical bridge method on each granitic rock saturated by 0.1 M KCl.

<table>
<thead>
<tr>
<th>Sample</th>
<th>D [cm² s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaltered Granite</td>
<td>5.5 × 10⁻⁶</td>
</tr>
<tr>
<td>Altered Granite 1</td>
<td>4.0 × 10⁻⁵</td>
</tr>
<tr>
<td>Altered Granite 2</td>
<td>4.3 × 10⁻⁵</td>
</tr>
</tbody>
</table>

Fig. 5. a) Breakthrough curve as a function of pore volume for altered Granite 2. b) Kd′ calculated from the breakthrough curve or altered Granite 2.

3.2. Pore geometry characteristics

Results of the characterization of rock properties, i.e. rock density, effective porosity, specific surface area and pore size measured by the nitrogen gas adsorption technique are shown in Table 2. The density of the rock has been slightly decreased by the alteration, probably due to open micro-fracture formation (see Fig. 2;b–2). The porosity of the altered rock has been increased to almost twice that of the unaltered rock. The estimates by the nitrogen adsorption isotherms with the BET and BJH analysis show that in altered rocks, the specific surface areas and the adsorption capacities for nitrogen have values that are more than 20 times higher than those in the unaltered rocks. The average pore size has also increased in the altered rocks (Table 2). These data imply that the pore geometries have been changed drastically during the alteration. The results indicate that the altered rock has a relatively high porosity that is accessible, and also has a relatively high surface area that could contribute to nuclide sorption.

3.3. Kd and flow-through migration experiments

The Kd values obtained from the batch experiments and the Kd′ values from the flow-through experiments are shown in Figs. 4 and 5(ab), respectively. Compared with the batch mode distribution coefficients (Kd) obtained from the unaltered rocks, those of altered granite samples are similar or a slightly higher (Fig. 4). Flow-through data were obtained only for the altered rock, since the focus of the work is to understand the potential ability of such rock to retard radionuclides. These flow-through data gave Kd′ values reached values near the Kd values obtained from the batch experiments, indicating retardation by sorption.

Although the cause of first peak shown in Fig. 5b is not clear, but rest of the Kd′ obtained from the flow-through experiment reached values near the Kd values obtained from the batch experiments, indicating retardation by sorption. These results are probably due to higher sorption capacities of the secondary minerals (e.g. chlorite, sericite and iron hydroxides) relative to the primary minerals, and the increase of specific surface area in the altered samples. However, the diffusion coefficients of the K+ ion in each rock, obtained by the electrical bridge method, are shown in Table 3. This result indicates that the interconnected porosities of the altered samples are higher than those of the unaltered samples. Thus, the increased interconnected porosities, and consequently higher specific surface areas, may also at least partly explain the higher Kds of the altered samples.

A porosity increase was also confirmed by EPMA examination of a thin section of altered Granite 2, following impregnation by a medium of high-contrast, as shown in Fig. 6. The existence of micro-pores (green area) in each mineral particle, especially in potassium-feldspar, was confirmed by the presence of the contrasting medium in the pores. The results shown in Fig. 6 also indicate that the pores in the altered rock are accessible to migrating fluid.

4. Discussion

The altered granitic rock is characterized by secondary micro-fractures and mica minerals such as chlorite and sericite that replace biotite and potassium-feldspar as shown in Fig. 2. Fe-oxhydroxides

Fig. 6. EPMA picture of accessible micro-fractures in the altered Granite-2 impregnated by a contrast medium (3Na₂WO₄·9WO₃; sodium metatungstate solution) reflected as green color (arrow) showing micro-fracture or pore distributed in the polished thin section. The green area indicates the existence of contrast medium introduced by the centrifuge technique. K-Feld: potassium-feldspar, Qz: quartz, Bt: biotite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
are also commonly observed along the grain boundaries and fill the micro-fractures at depths up to several hundred meters below the ground surface; about 300 m in the case of Toki granite (Nishimoto et al., 2008). These secondary minerals, especially Fe-oxyhydroxides, are considered to effectively influence nuclide retardation by sorption. This process has been clearly shown elsewhere by using analogous elements such as natural Uranium series nuclides (Akagawa et al., 2006). Additionally, the porosity that would be accessible by migrating nuclides has also been increased due to the formation of the micro-fracture network. Such micro-fractures might influence the barrier function negatively by forming fast pathways for fluid as well as nuclides. However, connected micro-fractures could influence the barrier function positively by enhancing retardation due to the diffusion of nuclides into rock matrix i.e. matrix diffusion (Steefel and Lichtner, 1994). It is therefore crucial to understand how these mineralogical and physical changes combine to affect the overall barrier retardation function of the altered granite rock.

The characteristics of rock shown in Table 2 provide indirect information about the sorption capacity as well as the physical structure of the pores. The Kds depend on the specific surface area of a sample, being a measure of a rock’s sorption capacity (IRI, 2007). The specific surface area clearly correlates positively with the extent of alteration. This result is to be expected in view of the greater degree of micro-fracturing and larger quantities of fine-grained secondary minerals in the more altered samples.

The Cs breakthrough curve given by the flow-through experiment shows that the acceleration method is applicable for estimating the Cs retardation behavior in the intact system, even in the micro-fractured altered rock. The estimated value is of a similar order of magnitude to the sorption capacities measured by the batch sorption experiment. This result suggests that the retardation of Cs probably occurs by sorption onto altered minerals in the intact system. The Kd value probably reflects mainly the influences of both the relatively high sorption capacities of secondary mica minerals and Fe-oxyhydroxides (e.g. Missana et al., 2003) and the large accessible porosity that is due to micro-fracture networks formed particularly in the potassium-feldspar grains shown in Fig. 5 as accessible pores. Less important is the accessibility of other, primary mineral grains, for example biotite. Thus, the present work suggests that sorption on secondary mineralization is relatively more important than sorption on primary grains, which has been previously investigated by sorption experiments (e.g. Johansson et al., 1998).

The diffusion coefficient of K+ obtained from the electrical bridge method is considered to be an acceptable measure of a rock’s diffusivity (Table 3). More than one order of difference in diffusivity between unaltered and altered granite is identified. Such change is also shown in other granitic rock in Japan e.g. Kamishi granite rock, measured by static through-diffusion experiment with NaCl solution (Yoshida et al., 2002).

The breakthrough curve shown in Fig. 5b has a plateau region but is not a simple sigmoid elution curve, indicating that more than one sorption mechanism is operating. Following the sorption experiments, heterogeneous sorption of Cs on the walls of micro-fractures cutting potassium-feldspar and biotite, and on inter-mineral particles around biotite were observed by EPMA analysis of thin sections of rock (Seida et al., 2007). The Kd values increased with decreasing particle sizes of crushed samples, but the Kds normalized by specific surface area of each sample revealed almost the same value (Seida et al., 2007). These results suggest that both geometrical factors and geochemical factors (including mineralogical changes in altered rocks), will contribute to radionuclide retardation and hence the maintenance of the geosphere barrier function. In the granite, the proportion of potassium-feldspar grains is usually larger than the proportion of biotite grains. The physical and chemical contribution of potassium-feldspar grain alteration to the total barrier function of the intact granitic host rock will therefore potentially be important, even if the alteration occurred during past orogenic activity.

The implications of these results for the retardation of radionuclides in fractured granitic rock can be illustrated by calculating retardation factors, RΓ, as follows:

\[ R_f = \gamma \left( 1 + \frac{\nu K_d \rho}{\phi} \right) \]

where: \( R_f \) is the retardation factor, \( \gamma \) is a dimensionless exclusion factor for the species being transported, \( \rho \) is the bulk density of the rock in kg m\(^{-3}\), Kd is the distribution coefficient in m\(^3\) kg\(^{-1}\) and \( \phi \) is the dimensionless porosity. The exclusion factor, \( \gamma \) represents the proportion of the pore space of the rock that is accessible to a migrating solute. In practice, the term is typically used to account for the process of anion exclusion, by which negatively charged mineral surfaces act to repel anions, thereby preventing them from entering the rock’s porosity (e.g. Nirex, 2003). In contrast, cationic species and neutral species may be able to access the pores readily.

Values of \( R_f \) for the unaltered and altered granite samples, calculated using the parameter values given in Table 2 and Fig. 3, are given in Table 4. In making the calculations, the exclusion factor has been set to 1 in all cases, in recognition of the fact that Cs will be transported predominantly as Cs\(^+\), so that anion exclusion will not occur. However, the observed pore geometries and the measured diffusivities of K\(^+\) (an analogue for Cs\(^+\)) described above suggest that, compared to the altered granite, a smaller proportion of the fresh granite’s porosity will be accessible to migrating Cs. Although appropriate values for \( \gamma \) cannot be chosen confidently, it can be stated that the retardation factor for the intact granite in Table 4 overestimates the true value due to the exclusion factor. Furthermore, the differences between the retardation factors of the altered and unaltered granites given in this table are likely to be maximum values because of the changes of porosity by alteration.

The calculation suggests that Cs migrating through either the fresh or altered granite would be retarded by a factor in the order of 10\(^4\) relative to the flowing water. The transmissivity of the altered zones is unknown, so the actual increase in travel time for a given head gradient cannot be estimated. However, at Kamishi, the logarithmic mean transmissivity of fractures in granodiorite, as determined by double packer tests, was 1 × 10\(^{-9}\) m\(^2\) s\(^{-1}\) (JNC, 2000). To illustrate the potential effects of retardation, a plausible maximum hydraulic gradient of 1 can be assumed. This value compares with the maximum value of about 0.4 that has been observed in deep (> a few hundred meters) groundwater systems in Japan (JNC, 2000); a value of 1 would be appropriate for the disturbed zone around an underground excavation (beyond the “skin” surrounding the excavation). Such a high hydraulic gradient would cause Cs to be transported at a maximum velocity in the order of 10\(^{-13}\) m s\(^{-1}\). That is, the Cs would be to all intents and purposes be immobile. It must also be remembered that the half-life of Cs\(^{137}\) is only 30.23 years. Thus, it
seems inconceivable that any Cs\textsuperscript{137} migration from any future repository could occur over a significant distance.

The results presented in this paper give insights into nuclide retardation processes that are expected to be occurring in any altered and fractured granitic rock. However, additional site-specific information would be needed to judge the overall implications of these processes for safety at any actual radioactive waste repository site. In particular, it will be important to obtain information about the nature of fracture surfaces and the nature and abundances of mineral coatings that might prevent migrating solutes from accessing the rock matrix. Transmissivity data for the fractures in altered and unaltered rock, and the numbers and spacing of these different kinds of fractures will also be required.

5. Conclusions

Alteration occurs widely along fractures and fault zones in deep granitic rocks distributed in the orogenic areas of Japan and likely to be encountered when a large underground facility is constructed within Japanese granitic rock. It is therefore important to evaluate the influence of this alteration on the barrier function of the geosphere with respect to radionuclide migration. Such an evaluation will help to build confidence in the long-term safety of any high level radioactive waste (HLW) repository that might be sited within Japan in granitic rock.

Microscopic observations, including examination of pore geometries, combined with flow-through experiments, suggest that altered granite has a large pore volume that would be accessible to migrating radionuclides. These nuclides would then be sorbed on the surfaces of minerals that connected or intersected by micro-cracks and pores. The sorption capacity is probably contributed mostly by secondary mica minerals and Fe-oxyhydroxides. These results suggest that altered granite has a capability to retard radionuclides. Consequently, it would be conservative to treat such alteration as an adverse factor when assessing radionuclide migration. Such an evaluation will help to build confidence in the long-term safety of any high level radioactive waste (HLW) repository. However, it must be recognized that the overall effect of fracturing and faulting on the barrier function of the geosphere will reflect the relative influences of these radionuclide retardation processes and any enhancement in hydraulic conductivity that might be caused by the fracturing and faulting. These relative influences will need to be determined on a site-by-site basis.

The results of this investigation could be used to contribute to a safety case by building confidence in the long-term barrier function if a repository site will be chosen at the area of granitic rocks under the orogenic stress field presented in Japan. The knowledge may also be useful for other tectonic settings as well as for characterizing the altered granitic rocks for the possible site of a HLW repository.

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