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Eustatic change modulates exhumation in the Japanese Alps

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ABSTRACT

The exhumation of bedrock is controlled by the interplay between tectonics, surface processes, and climate. The highest exhumation rates of centimeters per year are recorded in zones of highly active tectonic convergence such as the Southern Alps of New Zealand or the Himalayan syntaxes, where high rock uplift rates combine with very active surface processes. Using a combination of different thermochronometric systems including trapped-charge thermochronometry, we show that such rates also occur in the Hida Mountain Range, Japanese Alps. Our results imply that centimeter per year rates of exhumation are more common than previously thought. Our thermochronometry data allow the development of time series of exhumation rate changes at the time scale of glacial-interglacial cycles, which show a fourfold increase in baseline rates to rates of ~10 mm/yr within the past ~65 k.y. This increase in exhumation rate is likely explained by knickpoint propagation due to a combination of very high precipitation rates, climatic change, sea-level fall, range-front faulting, and moderate rock uplift. Our data resolve centimeter-scale sub-Quaternary exhumation rate changes, which show that in regions with horizontal convergence, coupling between climate, surface processes, and tectonics can exert a significant and rapid effect on rates of exhumation.

INTRODUCTION

The topography of mountain ranges evolves in response to rock uplift and erosion by climatically modulated surface processes, which together determine rates of rock exhumation. The highest bedrock exhumation rates are reported for actively converging mountains such as the Southern Alps of New Zealand, Taiwan, or the Himalayan syntaxes. Models predict that in rapidly uplifting orogens, the response time of an orogen to climatic change is short (Whipple and Meade, 2006). However, direct measurements are lacking, in part because of the temporal mismatch between climatic changes and tectonic time scales. We show that centimeter per year exhumation rates may be more common than previously thought and that coupling between tectonics and surface processes can profoundly modify rates of exhumation. We do this by applying a range of different thermochronometric methods that have different thermal sensitivities and thus record different stages of rock cooling throughout exhumation. The recently established trapped-charge thermochronometry methods (Guralnik et al., 2015; King et al., 2020) are sensitive to changes in exhumation at the time scale of glacial-interglacial cycles, allowing the response time of an orogen to such climate transitions to be resolved.

The Japanese Alps reach elevations of 3000 m, bisect the main Japanese island of Honshu, and are thought to have formed ~3 m.y. ago (Harayama et al., 2003; Sueoka et al., 2016) in response to convergence between the Philippine Sea plate (PSP) and the Amur plate (Townend and Zoback, 2006). Strain partitioning along the Tokai–south Kanto block (Fig. 1A; Mazzotti et al., 2001) results in maximum deformation being accommodated in the northern Japanese Alps, corresponding to WNW-ESE shortening of 100–200 × 10^{-9} yr^{-1} (Mazzotti et al., 2001; Townend and Zoback, 2006). The Hida Mountain Range (HMR) is the most northern and most extensive range of the Japanese Alps, and it was uplifted in two stages: ca. 2.7–1.5 Ma following volcanism in the late Pliocene (Harayama et al., 2003; Oikawa, 2003), and ca. 1.4–0.5 Ma with magmatism (Ito et al., 2021) and east-west compression since the Pleistocene (Oikawa, 2003). High water availability and high heat flow caused by subduction of the PSP cause crustal weaking and focus deformation in this region (Townend and Zoback, 2006). Partially molten rock, inferred from low-seismic-wave-velocity zones, is thought to occur at depths of 12–20 km and 2–4 km beneath the HMR (Matsubara et al., 2000), consistent with active magmatism resulting in regional topographic bulging and rock uplift (Townend and Zoback, 2006). Geodetic surveys indicate contemporary rock uplift rates of 3–5 mm/yr in the HMR (El-Fiky and Kato, 2006), comparable to catchment-averaged denudation rates of ~4 mm/yr (Fujiwara et al., 1999; Korup et al., 2014). The Kurobe catchment of the HMR has been estimated to yield the highest erosion rates in Japan (Yoshikawa, 1974).

Our study area is the Kurobe Gorge, one of the steepest gorges in Japan. The Kurobe Gorge descends 1 km over 5 km distance and is drained by the 85-km-long Kurobe River, which discharges 1.8 km^3/yr of water into the Toyama basin and transported 1–2 Mt/yr of coarse sediment (sand and gravels) before the river was dammed between 1956 and 1963 (Uda and Omata, 1989). The HMR is one of the snowiest

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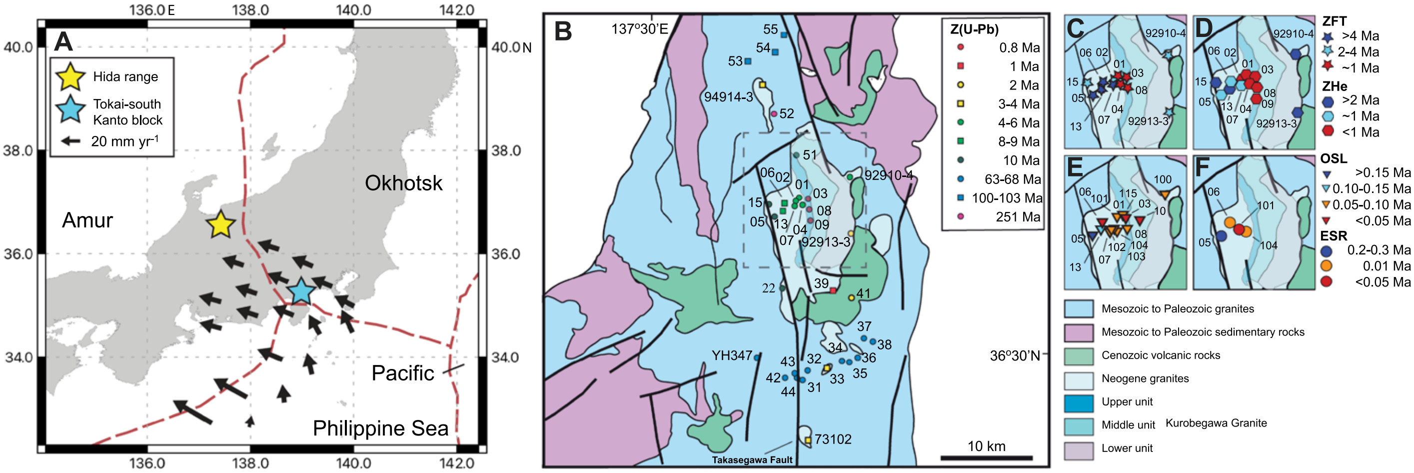

Figure 1. Sample location and thermochronometric ages. (A) Tectonic setting and accommodation of the Philippine Sea/Amur plate convergence (Mazzotti et al., 2001). (B) Geologic map showing key faults (solid lines) and zircon U-Pb ages, denoted Z(U-Pb) (modified from Ito et al., 2013). (C) Zircon fission-track (ZFT; Yamada, 1999); (D) zircon helium (ZHe; this study), (E) optically stimulated luminescence (OSL; King et al., 2020; this study), and (F) electron spin resonance (ESR; King et al., 2020) ages.

places on Earth, with a total annual precipitation of 4000 mm/yr (Uda and Omata, 1989) and annual snowfall between November and April of >9 m/yr. Peak snowmelt occurs in mid-April (Yamanaka et al., 2012), although peak discharge measured at the Kurobe dam usually occurs in the summer months (Wada et al., 2004) following convective rainfall. Multiple granitic intrusions have been recognized within the Kurobe region, ranging from >50 Ma in age to the ca. 0.8 Ma Kurobegawa granite, which has recently been shown to be the youngest surface-exposed granite yet dated on Earth (Ito et al., 2013). Geobarometry data show that granites in the Kurobe region were emplaced at 4–10 km depth (Yamaguchi et al., 2003). The presence of the Kurobegawa granite at the surface together with preliminary thermochronometric data (Yamada, 1999; Ito et al., 2013; King et al., 2020) and dam-sedimentation rates (Fujiwara et al., 1999; Esmaeili et al., 2017) indicate very high rates of erosion in this region, although the cause of these rates remains unclear.

METHODS

Samples of granite were taken to form an elevation transect along the main trunk of the Kurobe River and a tributary catchment, while three additional samples were taken from farther east, from Mount Karamatsu and Mount Kashimayarigadake (Fig. 1). We combined 12 new zircon (U-Th)/He (ZHe) ages and 11 new feldspar multiple optically stimulated luminescence (OSL) thermochronometry ages with existing thermochronometric data (Fig. 2; Yamada, 1999; Ito et al., 2013; King et al., 2020). Infrared stimulated luminescence (IRSL) measurements were made at 50, 100, 150, and 225 °C, allowing the different thermal stabilities of the luminescence signals to be exploited; because the 50 °C IRSL data were in athermal steady state (see the Supplemental Material[1]), they were not included in the analyses. We combined the thermochronometric data using a one-dimensional (1-D) thermal model (Biswas et al., 2018), which allowed the generation of a time series of exhumation rate changes (Fig. 3). To understand the causes of exhumation rate changes in Kurobe, we used stream-power modeling to track the migration of knickpoints throughout the catchment (Fig. 4) and evaluated the glacial history of the catchment by estimating the equilibrium line altitude from climate records (Anderson et al., 2019). Full methodological details are given in the Supplemental Material.

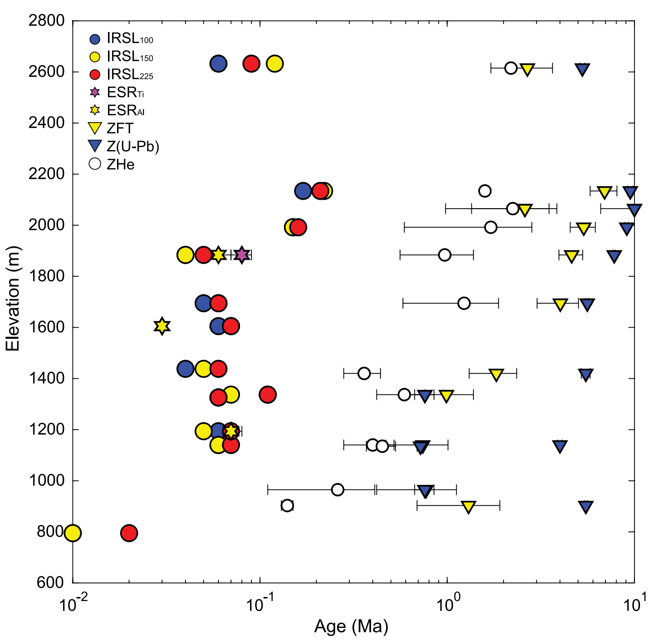

Figure 2. Age-elevation relationship of thermochronometric data. Infrared stimulated luminescence (IRSL) data are from King et al. (2020) and this study (where subscripts denote temperature), electron spin resonance (ESR) data are from King et al. (2020), ZHe data are from this study, zircon fission-track (ZFT) data are from Yamada (1999), and zircon U-Pb ages, denoted Z(U-Pb), are from Ito et al. (2013). Uncertainties for IRSL and Z(U-Pb) data are within size of data points.

EXHUMATION RATES

In agreement with existing thermochronometric data, the OSL and ZHe ages obtained are extremely young, yielding minimum ages of 8 ka and 0.1 Ma, respectively, for samples from the main river valley (Figs. 1 and 2). The combined conversion of the zircon fission-track (ZFT) and ZHe data into exhumation rates yielded a rate of <0.2 mm/yr until 2.5 Ma, when rates increased, reaching ~2 mm/yr at around 1 Ma (Fig. 3A). Rates peaked at 6–14 mm/yr within the past 0.3 m.y. (Fig. 3A). In contrast, samples from the area east of the HMR from Mount Karamatsu and Mount Kashimayarigadake revealed peak

[1]Supplemental Material. Sample preparation and measurement details, thermochronometry, and stream and equilibrium line altitude modeling. Please visit https://doi.org/10.1130/GEOL.S.21520938 to access the supplemental material and contact editing@geosociety.org with any questions.

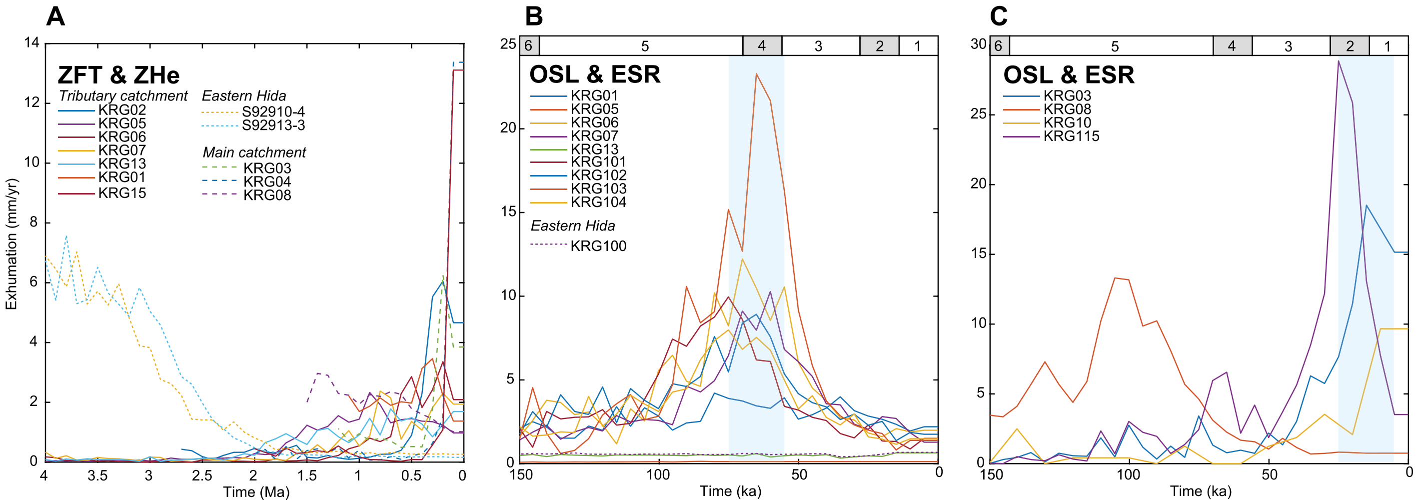

Figure 3. Exhumation rates calculated from inversion of thermochronometric data using a one-dimensional thermal model (Biswas et al., 2018): (A) zircon fission-track (ZFT) and zircon helium (ZHe) data; (B) optically stimulated luminescence (OSL) and electron spin resonance (ESR) data for samples from tributary valley; and (C) samples from main trunk of Kurobe River. Yellow and red sample locations are shown in Figure 4A. Shading highlights timing of peak exhumation, with duration of ~15 k.y. Marine isotopic stages (MISs) are indicated at top.

exhumation of 6 mm/yr around 4 Ma and rates of <0.2 mm/yr since 2 Ma (Figs. 1 and 3A). Performing the same exercise using the OSL and electron spin resonance (ESR) data revealed a complex exhumation rate history over the past 0.15 m.y. (Figs. 3B and 3C), resolved because of the sensitivity of trapped-charge dating systems over thousand-year time scales. Whereas samples from the main Kurobe River were exhumed rapidly with rates of >10 mm/yr over the past ~20 k.y., samples from the tributary catchment were exhumed rapidly with rates of ~10 mm/yr ca. 65 ka before rates decreased to <5 mm/yr over the past 50 k.y. (Figs. 3B, 3C, and 4A).

The high rates of exhumation recorded for the study area are commensurate with rates elsewhere in the HMR (Spencer et al., 2019) but are anomalous relative to the Japanese Alps more

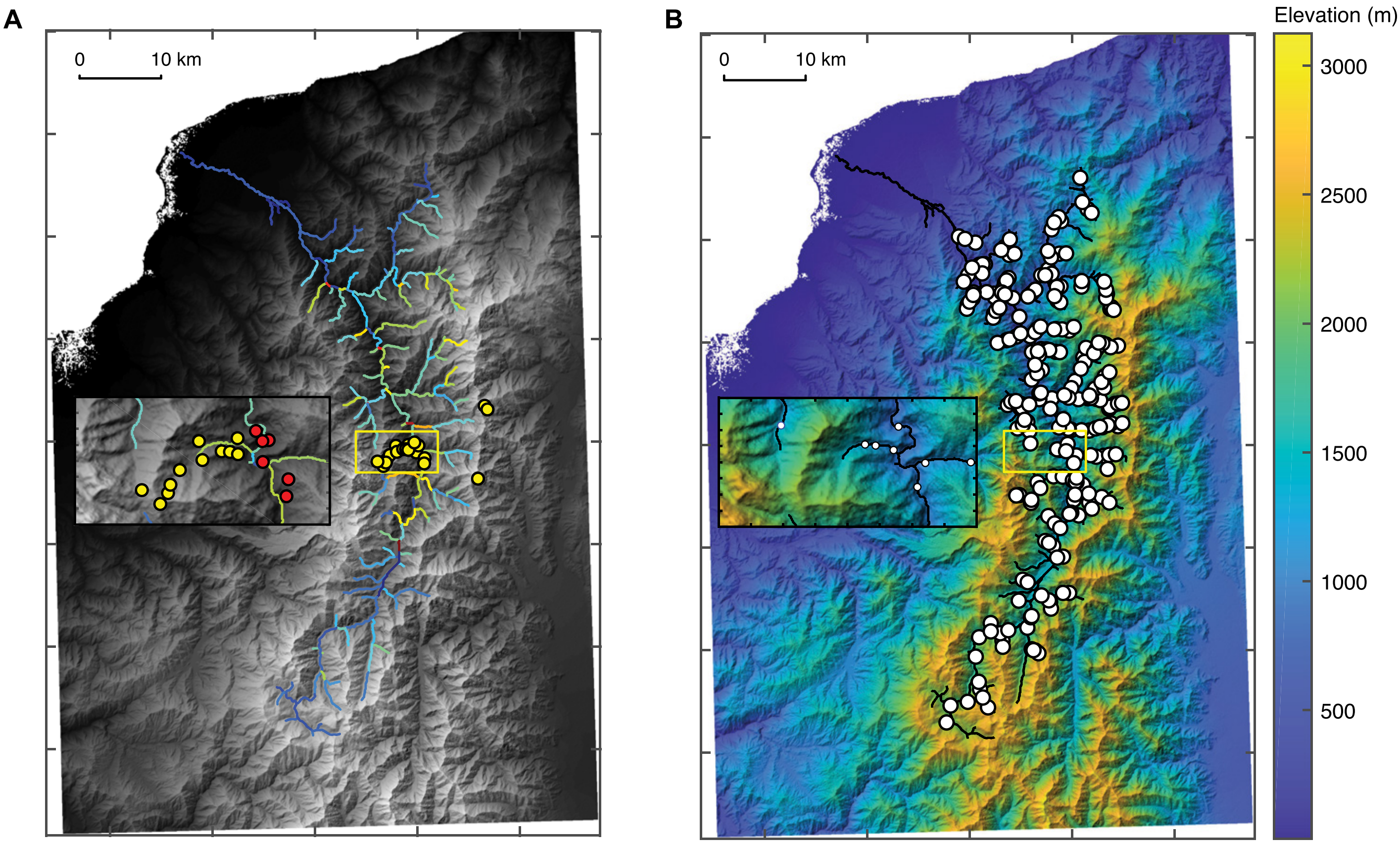

Figure 4. Stream modeling of the Kurobe River, Japan. (A) Kurobe River is colored according to channel steepness (k_{sn}), where warmer colors indicate higher values. Sample locations are shown as filled circles. (B) Knickpoints (open circles) were identified using the knickpoint finder function in TopoToolbox (Schwanghart and Scherler, 2014).

generally (Korup et al., 2014; Yoshikawa, 1974). Ito et al. (2021) proposed that intrusion of the Kurobegawa granite by three phases of magmatism at 2.1–2.0 Ma, ca. 1.0 Ma, and 0.8–0.7 Ma resulted in uplift of the study area, contemporaneous with the increase in exhumation rates to ~2 mm/yr recorded by the ZHe and ZFT data (Fig. 3A).

The youngest granites are exposed in the main Kurobe River valley, coincident with the majority of samples that yielded the most recent phase of rapid exhumation (Figs. 3 and 4). However, the thousand-year time scale of exhumation rate changes revealed by the thermochronometric ages (Fig. 3) suggests that additional processes drive erosion rate changes in the Kurobe basin. We propose that the data are best explained by knickpoint propagation along the Kurobe River in response to the combined effects of eustatic changes, climate change, range-front faulting, and magmatism-induced uplift.

KNICKPOINT PROPAGATION

Knickpoints are a change in channel slope and form in river valleys in response to spatially variable tectonic uplift, base-level change, and/or fault activity (Whipple and Tucker, 1999; Steer et al., 2019). Rapid knickpoint retreat occurs in catchments with high stream power and bed-load transport (Cook et al., 2013). The large volumes of sediment mobilized in the Kurobe catchment are documented both by rapid rates of dam sedimentation (Esmaeili et al., 2017) and also by the extensive 120 km^2 Kurobe alluvial fan. Uplift of the HMR, range-front faulting, subsidence of the Toyama basin, and climatically driven sea-level changes have caused the Kurobe River base level to change extensively over the Quaternary. Sea-level lowstands of up to ~140 m occurred in the Japan Sea during the late Pleistocene (Oba and Irino, 2012), and the combination of eustatic change and uplift means that the Kurobe River base level has increased by ~80 m in the past 10 k.y. (Ishikawa, 1991). Calculation of the normalized channel steepness, a simplified proxy of river stream power, revealed peak values around the study site (Fig. 4A). The combination of high base-level change, high channel steepness, and high sediment transport means that during sea-level lowstands, rapid bedrock incision and knickpoint propagation occurred at the sample location.

Multiple knickpoints occur in the catchment, including between the main Kurobe River and the sampled tributary channel (Fig. 4B), where the river profile is oversteepened. This feature may relate to a change in lithology between different granitic intrusions (Fig. 1B), to localized faulting (Ito et al., 2013), or to knickpoint formation during glacial period sea-level lowstands and subsequent upstream knickpoint propagation. Analysis of the river profile indicates that the most significant knickpoint is coincident with the Kurobe dam around 10 km upstream of the study area (Supplemental Material). While the dam conceals the true scale of the knickpoint, steepening of the river channel indicates a minimum knickpoint elevation of 40 m. Assuming that this feature relates to base-level fall during the Last Glacial Maximum (LGM), 20 k.y. ago, basin-wide knickpoint propagation modeling (Crosby and Whipple, 2006) yielded a knickpoint retreat rate of ~3 m/yr (Supplemental Material). While this rate is high, the high sediment transport of the Kurobe River, coupled with its high discharge and steepness, plus sea-level fall of ~120 m during the LGM (Oba and Irino, 2012) mean that knickpoint retreat must have been rapid.

The difference in timing of peak exhumation revealed by the ESR and OSL data in the main river channel and the tributary valley (Figs. 3B and 3C) reflects more rapid rock cooling in the main channel. This likely relates to more significant exhumation of the main river channel, driven by its larger drainage area, but it may also be influenced by hydrothermal activity related to emplacement of the Kurobe granite (Ito et al., 2013). Nevertheless, data from both locations yielded a mean exhumation rate of ~9 mm/yr over 15 k.y., equating to ~130 m of exhumation. While ~40 m of this can be related to continued uplift of the HMR, as revealed by geodetic surveys (El-Fiky and Kato, 2006), dam sedimentation rates (Fujiwara et al., 1999), and detrital cosmogenic nuclide data (Korup et al., 2014), and is consistent with the baseline rates of 2–4 mm/yr revealed by the ESR, OSL, ZFT, and ZHe data (Fig. 3), the remainder likely relates to surface erosion and incision following base-level change of the Kurobe River due to climatic changes over the past ~65 k.y.

GLACIAL CLIMATE

In addition to eustatic change, enhanced erosion due to glacial or periglacial processes throughout the late Quaternary period will have also influenced the exhumation of the Kurobe study area. The peak in exhumation rates of ~9 mm/yr at ca. 65 ka in the tributary catchment (Fig. 3B) is contemporaneous with marine isotope stage (MIS) 3/4 and what is thought to have been the most extensive glaciation of Japan (Ono, 1991). Although global temperature was cooler during MIS 2 than MIS 3/4, more significant lowering of the Japan Sea level during MIS 2 reduced moisture availability to the Japanese Alps, preventing the establishment of large glaciers (Ono, 1991). During MIS 4, the altitude of maximum ice extent in the HMR ranged from ~2350 m in the west to ~1000 m in the east (Kawasumi, 2009); however, equilibrium line altitude modeling using local climate records suggests that it is highly unlikely that Kurobe was glaciated at this time (Supplemental Material), indicating that periglacial processes were dominant.

The HMR is one of the snowiest places on Earth, and under the cooler, humid conditions of MIS 3/4, it is possible that annual snowfall exceeded the modern average of 9 m/yr (Aoki and Hasegawa, 2003). Periglacial processes coupled with enhanced stream power and fluvial incision following snowmelt may have increased sediment supply to the Kurobe River, further increasing erosion (Cook et al., 2013). After ca. 50 ka, estimated exhumation rates in the tributary catchment reduced to ~2 mm/yr, commensurate with present-day rates (Fujiwara et al., 1999; Korup et al., 2014). We suggest that these rates are typical of interglacial periods and are likely controlled by a combination of precipitation- and earthquake-driven landsliding (Kariya et al., 2011), continued uplift due to east-west compression, and magma injection.

CONCLUSIONS

The exhumation rates recorded in Kurobe, Japan, are some of the highest recorded on Earth, implying that centimeter per year rates of exhumation are more common than previously thought. Kurobe is a high-strain setting and a combination of tectonic convergence and active magmatism results in high rates of uplift. It is debated whether tectonic activity or climate controls Cenozoic exhumation, and the role of global climatic cooling is at the center of the dispute (Molnar and England, 1990). Using a suite of thermochronometers, we showed that climatically modulated eustatic and surface process changes coupled with tectonics strongly controlled exhumation rates over sub-Quaternary time scales.

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