Relationship Between Faults Oriented Parallel and Oblique to Bedding in Neogene Massive Siliceous Mudstones at The Horonobe Underground Research Laboratory, Japan

Akira Hayano 1, Eiichi Ishii 1

1 Horonobe Underground Research Center, Japan Atomic Energy Agency, Hokkaido, Japan

E-mail address: hayano.akira@jaea.go.jp

Abstract. This study investigates the mechanical relationship between bedding-parallel and bedding-oblique faults in a Neogene massive siliceous mudstone at the site of the Horonobe Underground Research Laboratory (URL) in Hokkaido, Japan, on the basis of observations of drill-core recovered from pilot boreholes and fracture mapping on shaft and gallery walls. Four bedding-parallel faults with visible fault gouge, named respectively the MM Fault, the Last MM Fault, the S1 Fault, and the S2 Fault (stratigraphically, from the highest to the lowest), were observed in two pilot boreholes (PB-V01 and SAB-1). The distribution of the bedding-parallel faults at 350 m depth in the Horonobe URL indicates that these faults are spread over at least several tens of meters in parallel along a bedding plane. The observation that the bedding-oblique fault displaces the Last MM fault is consistent with the previous interpretation that the bedding-oblique faults formed after the bedding-parallel faults. In addition, the bedding-parallel faults terminate near the MM and S1 faults, indicating that the bedding-parallel faults with visible fault gouge act to terminate the propagation of younger bedding-oblique faults. In particular, the MM and S1 faults, which have a relatively thick fault gouge, appear to have had a stronger control on the propagation of bedding-oblique faults than did the Last MM fault, which has a relatively thin fault gouge.

1. Introduction

The development of a conceptual model of the geological structures observed in host rock at the site of construction for the disposal of high-level radioactive waste (HLW) is important for repository design and long-term safety assessment. In the case that the host rocks are treated as fractured rocks from a hydrological viewpoint, it is important for the success of geological modelling that the characteristics of faults and fractures are well understood on the basis of geological information obtained by borehole investigations and field mapping.

As part of the research and development program on the geological disposal of HLW, the Horonobe Underground Research Laboratory (URL) has been constructed in the Horonobe area, northern Hokkaido, Japan (e.g. [1]). The Horonobe URL is located in the Wakkanai Formation, which consists of Neogene siliceous mudstone (Figure 1). The mudstone is generally a single, massive and homogeneous lithofacies [2-4] with very weakly developed bedding planes that are only recognisable in resistivity images of borehole wall obtained by electrical micro-imaging [5]. Bedding-parallel faults and bedding-oblique faults are observed in the Wakkanai Formation based on fracture mapping on the...
outcrop scale [6, 7]. Because crosscutting relationships between bedding-parallel and bedding-oblique faults indicate that the latter always displaces the former, bedding-oblique faults are suggested to have formed after the bedding-parallel faults [6-9].

Previous studies have shown that joints are commonly perpendicular to lithologic contacts and elongate in one direction in bedded sedimentary rocks (e.g. [10]). These late-stage joints are likely to terminate at mechanical barriers such as a contact between two different adjacent lithofacies or pre-existing systematic joints (e.g. [10,11]). However, the lithofacies and fracture mechanisms described in previous studies are different from those of the Wakkanai Formation [9,12,13]. No previous study has focused on the relationship between bedding-parallel and bedding-oblique faults in massive rock such as the Wakkanai Formation in the Horonobe area.

To discuss the effect of bedding-parallel faults on the propagation of bedding-oblique faults, this study evaluates the relationships between bedding-parallel and bedding-oblique faults in the Wakkanai Formation in the area of the Horonobe URL, based on drill-core logs and fracture mapping on gallery walls.

**Figure 1.** Geological map and NE–SW geological cross-section of the Horonobe area (modified after [14]). Plate boundaries and directions of plate movement in the overview map (upper left) are modified from [15]

### 2. Geological setting

The Horonobe URL site is located in northwest Hokkaido, on the eastern margin of a Neogene to Quaternary sedimentary basin in a Quaternary active foreland fold-and-thrust belt near the boundary between the Okhotsk and Amurian plates (Figure 1; e.g. [15-17]). The Neogene to Quaternary basin fill consists of the (from the oldest to the youngest) Wakkanai, Koetoi, Yuchi, and Sarabetsu formations (Figure 1). The Wakkanai and Koetoi formations are exposed in shafts and galleries of the Horonobe URL. The Wakkanai Formation consists mainly of siliceous mudstones, including opal-CT, and the Koetoi Formation consists mainly of diatomaceous mudstone, including opal-A, but not opal-CT. The siliceous mudstone of the Wakkanai Formation formed from induration of the diatomaceous mudstone of the Koetoi Formation during progressive burial diagenesis of siliceous material; i.e., the conversion of opal-A to opal-CT [18]. Therefore, the Wakkanai Formation, which is the focus of this study, consists of more competent rocks than the Koetoi Formation and is affected by brittle fracturing [8,12,18,19]. The area east of the Horonobe URL site contains a map-scale fault, the NNW–SSE striking Omagari
Fault, and major folds that generally trend subparallel to the fault (Figure 1). At the Horonobe site, which is located on the western limb of an anticline, the contact between the Wakkanai and Koetoi formations strikes NW–SE and dips moderately to the west [20]. In the Wakkanai Formation, bedding-parallel and bedding-oblique faults are observed in outcrop and drill-core [6,7,13]. Bedding-parallel faults are mainly dip-slip faults, whereas bedding-oblique faults are predominantly strike-slip. The bedding-parallel faults formed during folding and are commonly displaced by the bedding-oblique faults [6-9].

The Horonobe URL has three shafts (the Ventilation, East, and West shafts) and three galleries (the 140 m, 250 m, and 350 m galleries) (Figure 2a). The Ventilation and East shafts are 380 m deep and the West shaft is 365 m deep. The 350 m gallery is ~760 m in total length, being the longest of the three galleries. The two pilot boreholes are ~500 m deep, relative to the ground surface. PB-V01 is located ~20 m NNE of the Ventilation Shaft and SAB-2 is ~30 m NW of the East Shaft (Figure 2a and b).

Fracture mapping has been carried out in the Ventilation and East shafts, and during excavation of the 350 m gallery. The depth of the contact between the Wakkanai and Koetoi formations is spatially variable and depends on the orientation of the contact. The contact was mapped at 236.5 m depth in PB-V01 [21], at 240.0 m in SAB-1 [22], 247.0 m in the Ventilation Shaft [23], and 261.0 m at the East Shaft [20]. These mapped contact depths were used to map the overall geometry of the contact (Figure 2a; [20]). The entire length of the 350 m gallery cuts through the Wakkanai Formation.

Figure 2. (a) Schematic model of the Horonobe URL and contact between Koetoi and Wakkanai formations. Red spheres show the depths at which bedding-parallel faults were observed in boreholes SAB-1 and PB-V01. (b) Example of a fault rock of a bedding-oblique fault (observed at 363.17 m depth in borehole PB-V01). (c) Example of the fault rock along a bedding-parallel fault (365.20 m depth in borehole PB-V01).

3. Occurrence of faults in the Wakkanai Formation at the Horonobe URL site

The bedding-parallel and bedding-oblique faults observed by fracture mapping are shown in Figure 3a and b. Although numerous other fractures are also observed, only continuous fractures associated with faults or of a certain length are shown. Fractures shown on a development plane of the shaft in Figure 3a are limited to fractures with a length more than a quarter of the circumference of the shaft, and these represent ~5% of all fractures observed during fracture mapping.

In both boreholes (i.e., PB-V01 and SAB-1), bedding-parallel faults occur at ~20 m, ~50 m, ~130 m, and ~160 m below the contact between the Koetoi and Wakkanai formations (Figure 2a). For this study,
these bedding-parallel faults are named (from top to bottom) the MM Fault, the Last MM Fault, the S1 Fault, and the S2 Fault. These faults are marked by fault rock that is mainly fault gouge in a zone that is 1–2 cm thick (Figure 2c).

The MM, Last MM, and S1 faults are encountered in the Ventilation Shaft, and the MM and Last MM faults are encountered in the East Shaft (Figure 3a). The Last MM and S1 faults also occur in the 350 m Gallery (Figure 3b). Bedding-parallel faults with continuously visible fault gouge are observed by fracture mapping on the shafts and galleries walls (Figure 4). The thickness of fault gouge upon the MM and S1 faults is generally 3–5 cm. The fault gouge upon the Last MM Fault is 1–3 cm, which is thinner than that upon the MM and S1 faults.

In addition to the bedding-parallel faults, some of the shear fractures occur subparallel to bedding planes and are locally filled by clay material in a zone that is commonly less than a few millimetres wide. The shear fractures are distinct from the bedding-parallel faults that are marked by visible fault gouge.

In Figure 5, the locations of the MM, Last MM, S1, and S2 faults are projected on a vertical cross-section through line B–B’ (see Figure 3b) based on the location and orientation of each fault. Accordingly, it is possible to correlate the four bedding-parallel faults among the exposed gallery walls of the Horonobe URL area based on their location and orientation (Figure 5). Although the MM Fault does not intersect the 350 m Gallery, the bedding-parallel fault that is observed in the two boreholes drilled from the 350 m Niche No. 5 can be correlated with the MM Fault (Figs. 3b and 5). The S2 Fault is not exposed in the shafts or galleries (Figure 5). These observations suggest that the bedding-parallel faults with visible fault gouge are spread over at least tens of metres in parallel along a bedding plane.

The bedding-oblique faults are more unevenly distributed, and only locally are observed below the 330-m-deep East Shaft and the southern part of the 350 m East Loop Gallery. Bedding-oblique faults are only locally observed in the footwall of the S1 Fault, and no faults are observed in the drillhole northeast of the 350 m East Loop Gallery (Figure 3a and b). In other areas, bedding-oblique faults are commonly observed. The bedding-oblique fault with the greatest length is observed in the area of the 350 m Niche No. 5, striking towards the 350 m West Loop Gallery. This fault has a length of at least 40 m, and strikes NNE and dips at 30° to the west (Figure 3b, d). The bedding-oblique faults are mainly associated with fault breccia, which differs from the bedding-parallel faults (Figure 2b). Estimating the length of bedding-oblique faults is more problematic than for the bedding-parallel faults, even for the bedding-oblique fault that is observed in the area of the 350 m Niche No. 5; consequently, it is not possible to correlate the bedding-parallel faults among drillholes and galleries.

The geometric relationships between the bedding-parallel and bedding-oblique faults are observed at three locations. The bedding-oblique fault that displaces the Last MM Fault is visible in the 350 m West Loop Gallery (Figure 3d). This supports the interpretation that the bedding-oblique faults formed after the bedding-parallel faults [6,7]. However, the bedding-oblique faults are not observed to displace the MM and S1 faults, but the bedding-oblique faults terminate near the MM and S1 faults (Figure 3c and e).
Figure 3. (a) Columnar section showing fractures on the Ventilation and East shaft walls at the Horonobe URL site. (b) Map showing fractures on a horizontal section at 350 m depth at the Horonobe URL. (c) Map showing fractures on the Ventilation Shaft wall at depths from 255 to 275 m. (d) Map showing fractures on the wall of the 350 m West Loop Gallery. (e) Map showing fractures on the wall of the 350 m East Loop Gallery.

Figure 4. (a) MM Fault observed on the Ventilation Shaft wall at depths from 269.0 to 270.8 m, (b) Visible fault gouge
4. Discussion
Cooke [24] performed numerical experiments to investigate the influence of deformation along bedding planes: they only considered the intersection between layer-perpendicular opening-mode fractures and bedding planes. The authors found that the properties of most of the bedding planes lie between the cases of fracture termination at weakly bonded bedding planes and fracture propagation through strongly bonded bedding planes. Such moderate-strength bedding planes may be the sites of step-over fractures. Although the bedding-oblique faults observed in this study are not opening-mode fractures, the relationships among the present faults are consistent with the model of [24]. The termination of the bedding-oblique fault near the MM and S1 faults suggests that the pre-existing bedding-parallel fault served as a mechanical barrier controlling the propagation of the later-stage bedding-oblique faults, if the fault zone was sufficiently thick. Because the Last MM Fault is displaced by the bedding-oblique fault, the cohesion upon this fault plane must be relatively strong. This view is supported by the fact that the fault gouge upon the Last MM Fault is thinner than that upon the MM and S1 faults. Therefore, the mechanical effect of the MM and S1 faults on the propagation of bedding-oblique fault seems to have been greater than that of the Last MM Fault. However, it is difficult to assess the effect of bedding-parallel faults on the propagation of bedding-oblique faults due to a lack of information regarding the displacement of bedding-oblique faults and the mechanical properties of the mudstone. The effect of the Last MM Fault on the propagation of bedding-oblique faults cannot be inferred solely from the relationship between bedding-parallel and bedding-oblique faults, as shown in this study.

5. Conclusions
This study investigated the relationship between bedding-parallel and bedding-oblique faults in Neogene massive siliceous mudstone based on analyses of drill-core from pilot boreholes and fracture mapping on shaft and gallery walls at the Horonobe URL site. The data lead to the following conclusions:

- Bedding-parallel faults with visible fault gouge are spread over at least tens of metres in parallel along a bedding plane.
- A bedding-oblique fault displaces the Last MM Fault at the 350 m West Loop Gallery, which is consistent with the interpretation of previous studies that bedding-oblique faults formed after the bedding-parallel faults.
- The MM and S1 faults act as a mechanical barrier against which the bedding-oblique faults were terminated. This effect is especially pronounced if the bedding-parallel faults have thicker fault gouge (e.g., the MM and S1 faults).
Acknowledgement(s)
We would like to thank A. Stallard for English corrections of the manuscript.

References

[1] Iwatsuki T, Sato H, Nohara T, Tanai K, Sugita Y, Amano K, Yabuuchi S, Oyama T, Amano Y, Yokota H, Niizato T, Tokiwa T, Inagaki D, Abe H, Nakayama M, Kurikami H (Eds.), 2011. Horonobe Underground Research Laboratory Project; Research and development plan (H22-H26). Tech. Rep. JAEA-Research 2011-009. Japan Atomic Energy Agency, Tokai-mura, Japan.

[2] Mitsui K, Taguchi K, 1977. Silica mineral diagenesis in Neogene tertiary shales in the Tempoku district, Hokkaido, Japan. Journal of Sedimentary Petrology, 47: 158–167.

[3] Iijima A, Tada R, 1981. Silica diagenesis of Neogene diatomaceous and volcanioclastic sediments in northern Japan. Sedimentology, 28: 185–200.

[4] Hiraga N, Ishii E, 2008. Mineral and Chemical Composition of Rock Core and Surface Gas Composition in Horonobe Underground Research Laboratory Project (Phase 1). Tech. Rep. JAEA-Data/Code 2007-022. Japan Atomic Energy Agency, Tokai-mura, Japan.

[5] Ishii E, Yasue K, Tanaka T, Tsukui R, Matsuo K, Sugiyama K, Matsuo S, 2006. Three-dimensional distribution and hydrogeological properties of the Omagari Fault in the Horonobe area, northern Hokkaido, Japan. The Journal of the Geological Society of Japan, 112: 301–314.

[6] Ishii E, Fukushima T, 2006. A case study of analysis of faults in Neogene siliceous rocks. Journal of the Japan Society of Engineering Geology, 47: 280–291.

[7] Ishii E, Funaki H, Tokiwa T, Ota K, 2010. Relationship between fault growth mechanism and permeability variations with depth of siliceous mudstones in northern Hokkaido, Japan. Journal of Structural Geology, 32: 1792–1805.

[8] Ishii E, Sanada H, Funaki H, Sugita Y, Kurikami H, 2011a. The relationships among brittleness, deformation behavior, and transport properties in mudstones: An example from the Horonobe Underground Research Laboratory. Japan. Journal of Geophysical Research: Solid Earth, 116, B09206. http://dx.doi.org/10.1029/2011JB008279

[9] Ishii E, 2012. Microstructure and origin of faults in siliceous mudstone at the Horonobe Underground Research Laboratory site, Japan. Journal of Structural Geology, 34: 20–29.

[10] Gross MR, 1993. The origin and spacing of cross fractures: examples from the Monterey Formation, Santa Barbara Coastline, California. Journal of Structural Geology, 15: 737–751.

[11] Helgeson DE, Aydin A, 1991. Characteristics of fracture propagation across layer interfaces in sedimentary rocks. Journal of Structural Geology, 13: 897–911.

[12] Ishii E, 2016a. Far-field stress dependency of the failure mode of damage-zone fractures in fault zones: Results from laboratory tests and field observations of siliceous mudstone. Journal of Geophysical Research: Solid Earth, 121: 70–91.

[13] Ishii E, 2016b. The role of bedding in the evolution of meso- and microstructural fabrics in fault zones. Journal of Structural Geology, 89: 130–143.

[14] Ishii E, Yasue K, Ohira H, Furusawa A, Hasegawa T, Nakagawa M, 2008. Inception of anticline growth near the Omagari Fault, northern Hokkaido, Japan. The Journal of the Geological Society of Japan, 114: 286–299.

[15] Wei D, Seno T, 1998. Determination of the Amurian plate motion. In: Mantle Dynamics and Plate Interactions in East Asia, Flower, M., Chung, S.L., Lo, C.H., Lee, T.Y. (Eds.), Geodynamics Series 27. American Geophysical Union, Washington, D.C., USA, 337–346.

[16] Yamamoto H, 1979. The geologic structure and the sedimentary basin off northern part of the Hokkaido Island. Journal of the Japanese Association of Petroleum Technologists, 44: 260-267.

[17] Ikeda Y, 2002. The origin and mechanism of active folding in Japan. Active Fault Research, 22: 67-70.
[18] Ishii E, Sanada H, Iwatsuki T, Sugita Y, Kurikami H, 2011b. Mechanical strength of the transition zone at the boundary between opal-A and opal-CT zones in siliceous rocks. *Engineering Geology*, 122: 215–221.

[19] Ishii E, 2015. Predictions of the highest potential transmissivity of fractures in fault zones from rock rheology: Preliminary results. *Journal of Geophysical Research: Solid Earth*, 120: 2220–2241.

[20] Nakayama M, Amano K, Tokiwa T, Yamamoto Y, Oyama T, Amano Y, Murakami H, Inagaki D, Tsusaka K, Kondo K, Yokota H, Nanjo I, Niizato T, Tanaka S, Ohara M, Jin K, 2012. Underground Research Laboratory Project: Investigation report for the 2011 fiscal year. Tech. Rep. JAEA-Review 2012-035. Japan Atomic Energy Agency, Tokai-mura, Japan.

[21] Funaki H, Tokiwa T, Ishii E, Hatsuyama Y, Matsuo S, Tsuda K, Koizumi A, Ishikawa T, Daijo Y, Sugiyama K, 2008. Horonobe Underground Research Laboratory Project: Overview of the pilot borehole investigation of the ventilation shaft (PB-V01); Geological investigation. Tech. Rep. JAEA-Data/Code 2008-013. Japan Atomic Energy Agency, Tokai-mura, Japan.

[22] Suko T, Takano H, Uchida M, Seki Y, Ito K, Watanabe Y, Munakata M, Tanaka T, Amano K, 2014. Research on validation of the groundwater flow evaluation methods based on the information of geological environment in and around Horonobe underground research area. Tech. Rep. JNES-RE-2013-9032. Japan Nuclear Energy Safety Organization, Tokyo, Japan.

[23] Nakayama M, Sano M, Sanada H, Sugita Y, 2009. Horonobe Underground Research Laboratory Project; Investigation report for the 2008 fiscal year. Tech. Rep. JAEA-Research 2009-032. Japan Atomic Energy Agency, Tokai-mura, Japan.

[24] Cooke ML, Underwood CA, 2001. Fracture termination and step-over at bedding interfaces due to frictional slip and interface opening, *Journal of Structural Geology*, 23: 223–238.