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Research paper

New approach to resolve the amount of Quaternary uplift and associated denudation of the mountain ranges in the Japanese Islands

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ABSTRACT

Low-temperature thermochronology is a widely used tool for revealing denudation histories of mountain ranges. Although this technique has been applied mainly to continental orogens, such as the European Alps, Himalayas, and Andes, recent technological development of low-temperature thermochronology has made it applicable to a wider variety of mountain ranges with various sizes and tectonic histories. The Japanese Islands comprise young and active island arcs, where an early stage of mountain range formation is observed. Numerous attempts have been made to constrain the uplift and denudation histories of the mountains in the Japanese Islands using geologic, geomorphologic, or geodetic methods. However, the number of thermochronometric attempts has been limited primarily due to the small amount of total denudation since the initiation of the uplift. In this review paper, we introduce the tectonic and geomorphic settings of the mountain ranges in the Japanese Islands, and discuss previous attempts to estimate uplift or denudation of the Japanese mountains using methods other than thermochronology. Furthermore, we discuss problems of the thermochronometric applications in revealing denudation histories of the Japanese mountains. Finally, we present a case study of the Kiso Range in central Japan and discuss the current effectiveness and applicability of low-temperature thermochronology to the Japanese mountainous areas.

1. Introduction

Low-temperature thermochronology, e.g., fission-track (FT), ^{40}Ar–^{39}Ar, and (U–Th–Sm)/He thermochronometers, has been successfully applied to major orogenic belts worldwide to reveal their denudation histories since the 1970s (see the compilation by Herman et al., 2013). Thermochronometric ages of rocks exhumed from the closure depth, i.e., depth of the closure temperature (Dodson, 1973), of a thermochronometer to the surface are apparently younger than their formation ages, providing information about the cooling history of the region (Fig. 1). However, the closure depths of thermochronometers generally range from a few to several kilometers under common geothermal structures. Therefore, denudation histories of mountains within young and small orogens, such as the Japanese Islands, have seldom been targets of thermochronometric studies due to the small total denudation after the onset of the uplift of the mountains. Nevertheless, over the past decade, the applicability of low-temperature thermochronology has been expanded considerably by the practical use of (U–Th–Sm)/He thermochronometry (e.g., Farley, 2002; Reiners, 2005), a more rigorous understanding of the annealing kinetics of the apatite fission-track (AFT) system (e.g., Carlson et al., 1999; Ketcham et al., 2007), improvement in inversion techniques for reconstructing thermal histories (e.g., Ketcham, 2005; Gallagher, 2012), and progress in the interpretation of thermochronometric data in terms of exhumation rates (e.g., Reiners and Ehlers, 2005; Braun et al., 2012; Fox et al., 2014). Such developments have enhanced the sensitivity and reliability of thermochronology and have broadened the range of its applicability (e.g., Reiners et al., 2005).

In this paper, we introduce the current states and potential of thermochronological applicability to the mountain ranges in the

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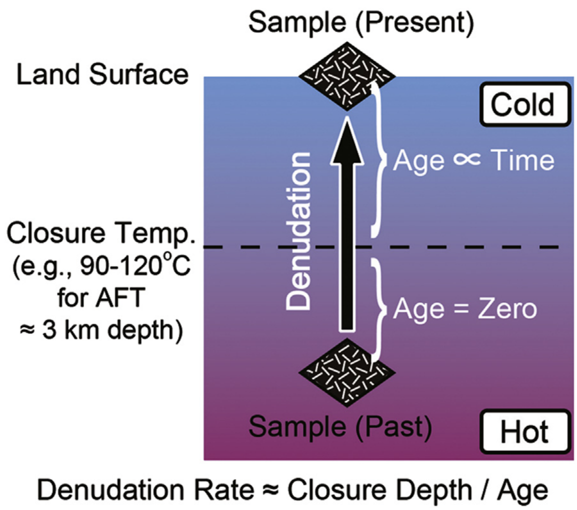

Figure 1. Schematic diagram illustrating the relationship between denudation rates and thermochronometric ages (Sueoka et al., 2015). Thermochronometric ages are reset at a greater depth than the closure depth, i.e., the depth of the closure temperature of a thermochronometer. The thermochronometric age of a rock formed at a great depth that was moved to the surface by denudation indicates the time required to move from the closure depth to the surface. Therefore, the denudation rate D is estimated by $D = d_c/t = (T_c - T_s)/G/t$, where d_c is the closure depth, t is the thermochronometric age, T_c is the closure temperature, T_s is the surface temperature, and G is the geothermal gradient. It should be noted that this model is approximate and is not always effective, particularly for slowly cooled/denuded samples.

Japanese Islands, i.e., island arcs wherein the topographic relief was formed mainly during the last few million years. We first explain the basic tectonic settings and characteristics of mountain ranges of the Japanese Islands, where dynamic landform evolutions are observed depending on the balance between rapid bedrock uplift and denudation; in this paper, denudation or exhumation are defined as difference between bedrock uplift and surface uplift (e.g., England and Molnar, 1990; Burbank and Anderson, 2001). Next, we introduce previous attempts to measure uplift or denudation of the Japanese mountains by the methods other than thermochronology, i.e., methods using elevations of low-relief erosional surfaces, volumes of deposits in catchments or basins, terrestrial *in situ* cosmogenic nuclides (TCN), geodesic surveys, and heights of marine and fluvial terraces. Then, we review several thermochronometric studies conducted to reveal the denudation histories of the Japanese mountains to illustrate problems and difficulties in applying thermochronological methods to young and small mountains. Although quite a few thermochronometric studies have been performed in the Japanese Islands, the applications to the Quaternary uplift/denudation of the mountains have been limited mainly due to the small total denudation since the initiation of the uplift. Finally, we introduce a case study of the Kiso Range in central Japan, and discuss the effectivity and applicability of low-temperature thermochronology on the Japanese mountainous areas. To examine the detailed denudation history of the Kiso Range, we examined a new interpretation scheme of thermochronometric datasets. It should be noted that the discussions in this review paper are based on the previous data—we present no new data. Major thermochronometric data used for the discussions are listed in Suppl. Table 1.

2. Tectonic and geomorphic settings of Japanese mountains

The Japanese Islands are active island arcs located at a convergence zone of the Eurasian, North American, Pacific, and Philippine Sea plates (Fig. 2). The main part of the Japanese Islands is divided into the NE Japan Arc and southwest Japan Arc by the Itoigawa–Shizuoka Tectonic Line (ISTL) and the Fossa Magna region to the east, whereas the SW Japan Arc is subdivided into inner and outer zones by the Median Tectonic Line (MTL). The Izu–Ogasawara Arc collides with the southern Fossa Magna region from the south.

The present tectonic conditions of the Japanese Islands are controlled mainly by subduction of the Pacific and Philippine Sea plates and are characterized by an E–W compression (e.g., Seno, 1999; Terakawa and Matsu'ura, 2010). The onset of the present E–W compressional stress field is estimated to have occurred during the Pliocene or earliest Pleistocene (e.g., Sato, 1994; Kimura et al., 2005; Takahashi, 2006), which is considered to have been derived from the oblique subduction of the Philippine Sea Plate beneath the Eurasian Plate (e.g., Takahashi, 2006).

Kaizuka and Chinzei (1986) classified the Japanese mountains according to their formation mechanisms and suggested that most of these mountains have been uplifted in relation to reverse faults, strike-slip faults, or folds under compressional stress fields. In contrast, normal fault blocks are distributed only in the northeastern part of the Kyushu Island (Fig. 3). The widths of the Japanese mountains are generally 10–20 km or less because the wavelengths of deformations due to listric faulting are limited by the thickness of the brittle crust (Ikeda, 1996). The elevations of the Japanese mountains are approximately 3 km at the highest point, except for volcanoes. Most of the topographic relief in this region is interpreted to have formed during the last few million years under the current tectonic setting (Fig. 4; Yonekura et al., 2001). Prior to the mountain building during the past few million years, peneplanation associated with slow denudation is believed to have prevailed from the late Cretaceous to the end of Neogene over most of the Japanese Islands (Ota et al., 2010).

Rapid denudation rates owing to the wet climate characterize the landforms of the Japanese Islands as well as active tectonics, as expressed by the term "tectonically active and intensely denuded regions" (Yoshikawa, 1984, 1985). Annual precipitation of 1000–2000 mm and relative humidity of around 70% are observed in major cities all over the Japanese Islands (http://www.data.jma.go.jp/obd/stats/data/en/normal/normal.html) due to Asian monsoon and typhoons. Paleo annual precipitation since 430 ka also ranged from 1000 to 2500 mm according to modern analogue technique (MAT) and pollen data obtained from borehole samples of Lake Biwa (Okuda et al., 2010). In the mountainous areas with high elevation and/or high latitude, periglacial erosion prevailed during glacial periods (e.g., Sugai, 1990, 1995). The maximum denudation rates inferred from sedimentary volumes of catchments range from several to >10 mm/yr; these rates are among the world's highest (Yoshikawa, 1974; Ohmori, 1983). Previous studies (e.g., Ahnert, 1970; Ohmori, 1978; Montgomery and Brandon, 2002) proposed that altitudes of mountain ranges attain steady states depending on the bedrock uplift rates when dynamic equilibrium between denudation and bedrock uplift is achieved with time (Fig. 5). According this concept, (1) mountain elevation does not indefinitely increase but converges with a critical value although the bedrock continues to be uplifted; (2) denudation rates are less than bedrock uplift rates before dynamic equilibrium is achieved; (3) approximately a few million years are generally required to achieve dynamic equilibrium; and (4) local relief remains constant in the culminating stage. Most of the Japanese mountains are considered to be at the developing or earliest culminating stage because only a few million years or less have passed since the initiation of their uplift. At the developing stage, denudation rates vary dramatically from the valley to the ridge because lateral denudation of the original surface by valley incision is dominant (Sugai and Ohmori, 1999).