Transient Response and Adjustment Timescales of Channel Width and Angle of Valley-Side Slopes to Accelerated Incision

Naoya Takahashi[1], J. Bruce H. Shyu[2], Shinji Toda[1], Yuki Matsushi[3], Ryoga Ohta[4], and Hiroyuki Matsuzaki[5]

[1]Tohoku University
[2]National Taiwan University
[3]DPRI, Kyoto University
[4]Chuo University
[5]University of Tokyo

January 20, 2023

Abstract

Studying bedrock rivers during their transient states helps understand the response of a fluvial system to changed boundary conditions. Although studies show how river form adjusts to changes in incision or rock uplift rates, field constraints on the timescale of this adjustment are limited. We present a method that uses knickpoint travel time to estimate the adjustment times of channel width and angle of valley-side slopes to accelerated incision. The travel time of knickpoints between their current positions and the points where changes in width or hillslope angle have just finished represents the time required for morphological adjustment after knickpoint passage. We documented channel slopes, channel widths, and hillslope angles along six rivers that cross an active normal fault in Iwaki, Japan, and identified river sections in a transient state. Channel slopes and basin-averaged erosion rates determined from ^{10}Be concentrations are distinct between rivers near and distant from the fault, suggesting that past increases in fault throw rates triggered the knickpoint formation and the observed transient response. Adjustment time depends on the slope exponent in the detachment-limited model and is 2–5 times greater for channel width than hillslope angle, indicating that catchment adjustment times can be much longer than times predicted only by knickpoint travel time. The fact that channel slope, channel width, and hillslope angle have distinct adjustment times underlines the importance of correctly identifying river sections that are fully adjusted to the new boundary conditions when inferring erosion or relative uplift rates for bedrock rivers.

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Naoya Takahashi[1,*], J. Bruce H. Shyu[2,*], Shinji Toda[3], Yuki Matsushi[4], Ryoga Ohta[5], and Hiroyuki Matsuzaki[6]

[1] Department of Earth Science, Tohoku University, 6-3, Aramaki Aza-Aoba, Aoba-ku, Sendai 980-8578, Japan

[2] Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan, ROC

[3] International Research Institute of Disaster Science (IRIDeS), Tohoku University, Aoba, 468-1, Aoba, Sendai 980-0845, Japan

[4] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji city, Kyoto 611-0011, Japan

[5] Faculty of Science and Engineering, Chuo University, 1-13-27, Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan

[6] Micro Analysis Laboratory, Tandem Accelerator (MALT), The University Museum, The University of Tokyo, 2-11-16, Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

Corresponding author:

Naoya Takahashi (naoya.takahashi.c5@tohoku.ac.jp) (orcid.org/0000-0003-4196-1409)

J. Bruce H. Shyu (jbhs@ntu.edu.tw) (orcid.org/0000-0002-2564-3702)

Key Points:

- We use knickpoint travel time to estimate the time between knickpoint passage and channel/hillslope adjustments to accelerated incision.
- The adjustment of channel width after the passage of a knickpoint takes 2–5 times longer than the adjustment of valley-side slope.
- Adjustment of the entire river basin takes much longer than the time a knickpoint takes to travel upstream to the channel heads.

Abstract

Studying bedrock rivers during their transient states helps understand the response of a fluvial system to changed boundary conditions. Although studies show how river form adjusts to changes in incision or rock uplift rates, field constraints on the timescale of this adjustment are limited. We present a method that uses knickpoint travel time to estimate the adjustment times of channel width and angle of valley-side slopes to accelerated incision. The travel time of knickpoints between their current positions and the points where changes in width or hillslope angle have just finished represents the time required for morphological adjustment after knickpoint passage. We documented channel slopes, channel widths, and hillslope angles along six rivers that cross an active normal fault in Iwaki, Japan, and identified river sections in a transient state. Channel slopes and basin-averaged erosion rates determined from ^{10}Be concentrations are distinct between rivers near and distant from the fault, suggesting that past increases in fault throw rates triggered the knickpoint formation and the observed transient response. Adjustment time depends on the slope exponent in the detachment-limited model and is 2–5 times greater for channel width than hillslope angle, indicating that catchment adjustment times can be much longer than times predicted only by knickpoint travel time. The fact that channel slope, channel width, and hillslope angle have distinct adjustment times underlines the importance of correctly identifying river sections that are fully adjusted to the new boundary conditions when inferring erosion or relative uplift rates for bedrock rivers.

Plain Language Summary

Bedrock rivers adjust their forms in response to changes in their boundary conditions, such as underlying rock types, climate, and tectonics, which means that establishing their quantitative relationships between these boundary conditions may enable us to infer rates of erosion or relative uplift from river morphologies. Although it is well known how river and hillslope forms adjust after an increase in erosion rates, the timescale of these adjustments is difficult to constrain in an actual landscape. This study presents a method to estimate the adjustment times of channel width and hillside slope angles along the sides of a valley. We studied a set of rivers that cross an active normal fault and documented the variations of channel and hillslope forms along their courses. These rivers are now changing their shapes after motion on the fault has

increased their erosion rates. Our analysis shows that channel width likely takes 2–5 times longer to complete its adjustment than does the hillslope angle. Our findings show that channel slope, channel width, and hillslope angle all have distinct adjustment times. It may take longer than previously thought for an entire river system to adjust to new boundary conditions.

1. Introduction

Because the incision of rivers into bedrock is a major element in the formation of mountain landscapes, quantifying incision rates and their relationships with external forces is important for understanding landscape evolution. The morphology of channels and hillslopes is closely related to erosion rates, and a long history of research has gone into establishing their functional relationships (e.g., Ahnert, 1970; Wobus et al., 2006a; Roering et al., 2007; Kirby & Whipple, 2012). A sudden increase in the rate of base-level fall (i.e., relative uplift) can enhance local incision rates and may generate a knickpoint that migrates upstream (e.g., Whipple & Tucker, 1999; Crosby & Whipple, 2006). As it does so, channels and hillslopes along its passage gradually adjust their forms to the accelerated incision rates. Knickpoints are common in tectonically active areas, and thus knowledge of the transient response of rivers to an increase in incision rates may enable researchers to infer a region's erosional or tectonic history from river morphologies.

Channel slope, channel width, and the angle of valley-side slopes are closely related to channel incision rates, and many studies have focused on quantifying relationships between morphologies of channel and hillslope and rates of incision or relative uplift (e.g., Whipple & Tucker, 1999; Snyder et al., 2000; Lavé & Avouac, 2001; Roering et al., 2001; Montgomery & Brandon, 2002; Reinhardt et al., 2007; Yanites & Tucker, 2010). The channel steepness index, expressing the channel slope normalized by upstream drainage area (e.g., Snyder et al., 2000), increases after the passage of a knickpoint in response to an increase in incision rates. Channel steepness downstream from the migrating knickpoint is assumed to reach a new steady-state value and is often positively correlated with uplift rates (e.g., Kirby & Whipple, 2012; Regalla et al., 2013; Chen et al., 2015; Gallen & Wegmann, 2017). Channel width can become wider or narrower in response to increased incision rates or be insensitive to incision rates (e.g., Lavé & Avouac, 2001; Snyder et al., 2003; Yanites & Tucker, 2010). According to a numerical study that considered the effects of sediment cover, channel narrowing occurs after the knickpoint passage, but as the knickpoint travels upstream the local sediment supply continues to increase, resulting in gradual widening of the channel (Yanites, 2018). A similar width adjustment was observed in a flume experiment (Baynes et al., 2022). Hillslope morphology is set by river incision at its base. The hillslope angle increases with incision rates until it reaches a threshold angle, above which it becomes insensitive to incision rate (e.g., Montgomery & Brandon, 2002). The threshold angle, usually ~30°–40°, is reached at relatively slow incision rates of 0.2–1.0 mm/yr (e.g., Montgomery & Brandon, 2002; Ouimet et al., 2009; DiBiase et al., 2012).

Whereas many studies have examined how river morphologies adjust to changes in incision rates, relatively few have attempted to quantify the adjustment timescales of channels and hillslopes to accelerated incision. Such studies require a chronology that specifies the times at which these morphological adjustments begin and end. However, in actual landscapes, it is very difficult to constrain those timings except for channel slope (e.g., Crosby & Whipple, 2006; Whittaker & Boulton, 2012). The arrival of a knickpoint triggers a change in channel slope from which a rate of knickpoint retreat can be calculated (e.g., Whipple & Tucker, 1999; Royden & Perron, 2013). Therefore, when the time and place a knickpoint is generated are known, the timescale of channel slope adjustment can be estimated based on the knickpoint's travel distance and travel speed (e.g., DiBiase et al., 2015).

The adjustment timescales of channel width and hillslope, unlike that for channel slope, are difficult to estimate by using field evidence. Instead, they have been studied by numerical modeling (e.g., Roering et al., 2001; Mudd & Furbish, 2007; Yanites, 2018; Turowski, 2020). Yanites (2018), modeling the evolution of channel width after knickpoint passage, showed that the full adjustment could take 10^5–10^6 years. Roering et al. (2001) used sediment transport models on hillslopes to estimate the adjustment time of valley-side slopes to a change in base-level lowering rates. The model parameters used in these studies were based on field observations. However, we still know little about the actual adjustment timescales of channel width and hillslopes, due to the difficulties in constraining when those adjustments started and finished.

This paper presents a method to quantify the adjustment timescales of channel width and the angle of valley-side slopes. We applied the method to bedrock rivers that cross an active normal fault near the city of Iwaki, Japan. Because changes in channel width and hillslope follow the passage of a knickpoint, we can use knickpoint travel times to estimate three quantities at any given location: response time, the time between the start and finish of a morphological adjustment; delay time, the lag time between the knickpoint arrival and the start of morphological adjustment; and adjustment timescale, the sum of response and delay times, representing the time between knickpoint passage and the finish of adjustment. Therefore, for the adjustment of channel slopes, the delay time at a given location is always zero, the response time is the time from the knickpoint passage until the channel slope attains a steady-state value, and the adjustment time equals the response time. We investigated channel slope, channel width, and hillslope angle along trunk streams and identified points at which morphological adjustments started and finished. Because we cannot know exactly when channel or hillslope adjustments have finished, we defined the end of adjustment as the condition where channel and hillslope forms are indistinguishable from those presumably at a steady state. We then calculated knickpoint travel times and estimated the response and delay times of channel width and hillslope angle. We use these results to discuss how the channel width and the angle of valley-side slopes change following an increase in channel incision rates, highlighting the need to inspect channels and hillslopes along a trunk stream and its tributaries when inferring incision or tectonic histories from river morphologies.

2. Background

2.1 Tectonic and Geologic Background

Iwaki is in the Tohoku region of northeastern Japan, which is subjected to E-W compression due to westward subduction of the Pacific plate under the Eurasia plate (Figure 1a). Although most earthquakes in Tohoku are characterized by reverse faulting, analysis of microearthquakes during 2003–2010 has revealed that the Iwaki area has been in an extensional stress regime since before the 11 March 2011 Mw 9.0 Tohoku-Oki earthquake (Imanishi et al., 2012). Shortly after the Tohoku-Oki event, a normal-faulting event of Mw 6.6 occurred in Iwaki on 11 April 2011. This earthquake produced surface ruptures along the Yunodake and Itozawa faults (Figure 1a) (e.g., Fukushima et al., 2013; Toda & Tsutsumi, 2013). The Yunodake and Itozawa faults are normal faults dipping SW and WSW, respectively, that form a half-graben between them (Mitsui, 1971), suggesting that this area has experienced extension on a geological timescale. The vertical slip rate of the Yunodake fault is unknown. A paleoseismic trenching study (Miyashita, 2018) showed that three surface-rupturing earthquakes including the 2011 event occurred on the Yunodake fault within the last 7 ky. If we assume that each of these produced vertical displacements similar to that in 2011 (~80 cm: Toda & Tsutsumi, 2013), a rough estimate of the fault throw rate is ~0.34 mm/yr.

Bedrock around the Yunodake fault consists of metamorphic and granitic rocks of Cretaceous age and sedimentary rocks of Miocene age (e.g., Kubo et al., 2007) (Figure 1b). Cretaceous metamorphic rocks include siliceous, mafic, pelitic and calcareous rocks (Kano et al., 1973; Hiroi et al., 1987; Kubo et al., 2007). Cretaceous granodiorite and porphyritic granodiorite occur along the middle and eastern part of the Yunodake fault (Kubo et al., 2007). Miocene sedimentary rocks southwest of the Yunodake fault include marine and nonmarine clastic rocks (Kubo et al., 2007) that overlie Cretaceous metamorphic rocks (Mitsui, 1971).

We focus on six trunk streams, numbered 1 through 6, along the Yunodake fault (Figure 1). Their drainage areas range from 1.6 to 24.1 km^2 and average 7.4 km^2 (Table S1). The substrates are either metamorphic or granitic rocks. Riverbeds are typically covered with gravel in reaches of metamorphic rocks and with sand in reaches of granitic rocks. Although Basins 2–6 intersect with or are very close to the fault, Basin 1 does not cross the fault. Basins 2–6 are characterized by steeper downstream reaches and gentler upstream reaches of smaller relief (Figure 1c).

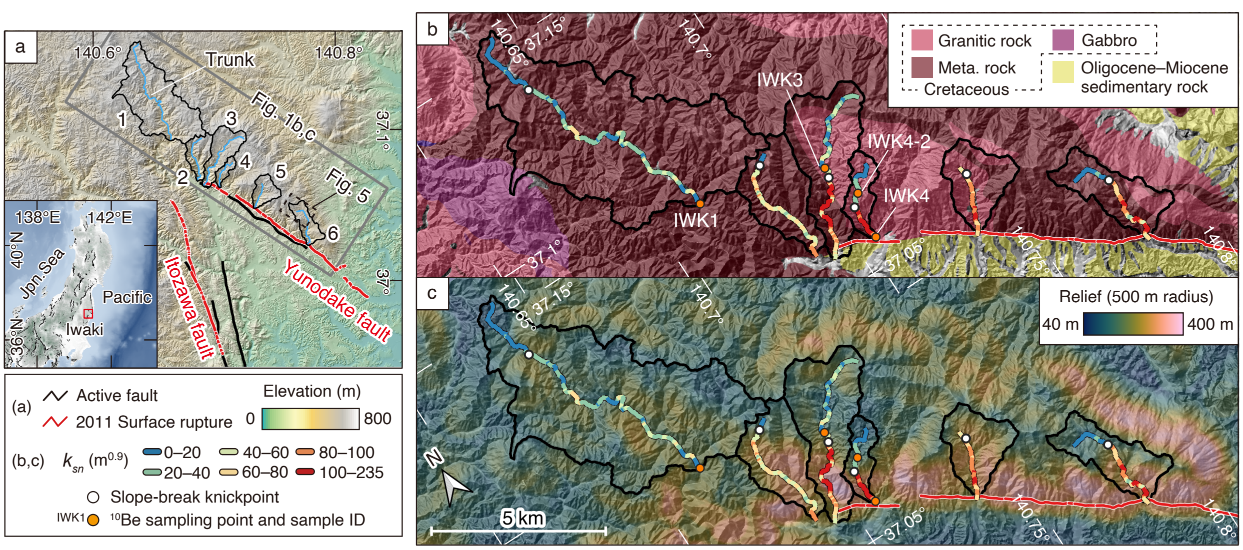

Figure 1. (a) Location and topography of the study area. Drainage basins and their trunk streams are labeled with their identification number (1–6). The inset map shows topography and active fault traces in eastern Japan. Active fault traces are from Nakata and Imaizumi (2002). Surface rupture traces are after Toda and Tsutsumi (2013). (b) Geologic map around the Yunodake fault (Kubo et al., 2007; Geological Survey of Japan, 2020). (c) Topographic relief in the area of (b) within circular windows of 500 m radius.

2.2. Channel and Hillslope Morphology

2.2.1. Channel Slope

In a stream at steady state, local channel slope (S) is a function of flow discharge, which is commonly represented by upstream drainage area (A):

$$S = k_s A^{-\theta}, \tag{1}$$

where k_s is a steepness index and θ is a concavity index (e.g., Flint, 1974; Snyder et al., 2000). Equation (1) holds only above a critical drainage area ($A > A_{\mathrm{crt}}$), at which the dominant erosional process changes from colluvial (debris flows) to fluvial processes (e.g., Montgomery & Foufoula-Georgiou, 1993; Stock & Dietrich, 2003). In drainage areas smaller than A_{crt}, channel slope either increases with or is independent of drainage area. The concavity index typically ranges between 0.4 and 0.6 (e.g., Kirby & Whipple, 2012).

The standard stream power model (e.g., Howard & Kerby, 1983) predicts a relation between channel slope and upstream drainage area similar to equation (1):

$$S = (E/K)^{1/n} A^{-m/n}, \tag{2}$$

where E is a local erosion rate, K is erodibility, m is related to the dominant erosion process and n is related to the hydraulic scaling relationships among channel width, flow discharge, and drainage area (e.g., Whipple & Tucker, 1999). From equations (1) and (2), under a steady state where local erosion rates match local uplift rates (U), channel steepness can be written as

$$k_s = (E/K)^{1/n} = (U/K)^{1/n}. \tag{3}$$

Because the concavity index is independent of uplift rates when the gradient of local uplift rates within a basin has a negligible impact on a channel profile (e.g., Snyder et al., 2000), a fixed concavity index ($\theta = \theta_{ref}$, equation (1)) is used to calculate k_s, and the resulting channel steepness is termed a normalized steepness index (k_{sn}; Wobus et al., 2006a).

A sustained increase in the rate of base-level lowering can generate a knickpoint (or a knickzone). This knickpoint propagates upstream and separates the longitudinal river profile into two segments: an adjusted segment downstream with higher steepness and a pre-adjusted segment upstream with lower steepness. This mobile knickpoint, called a slope-break knickpoint (e.g., Whipple et al., 2013), is readily distinguished from a stationary knickpoint (vertical-step knickpoint) that has different origins, such as a local decrease in bed erodibility associated with resistant substrates.

2.2.2. Channel Width

The channel width (W) of bedrock rivers is a power function of drainage area (e.g., Montgomery & Gran, 2001):

$$W = k_w A^b, \tag{4}$$

where k_w (unit: m^{1-2b}) is a wideness index (e.g., Allen et al., 2013) and b is a positive exponent that is typically 0.3–0.5 at a steady state (e.g., Whipple, 2004). A larger wideness index indicates a wider channel. Similar to k_{sn} and θ_{ref}, k_w calculated using a fixed value of b (b_{ref}) is a normalized wideness index (k_{wn}). An adjustment in channel width in response to accelerated incision should appear as a break in the hydraulic scaling of equation (4) or a change in average k_{wn} values with distance along the stream.

2.2.3. Angle of Valley-Side Slopes

In mountainous landscapes, drainage basins consist primarily of hillslopes, and material transport on hillslopes dictates the sediment supply to channels (e.g., Roering, 2008). Following the passage of a knickpoint produced by increased base-level lowering rates, hillslopes become steeper such that hillslope lowering keeps pace with channel incision (e.g., Roering et al., 2001). A downstream increase in hillslope angle is expected downstream of a slope-break knickpoint, and our analysis focused on this transition.

2.3. Knickpoint Travel Speed and the Timescales of Channel Width and Hillslope Angle Adjustments

Following the passage of a slope-break knickpoint, the channel width and the angle of valley-side slopes are expected to change until the local incision rate matches the local uplift rate. This morphological adjustment is characterized by a response time and a delay time, as defined in section 1. We estimated the response and delay times for channel width and hillslope angle based on knickpoint travel time.

Figure 2 schematically illustrates the response of a valley-side slope to accelerated incision. Hillslopes downstream from the knickpoint can be divided into three sections representing the phases of morphological adjustment. The pre-adjustment hillslope extends from upstream to slightly downstream of the knickpoint, and its angle reflects the incision rate before acceleration. The adjusted hillslope, well downstream from the knickpoint, has an angle that is fully adjusted to the accelerated incision. Between these two sections is the adjusting hillslope, with an angle that is currently changing in response to the accelerated incision. Because the knickpoint propagates upstream, its travel time from the boundary between the pre-adjustment and adjusting sections to the current knickpoint position represents the delay time. The knickpoint travel time from this boundary to the boundary between the adjusting and adjusted sections is the response time. The adjustment time is the sum of the response and delay times.

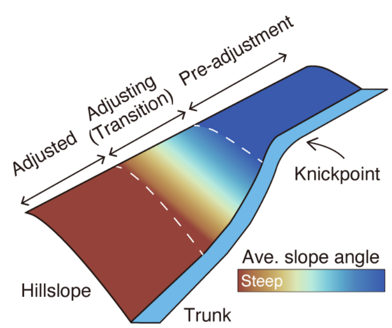

Figure 2. Schematic diagram of the right bank of a stream showing the response of hillslope angle to accelerated incision. The hillslope angle starts to change at the boundary between the pre-adjustment and adjusting sections and finishes at the boundary between the adjusting and adjusted sections.

Following a sustained increase in incision rates, knickpoint travel distance in χ-space is written as (Royden & Perron, 2013; Mitchell & Yanites, 2019):

$$\chi_{kp}(t) = \begin{cases} \dfrac{nU_{ini}}{\left(\frac{U_{ini}}{K}\right)^{\frac{1}{n}} A_0^{-\frac{m}{n}}} t & n < 1 \quad \text{(5a)} \\ K A_0^{\frac{m}{n}} t & n = 1 \quad \text{(5b)} \\ \dfrac{U_{fin} - U_{ini}}{\left(\left(\frac{U_{fin}}{K}\right)^{\frac{1}{n}} - \left(\frac{U_{ini}}{K}\right)^{\frac{1}{n}}\right) A_0^{-\frac{m}{n}}} t & n > 1 \quad \text{(5c)} \end{cases}$$

where $\chi_{kp}(t)$ is a χ of a mobile knickpoint at time t since knickpoint generation. A_0 is a reference drainage area, which was set at 1 in this study. Subscripts ini and fin represent the initial and final steady state, respectively; thus U_{ini} and U_{fin} are initial and final uplift rates ($U_{ini} < U_{fin}$). Substituting equation (3) for equation (5) and solving equation (5) with respect to t, the knickpoint travel time since the incision rate increase (t = 0) is

$$t = \begin{cases} \dfrac{k_{sn\,ini}}{nU_{ini}} \chi_{kp}(t) & n < 1 \quad \text{(6a)} \\ \dfrac{1}{K} \chi_{kp}(t) & n = 1 \quad \text{(6b)} \\ \dfrac{k_{sn\,fin} - k_{sn\,ini}}{U_{fin} - U_{ini}} \chi_{kp}(t) & n > 1. \quad \text{(6c)} \end{cases}$$

2.4. Basin-Averaged Erosion Rate Determined from Cosmogenic ^{10}Be Concentration

The ^{10}Be concentration in fluvial sediment ($\bar{C}$: atoms/g) is used to estimate the average erosion rate within a catchment ($\bar{D}$: g/m^2 yr) (e.g., Brown et al., 1995a; Bierman & Steig, 1996; Granger et al., 1996) by

$$\bar{D} = P_0 \Lambda / \bar{C}, \tag{7}$$

where P_0 (atoms/g yr) is the cosmogenic ^{10}Be production rate at the surface and Λ (g/cm^2) is the attenuation length of particles responsible for ^{10}Be production. Because the total sediment mass produced in a catchment is the sum of the sediment from its nested sub-catchments, average erosion rates within and outside the sub-catchments can be estimated by analyzing ^{10}Be samples from multiple sites in the catchment (e.g., Regalla et al., 2013):

$$\bar{D} = \sum_{i=1}^{j} D_i A_i \,/ \sum_{i=1}^{j} A_i \,, \tag{8}$$

where D_i and A_i are the average erosion rate and drainage area of sub-catchment i, respectively, and j is the number of subcatchments.

3. Method

3.1. Observations of Channel and Hillslope Morphology

We compiled observations of the along-trunk variations of channel slope, channel width, and hillslope angle as detailed below. We used the channel slope data to identify the current knickpoint position, and we used the other observations to determine the points where the adjustments of channel width and hillslope angle started and finished.

3.1.1. Normalized Steepness Index

We analyzed a digital elevation model (DEM) of the study area to calculate the normalized steepness index k_{sn} every 50 m along trunk streams using Topotoolbox 2 (Schwanghart & Scherler, 2014). The DEM, obtained from the Geospatial Information Authority of Japan, has a resolution of 10 m. We first determined A_{crt} and then calculated k_{sn} for channel reaches with $A > A_{crt}$. We also calculated χ (Perron & Royden, 2013) and constructed χ-elevation (z) plots (χ-plots):

$$\chi = \int_{x_b}^{x} (A_0/A(x))^{\frac{m}{n}}\, dx \tag{9}$$

$$z(x) = z(x_b) + (E/KA_0^m)^{\frac{1}{n}} \chi \tag{10}$$

where x is the distance along a stream course measured from the outlet of the channel reach, x_b is the distance at the outlet (thus $x_b = 0$). Equation (10) is the integral form of equation (2) under the assumption of a spatially uniform E and K, and it predicts that the slope of a χ-plot represents a reach-averaged value of k_{sn}. A knickpoint appears as a kink in a χ-plot. We used the k_{sn} values and χ-plots to determine the current positions of slope-break knickpoints (at the upstream end of knickzones), where the adjustment of channel slope begins.

3.1.2. Field Measurement of Channel Width

We measured bankfull channel widths in the field every 30–100 m along trunk streams using a laser rangefinder (TruPulse 360B Laser Technology). Measurement error is approximately ±30 cm. Width measurements depend on how one defines flow depth at bankfull stage. The bankfull depth is typically identified based on the limits of active abrasion, vegetation boundaries, and remnants of flood debris (e.g., Whittaker et al., 2007). Where there were multiple candidates for the high-flow depth, we measured channel widths at each candidate level and calculated their average. The measured width of each trunk river was fitted to equation (4) to estimate exponent b based on least squares. We determined b_{ref} by averaging b of all river segments whose width variations were consistent with the general scaling of equation (4). We then used the resulting b_{ref} values and upstream drainage areas calculated from the 10 m DEM to calculate the normalized wideness index k_{wn}.

3.1.3. Average Angle of Valley-Side Slopes

We calculated the angles of hillslopes adjacent to trunk streams using the 5 m DEM provided by the Geospatial Information Authority of Japan. We used this high-resolution DEM because the accuracy of hillslope angles depends on the DEM grid size. Because the available 5 m DEM lacks data along the streams, we could not use it for the channel analysis. We mapped hillslopes along trunk streams based on the upstream drainage area, slope aspect, and slope curvature. We did not include hillslopes along tributaries with drainage areas greater than A_{crt} as our focus was on trunk streams. Although it was difficult to determine a clear threshold, we also excluded hillslopes along small tributaries (maximum area < A_{crt}) visible on the 5 m DEM (Figure S1). We then segmented mapped valley-side slopes every 50 m along trunk streams and calculated average angles for each hillslope segment.

3.1.4. Identifying Sections of Transient Response

To identify river sections where hillslopes and channels are undergoing transient response to a knickpoint passage, we calculated 8-point moving averages of k_{wn} and hillslope angle. Given the large natural variability in channel width and hillslope angle, we augmented the moving averages with statistical tests to identify the sections in transience. The Kolmogorov-

Smirnov test showed that in Basin 1, k_{wn} values were normally distributed (p = 0.64) and hillslope angles were not normally distributed (p << 0.01) at the 5% significance level. Therefore, we applied the Student's t test for k_{wn} data and the Mann-Whitney U test for hillslope angle data. In these tests, we used 16 contiguous samples and determined whether the difference between the upstream 8 samples and the downstream 8 samples was statistically significant. Despite trying various significance levels, we could not properly identify sections experiencing transient response. Therefore, we defined transient sections as those where the moving average values showed a gradual decrease or increase and where the p-value of statistical tests was smaller than those of adjacent channel sections.

3.2. Adjustment Timescales of Channel Width and Hillslope Angle

Using equation (6), we calculated knickpoint travel time for n values of 2/3, 1, and 5/3 (e.g., Whipple et al., 2000) and estimated the delay, response, and adjustment times of channel width and valley-side slope angles in response to a sustained increase in incision rates. Normalized channel steepness at the initial and final steady state were defined as the average k_{sn} upstream and downstream of a slope-break knickpoint, respectively. We assumed that the erodibility constant (K) was uniform over time and calculated K using k_{sn} and ^{10}Be-derived erosion rates with equation (3).

3.3. Basin-Averaged Erosion Rate Determined from Cosmogenic ^{10}Be Concentration

We collected four sand samples (diameter < 2 mm) from trunk streams and measured ^{10}Be concentrations of quartz grains to determine basin-averaged erosion rates (Figures 1 and S2). We purified quartz following a method adapted from Kohl and Nishiizumi (1992). We first crushed and sieved samples to obtain grains 0.25–1 mm in diameter. These were heated in 9% HCl to remove carbonates, iron oxides, and organic materials, then quartz was separated from the samples using sodium polytungstate. The extracted quartz was leached using a 1% HF and HNO_3 solution to remove residual feldspars and meteoric ^{10}Be. Then, after adding a ^{9}Be spike, the quartz was dissolved with HF, HNO_3, and $HClO_4$. After the solution was used in anion- and cation-exchange chromatography, NH_4OH was added, and the precipitant was heated to obtain

BeO. $^{10}Be/^{9}Be$ ratios were measured using accelerator mass spectrometry at Micro Analysis Laboratory, Tandem Accelerator, the University of Tokyo (Matsuzaki et al., 2007).

^{10}Be production rates were calculated using scaling factors presented in Stone (2000). We computed topographic shielding factors for all sampled points using the 10 m DEM and an algorithm developed by Li (2013). Attenuation lengths for neutrons, slow muons and fast muons were set at 160, 1500, and 5300 g/cm^2, respectively (Brown et al., 1995b; Gosse & Phillips, 2001; Braucher et al., 2003). Contributions of slow and fast muons to the total ^{10}Be production at the surface were assumed to be 1.2% and 0.65%, respectively (Braucher et al., 2003). We assumed a bulk density of 1.63 g/cm^3 for the shallow subsurface materials on hillslopes (Nakamura et al., 2014). Although it sometimes snows in Iwaki, we did not consider the effect of snow shielding on ^{10}Be production because the snow cover was mostly less than several centimeters deep during 1960–2008 (Japan Meteorological Agency, 2021).

4. Results

4.1. Channel and Hillslope Morphology

4.1.1. Steepness of Stream Channels

Calculated values of normalized channel steepness (k_{sn}) are summarized in Figure 3. Each of the six drainage basins contains a slope-break knickpoint dividing the trunk streams into a downstream segment with greater k_{sn} and an upstream segment with smaller k_{sn} (Figures 1 and 3). Downstream segments of Basins 2–6 are much steeper than that of Basin 1, suggesting that incision rates in Basin 1 are much slower than in other basins. The channel steepness in the downstream segment of Basin 1 is three times greater than that of the upstream segment (Figure 3), suggesting that Basin 1 may be at a transient state. However, because the trunk stream of Basin 1 does not cross the Yunodake fault and we cannot know where the knickpoint formed, we will not discuss its morphological characteristics in detail. A slope-break knickpoint in Basin 3 occurs near a boundary between granitic rocks and schist (Figure 1), presenting the possibility that differential rock erodibility may explain the observed increase in k_{sn}. However, channel steepness does not change significantly at similar lithologic boundaries in Basins 3 and 4

(Figures 1b and S2). Therefore, we assumed that factors other than differential rock erodibility contributed to the formation of the knickpoint in Basin 3.

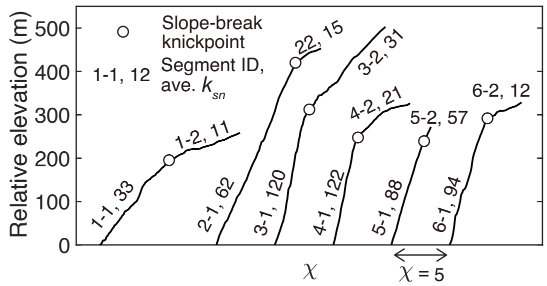

Figure 3. A χ-plot for the trunk streams in Basins 1 to 6. Relative elevation (y-axis) denotes the elevation above the basin outlet.

4.1.2. Channel Width

We measured channel width and depth at 308 points, which are presented in the supporting information (Table S2). Channel width in Basins 1, 2, and 4 increases monotonically with drainage area and follows the general hydraulic scaling of equation (4) (Figure 4; Table 1). Normalized wideness index (k_{wn}, b_{ref} = 0.42) in Basins 1, 2, and 4 do not vary significantly over their entire reaches (Figure 4). It is noteworthy that k_{wn} for the trunk streams of Basins 1 and 2 are identical despite their twofold difference in k_{sn}. This result implies that their channel widths are insensitive to changes in channel incision rates or that they have not started to adjust to the accelerated incision (e.g., Snyder et al., 2003; Zhang et al., 2017).

While channel width increases with drainage area in upstream segments of Basins 3 and 5, in their downstream segments channel width decreases or does not change significantly with increasing drainage area (Figure 4). In Basin 3, channel width starts to decrease at A = ~5.2 km^2, and that transition occurs near the lithologic boundary between granitoids and metamorphic rocks (Figures 4e and 4f). These results suggest that substrate property may partly control channel width. However, the break in the scaling relationship for channel width observed in Basin 3 cannot be solely attributed to the difference in substrates because the channel width continues to decrease downstream from the lithologic boundary (Figure 4e and 4f).

In Basin 6, the channel width changes by a factor of 2 at A = 1.5 km^2 (Figure 4k and 4l) and clearly deviates from the general trend of equation (4). Downstream from this point, bedrock extensively crops out in the riverbed and channel width decreases with drainage area, which is likely associated with accelerated river incision as in Basins 3 and 5. The upstream reaches are covered by thick alluvium. Aerial photographs taken in 1976 and 1986 show that many trees upstream in Basin 6 were cut during this period and the surrounding areas were widely excavated (Figure 5). This human activity displaced large amounts of soil, which currently occupies the channel and results in channel narrowing upstream of the knickpoint.

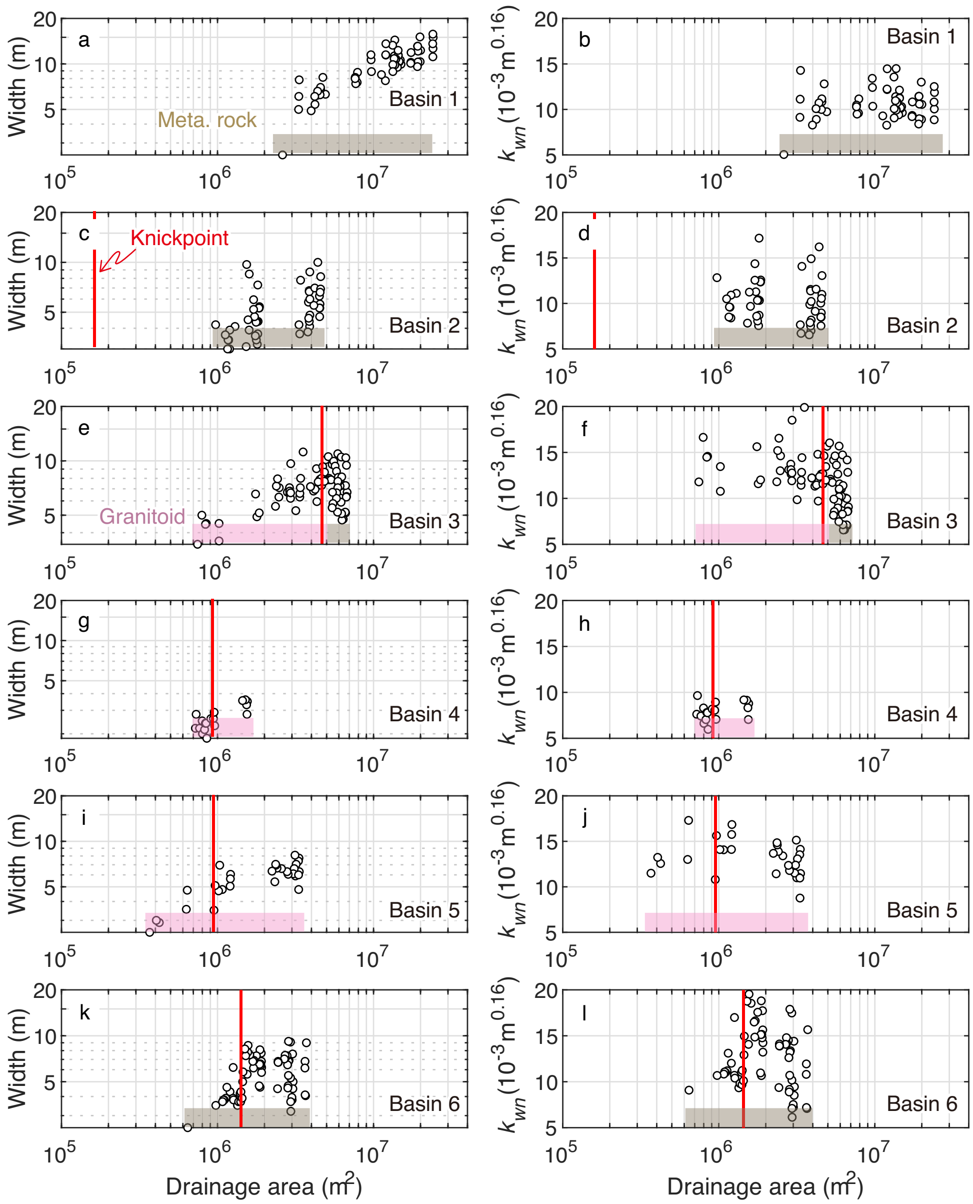

Figure 4. (Left) Channel width versus drainage area for the trunk streams. (Right) Normalized channel wideness (b_{ref} = 0.42) versus drainage area. Colored bars at the bottom of each diagram indicate substrate rock types in the corresponding river sections. Red vertical lines indicate positions of slope-break knickpoints.

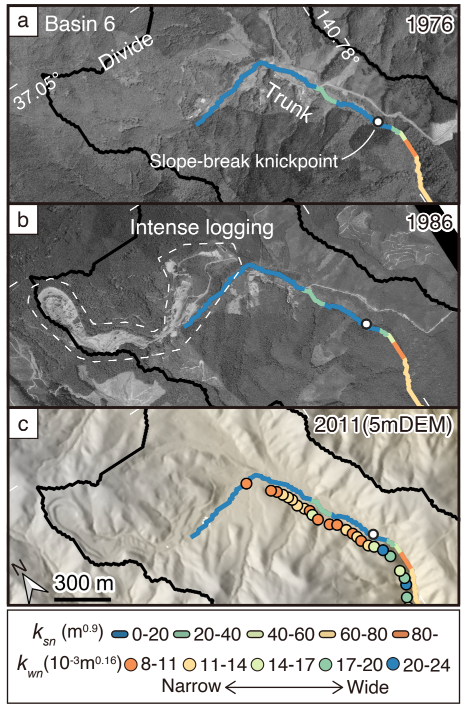

Figure 5. Deforestation in the headwater area of Basin 6. (a, b) Aerial photographs taken in 1976 and 1986, respectively. (c) Relief map created from the 5 m DEM issued in 2011 by the Geospatial Information Authority of Japan. Colored points along the trunk stream show normalized channel wideness at nearby sites.

Table 1
Results of Field Measurement and Regression of Channel Width

Basin/ segment	Max. area (km^2)	Min. area (km^2)	k_w	b^*	R^2	Ave k_{wn} (10^{-3} $m^{0.16}$)
1	24.1	0.025	3.45	*0.43*	0.73	10.6
2	4.6	0.021	3.43	*0.40*	0.41	10.2
3	6.9	0.021	5.37	0.20	0.20	12.0
3-downstream	6.9	6.2	2.52	0.52	0.03	9.2
3-upstream	5.4	0.021	4.70	*0.35*	0.51	13.2
4	1.6	0.1	2.69	*0.52*	0.73	8.1
5	3.4	0.4	4.75	0.30	0.64	13.4

5-downstream	3.4	2.8	5.28	0.18	0.00	12.1
5-upstream	2.4	0.4	4.79	*0.39*	0.65	14.3
6	3.8	0.3	4.73	0.26	0.13	12.8
6-downstream	3.8	1.7	7.19	−0.17	0.03	12.6
6-upstream	1.6	0.3	2.96	1.77	0.53	12.7

*Numbers in italics were used to calculate b_{ref}.

4.1.3. Angle of Valley-side Slopes

As illustrated in Figure 2, hillslopes in Basins 1–6 consist of three sections: an upstream section with gentler slopes, a downstream section with steeper slopes, and an intervening transition section. Hillslope angles in the upstream sections were positively correlated with normalized channel steepness (Figure 6). In the downstream sections, hillslope angles were less sensitive to channel steepness and clustered at 35°–38°, suggesting that these are predominantly threshold hillslopes (e.g., Ouimet et al., 2009). Left-skewed distributions of hillslope angles also support the interpretation that the downstream sections have threshold hillslopes (Figure 6b) (DiBiase et al., 2012). These transitions from gentler to steeper hillslopes occur downstream of the knickpoints and presumably result from the change in incision rates. Also, it is worth noting that the histograms for hillslope angles along the trunk stream distinctly differ from those for the whole basin (Figure 6b and 6c).

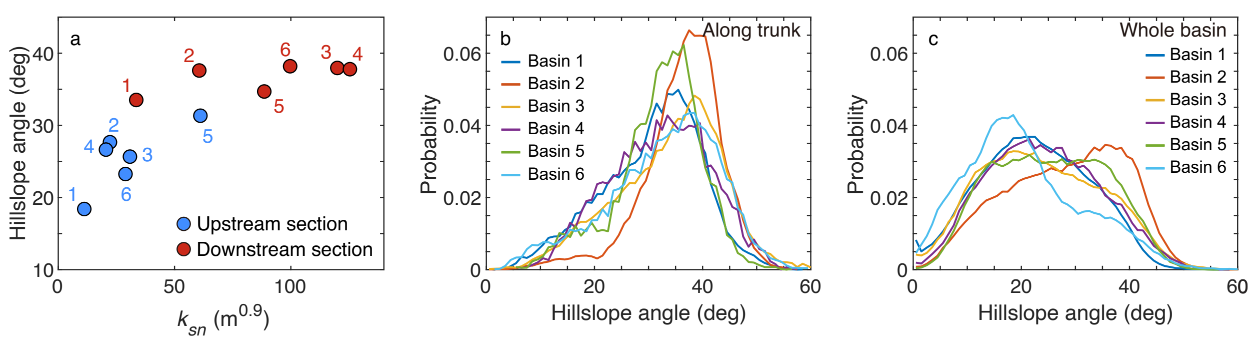

Figure 6. (a) Hillslope angle versus normalized channel steepness for upstream and downstream segments of the six basins. (b) Histogram of hillslope angles along trunk streams. (c) Histogram of hillslope angles in each entire basin. The bins in (b) and (c) are 1° wide.

4.1.4. Identifying Sections undergoing Transient Response

We used the moving averages of channel and hillslope parameters and the *p*-values from statistical tests to identify river sections experiencing transient response to accelerated incision. Figure 7 shows the along-trunk variations of channel and hillslope morphology in Basin 3, and those for the other basins are shown in Figure S5. As mentioned in section 4.1.1, we excluded Basin 1 from further analysis because its trunk stream does not cross the Yunodake fault. Also, we do not discuss hillslope adjustment time for Basin 5 because the observed increase in hillslope angle starts upstream of the knickpoint.

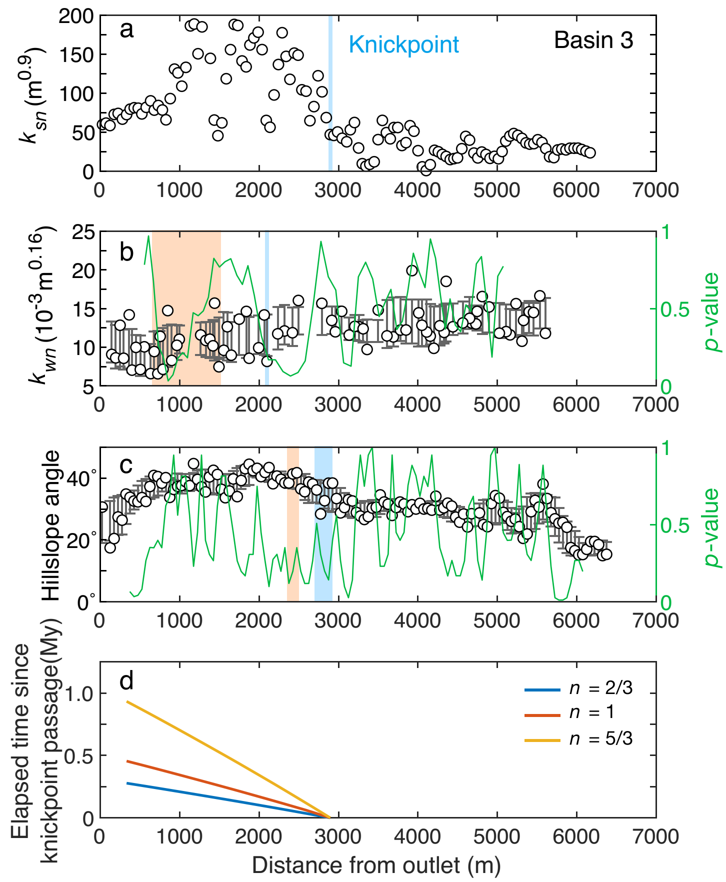

Figure 7. Variations of channel width and hillslope morphology along the trunk stream in Basin 3. (a) Normalized channel steepness (k_{sn}). The blue line indicates the current knickpoint position. (b) Normalized channel wideness (k_{wn}). The green line indicates the *p*-value from Student's *t* test. (c) Average hillslope angle in each 50 m segment of the trunk stream. The green line indicates the *p*-value from the Mann-Whitney U test. Gray bars in (b) and (c) represent standard deviation of 8-point moving averages and blue and orange areas indicate sections where

adjustments start and finish, respectively. (d) Time elapsed since knickpoint passage (knickpoint travel time) for three different values of n.

4.2. Substrate Erodibility Calculated from Basin-Averaged Erosion Rates

The basin-averaged erosion rates of our study basins ranged between 260 and 400 g/m^{2}yr, equivalent to 0.16–0.25 mm/yr (Table 2). Basin 4 differs from the others in consisting almost entirely of granitic rock. It also lacks evidence of recent large slope failures, which dilute the average ^{10}Be concentration of fluvial sand downstream by supplying material with low ^{10}Be concentrations. Thus, we used equation (8) to calculate the basin-averaged erosion rate of the downstream half of Basin 4 (IWK4-1, Table 2) and found that it is faster than that of the upstream half of Basin 4 (IWK4-2, Table 2). Overall, basin-averaged erosion rates were positively correlated with average k_{sn} (Table 2, Figure S3). Therefore, we assume that the erosion rates determined from the ^{10}Be concentrations reflect channel incision rates and can be used to calculate the erodibility K in equation (2).

Using k_{sn} and basin-averaged erosion rates, we determined the erodibility coefficient K for granitic and metamorphic rocks. These were 1.77×10^{-5} (n = 2/3), 4.85×10^{-6} (n = 1), and 3.70×10^{-7} (n = 5/3) m$^{0.1}$/yr for granitic rocks. To verify these estimates, we calculated erodibility coefficients for similar granitic rocks in the Abukuma massif (Kubo & Yamamoto, 1990) north of the study area using the same DEM and procedure we used in Iwaki (Figure S4; Tables S3, S4). We relied on ^{10}Be concentrations of fluvial sand reported by Regalla et al. (2013), Nakamura et al. (2014), and Matsushi et al. (2014) to recalculate basin-averaged erosion rates using the same method used in Iwaki. The resulting erodibility coefficients were similar to those obtained in Iwaki: 1.58×10^{-5} (n = 2/3), 4.52×10^{-6} (n = 1), and 3.90×10^{-7} (n = 5/3) m$^{0.1}$/yr. The coefficients for metamorphic rocks in Iwaki were 1.64×10^{-5} (n = 2/3), 5.21×10^{-6} (n = 1), and 5.30×10^{-7} (n = 5/3) m$^{0.1}$/yr, which were not very different from those for granitic rocks. Although sample limitations may affect the accuracy of the coefficient for metamorphic rocks, considering that the reaches of granitic and metamorphic rocks have comparable channel steepness (Figure 1b), our results indicate that these two rock types have similar erodibility.

4.3. Knickpoint Travel Time

To estimate knickpoint travel time, we first calculated uplift (erosion) rates at the initial and final steady states, using equation (6), based on the standard detachment limited model of equation (3) (Table 3). Given the erosion rates derived from ^{10}Be data (Table 2), a slope exponent of $n = 2/3$ yields the most probable estimates of initial and final uplift rates (Table 3). When calculating knickpoint travel time, we assumed that knickpoints were generated where the stream intersects the Yunodake fault. The resulting knickpoint travel times were somewhat similar among Basins 3−6, while the travel time for Basin 1 was much longer than those for the other basins (Table 4).

Table 2
Basin-averaged Erosion Rates Determined from ^{10}Be Concentrations

Sample ID	Mass sample (g)	Mass ^{9}Be carrier (g)	$^{10}Be/^{9}Be$ ($\times10^{-14}$)[a]	^{10}Be concentration (atoms/g)	^{10}Be production rate (atoms/g yr)[b]	Erosion rate (g/m^{2}yr)	Erosion rate (mm/yr)[c]	Upstream ave. k_{sn} ($m^{0.9}$)[d]
IWK1	26.4364	3.4882	7.5 ± 0.51	55627 ± 4929	7.0 ± 0.4	261 ± 37	0.16 ± 0.03	28
IWK4	39.3525	2.4981	17.5 ± 2.2	67402 ± 9578	6.6 ± 0.4	391 ± 63	0.24 ± 0.04	59
IWK3	39.4954	2.4994	10 ± 0.90	34884 ± 4041	7.2 ± 0.4	405 ± 62	0.25 ± 0.04	25
IWK4-2	40.0002	2.4809	10.6 ± 0.88	36878 ± 3920	6.9 ± 0.4	329 ± 46	0.20 ± 0.03	17
IWK4-1*						444 ± 78	0.28 ± 0.05	90

Note. * Average rate for the downstream sub-catchment of Basin 4 calculated from equation (10).
[a] Results based on the KNB5-1 ^{10}Be standard (Nishiizumi et al., 2007). The $^{10}Be/^{9}Be$ ratio for the chemical blank was $1.8\times10^{-14} \pm 0.30\times10^{-14}$.
[b] We used the production rate at sea level and high latitude of 4.68 atoms g^{-1} yr^{-1}, corrected from the value proposed by Stone (2000) assuming a ^{10}Be half-life of 1.387 My (Chmeleff et al., 2010; Korschinek et al., 2010).
[c] The bulk density of samples was 1.63 g/cm^3 (Nakamura et al., 2014).
[d] Average k_{sn} for trunk and tributaries upstream from a sampling point.

Table 3
Initial and Final Uplift Rates Used to Calculate Knickpoint Travel Time

			$n = 2/3$		$n = 1$		$n = 5/3$	
Basin	$k_{sn\ ini}$	$k_{sn\ fin}$	U_{ini} (mm/yr)	U_{fin} (mm/yr)	U_{ini} (mm/yr)	U_{fin} (mm/yr)	U_{ini} (mm/yr)	U_{fin} (mm/yr)
2	15.1	61.7	0.10	0.26	0.08	0.32	0.05	0.51

3	31	120	0.17	0.40	0.15	0.63	0.11	1.54
4	20.5	122.4	0.13	0.44	0.10	0.59	0.06	1.12
5	57.2	87.9	0.26	0.35	0.28	0.43	0.31	0.64
6	12	94	0.09	0.37	0.06	0.46	0.02	0.72

Note. Uplift rates were calculated using normalized channel steepness and ^{10}Be analyses.

Table 4

Knickpoint Travel Time

Basin	Knickpoint position (m)	Travel time, n = 2/3 (My)	Travel time, n = 1 (My)	Travel time, n = 5/3 (My)
2	3908	0.73	1.38	2.16
3	2896	0.28	0.45	0.93
4	1154	0.21	0.42	0.69
5	1933	0.40	0.53	0.98
6	2550	0.28	0.62	0.97

4.4. Adjustment Timescales

The delay times for hillslope angle ranged between 0 and 0.3 My and were much shorter than those for channel width (Figure 8). The response times, too, were shorter for hillslope angle than for channel width. The most preferred case (n = 2/3) predicted that the change in hillslope angle was finished within 5-230 ky after the knickpoint passage. This result is consistent with response timescales reported in the Oregon Coast Range (Roering et al., 2001) and the Feather River basin, California (Hurst et al., 2012), which were estimated from sediment transport laws. The adjustment time for channel width was 2–5 times longer than those of hillslope angles.

While it is relatively easy to classify hillslopes into sections based on their degree of adjustment to the new boundary conditions (Figures 2 and 7), doing the same for channel width is tricky (Figures 4 and 7). One reason is the large variability in channel width (Figure 4); another is the large uncertainty in determining when an adjusting channel has achieved the steady-state form predicted by equation (4). Although we determined that the most downstream sections in Basins 3, 5, and 6 have adjusted to accelerated incision, it is also possible that our interpretation is wrong. Therefore, the response and adjustment times of channel width shown in Figure 8 are minimum estimates.

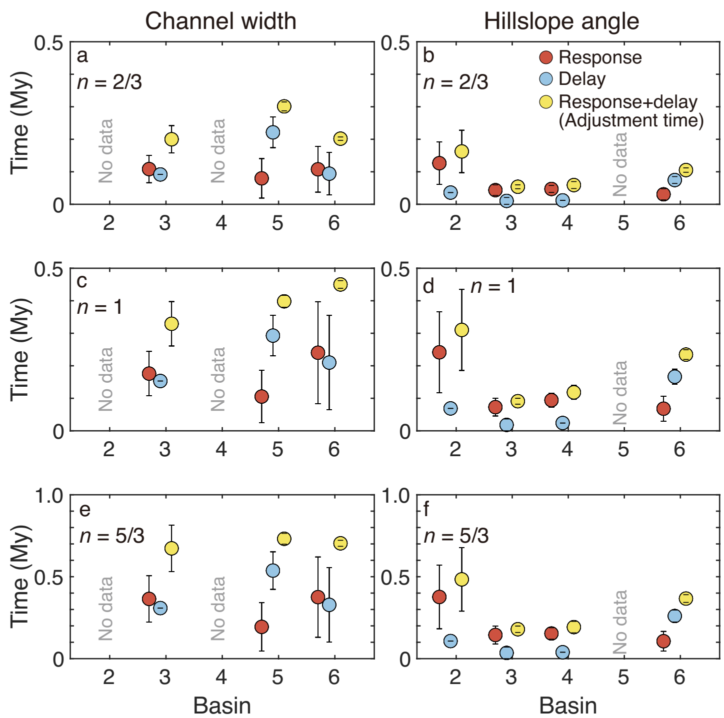

Figure 8. Delay, response, and adjustment times of channel width (a–c) and hillslope angle (d–f) in response to an increase in incision rates for three different values of *n*.

5. Discussion

5.1. Cause of Knickpoint Formation

The common occurrence of slope-break knickpoints and the similar erodibility coefficients between granitic and metamorphic rocks suggest that incision rates have increased in the study area. The average erosion rates in Basin 3, which are different upstream and downstream of the slope-break knickpoint, support the idea that accelerated river incision is responsible for the observed transient behavior.

We interpret the increase in incision rates to the activity of the Yunodake fault because rivers flowing across the fault (Basins 2–6) are much steeper than the river in Basin 1, away from the fault (Figure 1). Awata and Kakimi (1985) and Awata (1988) estimated initiation ages of active faulting in the current stress regime on the Pacific side of Tohoku on the basis of average slip rates and cumulative displacement. They found that many faults became active after 0.5–1.0 Ma. Doke et al. (2012) conducted an extensive literature review and reached a similar conclusion. Our modeled knickpoint travel times in Iwaki (Table 4) ranged between 0.2 and 0.7 My, consistent with the inferred onset of fault activity in Tohoku. Therefore, although there is no direct evidence of the throw rate of the Yunodake fault increasing during the middle Pleistocene, we attribute the generation of slope-break knickpoints to changes in throw rates of the fault.

5.2. Implications for Transient Response

The delay and response times of channel width are 2–5 times longer than those of hillslope angle. Depending on the erosion process (the slope exponent n in equation (2)) and the magnitude of the acceleration of river incision, width adjustment can take 0.16–0.81 My after the knickpoint passage (Figure 8). In addition, our observations confirmed that the transient response takes place at different spatiotemporal scales for channel slope, channel width, and hillslope angle. Thus channel width and hillslope angle may be continuing to adjust even when the river lacks a prominent knickpoint. Since channel characteristics and hillslope morphology are the primary controls of river incision (e.g., Whipple & Tucker, 2002), correctly identifying the adjusted sections within a catchment is essential for assessing the transient response to an increase in incision rates.

Another inference from our observation is on the transient response of channel width. The ratio of sediment supply to transport capacity dictates the dynamics of channel width adjustment (e.g., Finnegan et al., 2007; Yanites & Tucker, 2010; Baynes et al., 2020). Because the total sediment supply into a channel is modulated by the form of upstream hillslopes (e.g., Roering et al., 2007), the adjustment of channel width is expected to continue until a slope-break knickpoint reaches the headwaters and adjacent hillslopes achieve their steady-state forms. However, despite the fact that most hillslopes exhibit pre-adjustment forms in Basins 3, 5, and 6 (Figures 6b and 6c), the channel widths in their downstream sections appear to be adjusted to the accelerated incision (Figures 4 and S5, Table S4). It appears, then, that the dynamics of width adjustment are not simply a response to the increase in total sediment supply from upstream.

An alternative interpretation is that the channel width adjustment has not in fact been completed, and the ongoing changes in the channel are too small to be confidently detected due to measurement error and natural variability. This interpretation is compatible with the result of numerical modeling, which predicts that the response of channel width is rapid at first, then decays as the response progresses (Yanites, 2018). We speculate that this gradual decrease is related to the downstream fining of sediment. Abrasion and selective transport are the main drivers of downstream fining (i.e., mass reduction) of sediment (e.g., Parker, 1991). Their effects typically scale with travel distance and can be significant even after only a few kilometers of transport (e.g., Parker, 1991; Phillips & Jerolmack, 2014; Miller et al., 2014). Therefore, the rate of increase in sediment supply at a point downstream should slow as the knickpoint travels upstream, as demonstrated by numerical experiments (Yanites, 2018). Given the dependence of channel width on grain size and the ratio of sediment supply to transport capacity (e.g., Yanites & Tucker, 2010; Finnegan et al., 2017), we attribute the decay in the response speed of channel width to a decline in the rate of increase in sediment supply.

5.3. Timescale of Catchment-Scale Adjustment

The adjustment of an entire catchment is a more complex matter than the adjustment of a trunk stream. Knickpoint travel speed depends on stream discharge (e.g., Whipple & Tucker, 1999; Hayakawa & Matsukura, 2003; Bishop et al., 2005), and the travel time from its origin to the channel head is on the order of 10^5–10^6 years (Whipple, 2001; Whittaker and Boulton, 2012). The adjustment of channel slopes in tributaries must also be considered; this is sometimes prolonged where hanging valleys are present (Wobus et al., 2006b; Crosby et al., 2007; DiBiase et al., 2015). Adjustments of channel width and hillslope require hundreds of thousands more years after a knickpoint has finished propagating to the heads of the trunk and tributaries. Moreover, other aspects of channels and hillslopes respond to changes in channel incision rates, such as channel sinuosity (Turowski, 2018) and hilltop curvature (Gabet et al., 2021). Morphological adjustments of these variables are also triggered by climate variability and occur at timescales of 10^5–10^6 years (e.g., Whipple, 2001), although fluvial systems might not fully adjust to high-frequency climatic oscillations such as Milankovitch cycles (Armitage et al., 2013; Goren, 2016). Given all these factors, it is clear that catchment-scale adjustment to accelerated incision takes much longer than the knickpoint travel time within the trunk stream. This further confirms that to estimate rates of erosion or base-level fall, one must consider whether the river system has reached a steady state even when it contains no prominent knickpoint.

6. Conclusions

Based on the observed channel and hillslope geometries and knickpoint travel time, we have estimated their adjustment times to accelerated incision. Our approach enables us to estimate both delay and response times of channel width and hillslope angles, which are otherwise difficult to constrain in an actual landscape. Our results indicate that hillslope adjustment starts and finishes much earlier than channel width adjustment. Change in hillslope angle starts soon after the passage of a knickpoint (10^0–10^4 yr) and generally finishes on the order of 10^5 years later. Channel width adjustment takes 2–5 times longer than hillslope adjustment. Unlike hillslope angle, channel width has adjustment times that are not always negligible compared to that of channel slope, which depends closely on knickpoint travel time.

The longevity of catchment-scale adjustment time and the different adjustment timescales among channel slope, channel width, and hillslope angles remind us that we need to infer erosion or uplift rates from channel reaches that are in a well-defined steady state. Our findings also suggest that it is important to understand the temporal evolution of erosion rates during the adjustment of individual channel and hillslope components. Lastly, it has to be noted that our estimates of knickpoint travel time do not explicitly consider important factors including the effects of sediment characteristics and temporal changes in precipitation. Because these factors may significantly alter estimates of adjustment time, inter-model comparisons or more sophisticated models of migrating knickpoints are necessary to better understand the transient response of bedrock rivers.

Acknowledgments

We thank Chia-Yu Chen (National Taiwan University) for helpful comments and A. Morikawa, K. Kitamura (Kyoto University), N. Miyauchi, and Y. Tsuchiya (The University of Tokyo) for their assistance during preparation of the ^{10}Be samples. This work was supported by the International Joint Graduate Program in Earth and Environmental Sciences, Tohoku University. N. Takahashi and R. Ohta thank the staff at Yunodake sanso in Iwaki for their generous support during our fieldwork. We obtained DEM data from the Geospatial Authority of Japan and NOAA (ETOPO1). Some color maps were obtained from Crameri (2018).

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Supporting Information for

Transient response and adjustment timescales of channel width and angle of valley-side slopes to accelerated incision

Naoya Takahashi[1,*], J. Bruce H. Shyu[2,*], Shinji Toda[3], Yuki Matsushi[4], Ryoga Ohta[5], and Hiroyuki Matsuzaki[6]

[1] Department of Earth Science, Tohoku University, 6-3, Aramaki Aza-Aoba, Aoba-ku, Sendai 980-8578, Japan

[2] Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan, ROC

[3] International Research Institute of Disaster Science (IRIDeS), Tohoku University, Aoba, 468-1, Aoba, Sendai 980-0845, Japan

[4] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji city, Kyoto 611-0011, Japan

[5] Graduate School of Science, Kyoto University, Kitashirakawa Oiwake-cho, Kyoto city (JSPS Research Fellow), Kyoto 606-8502, Japan

[6] Micro Analysis Laboratory, Tandem Accelerator (MALT), The University Museum, The University of Tokyo, 2-11-16, Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

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Tables S1, S3, and S4

Introduction

This document contains Tables S1, S3, and S4. Table S2 is provided separately.

Table S1

Basin Characteristics along the Yunodake Fault

Basin/ segment ID	Min. area (km^2)	Max. area (km^2)	θ*	Ave k_{sn} ($m^{0.9}$)
1	0.025	24.1	0.19	28 ± 17
1-1	2.5	24.1	0.53	33 ± 16
1-2	0.025	2.5	0.34	11 ± 6
2	0.2	4.6	0.24	57 ± 19
2-1	0.2	4.6	0.46	62 ± 14
2-2	0.021	0.2	0.10	15 ± 5
3	1.0	6.9	0.11	69 ± 54
3-1	4.9	6.9	1.66	120 ± 46
3-2	0.021	4.7	0.48	31 ± 15
4	0.2	1.6	−1.05	61 ± 53
4-1	0.9	1.6	0.40	122 ± 21
4-2	0.1	0.9	−0.52	21 ± 11
5	0.3	3.4	0.26	83 ± 15
5-1	1.0	3.4	0.38	88 ± 11
5-2	0.4	1.0	0.88	57 ± 9
6	0.3	3.8	−0.69	64 ± 53
6-1	1.5	3.8	0.31	94 ± 44
6-2	0.3	1.4	0.68	12 ± 8

* Calculated by fitting channel slope and drainage area to equation (1).

Table S3

Results of ^{10}Be analysis in Abukuma Massif

Sample ID	^{10}Be concentration ($\times 10^4$ atoms/g) [d]	Production rate (atoms/g yr) [e]	Erosion rate (g/m^2 yr)	Erosion rate (mm/yr) [f]	Upstream area (km^2)	Upstream ave. k_{sn} (m$^{0.9}$) [g]
ABK-R1[a]	6.96 ± 0.36	7.3	219 ± 27	0.13 ± 0.02	7.6	45.9
ABK-R3[a]	4.80 ± 0.22	6.8	296 ± 36	0.18 ± 0.02	97.2	30.1
Be1[b]	5.22 ± 0.12	6.8	272 ± 31	0.17 ± 0.02	104.8	30.1
Be2[b]	3.10 ± 0.09	6.1	412 ± 48	0.25 ± 0.03	24.1	47.6
Be3[b]	5.05 ± 0.13	6.5	268 ± 31	0.16 ± 0.02	27.8	46.6
Be4[b]	5.04 ± 0.12	7.1	296 ± 34	0.18 ± 0.02	161.3	35.0
Be5[b]	4.49 ± 0.15	6.5	301 ± 35	0.18 ± 0.02	13.9	58.1
Be6[b]	7.92 ± 0.16	6.7	178 ± 20	0.11 ± 0.01	101.6	17.5
Ab-21[c]	5.86 ± 0.29	7.0	250 ± 31	0.15 ± 0.02	5.3	30.8

[a] Nakamura et al. (2014). [b] Regalla et al. (2013). [c] Matsushi et al. (2014) [d] KNB5-1 ^{10}Be standard (Nishiizumi et al., 2007). [e] The production rate at sea level and high latitude was 4.68 atoms g^{-1} yr^{-1} corrected from the value proposed by Stone (2000) assuming a ^{10}Be half-life of 1.387 My (Chmeleff et al., 2010; Korshinek et al., 2010). [f] The bulk density of samples was 1.63 g/cm^3 (Nakamura et al., 2014). [g] Average k_{sn} for trunk and tributaries upstream from a sampling point.

Table S4

Erodibility Coefficient (m$^{0.1}$/yr) for Granitic Rocks in Iwaki and Abukuma Massif

	$n = 2/3$	$n = 1$	$n = 5/3$	Reference
Iwaki	1.77E-05	4.85E-06	3.70E-07	This study
Abukuma	1.58E-05	4.52E-06	3.90E-07	Nakamura et al. (2014), Regalla et al. (2013), Matsushi et al. (2014)

Journal of Geophysical Research: Earth Surface

Supporting Information for

Transient response and adjustment timescales of channel width and angle of valley-side slopes to accelerated incision

Naoya Takahashi[1,*], J. Bruce H. Shyu[2,*], Shinji Toda[3], Yuki Matsushi[4], Ryoga Ohta[5], and Hiroyuki Matsuzaki[6]

[1] Department of Earth Science, Tohoku University, 6-3, Aramaki Aza-Aoba, Aoba-ku, Sendai 980-8578, Japan

[2] Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan, ROC

[3] International Research Institute of Disaster Science (IRIDeS), Tohoku University, Aoba, 468-1, Aoba, Sendai 980-0845, Japan

[4] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji city, Kyoto 611-0011, Japan

[5] Graduate School of Science, Kyoto University, Kitashirakawa Oiwake-cho, Kyoto city (JSPS Research Fellow), Kyoto 606-8502, Japan

[6] Micro Analysis Laboratory, Tandem Accelerator (MALT), The University Museum, The University of Tokyo, 2-11-16, Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

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Figures S1 to S5

Introduction

This document contains Figures S1 to S5.

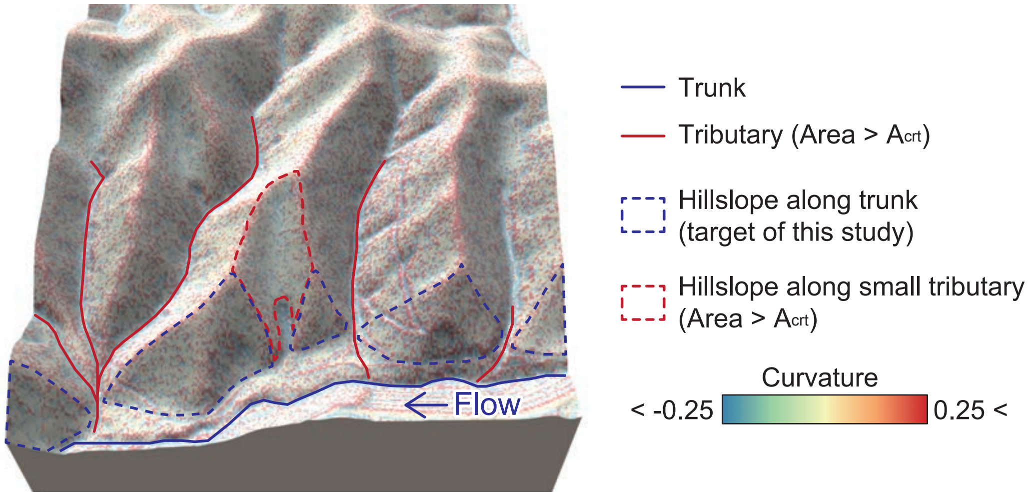

Figure S1. Results of hillslope mapping. Hillslopes along the trunk stream are used in the analysis. The base map is a shaded relief map colored by topographic curvature.

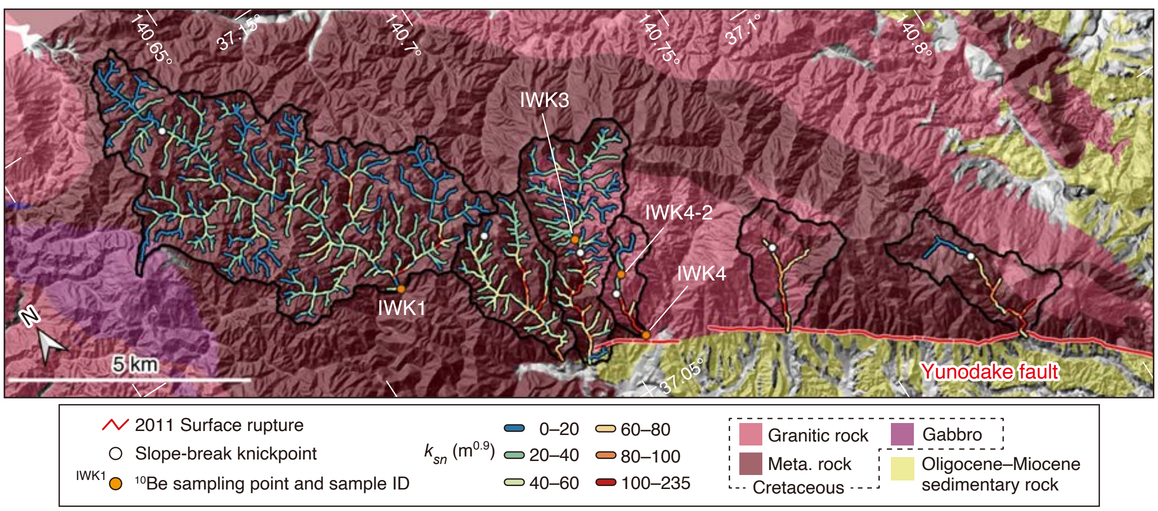

Figure S2. ^{10}Be sampling points and normalized channel steepness for the trunk and tributaries. The 2011 surface rupture trace is after Toda and Tsutsumi (2013). Geologic units are after Kubo et al. (2007) and Geological Survey of Japan (2020).

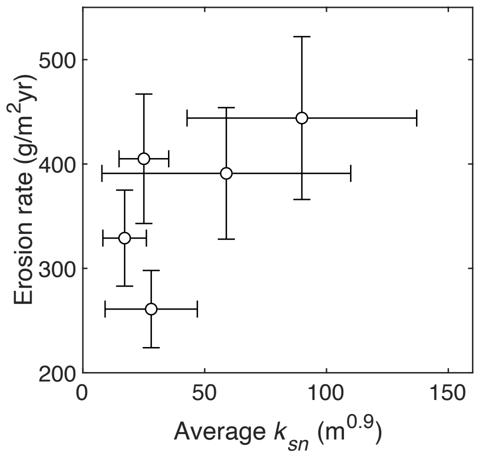

Figure S3. Basin-averaged erosion rates and average normalized channel steepness upstream of the ^{10}Be sampling points. Vertical and horizontal bars indicate 1 sigma error ranges.

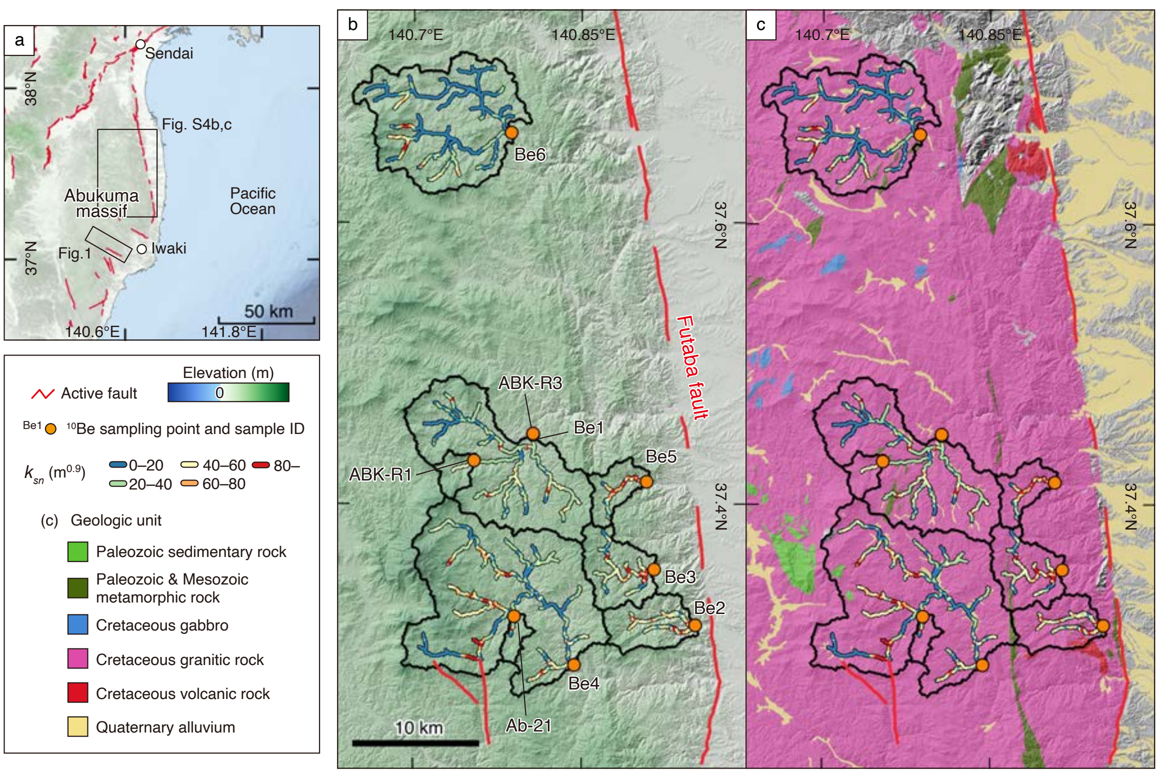

Figure S4. Normalized channel steepness and ^{10}Be samples in the Abukuma massif. (a) Topography and active faults around the Abukuma massif. (b) Normalized channel steepness and ^{10}Be samples. Results of the ^{10}Be analysis and references are shown in Table S2. (c) Geologic map (Geological Survey of Japan, 2020). Active fault traces are after Nakata and Imaizumi (2002).

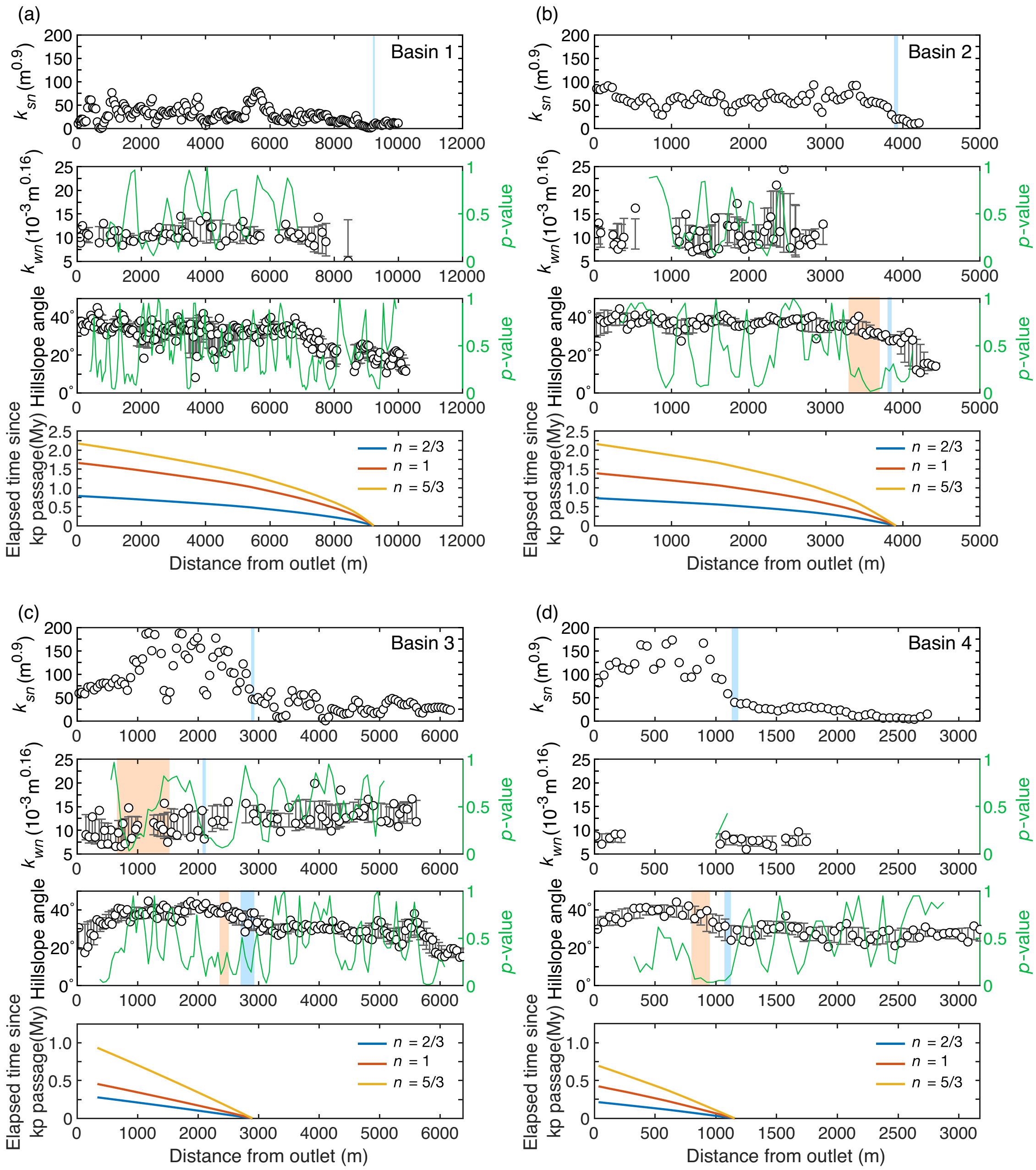

Figure S5. Along-trunk variations of channel and hillslope morphologies and knickpoint (kp) travel time in Basins 1–6. Average hillslope angle is calculated every 50 m along trunk streams. Gray bars in the upper and lower middle figures represent 8-point moving average and standard deviation. The green line in the upper middle figure indicates *p*-value of Student's *t* test. The green line in the lower middle figure indicates *p*-value of the Mann-Whitney U test. Blue and orange areas indicate sections where adjustment starts and finishes.

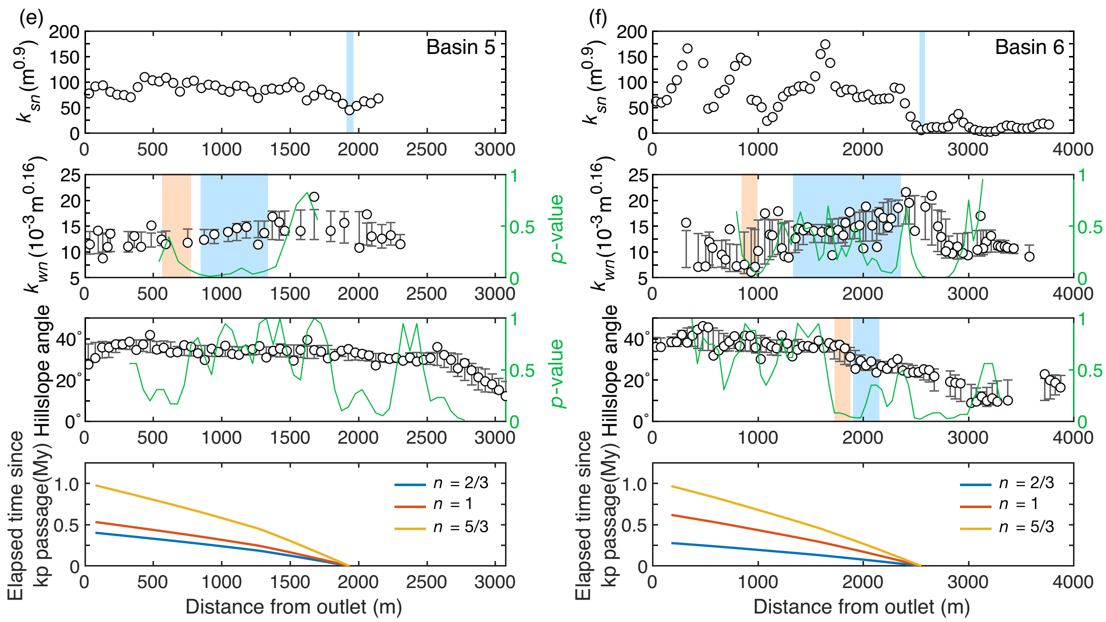

Figure S5. Continued.

Latitude (E)	Longitude (N)	Basin	Area (m^2)	Distance from outlet (m)	width (m)	width uncertainty (±, m)	flow depth (m)	flow depth uncertainty (±, m)
140.6414	37.1359	1	3308724	7740	5	1	0.5	0
140.6499	37.1200	1	9697008	4860	8.9	1.1	0.7	0
140.6471	37.1192	1	9624754	5160	11.5	1	0.85	0.05
140.6571	37.1087	1	14398559	2495	11.45	1.95	0.01	0.1
140.6422	37.1287	1	4546321	6755	6.25	0.15	0.7	0.1
140.6427	37.1258	1	4914795	6285	6.3	0.2	1.2	0.1
140.6438	37.1221	1	7619083	5685	8	0.3	0.6	0.1
140.6444	37.1218	1	7632594	5620	8.15	0.15	0.5	0.1
140.6456	37.1202	1	7853117	5390	7.55	0.15	0.8	0.1
140.6646	37.0935	1	23956273	295	13.6	0.2	0.9	0.1
140.6428	37.1337	1	3981009	7375	4.9	0.1	0.7	0.1
140.6429	37.1298	1	4383003	6900	6.6	0.1	0.8	0.1
140.6462	37.1194	1	7893658	5245	8.8	0.1	0.6	0.1
140.6571	37.1049	1	14998044	2025	9.95	0.45	0.7	0.1
140.6571	37.1075	1	14578487	2350	10.4	0.6	1	0.1
140.6624	37.0969	1	19837173	820	15.1	0.5	1.1	0.1
140.6515	37.1191	1	11240483	4630	8.5	0.5	0.6	0.1
140.6567	37.1118	1	13843767	2910	10.7	0.3	0.8	0.1
140.6558	37.1137	1	13684863	3150	9.85	0.15	0.7	0.1
140.6418	37.1280	1	4571816	6655	7	0.1	0.95	0.15
140.6416	37.1354	1	3320389	7625	6.1	0.1	0.75	0.15
140.6624	37.0986	1	19280323	1030	12.15	0.65	0.95	0.15
140.6617	37.1018	1	19103742	1415	9.6	0.1	0.95	0.15
140.6542	37.1177	1	11967646	4195	11.5	0.1	0.95	0.15
140.6572	37.1106	1	13905837	2760	10.8	0.6	1.15	0.15
140.6576	37.1099	1	14228164	2655	9.5	0.1	0.85	0.15
140.6621	37.1007	1	19141110	1280	13.1	0.8	0.7	0.2
140.6553	37.1146	1	13588868	3280	11.3	0.2	1.1	0.2
140.6643	37.0919	1	24004851	105	11.15	0.75	1.1	0.2
140.6480	37.1193	1	9646482	5075	10.65	0.85	0.9	0.2
140.6450	37.1211	1	7688725	5510	7.4	0.3	0.7	0.2
140.6645	37.0909	1	24098780	0	14.95	0.25	1	0.2
140.6420	37.1346	1	3338568	7505	7.85	0.55	1.1	0.2
140.6592	37.1038	1	17300336	1755	10.1	0.1	0.8	0.2
140.6599	37.1032	1	17347565	1655	10.25	0.55	1	0.2
140.6627	37.0958	1	19896455	690	10.35	0.55	0.7	0.2
140.6610	37.1025	1	17398887	1520	11.9	0.3	0.8	0.2
140.6624	37.0996	1	19177671	1155	13.1	0.1	1.1	0.2
140.6554	37.1176	1	11993823	4020	13.6	0.3	1.1	0.2
140.6561	37.1128	1	13723230	3050	9.9	0.1	1.4	0.2
140.6539	37.1156	1	13299245	3625	8.9	0.4	0.8	0.2
140.6428	37.1306	1	4349641	6990	6.2	0.8	0.75	0.25
140.6375	37.1402	1	2610286	8435	2.5	1	0.75	0.25
140.6418	37.1275	1	4577308	6590	6.8	0.1	1.55	0.25
140.6428	37.1332	1	4198735	7295	6.1	0.3	0.85	0.25
140.6425	37.1326	1	4213944	7220	5.4	0.5	1.15	0.25
140.6569	37.1064	1	14603660	2220	10.3	0.1	0.95	0.25
140.6538	37.1148	1	13303144	3445	9.9	0.1	0.95	0.25
140.6644	37.0924	1	24008208	165	15.75	0.25	1	0.3
140.6643	37.0917	1	24040634	85	12.65	0.35	0.9	0.3
140.6573	37.1091	1	14376733	2555	12.3	0.2	0.9	0.3
140.6571	37.1081	1	14403072	2425	11.4	0.4	1	0.3
140.6646	37.0940	1	20017949	350	12.3	0.7	1.2	0.3

140.6623	37.0989	1	19249199	1065	10.3	0.3	0.8	0.3
140.6523	37.1177	1	11910837	4455	7.75	0.25	1	0.3
140.6554	37.1168	1	13257232	3835	13.3	0.7	1	0.4
140.6414	37.1267	1	4734345	6490	8.15	1.35	1.1	0.44
140.6544	37.1180	1	11983181	4155	11.45	1.75	1.2	0.5
140.6543	37.1146	1	13552123	3380	10.85	0.55	1.3	0.5
140.6569	37.1053	1	14844375	2080	10.6	1	1.2	0.6
140.6556	37.1142	1	13688090	3225	14.4	0.4	1.35	1.15
140.6827	37.0808	2	1294430	2605	4.1	0.3	1	0.1
140.6878	37.0736	2	3826125.9	1460	5.75	0.15	1.7	0.1
140.6880	37.0729	2	3870734	1365	6.65	0.55	1.5	0.1
140.6881	37.0722	2	3895254	1270	4.1	0.3	0.7	0.1
140.6881	37.0719	2	3907132	1230	6	0.1	0.7	0.1
140.6867	37.0755	2	1856689	1725	5.4	1	0.8	0.1
140.6874	37.0741	2	3364863	1520	3.7	0.2	0.5	0.1
140.6876	37.0739	2	3794934	1495	3.8	0.2	0.8	0.1
140.6881	37.0718	2	3907132	1225	4.8	0.6	0.7	0.1
140.6877	37.0663	2	4504252	350	5.3	0.9	0.8	0.1
140.6876	37.0663	2	4514968	305	4.7	0.3	0.9	0.1
140.6845	37.0794	2	1594915	2320	3.9	0.1	0.8	0.1
140.6852	37.0792	2	1703111	2245	5.2	0.4	0.8	0.1
140.6854	37.0789	2	1727083	2205	4.7	0.3	0.6	0.1
140.6855	37.0784	2	1747590	2130	3.6	0.2	0.8	0.1
140.6825	37.0812	2	1195143	2660	3	0.3	0.6	0.1
140.6826	37.0809	2	1197940	2610	3.9	0.3	0.9	0.1
140.6828	37.0804	2	1526529	2540	3.1	0.1	0.6	0.1
140.6855	37.0780	2	1766827	2095	4.35	0.45	0.7	0.1
140.6857	37.0778	2	1772874	2045	3.4	0.2	0.6	0.1
140.6859	37.0775	2	1785656	2005	4.4	0.5	0.7	0.1
140.6819	37.0828	2	1121721	2860	3.65	0.35	0.6	0.1
140.6820	37.0825	2	1160326	2815	3	0.4	0.6	0.1
140.6821	37.0822	2	1168761	2785	3.4	0.1	0.8	0.1
140.6841	37.0796	2	1597571.8	2360	8.5	0.1	1.85	0.15
140.6880	37.0663	2	4500153.1	380	6.25	1.15	2.25	0.15
140.6873	37.0743	2	3406932.8	1565	7.8	0.1	2.95	0.15
140.6872	37.0660	2	4527040	255	5.3	0.5	0.75	0.15
140.6838	37.0798	2	1569351	2405	4.5	0.2	0.75	0.15
140.6861	37.0771	2	1797879	1945	3.2	0.3	0.75	0.15
140.6822	37.0837	2	972554	2965	4.2	0.1	0.55	0.15
140.6880	37.0724	2	3870734	1290	6.75	0.35	2	0.2
140.6892	37.0668	2	4394018	530	10	0.5	1	0.2
140.6872	37.0748	2	3328024	1610	4.2	0.3	0.6	0.2
140.6871	37.0659	2	4545847	240	6.6	0.5	0.7	0.2
140.6871	37.0643	2	4583548	55	8.2	0.4	1.2	0.2
140.6861	37.0769	2	1810704	1915	3.7	0.5	0.8	0.2
140.6865	37.0757	2	1851546	1745	5.3	0.7	0.7	0.2
140.6823	37.0819	2	1179305	2740	3.4	0.7	0.8	0.2
140.6849	37.0793	2	1703272.7	2285	5.95	0.15	1.45	0.25
140.6878	37.0727	2	3873735	1340	4.4	0.4	0.65	0.25
140.6882	37.0708	2	4145042	1100	5.5	0.5	0.95	0.25
140.6879	37.0733	2	3842232	1415	4.6	1.6	0.6	0.3
140.6871	37.0645	2	4577092	80	6.9	0.1	1.5	0.3
140.6863	37.0764	2	1811177.8	1850	7.3	0.1	1.45	0.35
140.6864	37.0760	2	1843649	1820	5.3	1.3	0.85	0.35
140.6863	37.0766	2	1820473	1875	4.4	0.6	1.1	0.4
140.6882	37.0716	2	3904754.9	1185	8.75	0.05	3.25	0.45

140.6873	37.0662	2	4536126.9	290	5.6	0.4	1.55	0.55
140.6882	37.0705	2	4200503	1060	7	0.2	1.45	0.75
140.6834	37.0799	2	1537922.2	2455	9.7	2.2	1.8	1
140.6962	37.0707	3	5898270	1420	7.1	0.1	0.85	0.05
140.7125	37.0892	3	2352413	5025	5.6	0.1	0.55	0.05
140.7131	37.0897	3	1850815	5110	5.15	0.05	0.55	0.05
140.7104	37.0876	3	2473778	4730	6.3	0.5	0.55	0.05
140.7110	37.0881	3	2426911	4810	7.95	0.25	0.65	0.05
140.7116	37.0885	3	2383658	4895	7.25	0.05	0.85	0.05
140.7135	37.0913	3	1022951	5310	3.6	0.2	0.55	0.05
140.7095	37.0851	3	2941119	4275	6.65	0.05	0.65	0.05
140.7083	37.0842	3	3371319	4110	6.6	0.1	0.75	0.05
140.7043	37.0818	3	4307440.2	3500	9.05	0.55	0.85	0.05
140.6930	37.0619	3	6716988	195	6.35	0.15	0.9	0.1
140.6966	37.0702	3	5927040	1330	7.6	0.1	0.7	0.1
140.7131	37.0901	3	1788066	5160	4.9	0.1	0.5	0.1
140.7165	37.0918	3	744715	5605	3.45	0.15	0.4	0.1
140.7052	37.0805	3	4417392	3310	7.65	0.25	0.6	0.1
140.7035	37.0781	3	4841621	2960	7.7	0.2	0.6	0.1
140.7046	37.0796	3	4634590	3205	8	0.5	0.6	0.1
140.7158	37.0917	3	793692	5535	5	0.2	0.5	0.1
140.7150	37.0916	3	837159	5455	4.45	0.05	0.4	0.1
140.7137	37.0914	3	1022951	5330	4.5	0.1	0.8	0.1
140.7133	37.0906	3	1753550	5235	6.55	0.25	0.5	0.1
140.7097	37.0855	3	2936062	4330	6.2	0.1	0.7	0.1
140.7094	37.0865	3	2906345	4440	6.55	0.25	0.4	0.1
140.7094	37.0868	3	2900072	4565	6.8	0.2	0.5	0.1
140.7058	37.0838	3	3942294	3850	7.2	0.3	0.7	0.1
140.7087	37.0844	3	3365939	4155	6.3	0.3	0.9	0.1
140.7066	37.0839	3	3535936	3925	11.2	1	0.4	0.1
140.7050	37.0800	3	4536687.1	3260	7.9	0.1	0.6	0.1
140.7041	37.0825	3	4224177	3610	6.95	0.15	0.5	0.1
140.7048	37.0830	3	4124839.5	3690	6.8	0.2	1.1	0.1
140.7045	37.0793	3	4644569.1	3135	7.3	0.2	0.8	0.1
140.6932	37.0623	3	6704268.3	250	9.45	0.25	0.01	0.1
140.6960	37.0709	3	5899700	1440	10.95	0.15	1.1	0.1
140.6941	37.0630	3	6640856	365	10.4	1	0.01	0.1
140.6952	37.0659	3	6255185.3	755	8.15	0.15	1.9	0.1
140.6944	37.0632	3	6620069	400	5.15	0.45	0.75	0.15
140.6953	37.0649	3	6394511	635	4.75	0.25	0.75	0.15
140.6950	37.0639	3	6587952	505	5.2	0.2	0.85	0.15
140.7144	37.0916	3	846670	5400	4.5	0.5	0.65	0.15
140.6958	37.0712	3	5878451	1495	5.2	0.2	1	0.2
140.6997	37.0736	3	5429703	2100	5.5	0.1	1.1	0.2
140.6958	37.0675	3	6104440	965	7.25	0.45	0.6	0.2
140.7051	37.0809	3	4334233	3360	5.95	0.05	0.7	0.2
140.7079	37.0839	3	3392881	4050	7.1	0.1	0.8	0.2
140.7098	37.0874	3	2804691	4675	6.7	0.2	0.5	0.2
140.7105	37.0877	3	2486284	4745	7.1	1	0.6	0.2
140.7074	37.0838	3	3409800.9	4010	8	0.1	1.1	0.2
140.7091	37.0846	3	3174725.5	4200	5.3	0.5	1	0.2
140.7015	37.0739	3	5196032.5	2320	8	0.2	1.8	0.2
140.7016	37.0753	3	5126678	2495	10.55	0.85	0.9	0.2
140.6959	37.0720	3	5787847.8	1600	8.75	0.65	1.2	0.2
140.6967	37.0729	3	5669979.7	1750	9.35	0.35	2.3	0.2
140.7034	37.0768	3	4940907.9	2790	10.15	0.15	0.8	0.2

140.7033	37.0778	3	4849706.7	2915	8.65	0.65	1.1	0.2
140.7039	37.0787	3	4723068.9	3040	9.3	0.2	1.1	0.2
140.7052	37.0835	3	3946647	3780	7.2	0.1	0.9	0.2
140.6926	37.0615	3	6767403.8	145	6.7	1	1.7	0.2
140.6967	37.0696	3	5935793.6	1265	8.1	0.8	1.1	0.2
140.6953	37.0662	3	6244268	790	5.1	1.1	0.75	0.25
140.7095	37.0872	3	2892702	4650	7.1	0.5	0.65	0.25
140.6958	37.0716	3	5804772	1555	6.65	0.95	0.9	0.3
140.6966	37.0705	3	5905866	1380	7.7	1	0.9	0.3
140.6990	37.0730	3	5458882	1995	6.7	0.3	1	0.3
140.6978	37.0731	3	5495334	1875	5.8	0.5	0.8	0.3
140.6953	37.0657	3	6280473	725	4.7	0.4	1	0.3
140.6946	37.0635	3	6613613	450	7.3	0.5	0.9	0.3
140.6954	37.0671	3	6194839	900	5.9	0.2	0.8	0.3
140.7098	37.0857	3	2946423.9	4355	9.65	0.25	0.9	0.3
140.7017	37.0747	3	5196032.5	2420	7.85	0.75	2.1	0.3
140.6975	37.0732	3	5556673.5	1840	9.95	0.55	1.6	0.3
140.6951	37.0643	3	6499995.2	555	7.3	0.2	1.8	0.3
140.6953	37.0653	3	6373465.9	680	6.8	0.2	1.9	0.3
140.6961	37.0724	3	5782909	1650	6.2	0.2	1.05	0.35
140.6960	37.0677	3	6102349.9	995	7.8	0.2	1.95	0.35
140.7009	37.0735	3	5343339.6	2235	7.85	0.65	1.3	0.4
140.6951	37.0668	3	6206045	850	10.5	0.3	1.5	0.4
140.6935	37.0625	3	6688885	295	6.3	0.1	1.4	0.7
140.6994	37.0734	3	5434437.1	2065	9.55	0.75	2.25	0.75
140.7060	37.0606	4	1535653	125	3.3	0.3	0.55	0.05
140.7059	37.0690	4	906589	1210	2.6	0.1	0.45	0.05
140.7063	37.0691	4	853621	1250	1.85	0.05	0.45	0.05
140.7078	37.0708	4	797457	1575	2.5	0.1	0.55	0.05
140.7082	37.0711	4	767471	1630	2.2	0.1	0.35	0.05
140.7073	37.0701	4	826249	1420	2.15	0.05	0.45	0.05
140.7075	37.0705	4	801869	1465	2	0.2	0.55	0.05
140.7063	37.0596	4	1553438	10	3.5	0.5	0.7	0.1
140.7055	37.0612	4	1446986	220	3.55	0.35	0.7	0.1
140.7058	37.0608	4	1509411	170	3.6	0.2	0.6	0.1
140.7061	37.0680	4	951681	1080	2.9	0.1	0.4	0.1
140.7059	37.0685	4	941255	1145	2.6	0.2	0.4	0.1
140.7061	37.0677	4	959299	1035	2.3	0.2	0.4	0.1
140.7093	37.0714	4	721411	1745	2.2	0.2	0.5	0.1
140.7068	37.0693	4	844938	1300	2.4	0.2	0.5	0.1
140.7071	37.0696	4	837159	1350	2.4	0.2	0.4	0.1
140.7086	37.0712	4	729674	1680	2.8	0.1	0.65	0.15
140.7062	37.0600	4	1544949	60	2.8	0.2	0.8	0.2
140.7390	37.0535	5	2370076	1110	6.95	0.05	0.85	0.05
140.7402	37.0548	5	2234767	1310	6.35	0.45	1.05	0.05
140.7369	37.0495	5	3102455	560	6.6	0.2	0.95	0.05
140.7414	37.0626	5	367425	2305	2.5	0.1	0.5	0.1
140.7413	37.0620	5	405436	2235	3	0.1	0.6	0.1
140.7414	37.0614	5	423421	2170	2.9	0.1	0.4	0.1
140.7414	37.0586	5	1016366	1795	4.7	0.7	0.9	0.1
140.7411	37.0568	5	1073498	1575	4.8	0.7	0.7	0.1
140.7420	37.0607	5	639941	2060	4.75	0.15	0.7	0.1
140.7393	37.0541	5	2359030	1180	7.05	0.05	1	0.1
140.7406	37.0557	5	1208936	1420	5.65	0.15	1.1	0.1
140.7405	37.0552	5	1212906	1370	6.05	0.05	1.1	0.1
140.7363	37.0481	5	3191251	360	7.05	0.45	1.4	0.1

140.7376	37.0507	5	2837382	750	6.05	0.45	1.2	0.1
140.7356	37.0467	5	3305687	165	6	0.2	1	0.1
140.7418	37.0609	5	631100	2095	3.55	0.15	0.45	0.15
140.7421	37.0603	5	949196	2005	3.5	0.1	0.45	0.15
140.7354	37.0465	5	3312875	130	4.8	0.5	0.85	0.15
140.7357	37.0468	5	3301577	185	7.4	0.8	1.1	0.2
140.7412	37.0576	5	1033280	1675	6.95	0.15	0.75	0.25
140.7416	37.0595	5	965787	1895	5.1	0.5	0.85	0.25
140.7347	37.0459	5	3341322	35	6.3	0.1	1.15	0.25
140.7352	37.0463	5	3327916	95	7.75	0.25	0.85	0.25
140.7364	37.0477	5	3247641	315	6	0.6	0.95	0.25
140.7382	37.0517	5	2792834	870	6.3	0.3	1.05	0.25
140.7386	37.0531	5	2407608	1045	6.65	0.15	1.2	0.3
140.7362	37.0485	5	3157941	410	5.9	0.3	1.3	0.3
140.7370	37.0498	5	3062484	590	6.1	0.5	1.3	0.3
140.7408	37.0560	5	1204449	1460	5.05	0.15	0.9	0.4
140.7383	37.0523	5	2571722	945	6.6	0.8	1.2	0.4
140.7397	37.0547	5	2330283	1265	5.4	0.4	1.1	0.4
140.7365	37.0490	5	3137767	485	8.1	0.4	1.1	0.4
140.7817	37.0231	6	3666963	430	4.05	0.25	0.95	0.05
140.7809	37.0259	6	3006880	795	3.8	0.1	0.95	0.05
140.7803	37.0368	6	1549769	2490	5.6	0.4	0.65	0.05
140.7803	37.0364	6	1562121	2435	7.8	0.4	0.95	0.05
140.7779	37.0410	6	1266843	3085	3.8	0.2	0.55	0.05
140.7770	37.0429	6	1089529	3345	3.8	0.1	0.55	0.05
140.7815	37.0236	6	3643185	500	4.1	0.2	0.8	0.1
140.7796	37.0268	6	2940086	1000	5.3	0.1	1.1	0.1
140.7791	37.0274	6	2851903	1190	9.2	0.5	1.1	0.1
140.7806	37.0265	6	2997584	870	3.95	0.45	0.7	0.1
140.7795	37.0316	6	1914983	1810	5.75	0.55	1.2	0.1
140.7793	37.0310	6	2444179	1690	6.7	0.5	1.3	0.1
140.7802	37.0361	6	1570556	2405	8.65	0.25	0.7	0.1
140.7796	37.0345	6	1711503	2190	6.9	1.1	0.7	0.1
140.7776	37.0418	6	1203062	3170	4.3	0.2	0.5	0.1
140.7767	37.0432	6	1076790	3370	3.7	0.2	0.5	0.1
140.7771	37.0427	6	1104549	3305	3.8	0.2	0.5	0.1
140.7755	37.0443	6	643944	3580	2.5	0.2	0.3	0.1
140.7765	37.0434	6	975244	3430	3.5	0.1	0.4	0.1
140.7773	37.0421	6	1148103	3215	4.6	0.2	0.6	0.1
140.7810	37.0227	6	3713250	315	9	0.2	0.65	0.15
140.7790	37.0268	6	2876133	1110	6.9	0.7	0.45	0.15
140.7800	37.0268	6	2943744	970	3.7	0.5	0.85	0.15
140.7815	37.0242	6	3633330	565	6.15	0.55	0.55	0.15
140.7803	37.0268	6	2950329	935	3.2	0.2	0.65	0.15
140.7814	37.0251	6	3041052	690	4.5	0.5	0.95	0.15
140.7795	37.0311	6	2426222	1705	4.5	0.1	0.75	0.15
140.7803	37.0377	6	1516243	2590	7.4	0.1	0.65	0.15
140.7797	37.0337	6	1860283	2085	6.5	0.5	0.75	0.15
140.7796	37.0342	6	1775091	2150	7.4	0.1	1.15	0.15
140.7787	37.0403	6	1365484	2945	3.7	0.3	0.55	0.15
140.7783	37.0405	6	1342717	2995	3.5	0.1	0.45	0.15
140.7773	37.0425	6	1129640	3280	3.9	0.5	0.55	0.15
140.7790	37.0399	6	1395825	2895	4.2	0.5	0.55	0.15
140.7802	37.0381	6	1497952	2650	8.2	0.2	0.65	0.15
140.7798	37.0385	6	1457024	2710	5.8	0.7	0.55	0.15
140.7796	37.0387	6	1450052	2740	5	0.3	0.85	0.15

140.7792	37.0266	6	2935395	1065	9.1	0.1	0.8	0.2
140.7788	37.0279	6	2834731	1250	4.7	0.3	1.1	0.2
140.7790	37.0271	6	2855002	1135	6.8	0.5	0.9	0.2
140.7811	37.0254	6	3029023	730	7.6	0.1	0.8	0.2
140.7815	37.0239	6	3638408	535	6.8	0.1	0.6	0.2
140.7796	37.0313	6	1917307	1760	6.2	0.4	0.9	0.2
140.7796	37.0322	6	1906160	1870	7.7	0.7	0.9	0.2
140.7785	37.0289	6	2793157	1380	7.4	0.1	1.1	0.2
140.7785	37.0286	6	2811448	1355	6.45	0.05	1.1	0.2
140.7785	37.0305	6	2454347	1605	6.7	0.1	0.9	0.2
140.7795	37.0333	6	1870138	2025	8.1	0.1	0.9	0.2
140.7793	37.0331	6	1874055	2000	4.6	0.4	1.2	0.2
140.7793	37.0393	6	1413062	2810	4.3	0.9	0.7	0.2
140.7792	37.0396	6	1407747	2845	3.7	0.1	0.7	0.2
140.7796	37.0325	6	1895315	1920	6.4	0.5	1.25	0.25
140.7787	37.0291	6	2720381	1430	7.15	0.05	0.85	0.25
140.7786	37.0282	6	2823369	1290	4.55	0.35	0.85	0.25
140.7784	37.0299	6	2681304	1530	7.05	0.55	1.35	0.25
140.7798	37.0356	6	1610882	2330	7.5	0.6	0.95	0.25
140.7796	37.0352	6	1684002	2265	6.8	0.2	0.85	0.25
140.7778	37.0416	6	1257676	3140	3.9	0.5	0.65	0.25
140.7778	37.0414	6	1259828	3115	6.2	1	0.55	0.25
140.7794	37.0391	6	1438389	2785	3.9	0.1	0.65	0.25
140.7815	37.0248	6	3050132	655	5	0.1	1.1	0.3
140.7794	37.0328	6	1884211	1965	6.55	0.75	1.5	0.3
140.7795	37.0318	6	1912100	1830	6.8	0.8	1	0.3
140.7791	37.0309	6	2444179	1670	6.8	0.7	1.1	0.3
140.7797	37.0340	6	1850212	2130	4.7	0.2	1	0.3
140.7796	37.0349	6	1701002	2235	6.15	0.15	1	0.3
140.7790	37.0276	6	2847104	1225	5.5	1	0.95	0.35
140.7787	37.0294	6	2711559	1470	7.45	1.25	1.3	0.6