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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 a more rapid transport pathway 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.

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 practicably 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

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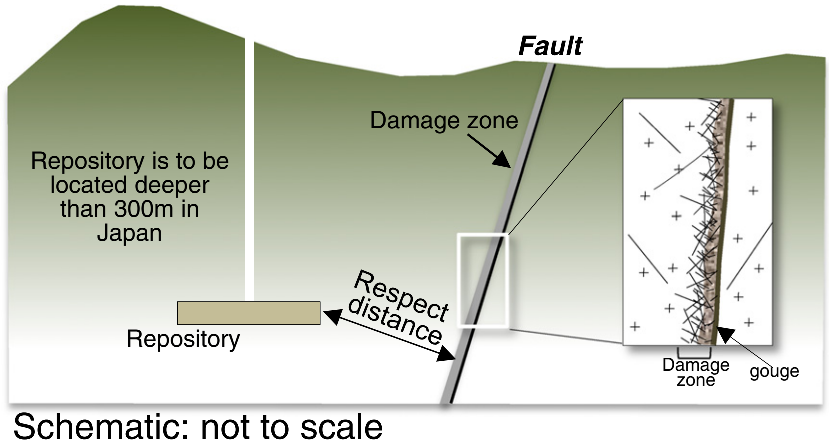

Fig. 1. Schematic illustration of a repository and its relationship to the damage zone along a fault, showing the 'respect distance' that must be specified to avoid significant faulting effects in the vicinity of the repository. Using information gathered from throughout Japan a 'respect distance' of 10 km was suggested conservatively in the H12 report (JNC, 2000a), but it was noted that a reduced distance might be defined based on site-specific data.

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 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 natures 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