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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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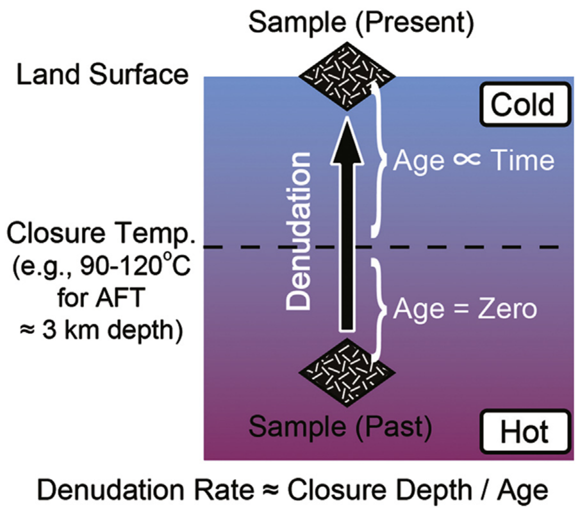


**Figure 1.** Schematic diagram illustrating the relationship between denudation rates and thermochronometric ages (Sueoka et al., 2015). Thermochronometric ages are reset at a greater depth than the closure depth, i.e., the depth of the closure temperature of a thermochronometer. The thermochronometric 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).

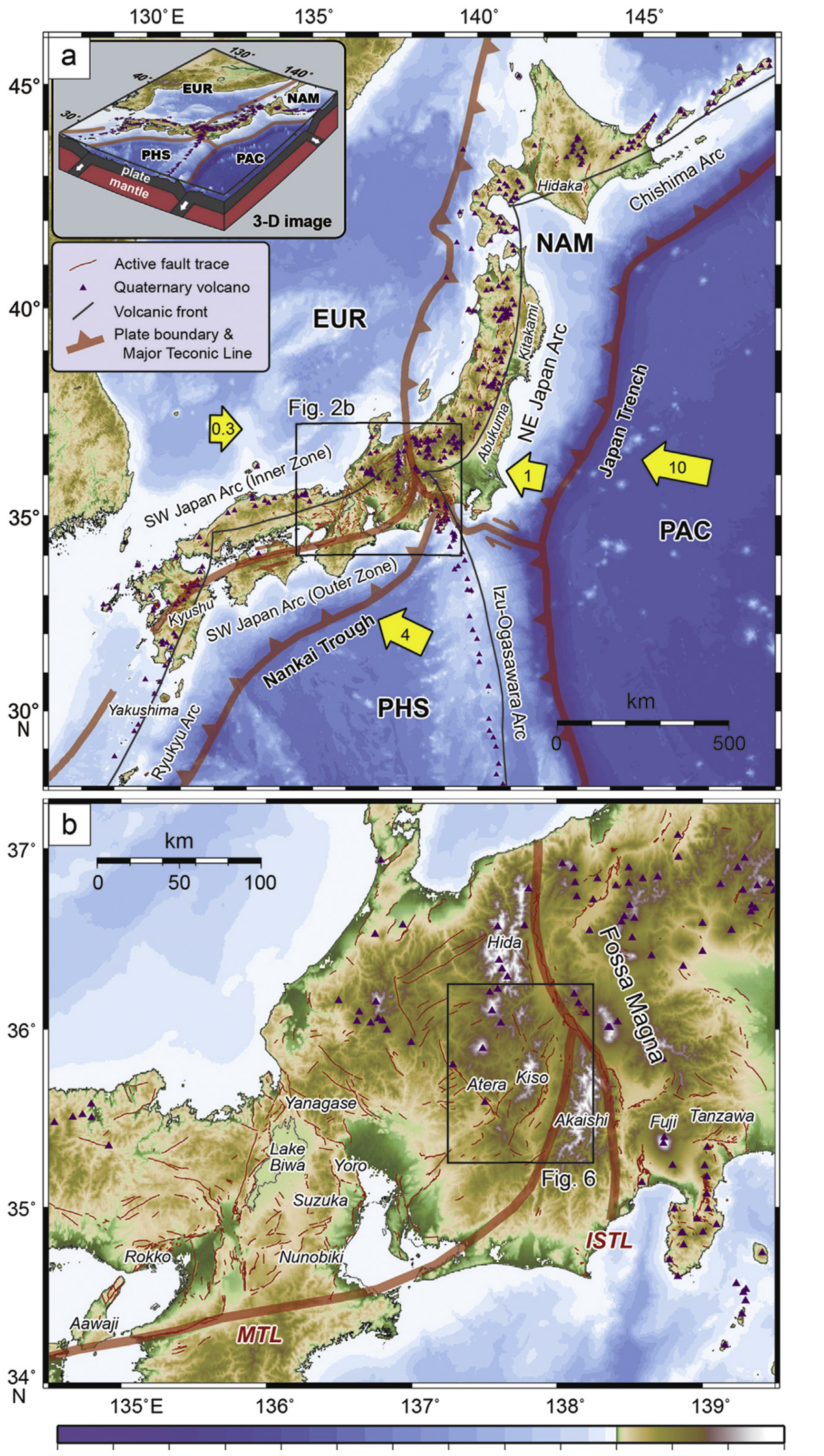


**Figure 2.** Tectonic setting and index map of the Japanese Islands. The figures were drawn by using Generic Mapping Tools (GMT; Wessel and Smith, 1991) and the GEBCO_08 Grid of the General Bathymetric Chart of the Oceans. (a) Tectonic setting of the Japanese Islands. Active fault traces are after Nakata and Imaizumi (2002). Quaternary volcanoes are after Committee for Catalog of Quaternary Volcanoes in Japan (1999). Volcanic fronts are after Sugimura (1978). Yellow vectors indicate directions and rates in centimeters per year of the plate motions after Isozaki (1996). The plate boundary along the eastern Japan Sea is a nascent convergent zone along which EUR has subducted beneath NAM since 2–1 Ma (Nakamura, 1983). MTL is a right-lateral strike-slip fault related to the oblique subduction of PHS beneath EUR (Fitch, 1972). (b) Major mountains in central Japan. EUR: Eurasian Plate, NAM: North American Plate, PAC: Pacific Plate, PHS: Philippine Sea Plate, *MTL*: Median Tectonic Line, *ISTL*: Itoigawa–Shizuoka Tectonic Line.

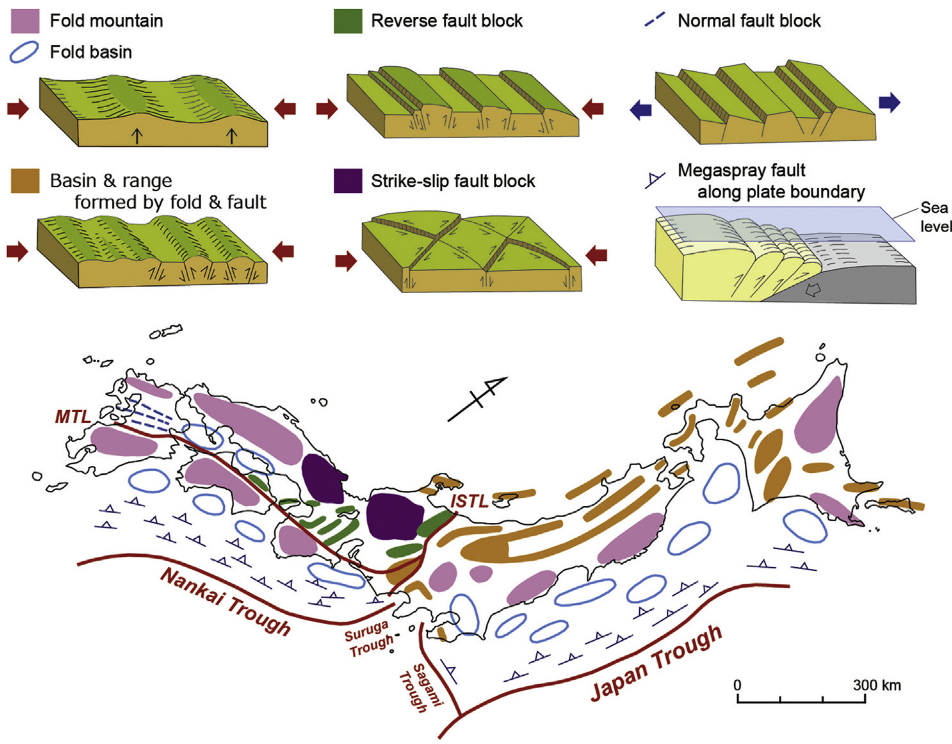


**Figure 3.** Classification and distribution of tectonic mountains in Japan (modified from Kaizuka and Chinzei, 1986). Most of the Japanese mountains were uplifted under compressional tectonics. The uplift mechanisms of some mountains remain under debate such as the Hida Range and Akaishi Range (e.g., Ikeda, 1990; Kano, 2002; Ito et al., 2013). MTL: Median Tectonic Line, ISTL: Itoigawa–Shizuoka Tectonic Line.

## 3. Uplift and denudation rates of the Japanese mountains

A variety of methodology has been applied to measure the uplift or denudation rates of the Japanese Island (Table 1). In this section, we will introduce several previous studies and discuss the potential problems of each method.

### 3.1. Elevations of low-relief erosional surfaces

One of the earliest quantitative estimations of uplift of the Japanese mountains was conducted by measuring the elevation of the low-relief erosional surfaces (e.g., Research Group for Quaternary Tectonic Map, 1968). This method assumes that low-relief erosional surfaces observed at mountain ridges are uplifted remnants of peneplains, i.e., low-relief surfaces formed near sea level prior to the end of Neogene that were uplifted to their present heights during the Quaternary (e.g., Research Group for Quaternary Tectonic Map, 1968). The maximum uplift during the Quaternary is estimated to be approximately 1700 m in the Hida Range (Research Group for Quaternary Tectonic Map, 1968). However, it is generally difficult to accurately date the surface and to estimate the initial elevations of the surfaces. In addition, low-relief surfaces at mountain ridges can be formed near the present elevation by other processes such as dynamic equilibrium between bedrock uplift and denudation (Hirano, 1972; Ohmori, 1978, 1985), periglacial erosion (Sugai, 1990, 1992, 1995), and gravitational deformation (Mokudai and Chigira, 2004). Higher mountains undergoing these processes provide underestimations of the uplift rates if the erosional surfaces are regarded as uplifted remnants of peneplains. Currently, elevations of low-relief surfaces are seldom used as indicators of bedrock uplift.

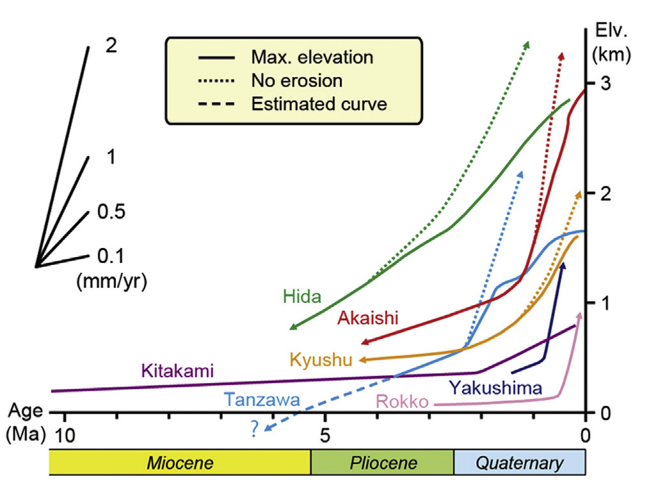


**Figure 4.** Relief development of the Japanese mountains (modified after Yonekura et al., 2001). The locations of the mountains are given in Fig. 2.

### 3.2. Volumes of deposits in catchments or basins

Spatially averaged erosion or denudation rates in catchment areas are calculated by measuring the depositional volumes in catchments (e.g., Yoshikawa, 1974; Ohmori, 1978) or basins (e.g., Tanaka, 1982). Such studies indicated that the Japanese mountainous areas were denuded at extraordinary high rates ranging up to a few to >10 mm/yr. On the basis of the denudation rates inferred from the method, it is also revealed that several geomorphic parameters, such as variance of altitude, relief, or slope, of catchment areas correlate well with the denudation rates. On the basis of these correlations, denudation rates were calculated using digital elevation models (DEM) (Fujiwara et al., 1999; Okano et al., 2004; Hasegawa et al., 2005).

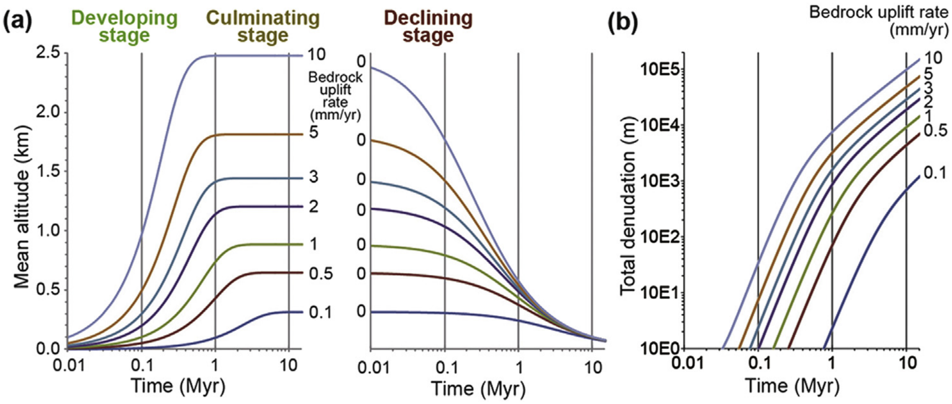


**Figure 5.** Dynamic equilibrium between bedrock uplift and denudation (modified from Ohmori, 1985). (a) Landform evolution by uplift and denudation is divided into the following three stages: (1) the developing stage during which landforms approach steady state by concurrent uplift and denudation, (2) the culminating stage during which steady-state landforms are maintained in the dynamic equilibrium of uplift and denudation, and (3) the declining stage during which landforms are reduced down to sea level by denudation after uplift ceases (Yoshikawa, 1984, 1985). The steady-state altitude depends on the bedrock uplift rate. (b) Cumulative denudation computed from Fig. 5a. Cumulative denudation is shown to rapidly increase a few million years after the initiation of the uplift.

### 3.3. Terrestrial in situ cosmogenic nuclides

Techniques using terrestrial *in situ* cosmogenic nuclides (TCN) have been rapidly developed since the 1980s (e.g., Gosse and Phillips, 2001) and have been introduced and applied in Japan through the 2000s (e.g., Wakasa et al., 2004; Yokoyama et al., 2005; Matsushi et al., 2007). These methods have been applied to estimate denudation rates for $10^2$–$10^4$ mm/yr in the Boso Peninsula (Matsushi et al., 2006), Abukuma Mountains (Shiroya et al., 2010; Nakamura et al., 2014), Hida Range (Hattanji et al., 2014; Matsushi et al., 2014a), Rokko Mountains (Matsushi et al., 2014b), and Yakushima Island (Shiroya et al., 2014). The estimated denudation rates range from $10^{-2}$–$10^0$ mm/yr, varying greatly from region to region. It is also noteworthy that TCN methods have been recently applied to date landslide deposits in the Japanese mountains (e.g., Kariya et al., 2014; Kurosawa et al., 2014), which is essential for understanding the erosional process in mountainous areas.

### 3.4. Geodesic surveys

Modern geodetic surveys have been conducted in Japan since the late 19th century. Vertical deformation in the Japanese Islands during ~70 (Dambara, 1971) and ~100 years (Kunimi et al., 2001) were computed on the basis of leveling data. Vertical deformation observed by Global Positioning System (GPS) during <10 years was also calculated (Murakami and Ozawa, 2004; Yoshii, 2005). In the Japanese Islands, different deformation patterns were identified depending on the observational time interval. For example, leveling surveys and InSAR analyses revealed a ~20-cm uplift of the Rokko Mountains during the 1995 Kobe earthquake ($M_w$ 6.9) (e.g., Hashimoto, 1995), whereas the area has subsided during the last decade or century (Kunimi et al., 2001; Murakami and Ozawa, 2004; Yoshii, 2005). In addition, the strain rates of the Japan Islands during the past ~100 years were estimated to be $10^{-7}$/yr from geodetic surveys, whereas those in the past $10^6$ years were inferred to be $10^{-8}$/yr on the basis of geomorphic and geologic observations (Ikeda, 1996; Ikeda et al., 2012). Detailed comparisons between short-term and long-term deformation patterns and rates in each area are necessary for understanding the physical characteristics and deformation process of the Japanese Islands (e.g., Ikeda et al., 2012; Nishimura, 2014).

### 3.5. Heights of marine and fluvial terraces

Marine and fluvial terraces, particularly those formed at marine isotope stage (MIS) 5e, are widely distributed in Japan, providing indicators of regional uplift rates. The heights and ages of marine terrace surfaces along the Japanese coasts have been mapped and cataloged (Ota and Omura, 1991; Koike and Machida, 2001; Okuno et al., 2014). The relative heights of fluvial terrace surfaces or buried valleys formed at various interglacial (glacial) stages can also be used as indicators of uplift during the interglacial–interglacial (glacial–glacial) period, assuming that graded river profiles are uniform at the various interglacial (glacial) stages (Yoshiyama and Yanagida, 1995). These methods were applied to inland areas, and the uplift rates were estimated to be −1.1 to 1.0 mm/yr in the Tohoku area (Tajikara and Ikeda, 2005), 0.11 to 0.16 mm/yr in the Toki area (Tajikara et al., 2011), and −1.2 to 0.5 mm/yr in the Ise Bay area (Ishimura, 2013). In Japan, the ages of marine and fluvial

**Table 1**
Methodology and indicators used to measure uplift/denudation rates. *U* represents uplift, including both surface uplift and bedrock uplift; *D* indicates denudation or erosion.

| Methodology or Indicator | Uplift or denudation | General time range (yr) | Note |
|---|---|---|---|
| GPS survey | *U* | <10 | Less bench marks in mountainous areas |
| Leveling | *U* | <100 | Less bench marks in mountainous areas |
| Height of low-relief erosional surface | *U* | $\sim10^6$ | Few information about the formation ages and initial heights |
| Height of marine/fluvial terraces | *U* | $10^3$–$10^5$ | Available only along coastlines or rivers |
| Volume of catchment deposits | *D* | 10–$10^2$ | Low spatial resolution (mean rates in the drainage areas) |
| Volume of basin deposits | *D* | $\sim10^6$ | Low spatial resolution (mean rates in the drainage areas) |
| *In situ* cosmogenic nuclide | *D* | $10^2$–$10^4$ | Occurrence of the target minerals |
| Thermochronometry | *D* | $10^6$–$10^8$ | Occurrence of the target minerals |

terraces were determined mainly by radioactive carbon dating and tephrochronology because lots of widespread tephras are well documented (Machida and Arai, 2003). Optically stimulated luminescence (OSL) dating of terrace deposits has been also attempted because this method can date terrace deposits older than ∼100 ka, which is beyond the limit of radioactive carbon dating (e.g., Tanaka et al., 1997, 2001; Tokuyasu and Tanaka, 2013). In particular, the post-infrared infrared stimulated luminescence (pIRIR) method of K-feldspar (Thomsen et al., 2008) is highlighted because it has a potential to date deposits within ∼1 Ma (Zander and Hilgers, 2013). Dating of terrace deposits using the pIRIR method has been attempted for both marine and fluvial terraces in Japan (e.g., Kondo et al., 2013; Maruyama et al., 2013).

## 4. Difficulties in thermochronometric applications to the Japanese mountains

Quite a few thermochronometric studies have been conducted to reveal the cooling or denudation histories of bedrocks of the Japanese Islands (e.g., Tagami et al., 1988; Hasebe et al., 1997; Hasebe and Tagami, 2001). Nonetheless, cooling or denudation of uplifting fault-block mountains in the Quaternary has seldom been the target of thermochronometric studies probably because of difficulties unique to the Japanese islands, young island arcs. In this section, we discuss such difficulties while introducing several previous thermochronometric studies in the Japanese mountainous regions. We use abbreviations of AFT, zircon fission-track (ZFT), apatite (U–Th)/He (AHe), and zircon (U–Th)/He (ZHe).

### 4.1. Small denudation since the initiation of the mountain uplifting

The current denudation rates of the Japanese mountainous regions are among the world's highest (e.g., Yoshikawa, 1974; Ohmori, 1983). However, because the onset of the mountain uplift is generally late, total denudation since the onset of the mountain uplifting is sometimes less than 2–3 km (Fig. 5b), which is equivalent to the AFT closure depth under a general geothermal gradient. Cooling ages of Mesozoic or Paleogene time were reported in some Japanese mountainous areas that have uplifted since the late Pliocene or Quaternary, e.g., AHe and AFT ages of the Awaji Island (max. elevation: 608 m; Ito, 2004, 2006), AFT and ZFT ages, including borehole samples at depths of 800–1200 m of the Rokko Mountains (max. elevation: 931 m; Sueoka et al., 2010), AFT and ZFT ages of the Atera Mountains (max. elevation: 1982 m; Yamada et al., 2012), and AFT ages of the Suzuka Range (max. elevation: 1247 m; Sueoka et al., 2014). These older ages are essentially attributable to peneplanation from the late Cretaceous to the end of Neogene (Goto, 2001; Sueoka et al., 2012).

On the contrary, young ages associated with the mountain uplift after the late Pliocene were reported in a few mountainous areas. In the Hida Range (northern Japanese Alps), one of the highest and largest mountain ranges in Japan, some young cooling ages were reported; ZFT and K–Ar ages were younger than 7 Ma in the eastern side of the Kurobe–Takasegawa fault zone, whereas the ages in the western side were older than 40 Ma (Ito and Tanaka, 1999; Yamada, 1999; Yamada and Harayama, 1999). These younger ages were interpreted to reflect rapid cooling and denudation of the eastern block during the past few million years. In addition, Yamada (1999) reported AFT ages of ∼0 Ma, implying multiple uplifting stages at ∼4 and < 1 Ma. However, it is also known that the world's youngest granitic bodies are distributed in the same region (Harayama, 1992; Ito et al., 2013). Thus, the younger thermochronometric ages may not directly reflect the denudation rate, but late formation of the granitic bodies, although exposures of such young granitic bodies require extraordinarily rapid denudation during the Quaternary. The rapid uplift and denudation may have been caused by not only compressional stress but also magmatic intrusion (Ito et al., 2013) and may be stimulated by isostatic rebound due to variations in surface rock density and thin effective elastic thickness of the lithosphere along the volcanic chain (Braun et al., 2014).

In the Tanzawa Mountains in the south Fossa Magna region, AHe ages of 2.0 ± 0.2 Ma, ZHe ages of 3.3 ± 0.2 Ma, and ZFT ages of 6.9–4.5 Ma were reported (Yamada and Tagami, 2008). Although the maximum elevation of the Tanzawa Mountains is only 1673 m, arc–arc collision between the south Fossa Magna region and Izu–Ogasawara Arc has led to extraordinary rapid uplift in this region. Yamada and Tagami (2008) estimated the denudation rates to be 0.5–1.5 mm/yr for 7–3.3 Ma, ∼2 mm/yr for 3.3–2.0 Ma, and 0.8 mm/yr for 2.0–0 Ma by assuming 40 °C/km for the geothermal gradient and 10 °C for the surface temperature. On the other hand, Tani et al. (2010) suggested rapid magma emplacement and cooling based on the newly obtained zircon U–Pb ages of approximately 5–4 Ma. Considering the young emplacement age, relatively low topographic relief, and slower cooling rate of 2.0–0 Ma, these young He ages may reflect the cooling of magma as well as denudation of the surface.

### 4.2. Effectiveness of age–elevation relationships in the Japanese mountains

Age–elevation relationships (AER) are among the most commonly used approaches for estimating the denudation rates of mountainous areas from thermochronometric datasets (e.g., Gleadow and Fitzgerald, 1987; Braun, 2002a,b). Assuming that continuing denudation brings rocks from the horizontal closure depth up to the land surface, the gradient of thermochronometric ages versus sample elevations indicates the regional denudation rate (Braun, 2002a). The basic concept of AERs assumes the following principles: (1) the total denudation after the onset of the mountain uplift is larger than the depth of the applied thermochronometer; (2) denudation and bedrock uplift rates over the mountain are spatially uniform; and (3) the topographic relief does not change. These assumptions have been largely valid in continental massive and mature orogens, although corrections were required in some cases (e.g., Braun, 2002b; Huntington et al., 2007; Mahéo et al., 2009; Valla et al., 2010).

In contrast to the continental orogens, most of the topographic relief in Japan has been formed during the last few million years (e.g., Ota et al., 2010), and the mountains are believed to have experienced generally less than a few kilometers of denudation since the onset of the uplift (Fig. 5b). In addition, most of the mountains have not achieved dynamic equilibrium between bedrock uplift and denudation. Therefore, temporal changes in the denudation rates should have occurred (Ohmori, 1978, 1985) in addition to those in spatially non-uniform denudation rates between the ridges and valleys (e.g., Sugai and Ohmori, 1999). Tilting uplift is also commonly observed for the fault-block mountains in Japan (e.g., Ikeda, 1990; Shikakura et al., 2012). Considering these characteristics, there is little advantage in applying AERs to the Japanese mountains rather than to continental large-scale orogens, although careful corrections may provide some successful applications.

### 4.3. Detrital thermochronology

Thermochronology of detrital minerals is also a powerful tool for estimating the denudation history of mountainous areas (e.g., Stock and Montgomery, 1996; Bernet and Garver, 2005; Vermeesch, 2007). The lag time between the thermochronometric and depositional ages of clastics reflects the denudation rates of the drainage

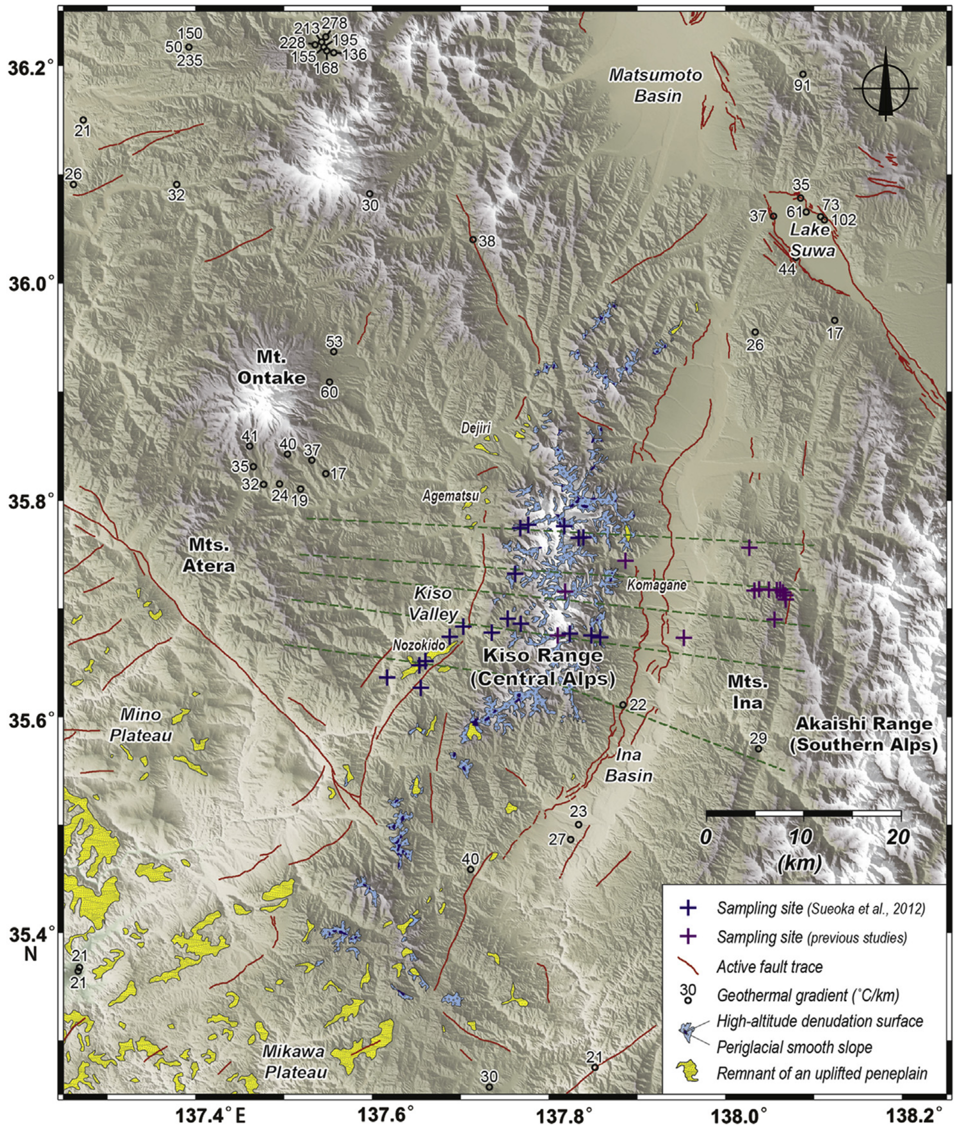


**Figure 6.** Tectonic settings of the Kiso Range (modified from Sueoka et al., 2012). Active fault traces are after Nakata and Imaizumi (2002). Geothermal gradients are from Tanaka et al. (2004). Geomorphic surfaces are after Sugai (1995). Green dashed lines indicate profiles of topographic cross-sections of Fig. 7. Sampling sites of previous studies include Tagami et al. (1988), Tagami and Shibata (1993), and Goto (2001), where AFT and/or ZFT ages were reported.

area at the time at which the clastics were denuded and deposited, assuming that the timing of erosion and sediment transport is regarded as geologically simultaneous. This method is useful for interpreting variation in denudation rates over several million years or longer periods.

Application of detrital thermochronology to the Japanese mountains is generally unsuccessful. A supply of clastics from a mountain to adjacent basins for several million years or longer is not expected for the Japanese mountains that have uplifted during the last few million years. In addition, the denudation rates increase rapidly due to the relief growth during the first few million years of the mountain uplift (Fig. 5). Thus, clasts record less denudation than samples collected from the present outcrops of the drainage area, implying that detrital thermochronometry is less successful than conventional thermochronometry when applied to the Japanese young and small mountains.

Nonetheless, several case studies of detrital thermochronology have been reported in the Hidaka Range, which has uplifted since the middle Miocene (e.g., Arita et al., 2001; Kawakami et al., 2004, 2006). On the basis of K–Ar, ZFT, and AFT ages performed on both clastic and outcrop samples, the cooling and denudation histories of the Hidaka Range were estimated. The results indicate that rapid denudation of a few to several mm/yr occurred near the end of the early Miocene or middle Miocene, associated with uplift of the Hidaka Range (Arita et al., 1993, 2001; Kawakami et al., 2006); the denudation rates decreased to 0.3–0.6 mm/yr after the middle Miocene (Arita et al., 2001); and thermochronometric ages become older to the east from the Hidaka Main Thrust Fault, indicating slower cooling/denudation rates to the east (Arita et al., 1993; Ono, 2002; Kawakami et al., 2006).

## 5. Thermochronological study of the Kiso Range

The Kiso Range (central Japanese Alps) is a reverse-fault-block mountain (e.g., Kaizuka and Chinzei, 1986; Ikeda, 1990) consisting of the Mesozoic granitic and metamorphic rocks (e.g., Yamada et al., 1990). The maximum elevation is 2956 m at Mount Kisokomagatake, and the width is less than 20 km (Fig. 6), producing one of the steepest slopes in the Japanese mountains. The onset of the uplift of the Kiso Range was estimated to be ~0.8 Ma because granitic gravels sourced from this range began to be deposited in the adjacent Ina basin at that time (Matsushima, 1995). No Quaternary volcano is known in the Kiso Range and the present geothermal gradient range is 20–40 °C/km in and around the Kiso Range (Fig. 6).

### 5.1. Thermochronometric ages of Kiso Range

Sueoka et al. (2012) performed AHe, AFT, and ZFT thermochronometric analyses on samples collected across the Kiso Range to discuss the denudation history and mountain formation processes (Figs. 6 and 7). The ZFT age range is 59.3–42.1 Ma, which is interpreted to reflect the timing of the intrusion of the granitic bodies. In contrast, AFT ages of 81.9–2.3 Ma and AHe ages of 36.7–2.2 Ma were obtained (Fig. 7). Although the thermochronometric ages are slightly older than the beginning of the uplift of the Kiso Range at ~0.8 Ma, the plots between AFT ages and AFT length imply that these ages reflect the cooling/denudation related to the uplift of the Kiso Range (Sueoka et al., 2012). The ages become younger from the ridges to both the eastern and western bases of the range, whereas the ages at the same altitude are systematically younger in the eastern slope than those in the western slope (Sueoka et al., 2012).

### 5.2. Thermochronological interpretation using T–d relationships

AERs are difficult to apply to the AFT and AHe datasets of the Kiso Range because the ages in the eastern slope are systematically younger than those in the western slope, implying tilted uplifting. In addition, the ages near the ridge and possibly those near the bases have been partially reset since the initiation of the uplift of the mountains, and substantial relief development since ~0.8 Ma is evident.

To examine a more detailed denudation history from the thermochronometric dataset, Sueoka et al. (2012) developed a new interpretation scheme based on the relationships between paleotemperature, *T*, and relative distance from the original surface, *d* (Fig. 8). Here, *T* is determined from cooling paths calculated by using the inversion software, such as HeFTy (Ketcham, 2005). The parameter *d* is computed from the elevation and horizontal distance of each sampling locality (Fig. 8a). If the sampling localities are contained in a fault block that includes uplifting and tilting without changing the positional relationships, plots of *T* versus *d* should be linear assuming a proper tilting angle (Fig. 8b and c); the slope indicates the geothermal gradient just before the onset of uplift (Fig. 8d). The denudation rate at each locality is therefore computed from the paleogeothermal gradient and each *T* by assuming a general paleo-surface temperature, whereas the maximum bedrock uplift rate is also estimated by considering the present elevation (Fig. 8e). It should be noted that this method assumes or requires that each sampling location is exhumed vertically with no horizontal shortening. Moreover, the land surface must have been peneplained before the uplift of the mountain, and the onset age of the uplift must be known.

In the Japanese mountainous areas, thermochronometric ages sometimes become younger according to the distance from a fault zone rather than the sample elevations (e.g., Tagami et al., 1988; Ono, 2002). This observation suggests the potential efficiency of the method based on *T*–*d* relationships. However, the Kiso Range is one of the highest mountain ranges in Japan; therefore successful application to the Kiso Range does not guarantee the validity of *T*–*d* relationships based mainly on AFT datasets. For wider application, more precise and accurate inverse calculations based on lower-temperature thermochronometry, such as the AHe method, are necessary.

Although we consider only vertical or subvertical exhumation and neglect horizontal shortening in *T*–*d* relationships, the

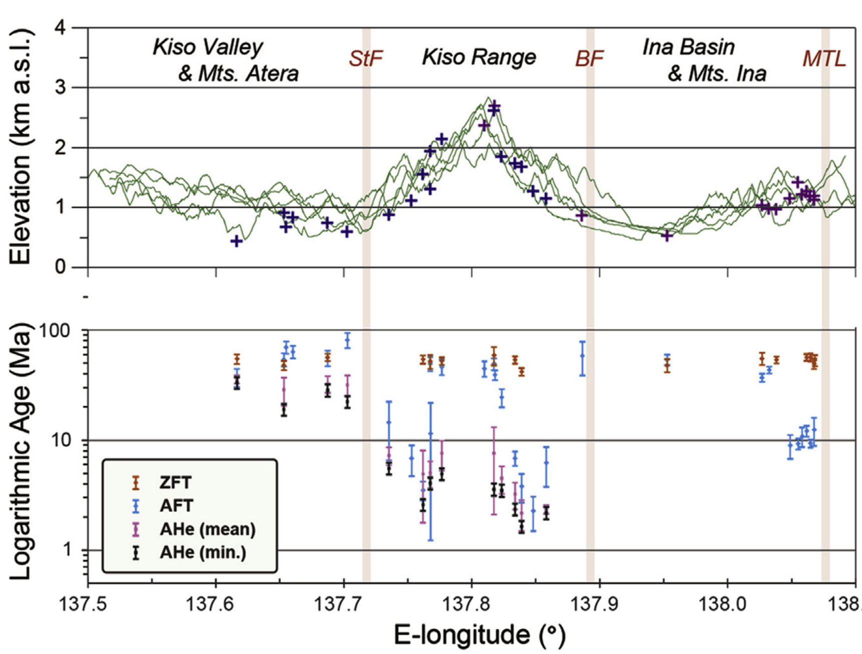


**Figure 7.** Thermochronometric ages across the Kiso Range (modified from Sueoka et al., 2012). The age data are from Tagami et al. (1988), Tagami and Shibata (1993), Goto (2001), and Sueoka et al. (2012). Error bars are ±2σ. The boundary fault of the Inadani fault zone (BF) and Seinaiji-toge fault (StF) are distributed along the eastern and western margins of the Kiso Range. The activity of MTL in this area is not obvious during the late Quaternary. Two major geologic events, i.e., granitic intrusion in the late Cretaceous and mountain uplifting in the Quaternary, are identified from the thermochronometric data. The previous K–Ar, Rb–Sr, and CHIME ages (e.g., Suzuki et al., 1995; Suzuki and Adachi, 1998; Yuhara et al., 2000; Yuhara and Kagami, 2006) and ZFT ages indicate the granitic intrusion and primary cooling in the late Cretaceous. On the other hand, lower-temperature thermochronometers, i.e., AFT and AHe ages, in the Kiso Range is interpreted to reflect the Quaternary mountain uplift event.

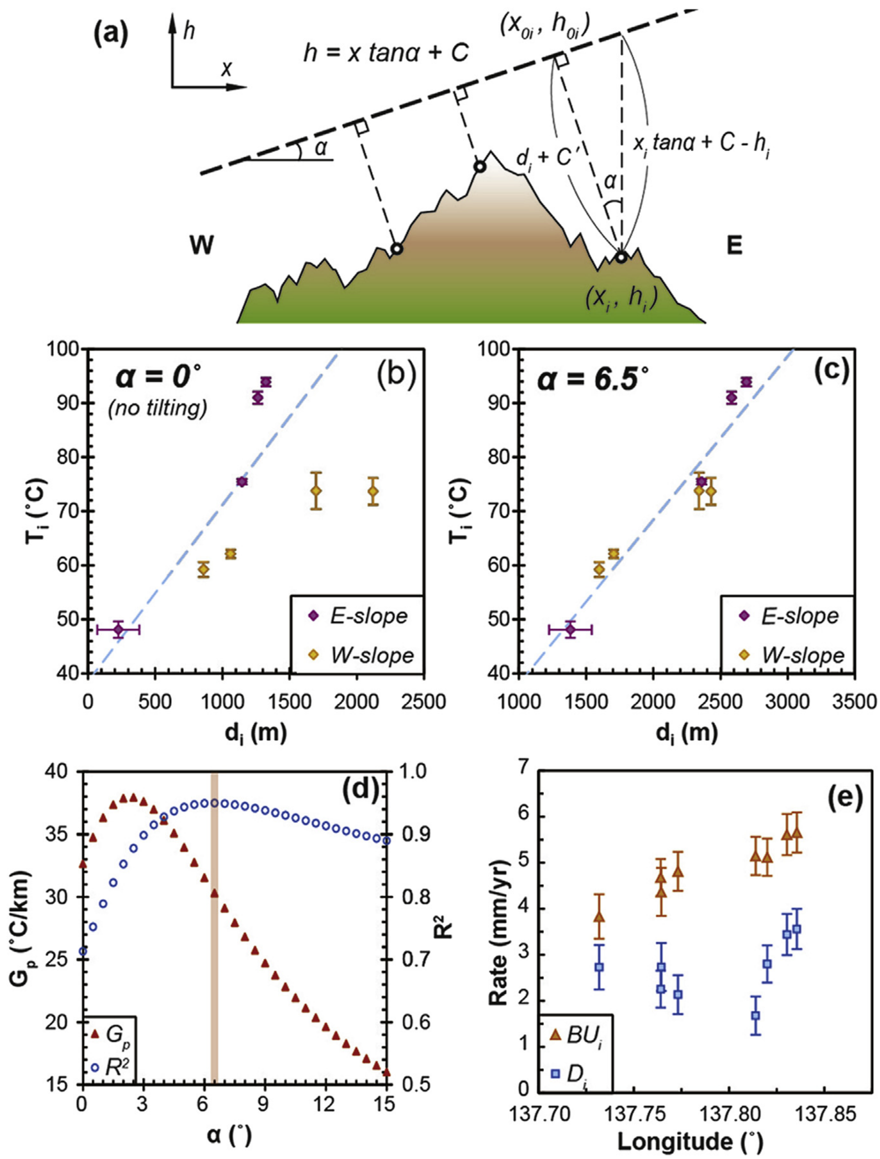


**Figure 8.** Concept of $T$–$d$ relationships (Sueoka et al., 2012). (a) Cartoon showing the basic concept. The relationship between the paleotemperature at the each sampling site just before the onset of the uplift of the mountain, $T_i$, and relative distance from the original surface to the each sampling site, $d_i$, is described by $T_i = G_p d_i + C$, where $G_p$ is the paleo geothermal gradient just before the onset of uplift of the mountains and $C$ is a constant. $d_i$ is described by $d_i = (x_i \tan\alpha + C' - h_i)\cos\alpha$, where $\alpha$ is the gradient of the original surface, $h_i$ is altitude of each sampling site, $x_i$ is relative horizontal distance of each sampling site, and $C'$ is a constant. $G_p$ can be calculated from the slope of the $d_i$ versus $T_i$ plots by using the least-squares method (Sueoka et al., 2012). (b) The $T$–$d$ relationships of the Kiso Range when $\alpha = 0°$. (c) The $T$–$d$ relationships of the Kiso Range when $\alpha = 6.5°$ and when $R^2$ between $D_i$ and $T_i$ is at the maximum. (d) $R^2$ and $G_p$ versus $\alpha$. $R^2$ attains the maximum when $\alpha = 6.5°$, producing $G_p = 30.3 \pm 0.8$ °C/km. (e) Assuming that the age of the onset of the uplift is 0.8 Ma (Matsushima, 1995), the denudation rates of 1.3–4.0 mm/yr and maximum bedrock uplift rates of 3.4–6.1 mm/yr can be computed.

importance of horizontal advection of heat and rocks was pointed out for interpreting thermochronometric data in maturer orogens, such as New Zealand, Himalayas, and Cascades (e.g., Batt and Braun, 1999; Batt and Brandon, 2002; Willett and Brandon, 2002; Herman et al., 2007, 2009, 2010a,b; Lock and Willett, 2008). However, the total displacements along the Japanese active faults are a few to 10 km at a maximum (e.g., Matsuda et al., 2004; Ota et al., 2010), which is still smaller than those of the mature orogens; for example, the total displacement along the Alpine fault, New Zealand, is estimated at about 450 km (e.g., Sutherland, 1999). This observation indicates a less development of horizontally shortening than in the mature orogens. Additionally, these smaller total displacements imply that ductile deformations associated with the active orogenesis are not generally recorded in the rocks near the surface in the Japanese Islands; the total exhumation is too small to expose such rocks. Therefore, the effects of horizontal advection in the Japanese Islands are considered not to be as significant as in the mature orogens.

### 5.3. Uplift and denudation of reverse-fault block mountains

Using the simple slope development model based on the advective diffusion equation (Hirano, 1972), the evolutions of fault blocks can be described, as shown in Fig. 9 (Sueoka et al., 2012). As shown in Fig. 8d, the Kiso Range was uplifted while being tilted westerly by the faults along the eastern and western margins. However, the topographic cross sections are nearly symmetric. The denudation rates are greater on the ridges than on the bases and are greater on the eastern slopes than on the western slopes. These

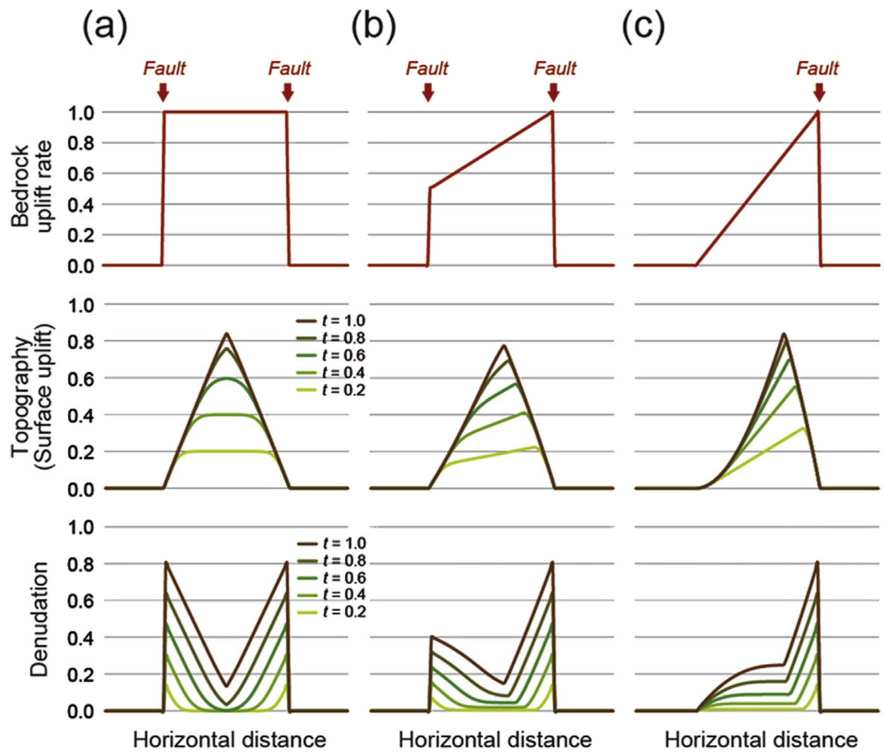


**Figure 9.** Numerical modeling of bedrock uplift and denudation based on the method of Hirano (1972) (modified after Sueoka et al., 2012). The surface uplift rate $\partial h/\partial t$ is given by $\frac{\partial h}{\partial t} = a\frac{\partial^2 h}{\partial x^2} - b\left|\frac{\partial h}{\partial x}\right| + u(x,t)$, where $x$ is distance, $h$ is elevation, $t$ is time, $u$ is the bedrock uplift rate, and $a$ and $b$ are positive constants known as the subduing coefficient and recessional coefficient, respectively (Hirano, 1972). All variables were normalized by the method of Hirano (1972). (a)–(c) are different in the distribution of the bedrock uplift rates.

characteristics are effectively explained by the model in Fig. 9b (Sueoka et al., 2012).

In the Akaishi Range (southern Japanese Alps), ZHe ages systematically younger to the east were reported and interpreted as a reflection of westward-tilted uplift of the northern part of the Akaishi Range related to faulting on the ISTL to the east (Sueoka et al., 2011). Although another major fault zone, the MTL, is distributed along the western margin of the Akaishi Range, activity of the MTL in this region was not significant during the late Quaternary (e.g., The Research Group for Active Faults of Japan, 1991). Therefore, the uplift and denudation of the Akaishi Range can be explained by the model in Fig. 9c such that bedrock uplift rates and accumulative denudation simply increase eastward to the ISTL, whereas the topographic cross section is asymmetric with steeper slopes on the eastern side (Sueoka, 2012). Although the model is simple, it is useful for categorizing the uplift and denudation type for mountains.

### 5.4. *Applicability of low-temperature thermochronology to Japanese mountains*

Sueoka et al. (2015) discussed the applicability of low-temperature thermochronology to Japanese mountains by comparing the accumulative denudation inferred from the model of Ohmori (1978; Fig. 5) with thermochronometric results of these mountains. The results imply that low-temperature thermochronology can access the recent denudation histories of the mountains if the following criteria are met: (1) the bedrock uplift rate is greater than 0.5–1.0 mm/yr; (2) the mountain attains a dynamic equilibrium between bedrock uplift and denudation, i.e., uplifted remnants of peneplains are not clearly visible; and (3) the maximum elevation of the mountain is more than ~1000 m (Sueoka et al., 2015). Here, we assumed that less than 1000 m of denudation cannot be detected by low-temperature thermochronology, which is equivalent to approximately 50 °C, i.e., the lower limit of the closure temperature of AHe system, under a general geothermal gradient of ~30 °C/km and surface temperature of ~20 °C. The previous thermochronometric studies mainly focused on reverse or strike-slip fault blocks in the SW Japan Arc (e.g., Ito, 2004, 2006; Sueoka et al., 2010, 2011, 2012; Yamada et al., 2012). Because the other types of mountains have not been studied, a definitive conclusion cannot be drawn. Nonetheless, for the reverse or strike-slip fault blocks in the SW Japan Arc, the thermochronometric results generally support Ohmori's model. Sueoka et al. (2014) detected rapid cooling during the past few million years by using HeFTy modeling (Ketcham, 2005) from Paleogene AFT ages in the Suzuka Range, a reverse-fault block mountain with a maximum altitude of 1247 m. Such rapid cooling patterns were not observed for the adjacent Yoro and Nunobiki mountains, reverse-fault blocks with maximum altitudes of 908 and 985 m, respectively (Sueoka et al., 2014). These results are useful for precisely constraining the lower limit of the applicability of the current AFT and AHe thermochronometries to the Japanese mountains.

## 6. Conclusions and prospects

Low-temperature thermochronology is useful for constraining the cooling and denudation histories of the Japanese mountains uplifted during the past few million years. Owing mainly to the small total denudation after the initiation of the uplift, application of thermochronometry has not been successful in this region, and some useful approaches developed in the continental orogens, such as AER or detrital thermochronometry, have not been directly applicable. However, by using alternative approaches, such as $T$–$d$ relationships, thermochronology can now be used to access the denudation histories of the Japanese mountains, which are considered to be at an early stage of mountain building.

Although, at present, applicability of thermochronology in Japan is considerably limited by the small denudation, this limitation may be overcome by recent and further developments in low-temperature thermochronology. For example, theoretical basis for thermal calculations by using He thermochronometric data sets has progressed thorough recent studies. Such research includes improvements of He diffusion models (e.g., Flowers et al., 2009; Gautheron et al., 2009, 2013; Guenthner et al., 2013), $^{4}He/^{3}He$ thermochronometry (Shuster and Farley, 2003), and reconstruction of thermal histories based on He age dispersions of broken crystals (Beucher et al., 2013; Brown et al., 2013). OSL thermochronometry is also promising because the closure temperature for fast component of quartz ranges 30–50 °C (e.g., Herman et al., 2010b; Li and Li, 2012; Guralnik et al., 2013), which is lower than that of AHe system. Furthermore, feldspar OSL system is expected to be used as a low-temperature thermochronometer (e.g., Guralnik et al., 2015a). However, further and more detailed studies on OSL characteristics for various rock types are required (e.g., Wu et al., 2012; Guralnik et al., 2015b).

Although we have emphasized that the Japanese Islands are optimum areas for studying an early stages of mountain building, another practical advantage of the Japanese Islands is the availability of abundant geomorphological, geological and geophysical data. Detailed geologic maps (e.g., Wakita et al., 2009), fault traces and activities (e.g., The Research Group for Active Faults of Japan, 1991; Nakata and Imaizumi, 2002), dense GPS networks (e.g., Nishimura, 2009; Sagiya, 2009), mapping of marine/fluvial terraces (e.g., Koike and Machida, 2001; Okuno et al., 2014), and geothermal gradient and heat flow (e.g., Tanaka et al., 2004) are available as many other resources. Such advantages indicate the potential for conducting further unique thermochronological studies.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.gsf.2015.06.005.

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