Geological characterisation of the active Atera Fault in central Japan: Implications for defining fault exclusion criteria in crystalline rocks around radioactive waste repositories

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Abstract

In the orogenic field of the Japanese archipelago, faults are inevitably distributed in all types of potential host rocks for high-level radioactive waste (HLW) repositories. These faults could have an adverse impact on a repository if they were to provide a short-circuit to the biosphere, so allowing any radionuclides released from the repository to more rapidly transport to the surface than would be the case otherwise. Associated with many faults is a damage zone with fault gouge and crushed rock developed in and alongside the main fault plane. The specific characteristics of a damage zone are considered to be a reflection of the process of faulting and may be used to understand the influence of fault movement on the surrounding host rocks. In order to clarify the geological characteristics by which potentially transmissive features of faults can be avoided when siting a radioactive waste repository for HLW in a crystalline host rock, the active Atera Fault, which is located in central Japan, has been studied. Relationships between the morphological features of the fault, its associated damage zone and the fracture frequency have been investigated. Detailed mapping of the damage zone shows that the fractures formed by later faulting activity can be distinguished from the early fractures developed in the rock by using the microscopic textures and the differences between fracture filling minerals. In particular, a network of shortly transected fractures filled by carbonate and iron-oxyhydroxide minerals was preferentially formed in the damage zone along the Atera Fault, probably by recent fault movement. The density of fractures also suggests that the mechanical damage zone formed by faulting extends for up to ca. 200 m on each side of the main fault plane. However, the geochemically influenced zone has been spatially restricted by geochemical buffering reactions involving crushed fracture-filling materials along the fault. The results provide a basis for defining exclusion zones around faults that might be identified in a future crystalline repository host rock. The methodology is applicable to site characterization and the appropriate allocation of repository panels and deposition holes for waste canisters.

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1. Introduction

In Japan extensive research has been undertaken during the last two decades to build the scientific basis for developing a deep geological repository for high level radioactive waste (HLW) (e.g., JNC, 2000a,b). During any repository site characterization, volcanic activity, active faulting and areas of high tectonic uplift will have been avoided by appropriate criteria at an early stage of the investigations (NUMO, 2002). Avoidance will be achieved by specifying a respect distance based on existing data compilations of the potential impacts on deep geological environments (e.g., Committee for Geological Stability Research, 2011; Figure 1).

However, inevitably, many smaller scale faults and their associated zones of fracturing (mechanical “damage zones” which impart width to the fault structure; Figure 1) are developed in brittle lithologies (e.g., Kim et al., 2004). Such structures may act as preferential pathways for radionuclide migration and may be sufficiently small in scale that practically they cannot be avoided during repository siting on the basis of data obtained from surface-based investigation. It is therefore crucial to consider how this kind of structure can be treated within a repository system.

Such structural features may be encountered during the detailed site characterization of a candidate repository site in crystalline rocks and can be sub-divided into three broad groups:

1) Relatively larger, so-called “layout-determining” faults (with traces that are typically 100's of metres or more) and associated fracture
zones have unfavourable geomechanical characteristics for repository construction and/or constitute potential transport pathways for radionuclides (e.g. SKB, 2011; Pere et al., 2012; McEwen et al., 2013). These faults/fracture zones must be avoided by the galleries/deposition tunnels of the repository.

2) Smaller faults (with traces may be up to a few tens of metres) that have geomechanical characteristics not significantly unfavourable for repository construction, but that could form pathways for the relatively rapid transport of radionuclides if hydraulically transmissive and interconnected. Such faults may intersect individual emplacement positions of waste canisters, provided that they have geometries that would prevent them from functioning as significant radionuclide transport pathways and are sufficiently small as to provide confidence that any future displacement along them would not damage the waste canisters (SKB, 2011; McEwen et al., 2013). Faults with traces of <50 m have been suggested to fulfill this latter criterion (McEwen et al., 2013). Faults with longer traces and/or that may form significant transport pathways must be avoided when siting waste canisters.

3) Fractures (with traces of up to a few metres) that are not sufficiently hydraulically conductive to call into question the barrier functions of the repository’s barrier system and need not be avoided when siting waste canisters. Indeed such fractures may be beneficial if they allow a small water flux and resaturate any bentonite barrier system that might be emplaced (SKB, 2011).

In reality there is likely to be a size continuum between these different groups of features and the precise criteria (e.g. trace lengths, width of associated damage zones, and acceptable degrees of hydraulic conductivity) that are used to distinguish them at a particular candidate site will depend upon the nature of the site (e.g. potential host rock characteristics) and disposal concept (e.g. the nature of buffer, backfill and seals that are to be used). However, to be able to specify such criteria at a particular site requires that appropriate data are obtained from the site characterization programme. This needs to be done as early as possible so that a repository can be designed in a timely fashion to take optimal advantage of the geosphere’s barrier function. Additionally, especially in tectonically active countries like Japan, it is necessary to build confidence that faults and their associated damage zones and chemical alteration will not evolve in future so as to compromise repository safety. It is therefore necessary to understand the properties of these structural and chemical features and, based upon this understanding, to identify what kinds of geological information are needed to define exclusion characteristics around faults.

An ideal structural model of the type of fault zones which should be excluded from the vicinity of a repository has been defined elsewhere (e.g. NUMO, 2002). This conceptual model is, however, highly simplified and requires ground verification if it is to be used as a guideline during repository site characterization. Here, to provide information that is structurally and geochemically analogous to that which might be obtained when characterizing a fault zone developed in crystalline rock, the active Atera Fault has been studied. This fault is located in central Japan and in the study area it displaces crystalline rock. Although the size of the fault is larger than the faults that are expected to be encountered during site characterization for a repository, the Atera Fault is one of the best characterized active faults in Japan. Consequently it is able to provide particularly valuable information about the history of faulting and the evolution of the zones of mechanical damage and chemical alteration around a fault. In particular, understanding the occurrence of a newly formed fracture geometry and mineralogical alteration by crushing and/or the hydrogeological influence of the host rocks' matrices due to continuous fault movement is crucial to clarify the potential for any damage zone around a fault to influence the evolution of the rock’s hydrogeological and the host rock barrier function. The study aimed to identify geological characteristics along the fault that may be used as a basis for defining potential exclusion zones in crystalline rocks elsewhere that may be used to host a repository.

1.1. Atera Active Fault

The Atera Fault is one of the major active faults in the north-eastern part of the Chubu area of central Japan (Figure 2). The total length of the fault is about 70 km, running through the Late Cretaceous Naegi granite, one of the extensive plutons of the Nohi-rhyolitic group of crystalline rocks (Suzuki and Adachi, 1998). Many detailed studies have already been carried out on this fault zone, and have covered many aspects, including the overall fault structure and the connectivity of different fault segments (e.g. Tsukuda et al., 1993), the occurrence of fault gouge and crushed zones and mineralogy of fault rocks (e.g. Nagatomo and Yoshida, 2009; Yoshida et al., 2009), and the history of faulting (e.g. Niwa et al., 2009). Based on these existing data, it appears that the Atera Fault was first formed at least 30 Ma ago and has moved almost continuously since then, with the most recent displacement during a major earthquake in 1586 (Toda et al., 1996).

During this long period of activity, the total horizontal displacement along the central part of the Atera Fault is estimated to be in the range of 6–7 km of left-lateral strike-slip, as assessed by the displacement of a granite porphyry dyke (Yamada, 1981). The Atera Mountains, northeast of the Atera fault, range from approximately 600 to 1200 m higher than the Mino Plateau, southwest of the fault (Yamada, 1981). The mean slip velocity of the Atera fault in the
late Pleistocene to the Holocene is estimated to be 2.8 m/ka horizon-
tally and 0.38 m/ka vertically, based on the distance of displacement
of 50 ka terrace deposits in Sakashita (e.g. Nakamura et al., 1992;
Tsukuda et al., 1993). The influence of such left-lateral movement
is also apparent from the rotation of fractures in the area of several
hundreds of metres along the fault (Yoshida et al., 2009; Niwa
et al., 2009).

The damage zone has been developed throughout this long period of
fault movement, which is much longer than the period that needs to be
considered by the safety assessment for an HLW repository, since typi-
cally such an assessment considers a period of about 1 Ma (e.g.
NUMO, 2002). However, the general characteristics of the damage
zone formed by fault movement in crystalline rock around the Atera
Fault can be considered analogous to the structural features of damage
zones around smaller scale faults, such as those that might be encoun-
tered in the vicinity of a repository for HLW. Consequently, studies of
the damage zone are relevant for helping to specify exclusion zone char-
acteristics or distances from faults to be respected when developing
such a repository.

2. Methodology

2.1. Damage zone characterization

In order to characterize the damage zone along the Atera Fault, the
occurrence and characteristics of fractures reported by previous studies
(Oshima and Yoshida, 2004; Nagatomo and Yoshida, 2009; Yoshida
et al., 2009) were compiled. These characteristics include fracture
density, fracture length and filling minerals from more than 100 out-
crops identified in an area of several square km along the fault. Detailed
fracture mapping was also carried out at major outcrops using a square
metre grid-mapping method and all fractures with lengths of more than
0.5 m were traced. The traceability of fractures in the damage zone with
lengths less than 0.5 m is not clear due to the dense fracture network.
The ‘density’ was defined by the number of fractures counted over
every metre of a grid line. The average was calculated by dividing the
total number by the number of grids at each outcrop. The density is
therefore an ‘apparent’ density observed at the surface in one dimension
rather than three dimensions. These outcrop observations have been
compiled with data obtained at larger spatial scales than individual out-
crops including trace length of fractures, fracture frequency and fracture
filling minerals (Oshima and Yoshida, 2004).

2.2. Gouge and fracture filling analysis

Fillings of fault gouge within the fault core and fractures distrib-
uted in the damage zone are effective indicators of the fault core
(Kim et al., 2004) and damage zone evolution during fault move-
ment (e.g. Nagatomo and Yoshida, 2009; Yoshida et al., 2013a). In
crystalline rocks, in particular, the fillings in any voids formed dur-
ing pluton intrusion, uplift and faulting are considered to record the
circulation of palaeo-fluids during tectonic activity (e.g. Bucher, K.
and Stober, I., 2010; Yoshida et al., 2013b).

Faults, fault gouge and fracture fillings were investigated in well-
preserved outcrops within a quarry located on the Atera Fault (Figure
3). As shown in Fig. 3, a major fault zone and associated six faults (A-
F) are identified. Rock specimens were sampled from these faults and their vicinities in order to understand the relationship between faults and fillings in the damage zone and to identify mineralogical indicators for water–rock interactions. During such sampling it is crucial to preserve the original textures of the fracture fillings, in order to be able to identify delicate microscopic textures formed during damage zone formation. Therefore, all the collected rock specimens were impregnated and embedded in epoxy resin (Epoxy-154) before and after coring to preserve the fragile fracture filling minerals. Polished thin sections were then prepared from the samples for investigation by optical microscope. After these observations, gouge and void fillings were also analyzed by X-ray diffraction (XRD; Rigaku, RAD-2C with 40 kV, 20 mA).

2.3. Geochemical analysis of the damage zone

In order to understand the extent of the chemically ‘altered zone’ within the damage zone, elemental re-distribution due to water–rock interaction along the fault was determined by analyzing major elements in the rock with an X-ray fluorescence spectrometer (XRF; Shimadzu SXF-1200 equipped with Rh X-ray tube operated at 40 kV and 70 mA). In each sample, to analyze major elements (SiO2, Al2O3, TiO2, total iron as Fe2O3 (hereafter, Fe2O3⩾), MnO, MgO, CaO, Na2O, K2O and P2O5), glass beads were prepared by fusing a mixture of 0.7 g powdered sample with 6.0 g lithium tetraborate. Each element was calibrated using standard rock samples issued by the Geological Survey of Japan (GSJ) (GSJ: Geochemical Reference Sample Data Base, http://www.aist.co.jp/RIODB/db012/welcome.html), and composite standards prepared by Yamamoto and Morishita (1997). Ferrous iron (FeO) was analyzed by the KMnO4 titration method and ferric iron (Fe2O3) was calculated by subtracting FeO from Fe2O3⩾, which was determined by XRF. In order to assess the degree of hydration of the minerals in the damage zone, the loss on ignition (LOI) of each sample was also measured by a gravimetric method after heating at 1000 °C. The standard deviation attained by both methods was less than 5% of the measured values and the uncertainty in any one analysis is small compared to the differences between the analyses.

3. Results and discussion

3.1. Fracture distribution

Different fracture densities were observed at the studied outcrops at different distances from the Atera Fault, as shown in Fig. 4. Based on the grid-mapping of these outcrops, fracture density shows a clear change from a greater density (more than 10 m⁻²) close to the fault plane, to around 2 m⁻² at distances of several hundreds of metres from the fault plane (Figure 5). The fracture density of ca. 2 m⁻² is defined as the ‘background fracture density’ and would appear to be a typical feature of crystalline rocks distributed in the orogenic field of Japan (Yoshida, 2012; Yoshida et al., 2013b). Most of these ‘background’ fractures have hydrothermal alteration minerals along their fracture planes and reflect fracture formation during cooling of the plutons (Nishimoto and Yoshida, 2010), mainly associated with the change from ductile to brittle deformation during temperature decrease (Muraoka et al., 1998). Evidence for this change is provided by data from the geological-young (1.9–0.8 Ma) Kakkonda granite pluton in the northern part of Japan, the central part of the pluton where temperatures are more than 400 °C being unfractured (Sasaki et al., 2003).

Towards the Atera Fault, compared to the background density, the fracture density increases drastically within a distance of ca. 200 m
from the main fault plane (see Figure 4a–d). This observation is consistent with the occurrence within this zone of fractures formed by fault movement, which are additional to the background fractures.

It was also observed that fractures of relatively short length have been additionally formed in the vicinity of the fault plane (Figure 5). The data shown in Fig. 5 are the fracture frequencies in different outcrops at different distances from the fault plane. Within approximately 40 m of the fault plane, the rock is intensely crushed and it is therefore difficult to count the number of fractures. However, it can still be seen that the lengths of fractures less than a few metres clearly increase towards the fault plane. These short features form a network-type structure (Oshima and Yoshida, 2004; Yoshida et al., 2009). Furthermore, the dense accumulation of these features is associated with crushing of the host rocks’ matrices (Figure 4c and d).

However, fractures that have a relatively long length (traceable for more than several metres) tend to not vary much in density, either in the damage zone along the fault plane or in the host rock distributed far from the fault plane (Figure 5). In outcrops, such single, traceable, straight fracture planes are readily distinguishable from the short, network-forming fractures. The frequencies of the traceable fractures within the vicinity of the fault plane are only slightly increased from that observed among the ’background’ fractures further from the fault plane.

3.2. Feature of fillings in gouge and fractures

The mineralogies of well-preserved fault gouge and fractures distributed along the fault in the quarry were examined. Fault A in the quarry is cut by the Fault B, which was presumably formed by recent fault movement because the zone between Fault B and C is hardly crushed and Fault B cross-cuts all other structures. Other small Faults D–F are almost parallel and displace a hydrothermally altered fracture. To investigate the relationship between the development of the structures and chemical alteration, detailed mineralogical and geochemical analyses were focused on the older fault (A) and younger faults (B and C).

First of all, microscopic observations (Figure 6) and XRD analyses revealed that hydrothermal minerals such as prehnite, quartz and chlorite occur in the fault gouge of Fault A shown in Fig. 3, whereas calcite and iron–oxyhydroxides are identified as fillings of the fractures distributed in the gouge zones of Fault B and C shown in Fig. 3. Microscopically, the texture of Fault A is characterized as cataclasite (Figure 6a), On the other hand, clayey gouge materials from along the Faults B and C show that
several tens of micron-sized grains are almost homogenously scattered through the rock matrices (Figure 6b).

Hydrothermal mineralization is observed in the fractures that contain euhedral crystals such as calcite and prehnite and that cut through the gouge zone of Fault B and Fault C (Figure 6c and d). These traceable fractures with long length are interpreted as having been formed during decreasing stress conditions caused by uplifting of the rock before the commencement of active faulting. On the other hand, calcite and iron-oxyhydroxide fillings in short-length fractures distributed in the adjacent wall rock of Fault C (Figure 6d) sometimes cut hydrothermally-altered minerals (e.g. feldspar), which is evidence that these fillings developed at a relatively late stage in the evolution of the rock mass. The fractures that are filled by these minerals were probably induced near the surface by faulting activity, which was accompanied by the penetration from the ground surface of oxidized water.

The results of XRF and isocon analyses are shown in Table 1 and Fig. 7, respectively. XRF data shows that the Fe concentration in the damage zone along the fault is generally higher than that of the host rock. In particular, the gouge of Fault C (Figure 3), which cuts other faults and fractures identified in the quarry, has a Fe content that is quite high and a Ca content that is quite low. On the other hand, major elements of the gouge from Fault A, which is cut by Fault C, do not show much change compared to the bulk elemental composition of the host rock. This observation implies that Fault A has been formed at a relatively early stage of host rock evolution, in contrast to Fault C.

3.3. Evolution and identification of the damage zone

Based on the field and microscopic mineralogical observations and geochemical analyses a conceptual model has been developed to explain the features of the damage zone of the Atera Fault.

Three main evolutionary stages (stages I–III) of the damage zone can be distinguished (Figure 8): stage I is plutonic intrusion and background fracture development during cooling; stage II is the formation of the Atera Fault during uplift of the host rock; and stage III is the period of fault activation after uplift and erosion of the ‘active fault’ in relatively recent geological time. Stage III is thought to have occurred during active faulting due to the current tectonic stresses. The damage zone of the Atera Fault has been formed mainly throughout stages II and III. The characteristics of the damage zone also evolved as a consequence of hydrothermal fluid or groundwater circulation. The main episodes and details of each stage are as follows (Fig. 9).

Stage I: The host rock stock type pluton, i.e. Naegi granite, intruded in Late Cretaceous time. After intrusion, the rock mass cooled and, firstly, background fractures were formed after the temperature decreased through the ductile–brittle transition (Sasaki et al., 2003). An example of such fracturing during cooling of a stock type pluton has been studied.

![Photomicrographs of fault rocks, and fault filling minerals. (a) Cataclasite of Fault A. (b) Fault gouge filled in Fault B. (c) Euhedral shape calcite formed in tension crack developed in fault gouge of Fault C. (d) Iron oxyhydroxide filled in the open fracture cutting through the brecciated rock fragment of Fault C. (e) Prehnite crystal in the long traceable fracture observed in the wall rock along the fault. Qz, quartz; Feld, feldspar. Partly referred from Nagatomo and Yoshida (2009).](image-url)
during a deep drilling programme that was undertaken to characterize the geothermal field in the Kakkonda granite, from Iwate prefecture, in the northern part of Japan (Muraoka et al., 1998). The temperature of the host rock was still high enough to allow hydrothermal alteration and fracture-filling minerals such as prehnite and chlorite were precipitated from hydrothermal water (Browne, 1978; Meunier et al., 1988). This hydrothermal reaction also altered the wall rock along the background fractures. The alteration is characterized by illitization of anorthite and chloritization of biotite and provided the elements that were then re-precipitated as fracture-filling and lining minerals. In particular, Ca, K and Na have been depleted from feldspar (Blum and Stillings, 1995).

Nishimoto and Yoshida, (2010) used the isocon method to analyze the detailed elemental migration that occurred along these fractures during the alteration identified in the Naegi Cretaceous granite, which is also distributed in central Japan. These results showed the mass balance of elements involved in the formation of the fracture filling crystals. Such fracture fillings were crushed during the subsequent stages of damage zone development.

Stage II: During this stage, one of the major fractures in the pluton developed to become a fault zone, with associated damaged wall rocks, and continuously developed to be identified as the ‘Atera Fault’. During the development of the fault and damage zone, crystal layers that fill and line the fractures in the surrounding host rock matrices remained uncru shed, owing to the relatively rapid uplift of the pluton accompanied by relatively rapid erosion (e.g. Yoshida et al., 2005). Presumably, movements of the rock mass were concentrated along the fault or damage zone itself, so that fractures in the rock matrix did not undergo displacement laterally. Additionally, rapid uplift could have kept these fractures in a state of tension (Yoshida et al., 2013b). Such uplift has been also reported in several plutons distributed in central Japan, for example the Takidani pluton (Harayama, 1992, 1994; Bando et al., 2003). Furthermore, sequences of infilling minerals in the

<table>
<thead>
<tr>
<th>Fault rock type</th>
<th>Fault A</th>
<th>Fault B</th>
<th>Fault C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$ (wt.%)</td>
<td>68.39</td>
<td>65.66</td>
<td>58.78</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.37</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>14.44</td>
<td>14.98</td>
<td>13.72</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>2.98</td>
<td>7.10</td>
<td>6.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.05</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>MgO</td>
<td>0.52</td>
<td>0.47</td>
<td>0.45</td>
</tr>
<tr>
<td>CaO</td>
<td>2.23</td>
<td>2.95</td>
<td>1.43</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>2.41</td>
<td>3.18</td>
<td>3.82</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>3.69</td>
<td>3.36</td>
<td>3.21</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>LOI</td>
<td>2.89</td>
<td>4.88</td>
<td>3.48</td>
</tr>
<tr>
<td>Total</td>
<td>98.23</td>
<td>102.60</td>
<td>100.34</td>
</tr>
</tbody>
</table>

Table 1: XRF analysis of chemical composition of fault rocks (A-C shown in Figure 3), i.e. cataclasite and fault gouges and non-altered host rock (after Nagatomo and Yoshida, 2009).

<table>
<thead>
<tr>
<th>Lithology of host rock</th>
<th>Nuhi Rhyolite (welded tuff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$ (wt.%)</td>
<td>68.44 71.75 69.27 69.87 70.78 69.63 70.46</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.36   0.38 0.37 0.36 0.33 0.27 0.28</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>3.01   3.19 3.35 3.50 3.05 3.42 3.40</td>
</tr>
<tr>
<td>MnO</td>
<td>0.05   0.09 0.06 0.06 0.06 0.05 0.05</td>
</tr>
<tr>
<td>MgO</td>
<td>0.42   0.49 0.41 0.46 0.59 0.39 0.42</td>
</tr>
<tr>
<td>CaO</td>
<td>2.26   2.53 2.74 2.67 2.98 2.69 2.84</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>3.03   4.05 3.32 2.85 3.33 3.10 3.18</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>3.63   3.59 3.56 3.58 3.54 3.65 3.72</td>
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<tr>
<td>P$_2$O$_5$</td>
<td>0.07   0.07 0.07 0.07 0.07 0.07 0.07</td>
</tr>
<tr>
<td>LOI</td>
<td>2.34   2.89 0.58 1.00 0.83 1.36 0.46</td>
</tr>
<tr>
<td>Total</td>
<td>98.00 99.47 98.43 98.08 100.25 99.12 99.85</td>
</tr>
</tbody>
</table>

Fig. 7. Grant-type isocon plot (Grant, 1986) of average composition of host rock Naegi granite versus chemical composition of fault rock. Almost no changes observed in Fault A. Changes are characterized by decreasing Ca (Faults B and C) in fault gouge. Modified from Nagatomo and Yoshida (2009).
fractures developed in the damage zone along the fault suggest that different fluids penetrated at different times. Euhedral forms of calcite that fills fractures within the damage zone shows that open apertures were maintained and that there was only a limited crystal deformation by faulting throughout the uplifting process; the crystal shapes were preserved over a long period of time, even in the damage zone along the active fault.

Stage III: After the uplifting surface erosion progressed and oxidized surface- or rain-water was able to penetrate the damage zone of the fault through the opening fractures developed by faulting activity, to

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**Fig. 8.** A schematic view of the evolution of the damage zone along the active Atera Fault, inferred from field observations, analyses of faults and fracture filling minerals, and geochemical and grain size analyses of the fault rocks. Modified from Nagatomo and Yoshida (2009).

**Fig. 9.** Schematic models of a fault and damage zone in crystalline rocks, and the relative situation of the fault and a HLW repository system.
the level investigated in the present study. The penetrating oxidized water underwent water–rock reactions with the fresh rock forming minerals. In particular, relatively acid surface water in the soil cover dissolved iron from iron bearing minerals and transported it into the shallower bedrock, where it precipitated as Fe-oxyhydroxides. These oxyhydroxides sporadically formed along microscopic grain boundaries, thereby creating reddish to brownish redox fronts along the fluid-conducting fractures of the damage zone. However, the spatial extent of the redox reaction was limited due to the relatively high redox-buffering capacity of the crushed clayey materials within the damage zone (Akagawa et al., 2006; Yamamoto et al., 2013). This observation is important because it shows how “geochemical damage” within the host rock of a geological repository for HLW would be spatially restricted and would not imply the total loss of the geosphere’s barrier function. This aspect is discussed in more detail in the following section.

3.4. Defining fault exclusion criteria in crystalline rocks for a repository system

The host rock of a deep geological repository for radioactive waste must fulfill several safety functions, the relative importance of which may vary over time, but will depend upon the nature of the host rock and the particular disposal concept (IAEA, 2011; NEA, 2013). In the context of the present paper, a “safety function” describes a particular way in which the geosphere contributes to safety.

In the case of crystalline host rocks the following general safety functions can be proposed (e.g. SKB, 2011; Posiva, 2013):

1) The host rock must provide a mechanically stable environment (with “mechanically stable” meaning that the rock will deform insufficiently and insufficiently rapidly, to call safety into question).
2) The host rock must provide favourable hydrogeological and fluid/solute transport conditions.
3) The host rock must provide chemically favourable conditions (e.g. redox conditions).
4) The host rock must provide favourable thermal conditions.

The present study sheds light on some of the characteristics of faults that must be determined in order to judge whether the first three of these safety functions can be met; these safety functions could be compromised by faults and/or faulting.

To judge whether or not these three safety functions are maintained at the potential repository sites being investigated in Sweden and Finland, SKB and Posiva respectively defined a number of performance indicators and criteria which these indicators should fulfill if the safety function is to be demonstrably attained (SKB, 2011; Posiva, 2013). In the case of the first of these safety functions, SKB (2011) proposed the following safety indicators and corresponding criteria: groundwater pressure, which should be ‘limited’ (a precise pressure was not specified by SKB); shear movements at the waste canister deposition hole location, which should be <0.05 m; and shear velocities at waste canister deposition hole locations, which should be < 1 m/s. Posiva (2013) has adopted similar criteria. The criteria for shear movements and shear velocities were specified taking into account the specific disposal concept being proposed in Sweden and Finland, namely the so-called ‘KBS-3’ concept. In this concept copper canisters containing spent fuel are emplaced in vertical deposition holes and surrounded by rings of compacted dry bentonite, which subsequently swells upon contact with groundwater, thereby forming a low-permeability buffer through which transport of water and solutes can occur only by diffusion.

In Japan the disposal concept for HLW has not been fixed and would probably differ from this concept. Therefore, eventually different shear movement and shear velocity criteria to those used by SKB (e.g. SKB, 2004, 2006) and Posiva may be appropriate in Japan. However, probably it will still need to be shown that future shear and tensile movements and movement velocities would be less than some defined values. The research described in this paper highlights indicators of past movement around an active fault and how these can be used to identify zones within a host rock in Japan where future unacceptable shearing is likely. A key finding from the work is that the volume of rock affected by shear deformation along this major active fault can be recognized by the development of short network-type fractures. However in the studied area the zone of influence (i.e. damage zone) has been restricted to within a few hundred metres of the main fault (Figure 5). The scale of the damage zone (i.e. ca. 200 m on each side of the main fault plane) is also consistent with the scale suggested by the relation between the width of damage zone (W) and length of fault (L) described as follows:

\[ W / L \approx 10^{-2} \]

(Vermilye and Sholz, 1998).

In contrast, ‘background fractures’ of the rock matrix around the main fault have not undergone much crushing related to active faulting (Figure 6e).

The observations contribute to building confidence that when siting waste canisters, it might not be necessary to avoid the much smaller faults with traces of a few metres to 10’s of metres, which would not be identified early in site characterization, provided that

1) They can be shown to be insufficiently transmissive to provide significant transport pathways for radionuclides.
2) It can be confirmed that trace lengths are inconsistent with whatever shear criteria are appropriate for the Japanese waste disposal concept that is eventually implemented (most likely including absence of evidence for past displacements of more than a few centimetres).

In other words, the observations help to build confidence that similar fault avoidance criteria (‘respect distances’) to those applied in projects to develop repositories in tectonically stable countries such as Sweden and Finland (SKB, 2011; McEwen et al., 2013; Posiva, 2013) may also be applied in the tectonically active Japanese archipelago. However, site-specific data will be needed to confirm this conclusion.

One measure of the second safety function, favourable hydrogeological and transport conditions, is the transport resistance, F, which is the ratio of the fracture surface area in contact with flowing water and the flow rate of the water along that path:

\[ F = 2W_qL_p/q \]

where \( W_q \) is the fracture width (m), \( L_p \) is the length of the migration path (m) and \( q \) is the flow rate (m\(^3\)/y).

Beyond a distance of approximately 200 m from the main Atera Fault, only background fractures occur and the lengths of transport pathways through these are unaffected by the active faulting. Thus again, an implication is that the zone within which faulting might affect transport resistance is restricted to a relatively narrow zone around the fault. However, it is also significant that fractures within the damage zone that are attributable to faulting have shorter traces than the background fractures, which are unrelated to faulting, and also form networks (Figure 4). These observations imply that transport pathways through the fault-related fracture network may have relatively long \( L_p \), such that the transport resistance \( F \) is higher than would be the case for the background fractures.

Fe-oxyhydroxides tend to sorb many radionuclides quite effectively; i.e. \( K_f \) values obtained by batch sorption when sorption sites in the intact system become saturated are relatively high (Yoshida et al., 2009). Therefore, the later fractures that contain Fe-oxyhydroxides, which are distributed within the damage zone of the Atera Fault (Figure 6), are likely to have relatively high \( K_f \) compared to other fractures. Thus, even where the faulting has produced structures in the host rock with relatively low \( F \)-factors, the ability of the rock to retard radionuclide transport has potentially increased.

For the third safety function, that geochemical conditions must be favourable, many of the safety function indicators and corresponding
criteria (e.g. proposed by SKB, 2011 or Posiva, 2013) are dependent upon the engineered barriers present in a particular disposal concept. Furthermore, the research reported here is not relevant to most of these indicators (e.g. total dissolved solids (TDS) of the groundwater, ionic strength of groundwater, and total cation concentration of the groundwater). However, a widely applicable safety function indicator is the redox condition of the groundwater–rock system, which has the corresponding widely applied general criterion that conditions will be reducing (e.g. SKB, 2011; Posiva, 2013). The present study has shed light on the way in which relatively oxidizing groundwater has penetrated the active Atera Fault during uplift. The relatively restricted distribution of Fe-oxyhydroxide-bearing fractures within later fractures that occur within the damage zone of the Atera Fault illustrates that even major fault activity does not necessarily lead to widespread loss of favourable reducing conditions, beyond a relatively restricted zone around the fault. This zone is a few hundred metres wide in the case of the Atera Fault, but again would be much more restricted in the very much smaller faults that might occur within the footprint of an HLW repository. Furthermore, the present study has provided evidence that the relatively fine-grained minerals within the damage zone of a fault may have an enhanced capability to reduce any inflowing oxidizing groundwater, thereby preventing perturbations to the redox conditions outside this relatively narrow zone.

It therefore follows that two main fault characteristics may be used to help define exclusion criteria for potentially unsuitable host rock volumes adjacent to faults that might be encountered within the footprint of a repository. Firstly, the increase in fracture density near to the fault can indicate where there is a potential for preferential pathways for radionuclide transport to have been developed, and where groundwater flows in the vicinity of the waste canisters has the potential to be acceptably high. The different geometries of the relatively short, network-forming fractures near the fault and the relatively long traceable joint type ‘background fractures’ imply that the former type has been formed additionally in the crushed zone by fault movement.

Secondly the fracture fillings identified in and around a fault can also be used to help define exclusion zones. These fillings are formed during plutonic intrusion and after faulting, and can be also used as an indicator of the extent of the damage zone. In crystalline host rock, fractures formed during the pluton cooling stage are mainly filled by minerals of high-temperature hydrothermal origin. Fractures formed by faulting after host rock uplift into the near-surface zone precipitated at much lower temperature during groundwater circulation. An important precipitated mineral is calcite, which is formed from Ca leached from feldspar in the rock (Iwatuski et al., 2005; Yoshida et al., 2013a,b). Additionally, oxyhydroxides formed by pore water redox and pH changes during surface water penetration (Yamamoto et al., 2013). Around the Atera Fault, euhalic calcite and iron-oxyhydroxides fillings were likely developed in the stage after the host rock had been uplifted relatively close to the ground surface.

4. Conclusions

The Atera Fault, one of the major active faults distributed in central Japan, has been studied as an analogue of the smaller scale inactive faults that might occur in the vicinity of a future geological repository in crystalline rocks for HLW. The understanding of damage zones provided by the study can be used to build confidence that appropriate geological characteristics are used as criteria for recognizing faulted rocks that should be excluded as hosts for HLW containers by specifying appropriate respect distances.

Features that distinguish damage zones in this kind of fault were identified. One kind of feature is the distinctive fractures that have been formed along the fault, in addition to the background, pre-existing fractures. The other kind of feature is the fracture filling formed during fault movement. Characteristic of the new fractures along the fault are their high density, their short traces lengths of less than a metre and their network-type pattern. These fractures overlap the initially formed straight, joint-type fractures that are traceable for several metres or more. The fillings of the more recent, fault-related fractures are characterized by low-temperature minerals such as calcite and Fe-oxyhydroxides that have been formed in the damage zone. These two characteristics together define the extent of the mechanically damaged zone along the fault.

Using these characteristics it can be shown that even around the very large Atera Fault the damage zone is only a few hundred metres wide. Outside this zone, there are only pre-faulting fractures along which no evidence for shearing during fault movement could be discerned. Thus, it may be possible to consider locating a potential future repository even within a few kilometres of such a fault. Furthermore, fault/fracture exclusion criteria similar to those adopted by SKB in Sweden (SKB, 2011) and Posiva in Finland (McEwen et al., 2013; Posiva, 2013) may be appropriate for application in the rocks outside the exclusion zones. That is, it may be acceptable for fractures with traces of up to a few tens of metres to intersect the sites of waste canister emplacement, provided evidence can be obtained that future shear displacements will be less than some criterion and that fractures are insufficiently transmissive to act as significant transport paths for water and solutes. However, the precise criteria to be adopted in Japan will depend upon the disposal concept that is eventually adopted and the characteristics of the eventual repository site.

Within the damage zones of these faults there are features of both the fracture network and the mineral infills that are expected to be capable of limiting radionuclide transport along the damage zones, should there be pathways from them to waste canisters located outside the damage zones. These features include relatively long transport pathways provided by the short-trace, network-forming fault-related fractures; the high sorption coefficients of Fe-oxyhydroxides and fine grained clastic material; and the probable low permeabilities of fault gouges.

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References


