Rates and mechanism of weathering-rind development on andesite gravel in fluvial terrace deposits

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2. Study Area

2.1. Geomorphological and geological setting

Nasuno-ga-hara consists of coalescing alluvial fans in the northeastern part of Tochigi prefecture, central Japan (Fig. 1). The fans have an area of *ca.* 400km^2 and altitudes from 120 m to 560 m above see level. Nasuno-ga-hara is surrounded by volcanoes, hills and mountains: Nasu Volcano to the north, Takahara Volcano to the northwest, Takaku Hills to the northeast, Kitsuregawa Hills to the southwest, and the Yamizo Mountains to the southeast. Four large rivers (R. Naka, R. Kuma, R. Sabi and R. Hoki) flow on the fans from northwest to southeast. The Naka River locates in the northwestern edge of the Nasuno-ga-hara alluvial fans, while the Hoki River locates in the southeastern edge of the fans. The Kuma River and the Sabi River are arroyos or wadis in the middle of the fans. The fans are composed of several geomorphic surfaces with different ages.

The geologic history of Nasuno-ga-hara and its surrounding areas can be summarized as follows:

(1) During late Pliocene or early Pleistocene, a large lake was formed in an area among Nasu volcano, Takahara Volcano and the Yamizo Mountains. Abundant gravels were accumulated in the lake.

(2) Takahara Volcano began to form in the middle Pleistocene. Subsequently, Nasu Volcano also started activity. Abundant lava flows came out from the volcanoes. A large amount of tuff breccia, pumice and gravel were also deposited at the foot of the volcanoes due to mudflow.

(3) In the late Pleistocene, Takahara Volcano became inactive, while Nasu Volcano went on growing higher through active volcanism. The drainage system of Nasuno-ga-hara, including the Naka, the Hoki, the Kuma and the Sabi Rivers, were formed and thick fan gravel was deposited along the four rivers. Subsequently river terraces were formed due to changes in the riverbed

level.

(4) In the Holocene, narrow terraces and floodplains along the four rivers have been formed by the processes of erosion and sedimentation.

Previous studies have proposed classifications of terraces and their deposits in Nasuno-ga-hara (Table 1). Koike (1961) identified seven geomorphic surfaces created by fluvial processes. Sasaki *et al.* (1958), Watanabe and Sagehashi (1960), Akutsu (1962) and Akagi and Koike (1978) classified terrace deposits and related formations. Although these researchers estimated the ages of terraces, their results should be re-examined based on the recent progress of tephrochronology. For example, Suzuki (1992) compiled the ages of tephra layers in and around Nasuno-ga-hara (Table 1). In the present study, terrace surfaces and deposits were re-classified into seven and their ages were estimated based on Suzuki (1992) (Table 1, Fig. 2). Among the seven geomorphic surfaces convenient descriptions were made on *Lower Terraces (II)* and *Middle Terraces*, because the terraces were out of the subject on the previous study.

(1) *Recent River Floodplain* (Fig. 3): Fluvial surfaces being formed at present. Their deposits are denoted as *Recent River Gravel*. The gravel is mainly composed of andesite with smaller amounts of rhyolite and diorite. Their diameter is 10-30 cm. The gravels are not visibly weathered.

(2) *Lower Terraces (II)*: The lowest terraced surface formed in Holocene. They correspond to "Post Volcanic-Ash Soil Terraces" of Koike (1961). The terraces distribute narrowly along the Hoki, the Sabi, the Kuma and the Naka Rivers. Their height from the present riverbed is 5-10 m (Fig. 4). The terrace deposits also consist mostly of andesite. The common diameter of the gravel is 10-30 cm. The gravels are scarecely weathered.

(3) *Lower Terraces (I)* (Fig. 5): These terraces are the broadest fluvial surfaces of Nasuno-ga-hara. Koike (personal communication) considered that they were formed at *ca.* 20 ka BP because they are not covered with the AT tephra layers fallen at 24 ka BP (Machida and Arai, 1992). Their height above Lower

Terraces II is about 5 m (Fig. 4; Fig. 6a, along the line AB in Fig. 2). These terraces are composed of abundant andesite gravel with a diameter of 20 cm. The gravels are denoted as *Nasuno Gravel*. It has slightly weathered layer with altered colour and a thickness of *ca.* 1 mm.

(4) *Middle Terraces*: Formed around 50 ka BP. Their gravels are almost directly overlain by the DKP tephra layer (48 ka BP; Machida and Arai, 1979). The present author could not find adequate outcrops to take rock samples because the terraces have spotty distribution.

(5) *Upper Terraces* (Fig. 7): Located mainly at the southeastern part of Nasuno-ga-hara. The terraces are covered with volcanic-ash soil layers with a thickness of *ca.* 1 m (Fig.7b). The terraces are considered to be formed around 300-350 ka BP, because their gravels are almost directly overlain by the Apm-U tephra layer dated as 300-350 ka BP by fission track method and loesschronometry (Suzuki and Hayakawa, 1990). The height between this terrace and *Lower Terraces (I)* is less than 10 m (Fig. 4; Fig6b, along the line CD in Fig. 2). Gravel in the terrace deposit consists mostly of andesite and rhyolite cobbles less than 10 cm in diameter. They are considerably weathered; rhyolite rocks are brittle enough to be broken by a weak hitting with a hammer, and andesite rocks have brittle weathering rinds with a thickness of 2-5 mm. However, the inner parts of andesite rocks are quite hard. The gravels composed of these terraces are denoted as *Torinome Gravel*.

(6) *Lower Hills* (Fig. 8): Corresponding to "Nasu Hills" in Koike (1961). They are distributed along the western and southern riverbank of the Hoki River. Their height above *Lower Terraces I* is *ca.* 100 m (Fig. 4; Fig. 6c, along the line EF in Fig. 2). These hills are covered with volcanic-ash soil layers with a thickness of more than 2 m. The hills are considered to be formed at 400-500 ka BP based on the dating of Nm-13 tephra layers (*ca.* 500 ka; Koike *et al.*, 1985). The gravel in the deposits of these hills is characterized by abundant andesite rocks including a small amount of rhyolites less than 30 cm in diameter. The gravel is intensely weathered. Rhyolite gravel can be easily

to discuss the influences of changes in weathering environment on rock properties. For example, details of climatic changes and fluctuations in groundwater levels in Nasuno-ga-hara have not been reconstructed. In addition, the influence of climatic and paleohydrological changes on rock weathering remains to be discussed because there are few findings related to this problems.

In the present study, the five kinds of gravels deposited in *Recent River Floodplain, Lower Terraces I, Upper Terraces, Lower Hills* and *Upper Hills* were selected for the investigation. The other two terraces (*Lower Terraces II* and *Middle Terraces*) were not used because of the lack of wide outcrops suitable for sampling. The investigation focused on andesite gravels because they occur most commonly in Nasuno-ga-hara. The studied geomorphic surfaces and gravel are, hereafter, called as 0-ka surface/0-ka rocks, 20-ka surface/20-ka rocks, 320-ka surface/320-ka rocks, 450-ka surface/450-ka rocks and 830-ka surface/830-ka rocks, respectively.

2.3. Sampling sites and rock samples for analyses

The locations of 10 rock-sampling sites, Loc. 1 to Loc. 10, are shown in Fig. 2. Each sampling point except that for 0-ka surface is set near the groundsurface of each terrace (Figs. 5b, 7b, 8b and 9b), to minimize the possible effect of groundwater levels on weathering (Nishiyama, submitted).

The characteristics of andesite gravels taken from the five geomorphic surfaces are described as follows.

(1) *0-ka rocks*: Sampled from Loc. 1 and Loc. 2 (Figs. 2 and 3). Fifty five andesite cobbles and boulders were randomly taken from these sampling sites (Table 2). Many types of andesite gravel are identified: pyroxene andesite, olivine andesite, propylite and dacite. The rocks taken from these sites are not visibly weathered: they have extremely hard surfaces with gray colour. The

average diameter of them is 8.1 cm (Table 2).

(2) *20-ka rocks*: Sampled from Loc. 3 and Loc. 4 (Figs. 2 and 5). Random sampling of forty-seven andesite cobbles and pebbles was carried out at the sites (Table 2). Types of andesite are the same as the 0-ka rocks. The rocks are quite hard but slightly weathered: their surfaces have altered coloured layer with brown or white with an average thickness of *ca.* 0.7 mm. The rocks taken from these sites are 7.5 cm in average diameter (Table 2).

(3) *320-ka rocks*: Sampled from Loc. 5 and Loc. 6 (Figs. 2 and 7). Twenty-eight andesite cobbles and pebbles were taken from these sites (Table 2). The types of andesite are the same as 0-ka and 20-ka rocks. The rocks have brittle altered layers of brownish colour (*i.e.*, weathering rind) on the surface with a thickness of 2-4 mm. However, the inner parts of the rocks are quite hard. Their average diameter is 9.0 cm (Table 2).

(4) *450-ka rocks*: Sampled from Loc. 7, Loc. 8 and Loc. 9 (Figs. 2 and 8). About seventy andesite boulders were taken from these sites (Table 2). The types of andesite are the same as 0-ka, 20-ka and 320-ka rocks. The rocks have brown weathering rinds with a thickness of 3-5 mm. The weathering rind of each rock is quite brittle but inner parts are relatively hard. Some of the rocks have a whitish-gray zone between the weathering rind and the inner part of the rocks.

(5) *830-ka rocks*: Sampled from Loc. 10 (Figs. 2 and 9). Although the exposure at this site is quite large, andesite gravel was rarely observed. Thus, only one andesite cobble could be taken from there. The type of the andesite block is pyroxene andesite. The size of the rock is 12 cm in diameter. The cobble has a brown weathering rind with a thickness of *ca.* 6 mm. The inner part of the rock is quite hard, while the weathering rind is brittle.

Four or five rocks from each 0-ka, 20-ka, 320-ka and 450-ka surface with the same texture of 830-ka rock were randomly selected for analyses (Figs. 10-15). The name of a sample denoted based on the age and site informations. For example, in the case of the name 450-B10, 450 is the age of the terrace (450 ka), B is the outcrop number, and 10 is the gravel number within the same terrace. All the rock samples were denoted in this way. Each rock sample has gray groundmass in the inner fresh-looking parts (*inner parts*) with some phenocrysts of feldspar and pyroxene. Some rocks have glassy groundmass with small amounts of phenocrysts in the inner parts (*e.g.*, 0-B1, 20-B2 and 450-B1; Figs. 10a, 11d and 13a, respectively), while other samples have plentiful phenocrysts of these minerals.