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Long-term stability of flow-path structure in crystalline rocks distributed in an orogenic belt, Japan

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Abstract

Most evaluations of the contaminant retardation processes likely to be important in geological disposal (e.g. for high level radioactive waste (HLW)) consider only the present characteristics of fractures and associated mineral infills. Relatively little attention has been given to possible long-term changes in these features, and their influence on groundwater flow. The work reported here seeks to provide analogous evidence that such changes are not likely to be important and hence to improve confidence in the presently adopted evaluation methodology and its long-term applicability.

In the orogenic belt that is formed by the Japanese islands, there are wide areas of crystalline rock. The rocks in each area have a distinctive age sequence which is partly reflected in the characteristics of the fracture systems and associated mineral fillings that occur. These characteristics generally imply that groundwater and solutes can be conducted through fracture networks, except in the cases of fault zones or crushed zones. The structural and mineralogical features of these networks readily illustrate how certain contaminants might react and be retarded by the fracture fillings and open pore geometry, due to chemical sorption and/or physical retardation.

Here, we describe the fracture systems developed in crystalline rocks with different ages that are intruded into the Japanese orogenic belt. The aim is to build a model for the long-term fracturing process and hence to evaluate fracture 'stability'. In particular, the comparisons are made between the fracture geometries and the frequencies observed in the 1.9–0.8 Ma Takidani Granodiorite (the youngest exposed pluton in the world), the ca. 67 Ma Toki Granite and the ca. 117 Ma Kurihashi Granodiorite located in central to northwest Japan. The observations show that all these crystalline rocks have similar fracture frequencies, with 1 to 2 fractures per meter in the massive part of rock bodies. Mineralogical studies and dating analyses of fracture fillings also suggest that fractures are relatively physically stable. Major new fractures tend not to be created in the massive part of rock bodies even when a pluton has been subjected to the regional stresses of plate movements with a duration of about 100 Ma. The results show the unique characteristics of the fracture forming process and the relatively stable geometries of fracture network systems in crystalline rocks distributed within the orogenic belt. This analogue also enables us to provide a model to build confidence in a technical approach applicable for modeling of hydrogeology and geology over long time scales under the

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orogenic stress field present in Japan. The model may also be useful for other stable tectonic settings as well as for a characterizing sites in crystalline rocks for the possible geological disposal of HLW and other toxic wastes.

Keywords: Fracture; Flow-path; Crystalline rocks; Long-term stability

1. Introduction

Fractures and joints are usually developed in any type of crystalline rock and have been studied both from geological and rock mechanical viewpoints (e.g. Barton and Zoback, 1990). Fractures are also expected to act as conduits, barriers, or combined conduit–barrier systems that enhance or impede groundwater flow and contaminant transport (e.g. Caine et al., 1996; Barton et al., 1995). The possibility that fractures may conduct water has inevitably to be taken into account by hydrological models and solute transport models of various kinds that are employed in connection with the subsurface disposal of long-lived waste, e.g. geological disposal of High Level Radioactive Waste (HLW) and heavy metal waste. Evaluations of the long-term influence of water conducting fractures are therefore important to provide a basic geological framework for simulating water and solute transport, particularly in possible host rocks that are located in relatively unstable tectonic settings such as accretionary complexes at continental margins (e.g. Isozaki, 1996). However, the processes of long-term fracturing and/or the regional stability of fractures developed in crystalline rocks distributed within an orogenic belt have not been well described.

Fractures generated in crystalline host rocks are key features to affect the functioning of a geological barrier. Particularly, fracture frequency, geometry and fracture fillings are important factors that may control the hydrological characteristics and retardation processes influencing solute migration in the geological environment (Steefel and Lichtner, 1994; Mazurek, 1994; Yoshida et al., 2000). The long-term stability of these structural features should be taken into account for the development of a realistic model to evaluate the processes of toxic element and/or nuclide migration from long-lived waste, especially for HLW geological disposal. However, fracture generation processes over long periods and the subsequent stability of fractures are relatively poorly known. This limitation limits confidence in the development of realistic configurations for the structural models on which long-term safety assessments are based.

In the orogenic belt of Japan, crystalline plutons with different ages, ranging from the order of 1 Ma to 100 Ma, have been identified. These plutons form massive areas, some of which may have a possibility to be selected as waste disposal sites in Japan. The fracture systems identified within these rock masses imply that groundwater and solutes may be conducted through the fracture network (Yoshida et al., 2000). It is expected that the solutes can be retarded by the processes of chemical sorption and/or physical retardation during migration (JNC, 2000). However, the present evaluation framework applied to the nuclide retardation processes as well as the hydrological modeling, usually takes into account only the present fracture geometry and gives little consideration to any changes of structural and mineralogical characteristics and their influence on the groundwater flow system over long periods of time. Such a framework may not be realistic when used for assessing the long-term behavior for long-lived waste, e.g. ca. 10^5 to ca. 10^6 years in the case of HLW.

The study presented here has tried to describe the ‘stability’ of fracture systems developed in host rocks located in the orogenic continental margin. The purpose is to characterize the long-term fracture growth patterns and the rates of fracture generation within crystalline rocks of different ages that are intruded into the Japanese islands. In particular, a comparison is made between the plutons of the 1.9–0.8 Ma Takidani Granodiorite (the youngest exposed pluton in the world; Harayama, 1992), the Toki Granite of around 67 Ma located in central Japan (JNC, 2002) and the Kurihashi Granodiorite of about 117 Ma (Suzuki et al., 1996) located in central to northwest Japan.

It is known that the plate tectonic setting of Japan has evolved during a rather complex tectonic history and the present setting is considered to have been formed at about 20 Ma (Jolivet et al., 1994; Sato, 1994). However, even though older plutons have different stress histories to more recent ones, after exposure, both old and young rock masses might have been subjected to the same regional stress field caused by tectonics and/or by plate movements in the Japanese orogenic belt. The comparison of the fractures identified in these plutons therefore provides unique insights into the characteristics of the fracturing and the geometrical formation processes. These insights enable us to develop an appropriate theoretical basis for assessing the development and long-term stability of fractures within an orogenic geological setting.

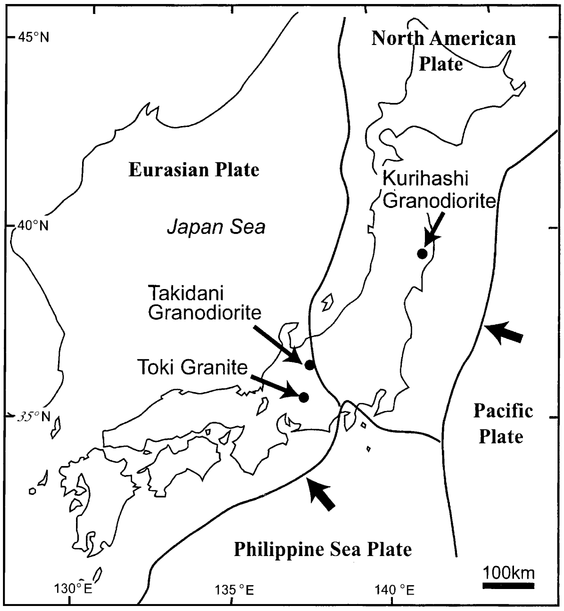

Fig. 1. Location map of plutons investigated their fracture system in Japan. Japanese islands are regionally subjected to the regional stress by the movement of several plates and their boundaries shown as subduction zone distributed around the continental margin.

2. Field observations and fracture analysis

Three crystalline rocks with different ages have been investigated to compare their fracture geometries, the characteristics of fracture growth patterns and the development of fracture network systems (Fig. 1). These are the Takidani Granodiorite (ca.1 Ma; Harayama, 1992), which is known as the youngest exposed plutonic rock in the world, the Toki Granite (ca. 67 Ma: JNC, 2002), which has been studied during the planning of a deep underground laboratory, and the Kurihashi Granodiorite (ca. 117 Ma: Suzuki et al., 1996), which is exposed in one of the biggest iron mines that was operated in Japan. This latter was also used as a prototype underground research facility aimed at understanding the deep geological environment (JNC, 1999). A brief geological description of each pluton is as follows.

2.1. Takidani Granodiorite

The youngest crystalline rock is identified in the central mountain range of Japan and is described by Harayama (1992). Rb–Sr, K–Ar and fission-track ages show that the pluton intruded at about 1.9–0.8 Ma. After intrusion, the pluton was uplifted to form one of the highest mountain ridges in central Japan with an elevation of about 2000 m. The Takidani Granodiorite is exposed within a wide rocky mountain range that is 13 km long and up to 4 km wide, with elevations between 1450 m and 2360 m above the sea level. This pluton intruded Mesozoic sedimentary basement rocks, Tertiary granitic rocks and Quaternary volcanic rocks. The Takidani Granodiorite is a vertically zoned pluton, grading from equigranular, medium-grained biotite–hornblende granodio-biotite granodiorite in the deeper parts, to hornblende-bearing porphyritic biotite granite in the shallowest parts (Harayama, 1992, 1994).

Detailed fracture analysis of newly exposed rock surfaces has been carried out in several valleys that traverse from the margins to the core of the pluton and their spatial characteristics have been reported (e.g. Kano et al., 2000). From the detailed field observations, a three dimensional fracture network system was identified and the fracture spacing was measured. The fracture spacing and the frequency of fracturing were found to vary from the margin to the core of the pluton from 1 to 3 per meter. However, the number of traceable fractures does not exceed more than 3 per meter (Table 1). Here, traceable fractures are defined as fractures that extend over length scales of several meters or greater. The mineral fillings of these

Table 1
Result of fracture spacing analysis carried out for Takedani pluto

	Sea level (m)	Number of data	Average (cm)
Margin	1550	33	33
↑	1810	46	57
Core	1820	15	117
	1835	6	151
↓	1840	15	101
Margin	1900	14	55

Number of data shows the measurement points in vary (out crop) crossed the pluton from margin to core part (modified from Kano et al., 2000). Average of fracture spacing suggests that the core part has relatively wider space than the margin, but not exceed more than 3 per meter.

traceable fractures were also identified. They are mainly composed by very thin-layers of calcite and partly iron oxide, suggesting that relatively oxidizing water has penetrated. The evidence suggests that the oxidized groundwater penetrated after the formation of fractures located close to the ground surface.

2.2. Toki Granite

The Toki Granite is one of the Ryoke type granitic rocks which were intruded during Cretaceous to Paleogene times (Suzuki and Adachi, 1998). It is distributed in central Japan and for more than 10 years has been investigated as a candidate for an underground research facility to investigate the deep geological environment (JNC, 2000).

The K–Ar age of the Toki granitic rock indicates that it intruded at about 70 Ma (Shibata and Ishihara, 1979). Recently a slightly younger age of ca. 67 Ma was obtained by using the CHIME method (JNC, 2002). The rock mainly consists of medium- to coarse-grained biotite and medium-grained hornblende–biotite porphyry, and is partly intruded by quartz porphyry and aplite dikes. Some rock mechanical properties such as tensile strength (ca. 12.4 MPa) and fracture toughness (ca. 2.4 MPa $m^{1/2}$) have also been characterized (Stephansson et al., 2003). The lithofacies and fracture density have been investigated in several deep boreholes with depths of around 1000 m. Core logging and detailed observations suggest that single fractures with infills occur at almost every meter in all core samples (Koide and Maeda, 2001). Fractures of this type are also observed in the outcrops of this area and typically form features that are quite traceable, with lengths of at least several meters. Except for highly fractured zones caused by faulting and/or stress release (Saegusa et al., 2003), that were identified from the rock fabric and microscopic structures, fracture analysis of the host rock indicated that the average fracture density of background fracturing is 1.5 to 2.8 per meter (Yoshida et al., 1989). Borehole TV data down to depths of 1000 meters also show that the frequency of such presumably traceable single fractures with infills varies little and suggests a relatively uniform distribution in the massive part of host rock (JNC, 2002).

The detailed fracture pattern and fracture fillings observed in the core specimens were also studied (Yoshida et al., 1989; Iwatsuki and Yoshida, 1999a). It is noted that calcite coating, iron oxide, sulfide and clay minerals on the fracture surface were identified. These fillings usually have a zonal structure parallel to the fracture surface, suggesting an episodic development process as the fracture opened during uplift and/or by tectonic stress variations. An isotopic study shows that the present groundwater originated mainly from rain water and suggests a relatively young age of at least some calcium carbonate precipitation (Iwatsuki and Yoshida, 1999b; Iwatsuki et al., 2002).

2.3. Kurihashi Granodiorite

The Kurihashi Granodiorite is one of several early Cretaceous (120–110 Ma) crystalline rocks that intruded into the Palaeozoic–Mesozoic sedimentary rocks in the Kitakami area (Kano and Nambu, 1975). Suzuki et al. (1996) estimated the age of intrusion to be around 117 Ma by using the CHIME method (Suzuki and Adachi, 1994).

Crystalline rocks of Early Cretaceous ages are widely distributed in the Kitakami area. The regional geological structure of the crystalline rocks, as well as the surrounding sedimentary rocks of this area, suggests that these granitic rocks have been subjected to tectonic processes (e.g. earthquake, faulting, etc.) after their intrusion by plate movement. A comparison of fracture geometry and its formation process among the Kurihashi Granodiorite and other younger crystalline rocks distributed in other areas of Japan is expected to provide information concerning the long-term fracturing process and geometrical changes within this type of host rock due to the stress of plate movement.

Fracture analysis and detailed mapping of the spatial distribution pattern were carried out using an underground drift excavated about 700 m below the ground surface. Typical features of the fracture distribution pattern are shown in Fig. 2. The fracture mapping showed approximately 1 or 2 traceable single fractures per meter along a 500 m interval of the drift. This drift was excavated almost perpendicular to the major orientation of the fracture networks distributed in this area, which were identified in previous boreholes to strike WNW–ESE and to predominantly dip vertically. The fracture frequency observed in the gallery is also quite similar to the frequency of fractures observed in many other Japanese Mesozoic crystalline rocks, as reported by data collated from dam construction site (Kojima et al., 1981).

The mineralogy and textures of fracture fillings were also studied and the results show that the fracture fillings are more or less layered parallel to the fracture planes. By studying fracture fillings of the traceable

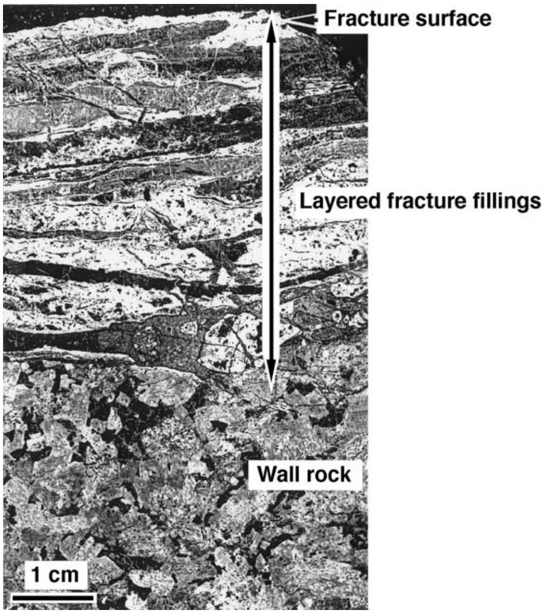

Fig. 3. Photomicrograph of cross-sectioned fracture filling and its typical zonal structure characterized by different minerals precipitation identified in the Kurihashi Granodiorite. This banded layer has been formed by different episodic secondary water–rock interactions after intrusion of the pluton occurred.

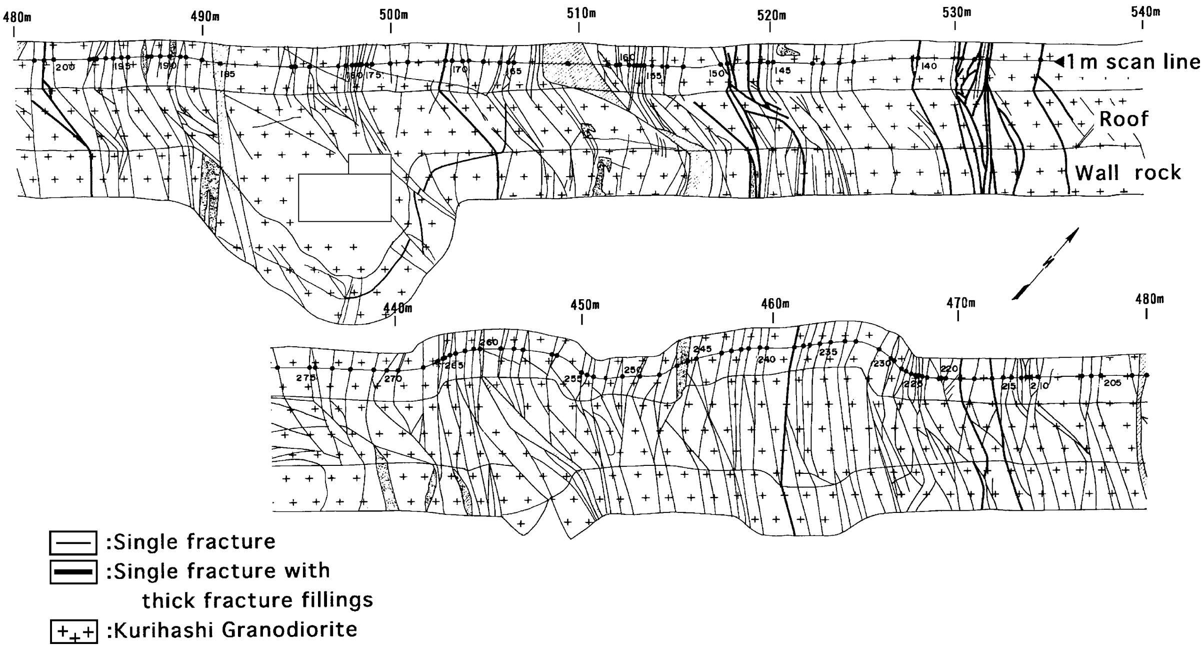

Fig. 2. An example of fracture distribution and the frequency observed in the Kurihashi Granodiorite. Fracture mapping has been carried out in the underground drift at depth of about 700 m from the ground surface. Fracture number measured by using a scan line and counting traceable single fractures. The drift was excavated almost perpendicular to the dominant fracture orientation.

single fractures in a direction from the host rock to the fracture planes, it has been found that the mineral assemblages change from relatively high-temperature assemblages, e.g. epidote, prehnite and laumontite, close to the host rock matrix to low temperature assemblages, e.g. zeolite and calcite, close to the unconfined fracture surfaces (Fig. 3). These fillings form thin-layered crystalline bands. It suggests that the fractures have grown under a relatively tensile stress field and that the fracture plane and fracture fillings have been formed over a prolonged period within which there were several episodes in which chemically distinct solutions circulated (Yoshida et al., 2000).

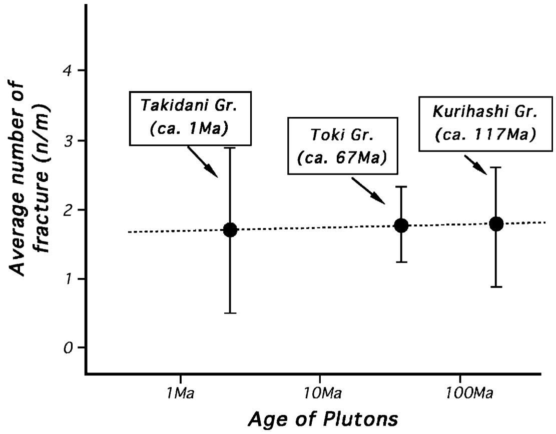

Fig. 4. Fracture frequency calculated within the three different plutons which have different ages. Almost the same number of fracture frequency shown as 'background' in the text has been measured.

3. Discussion

3.1. Model of fracturing and its stability

In general, fractures in crystalline rock have been considered to form as a result of cooling and/or uplift (Balk, 1959) and also in response to the establishment of any tectonic stress field. In the case of Japan, after a pluton has been exposed, the rock mass has continued to be subjected to the regional stress field caused by tectonic movement and/or by plate movements for long periods of geological time. For example, a recent detailed Paleomagnetic study carried out with rocks from the underground mine drifts in the Kurihashi Granodiorite suggests a counterclockwise rotation after intrusion in northeast Japan (Itoh et al., 2000). Results such as this suggest that older plutons would have been subjected to more complex movement and tectonics. Thus, the conceptual model that readily follows from the existing data and the observation is that the sizes and frequencies of fractures could increase according the local tectonic movement and/or regional tectonic stress.

However, the plutons studied here, with three different ages of 1 Ma, 67 Ma and 117 Ma, have quite similar fracture frequencies. Additionally, the geometrical features of fracture fillings in the different plutons are similar, except for their thicknesses, and the fillings show similar banded forms. The results of detailed observations and measurements of fracture frequency on the three different plutons shown in Fig. 4 imply that those rock masses have almost the same fracture frequency and spatial characteristics even after suffering prolonged local and/or regional tectonic stresses. This suggests that crystalline rocks distributed in Japan might have macroscopically similar fracturing characteristics within the scale of about kilometer order even when the rock masses have different ages and/or different locations.

Two general models of fracturing process can be proposed (Fig. 5). First of all, Fig. 5A shows a model in which fracture density has been increased due to new fracture formation owing to the tectonic activity after the pluton's intrusion. The model implies that there has been an increase in the number of fractures rather than an increase in the width of existing fractures and an associated increase in abundances of filling materials. On the other hand, Fig. 5B is a model showing that fracture frequency is relatively stable and that new fractures almost do not form, even under the tectonic geological conditions. In the case of model B, the width of single fracture has been increased due to the movement of existing fractures and additional fracture fillings have been formed by the opening of the fracture planes, probably due to the release of stress accompanied by groundwater penetration.

According to the field observations and analysis of fracture intensity measurements on the 1 Ma, 67 Ma and 117 Ma plutons in Japan, as shown in Fig. 4, fracture frequency is relatively similar even within

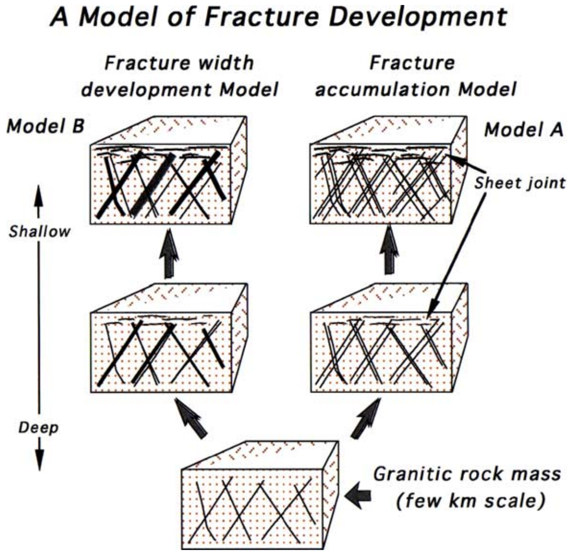

Fig. 5. Model of fracturing and those 'stability' in the plutons distributed in Japan. Model A is 'Fracture accumulation model' and model B is 'Fracture width development model', and these features can be considered to form during uplifting and tectonic movement. Due to the unloading during uplifting, sheeting joint might also be developed in the rock body.

plutons of different ages and subjected to local and/or regional tectonic stresses for different periods, up to about 100 Ma. Also, layered fracture fillings have been identified (Fig. 6) suggesting several episodes of secondary mineral precipitation, some of which must have been at higher temperature than present surface temperatures. This observation suggests that the crystalline rocks distributed in Japan might have fractures that were already formed by the time each pluton was exposed. We consider these fractures to be 'background' fractures and distinguish a 'background fracture frequency'. We propose that this latter is an important characteristic that should be determined when investigating plutons distributed in an orogenic belt. It is also assumed that the 'background' fractures basically formed at the relatively early stage of plutonic activity suggested by the dating of infilling minerals described in the following discussion. These fractures have probably acted mainly as features that have accommodated stress release by opening and increasing in widths, accompanied by fluid rock interactions, as shown in model B.

3.2. Fracturing process and its growth or sealing model

The mineralogies and microscopic textures of fracture fillings can also provide information about the fracturing processes, the geochemistry of groundwater and the water–rock interactions with the wall rock. Detailed observations of fracture fillings in plutons of different ages show that most of the

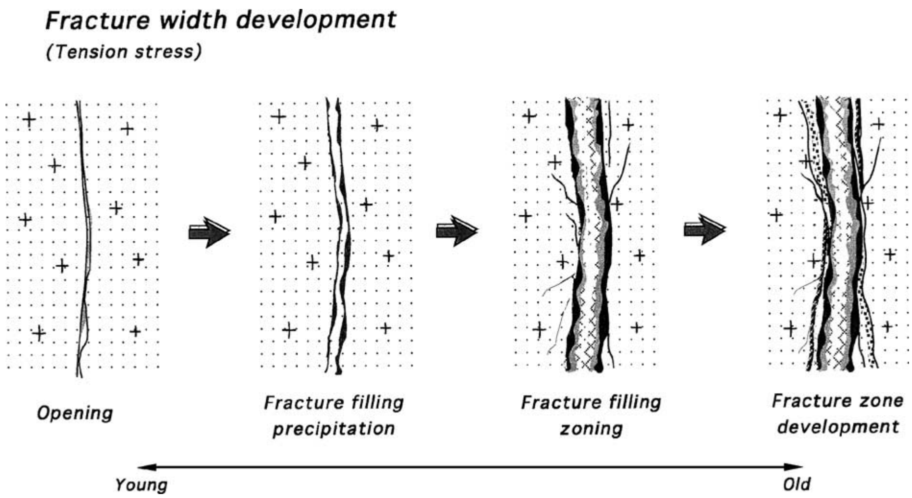

Fig. 6. A possible process of fracture width development by secondary fracture filling precipitation and forming different minerals layer as shown in Fig. 3 under relatively tension stress field or by opening of fractures due to probably unloading during uplifting. The thickness of fracture fillings also suggests the relative age of fracture formation.

fracture fillings have a layered structure, with layers of difference minerals between a few millimeters and a few centimeters in thickness. This finding suggests that the fracture fillings have precipitated from chemically different solutions and sealed the open pore space episodically at different times.

As an example, dating has been carried out on the fracture fillings and host rocks with the Rb–Sr, K–Ar and fission track methods, in order to understand the history of host rock cooling and fracturing processes in the Kurihashi Granodiorite. The results of these measurements are summarized and shown in Fig. 7.

The Rb–Sr method was used to generate a whole-rock isochron, the K–Ar method was applied to hornblende, biotite and sericite, and the fission track method was used for zircon and apatite. It is shown that the host rock, the Kurihashi Granodiorite, intruded around 115 Ma ago, consistent with the age derived by the chemical Th–U–total Pb isochron ages (CHIME method) of zircon and monazite (Suzuki et al., 1996). The dating of the host rock also suggests a relatively slow cooling rate (6.3 °C/Ma) until around 90 Ma. The K–Ar in sericite and, fission track in zircon and apatite fracture fillings showed that hydrothermal activity took place around 100 Ma, followed by cooling of the host rock until about 80 Ma. In short, the geochronological data from the wall rock and the fracture filling minerals are consistent. The data show that the fractures and fracture fillings were mainly formed between the time of intrusion and about 80 Ma. Most of the youngest filling minerals identified in the Kurihashi Granodiorite are zeolite group and calcite. These minerals also compose thin-layered mineral coverings and have euhedral crystal shapes at the fracture surface probably due to recent groundwater circulation and water–rock interactions. This kind of calcite precipitation and crystal formation are also observed in the Toki Granite (Iwatsuki et al., 2002). Detailed morphological studies of calcite crystals and the ratios of stable O and C isotopes show that these infillings are recording quite recent hydro-geochemical changes rather than tectonic geometrical changes.

The mineralogical and dating data suggest that few new fractures have been generated in the Kurihashi Grannodiorite after 70–60 Ma, even under the present compressional stress caused by the plate movement in northeastern Japan. This information is very important to build confidence that the present deep (up to 1000 m from the ground surface) geological environment can be expected to be physically stable for at least several tens of thousands of years in the future. It is likely that any new movements in the crystalline rocks after exposure will re-activate mainly pre-existing traceable or major fractures formed during cooling and/or uplift rather than create new major fractures.

4. Conclusions

The fracture systems developed in three crystalline rock bodies that were intruded into an orogenic belt at

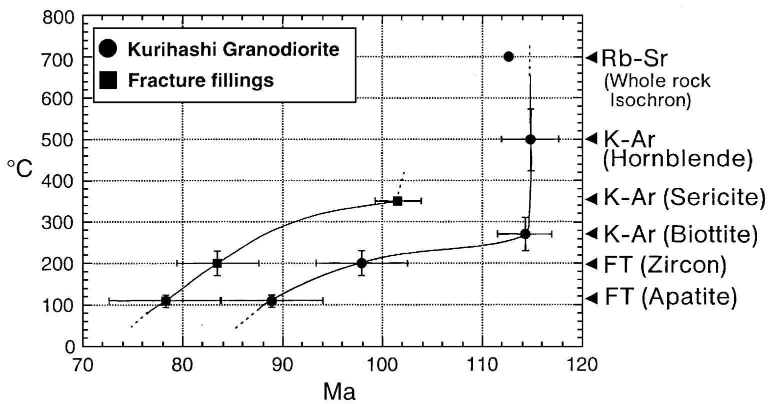

Fig. 7. An example of the dating results from Rb–Sr, K–Ar and FT (fission track) methods carried out in the fracture fillings of the Kurihashi Granodiorite showing the relative early stage of fracturing and fracture filling processes in the pluton (modified from Yoshida et al., 2000).

different times have been investigated in order to build a model for long-term fracture formation and the 'stability' of the resulting fracture networks. Comparisons between the 1.9–0.8 Ma Takidani Granodiorite (the youngest exposed pluton in the world) and the ca. 67 Ma Toki Granite, located in central Japan, and the ca. 117 Ma Kurihashi Granodiorite, in northeast Japan, provided a unique opportunity to develop such a model.

Detailed observations and measurements on the fracture densities of three different plutons reveal that the crystalline rocks distributed in Japan might have macroscopically similar fracture characteristics and fracture geometries. This finding in turn suggests that there is a 'background' fracture frequency that is present at different locations, even within rocks with substantially different ages, and different tectonic settings and/or histories. Mineralogical studies and dating of fracture infillings also suggest that the fractures are relatively stable physically. Stress has been accommodated by widening of existing fractures, rather than by the creation of major new fractures in the intact part of the host rock.

This is an important conclusion that contributes to building confidence in the conceptual models of long-term hydrological and solute transport processes applicable to a geological setting in an orogenic field. Development of such models will be a necessary component of a safety assessment for any waste repository that might be sited in such an orogenic setting. The proposed model for fracture formation may also be useful for other relatively stable tectonic settings, and should be considered when developing a site characterization methodology for crystalline rocks for the geological disposal of HLW geological or other long-lived toxic wastes.

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