King, G.E., et al., 2023, Eustatic change modulates exhumation in the Japanese Alps: Geology, https://doi.org/10.1130/G50599.1

**Supplementary Information for:**

**Eustatic change modulates exhumation in the Japanese Alps**

Georgina E. King1\*, Floriane Ahadi2, Shigeru Sueoka3, Frédéric Herman1, Leif Anderson1,Cécile Gautheron2, Sumiko Tsukamoto4, Nadja Stalder1, Rabiul Biswas 1,5, Matthew Fox6, Guillaume Delpech2, Stephane Schwartz7 and Takahiro Tagami8

1University of Lausanne, Institute of Earth SurfaceDynamics, 1015, Lausanne, Vaud, Switzerland

2Université Paris-Saclay, CNRS, GEOPS, 91405, Orsay, France

3Japan Atomic Energy Agency, Tono Geoscience Center, Jorinji Izumichu, 509-5102, Japan

4Leibniz Institute for Applied Geophysics, 30655 Hannover, Germany

5Indian Institute of Technology Kanpur, Department of Earth Sciences, Kanpur-208016, India

6University College London, Earth Sciences, London, WC1E 6BT, UK

7Université Grenoble Alpes, ISTERRE, 38610, Gières, France

8Graduate School of Science, Kyoto University, Kyoto, 606-8502, Japan

\*georgina.king@unil.ch

**Contents**

1. Sample selection

2. Luminescence thermochronometry

2.1 Luminescence sample preparation

2.2 Luminescence measurements

2.3 Luminescence results

3. (U-Th)/He zircon thermochronometry

3.1 (U-Th)/He zircon sample preparation

3.2 (U-Th)/He zircon measurement

3.3 (U-Th)/He zircon results

4. Inversion of thermochronometric data

4.1 Exhumation histories

4.2 Method validation

4.3 Influence of fluid flow

5. Stream modelling of knickpoints in the Kurobe Gorge

5.1 Calculation of knickpoint propagation

6. Ice equilibrium line altitude modelling

6.1 Glacier model description

6.2 Model results

References

**Supplementary Material for: Time series of Quaternary exhumation of the Hida Range, Japanese Alps**

**1. Sample selection**

Twenty-two bedrock samples were collected to coincide with previous thermochronometric ages from the study area (Yamada, 1999; Ito et al., 2003) over two field seasons. Sample locations are shown in Fig. 1 of the main text and are detailed in Table S.1. In this study, Eleven samples were prepared for luminescence dating and twelve samples were prepared for zircon (U-Th)/He (ZHe) dating to complement existing zircon fission track thermochronometry (ZFT) results on the same samples (Yamada, 1999). ESR and luminescence thermochronometry data of a further six samples from the same study area have also been reported previously (King et al., 2020).

**2. Luminescence thermochronometry**

2.1 Luminescence sample preparation

Samples were prepared for luminescence thermochronometry using the approach of King et al. (2016). All sample preparation was done under subdued red-light conditions at the University of Lausanne or the University of Bern. At least 1 cm was removed from the exterior of the samples using a water-cooled diamond saw. Samples were then hand-crushed and sieved to extract the 180-210 μm fraction before treatment with HCl and H2O2 to remove carbonates and any organic material respectively. The quartz (2.58<*ρ*<2.70 g cm-3) and K-feldspar (<2.58 g cm-3) fractions were then extracted by density separation using heavy liquids.

The environmental dose rate data for the different samples are listed in Table S.2. A representative portion of bulk bedrock from each of the samples was sent to Actlabs, Ancaster, Canada, for ICP-MS analysis to determine the U, Th, K and Rb concentrations. Furthermore, a thin-section was made from each of the samples so that the original sample grain-size could be estimated using the software of Buscombe (2013). Environmental dose rates were calculated using DRAC v.1.2 (Durcan et al., 2015, see Supplementary Data for the DRAC input and output tables). The conversion factors of Guérin et al. (2011) were used together with the feldspar beta grain-size attenuation factors of Guérin et al. (2012) and the alpha grain size attenuation factors of Bell et al. (1980). An a-value of 0.11 ± 0.02 was used for the K-feldspar fraction after Balescu and Lamothe (1992) and an internal K content of 12.5 ± 0.5% was assumed (Huntley and Baril, 1997). Rock water contents were estimated at 2 ± 2%. As the samples have only been at the surface for a relatively short time period, no cosmic dose rate was incorporated in the environmental dose rate calculation.

2.2 Luminescence measurements

All luminescence measurements followed a multiple elevated temperature single aliquot regenerative dose protocol (Li and Li, 2013) and were made on Risø TL-DA-20 instruments with dose rates ranging from ~0.05 to 0.10 Gy s-1 (the specific dose rate for each measurement is given in the raw data tables within the Supplementary Materials). Samples were preheated at 250 °C for 60 s before infrared stimulation at 50 °C, 100 °C, 150 °C and 225 °C for 100 s. All measurement cycles were followed by a high temperature optical wash at 290 °C for 100 s. The selected measurement protocol was validated using dose-recovery experiments.

Three measurements were used to constrain (i) the sample specific rate of athermal signal loss (anomalous fading), (ii) the trapped charge concentration of each of the samples and (iii) the thermal stability of the different samples. Athermal signal loss was measured for three aliquots of each sample and comprised giving the sample a dose of ~100 Gy, preheating and then storing the sample for different time delays (cf. Auclair et al., 2003). The resulting data was fitted with the model of Huntley (2006) to constrain *ρ’*; further details on data-fitting are given below. The trapped charge concentration of the samples was determined by constructing sample specific dose response curves, with a maximum regenerative dose of ~4.5 kGy (exact maximum dose dependent on instrument). The dose response curves were fitted using a single saturating exponential function, as although this led to some deviation between the measured values and the modeled data, King et al. (2018) have recently shown that using a general order kinetic model with an improved fit to the data (e.g. Guralnik et al., 2015) would result in an underestimation of the trapped charge concentration. The final experiment allowed the thermal sensitivity of the different samples to be constrained, and comprised administering a ~100 Gy dose, and then holding a single aliquot of the different samples at temperatures ranging from 170 °C to 350 °C for durations of 10 to 1280 s before measuring the remaining luminescence signal. These data were fitted using the band-tail states model (Li and Li, 2013) as implemented by King et al. (2016). Luminescence data and data fitting are shown in Figs. S1-17, raw luminescence data are available in the Supplementary Data table.

2.3 Luminescence results

All of the luminescence measurements could be accepted although for some samples the signal intensities of post-IR IRSL signals were almost an order of magnitude lower than the IRSL50 signal intensities, and similar between post-IR IRSL signals. The suitability of the measurement protocol was investigated for ten of the seventeen samples measured using a dose-recovery test (Fig. S.18). Three aliquots were measured for samples KRG01, KRG03, KRG07, KRG08, KRG10, KRG13, KRG100, KRG101, KRG111 and KRG112. Given doses ranged from 40 to 130 Gy dependent on sample and aliquots were sunlight bleached prior to dosing and measurement. An additional three aliquots of the same samples were measured following the same bleaching exposure to quantify the residual dose which was <6 Gy for all signals. All of the dose recovery ratios are residual subtracted. Whilst some individual samples under or overestimated the given dose (Fig. S.18), the average response of all samples is within error of the 10% threshold commonly used in luminescence dating investigations. The trend towards underestimation of the given dose for the IRSL50 signal may be a consequence of the high rates of anomalous fading measured from this signal for these samples (Table S.3). The dose recovery data have not been corrected for anomalous fading.

All samples were screened for field saturation (Fig. S.19, cf. Kars et al., 2008; Valla et al., 2016) and of the samples investigated, only two samples are in athermal steady-state for all of the measured signals: KRG05 and KRG100. The IRSL50 signals of five other samples are saturated, which is related to the high rates of anomalous fading recorded for this signal from this sample set (Table S.3). The high anomalous fading rates for the IRSL50 signals results in the calculation of anomalously old ages, relative to the other IRSL signals (Table S.2), indicating that the fading rates measured in the laboratory may not be accurate for this signal for these samples.

**3. (U-Th)/He zircon thermochronometry**

3.1 (U-Th)/He zircon sample preparation

Twelve samples were crushed using the Selfrag at the University of Bern, sieved (mesh <400 μm) and separated following density and magnetic methods at the University Paris Saclay (France). For each sample, zircons were selected based on their size and geometry. Sample length, width and height were measured in order to calculate the crystal weight, ejection factor (FT) sphere equivalent radius (Rs) (Ketcham et al., 2011). Between 1 to 8 single zircon crystals were then packed into a Nb tube following the protocol of Gautheron et al. (2021). The selected zircon crystals have ejection factors with values ranging from 0.74 to 0.89, and sphere equivalent radii ranging from 38 to 92 mm (Table S.4).

3.2 (U-Th)/He zircon measurement

The He, U and Th content were determined at the University Paris Saclay, following the protocol described in Gautheron et al. (2021). First, each Nb tube containing a zircon crystal was placed on a metallic planchette under a vacuum chamber. Each capsule was heated using a fibre laser at T>1200°C for 30 min, and the extracted gas purified and analyzed using quadrupole or sector magnetic mass spectrometer. Then, the Nb capsules were retrieved from the high vacuum chamber and the digestion was done in 350 μL PFA Parrish-style vials placed into a high-pressure–high-temperature dual-wall digestion vessel. Zircons were first spiked with 100 μL of 235U and 230Th, and digestion was performed following the protocol described in Gautheron et al. (2021). The U and Th content were determined using a high-resolution inductively coupled plasma mass spectrometer (HR-ICP-MS – ELEMENT XR). Fish Canyon standard zircon (U-Th)/He ages were analyzed at the same time yielding an age of 27.0±2.6 Ma (1 σ) (Gautheron et al., 2021).

For two samples (KRG-3 and KRG-8), a 5% correction has been added associated with U-Th contents that are in secular disequilibrium due to young crystallization ages (0.76±0.09 Ma). As the U and Th spikes that are used in this study will cover the U-Th disequilibrium, we used the crystallization age to perform the (U-Th)/He correction that is not important as at 0.76±0.09 Ma, the U-Th content of those zircons are almost at secular equilibrium that is reached at ~1 Ma.

3.3 (U-Th)/He zircon results

Zircon (U-Th)/He (ZHe) results are reported in Table S.4. The ZHe ages range from 0.1±0.1 Ma to 4.1±0.4 Ma, with U contents and Th/U ratios that range from 87 to 4538 ppm and 0.1 to 1.3 respectively. The (U-Th)/He ages present a slight dispersion of 20 % up to almost 70%, and the dispersion is not associated with the age, but for some samples, correlation between ZHe and eU content (eU content (eU=U+0.238×Th; equation of Cooperdock et al., 2019) or crystal size (Rs) can be observed. Correlation between ZHe and eU content is expected due to the impact of radiation damage on He diffusion (e.g., Gautheron et al., 2020; Guenthner et al., 2013), whereas correlation with crystal size will be associated with diffusion domain size (Reiners and Farley, 2001). Mean ZHe age was calculated for the purpose of modeling and some aliquots presenting very different ZHe age were rejected (see Table S.4). Mean ZHe ages are also reported in Table S.1.

**4. Exhumation histories**

4.1 Inversion of thermochronometric data

The data were inverted to determine exhumation rates using the approach of Biswas et al. (2018) which first involves solving the 1D heat transfer equation

[Eq. S1]

for a randomly generated depth-time history, where is thermal diffusivity (30 km2/Ma), is the temperature, is the depth, and is the exhumation rate. We then extracted time-temperature histories of rocks exhumed towards the surface and used these time-temperature histories to compute the thermochronometric data using the sample specific kinetic parameters listed in Table S.3 and Table 1 of King et al. (2020) for the luminescence and electron spin resonance data together with the kinetic models of King et al. (2016) and King et al. (2020) respectively. For the other thermochronometric systems, the literature kinetic parameters of Reiners and Brandon (2006) were used together with the Mad\_He algorithm (Braun et al., 2006).

We started the model with an initial condition of an unperturbed geothermal gradient of 70°C/km and ran the model for between 5 and 15 million years, depending on the ZFT age. As we solved the transient heat equation, the geothermal gradient evolved throughout the model and only models that yielded a final geothermal gradient of <200°C/km were accepted. Whilst this geothermal gradient is high, it is plausible within the extremely active location of Kurobegawa, as shown by the temperature of 166°C that was logged in a high-temperature tunnel at the sample location during its excavation (Yuhara and Yamamoto, 1983).

Sufficient iterations of the model were run to allow a minimum of 200 accepted paths, following filtering of the data for the maximum geothermal gradient and application of a misfit function (Wheelock et al., 2015):

[Eq. S2]

[Eq. S3]

where *M* is the misfit for *m* datasets, is the thermochronometric age or trapped-charge concentration, *σ* is the uncertainty, is the modelled age or trapped-charge concentration and *L* is the likelihood. An arbitrary uncertainty on of 5% was assumed for the luminescence data and of 10% for the other thermochronometric data. The accepted data were then used to construct a probability density function of sample exhumation (i.e. depth and time). Taking the derivative of the median model allows direct calculation of changes in exhumation rate (Figure 3 of the main text).

4.2 Method validation

To confirm the ability of the luminescence data to recover changes in exhumation histories over the past 150 ka, a series of synthetic modelling experiments were done using the kinetic parameters of two different samples: UNIL/NB123 (King et al., 2016) and KRG104 (King et al., 2020). A total of 14 different scenarios were tested, whereby exhumation rates were prescribed to generate a depth-time history, that was then converted to a time-temperature history. This was then used to grow synthetic (forward modelled) luminescence signals () using the sample specific kinetic parameters (King et al., 2016; Table S.3; e.g. Biswas et al., 2018). The data were then inverted to recover exhumation histories until a minimum of 200 paths were accepted. An initial geothermal gradient of 20 °C/km was used and time-temperature histories with geothermal gradients >100 °C were rejected.

The results of the forward and inverse modelling demonstrate that the luminescence thermochronometry system is able to recover changes in exhumation rates over the past 150 ka (Figs. S.20-23). For some scenarios where is within uncertainty of , only a minimum exhumation rate can be recovered (see models 3, 4 and 5 for both samples), which is consistent with previous observations (e.g. King et al., 2016) and highlights the resolution limitations of the luminescence system to high exhumation rates over short timescales. For models 3, 4 and 5, the trapped-charge population is indistinguishable from (black data points), meaning that the increase in exhumation rates over the past 50-75 ka cannot be determined for these specific experimental conditions. If the prior or latter exhumation rate were greater, then the system would be further from saturation, allowing recovery of the exhumation rate change as seen in model 6 for both samples, although the shift in exhumation rate is smoothed relative to the prescribed forward model. This is partly a consequence of binning the exhumation rate changes in 5 ka windows. It is also apparent that the luminescence system is capable of recording reductions in exhumation rate, as shown in models 9-14, although again the transition to reduced rates of exhumation is necessarily smoothed by binning of the model into 5 ka windows.

4.3 Influence of fluid flow

Luminescence thermochronometry integrates changes in exhumation rates over the final few kilometers of Earth’s crust. Within this zone, the geothermal gradient may be perturbed by the flow of groundwater (Forster and Smith, 1989), and this may be especially pertinent in the Hida range where precipitation rates are ~4000 mm/a. Using a modelling approach, Forster and Smith (1989) show that the geothermal gradient becomes depressed due to fluid flow towards the surface, and that this effect is especially pronounced in valleys. This phenomenon would result in an underestimation of the total amount of exhumation (Whipp and Ehlers, 2007) as more rock must be exhumed for the equivalent amount of rock cooling. Higher temperature thermochronometeric systems are relatively less affected, because the isotherm of their closure temperatures are less perturbed. To explore whether the exhumation rates inverted from the luminescence thermochronometry data could be predominantly explained by changes in the geothermal gradient, an inversion was run for the luminescence thermochronometry data of sample KRG06 where the diffusivity, was allowed to vary randomly between 0 and 150 W/Ma whilst solving the heat equation (Eq. S.1). Varying the diffusivity in this way approximates changes in heat-flow that might be anticipated within a perturbed geothermal field. The results are indistinguishable from those recorded where diffusivity is fixed at 30 W/Ma (data not shown). A more comprehensive investigation of the effects of ground-water circulation on trapped-charge thermochronometry and thermochronometry in general is beyond the scope of the present study.

4.4 Exhumation Results

Initially the luminescence and ESR data were inverted together, as were the ZHe and ZFT data. The luminescence and ESR data were then inverted together with the ZHe and ZFT data. Because of the different timescales that the trapped-charge and conventional thermochronometers integrate, for these samples there was no benefit in inverting the data together (data not shown). The results of the inversions are shown in Figs S.24-28. As fading correction of the IRSL50 signals yields anomalously high values relative to the other luminescence signals (Table S.3) and as this signal exhibits poor dose recovery (Fig. S.18), these data were not included in the inversion. Including these data results in the same general pattern of exhumation rate change, although both the maximum exhumation rate is greater and the final exhumation rate is lower (data not shown).

**5. Stream modelling of knickpoints in the Kurobe gorge**

Modelling knickpoint retreat in the Kurobe gorge is complicated by its intensive management, and specifically by the construction of five dams along the river’s length. We used a 30 m resolution DEM of the Kurobe region (downloaded from OpenTopography) and extracted the profile of the Kurobe River using TopoToolbox2 (Schwanghart and Scherler, 2014).

River profiles exhibit a power law relationship between slope () and drainage area ():

Eq. S.4

Where is the steepness index, (e.g. Whipple and Tucker, 1999), is drainage basin area and and are constants. For a river in topographic steady-state, i.e. with constant uplift and erosion, this equation can be rewritten such that:

Eq. S.5

and

Eq. S.6

where is the normalised channel steepness, is the slope and is the channel concavity. Using TopoToolbox2, we calculated values for the Kurobe River (Fig. 4a). We imposed a minimum downward gradient of 0.0001 m/m on our DEM and applied a minimum flow accumulation threshold of 0.06 km2. values were averaged over 2 km. The values are highest in the vicinity of the study site and yield a value of of 0.45, which is within the range of m/n ratios cited by Whipple and Tucker (1999; 0.35 ≤ m/n ≤ 0.60) although it should be noted that is equivalent to m/n only if rates of uplift and erosion are constant (Whipple and Tucker, 1999).

Following Perron and Royden (2013), we made a crude analysis of the Kurobe River catchment. The chiplot function in TopoToolbox2 (Scwhanghart and Scherler, 2014) was first used to determine the ratio. Catchments comprising fewer than 2000 nodes were excluded from the modelling and an value of 0.247 ± 0.005 was calculated. This value is significantly different to the value of calculated using the simpler slope-area approach above and is not surprising (cf. Mudd et al., 2018). We used the ratio to transform the river profile into space (Fig. S.29a). Rivers that are adequately described by the stream power model and that are in steady state should plot linearly with tributaries overlapping the main trunk of the river. This is not the case for the Kurobe River and rather it is apparent that the river is in a transient state. The steepness of tributaries located between 800 and 1000 m elevation is indicative of ongoing uplift, whereas the concavity of the main Kurobe channel below 1200 m elevation, is indicative of ongoing incision. The knickpointfinder function in Topotoolbox identifies numerous knickpoints along the main river trunk and along the major tributaries, consistent with this result (Fig. S.29b).

5.1 Calculation of knickpoint propagation

The trapped-charge thermochronology data suggest pulses of incision around ~20 kyr or ~65 kyr ago at the study site (Figs. 3b & c). The evolution of a river profile can be described as (Rosenbloom and Anderson, 1994; Whipple and Tucker, 1999):

[Eq. S.7]

where is a constant reflecting the efficiency of retreat (m1-2*m*/a), is the upstream drainage basin (m2), typically has a value of ~1, whilst has a value of ~0.45-0.50 (Whipple and Tucker, 1999). Note that the second term of the equation describes the advection velocity of an incision pulse along a catchment.

Assuming = 0 and rearranging the *dz* terms, this equation can be simplified to:

[Eq. S.8]

and, assuming that ,

[Eq. S.9]

which is analogous to the basin-wide propagation modelling approach of Crosby and Whipple (2006) and Berlin and Anderson (2007). We applied this approach to evaluate whether sea-level fall during MIS2 (i.e. 20 kyr ago) and MIS4 (i.e. 65 kyr ago) could have caused rapid incision at the location of the Kurobe dam where the most significant knickpoint in the catchment is located, by calculating the required rate of knickpoint propagation.

We test different values of and and select the value that yields an age closest to either 20 ka or 65 ka for the Kurobe dam ~65 km upstream. We allowed to vary between 0.2 and 1.3, and for to vary logarithmically between 10-12 and 10-3 and tested 1000 values following Berlin and Anderson (2007). We then repeated the exercise but fixed at 0.5 in agreement with previous studies (e.g. Whipple and Tucker, 1999; Berlin and Anderson, 2007).

Where the best-fit parameters were calculated, and values of 6.58 x 10-06 m0.32/a and 0.66 for the 20 ka scenario, and 1.87 x 10-09 m1.04/a and 1.02 for the 65 ka scenario, were obtained. These two scenarios equate to rates of knickpoint retreat at the Kurobe dam location of approximately 3.2 m/a and 1.0 m/a respectively (Fig. S.30). Where the value of was fixed at 0.5, a value of 1.52 x 10-04 m/a was calculated for the 20 kyr scenario and of 5.34 x 10-05 m/a for the 65 kyr scenario, yielding retreat rates of approximately 3.0 m/a and 1.0 m/a respectively (Fig. S.30).

Whilst knick-point retreat rates of ~1-3 m/a are high relative to many locations, retreat rates of 2-10 m/a have been calculated following the extreme base level fall of 1500 m during the Messinian Salinity Crisis (Loget and Van Den Driessche, 2009). Rapid rates of knickpoint retreat are anticipated for the Kurobe gorge because of its high channel steepness and sediment transport (e.g. Cook et al., 2012 and discussion in the main text).

**6. Ice equilibrium line altitude modelling**

6.1 Glacier model description

In order to estimate the timing of glacier presence in Kurobe over the last 100 thousand years we apply the ELA model developed by Anderson et al. (2019). The model is designed to evaluate ELA changes in time and is therefore a useful tool for determining when glaciers were present in a landscape. Each year the model finds the elevation at which end of melt-season snow melt is equal to snow accumulation. The principle of uniformitarianism is applied, as the model assumes that modern meteorological and melt parameters are steady in time. Modeled ELA changes in time are therefore based solely on variations in mean annual temperature and precipitation in the past. See Anderson et al (2019) for sensitivity tests and parameter uncertainties.

The model uses gridded temperature and precipitation data as input. To represent the modern annual temperature amplitude and variability in monthly temperature we use the ERA-Interim re-analysis product (Dee et al., 2011). The air temperature lapse rate is estimated using the near surface air temperature and air temperature one pressure level above each ERA-Interim pixel. The snow melt factor that relates positive air temperatures to snow melt is assumed to be 1.36 x 10^-2 [m /C/d] based on Sato et al. (1984).

We estimate the annual precipitation across Japan from 0.05°x 0.05°daily gridded precipitation output provided by the Aphrodite project (Kamiguchi et al., 2010; APHRO\_JP\_V1207; available at: http://aphrodite.st.hirosaki-u.ac.jp/index.html). The mean annual precipitation total in each approximately 5 x 5 km pixel was calculated using python over a 30 year period (1982 to 2011).

We force the ELA model with three different mean annual temperature and annual precipitation forcings based on pollen analyses from lake sediments from Honshu. We assume that the temperature and precipitation changes recorded in the pollen records represent the changes in precipitation and temperature where the model is being run. More specifically, the difference between the modern and past temperature (or the temperature anomaly, Tmodern - Tpast) derived from the pollen record is added to the mean annual temperature at each site of interest as derived from the ERA-interim output to represent past temperature. The factor of precipitation change from the pollen record (relative to the modern precipitation from the pollen record) is calculated and then applied to the precipitation locally estimated based on the modern Aphrodite high-resolution precipitation output.

The pollen records are derived from three lakes:

* The *Lake Mikata* temperature and precipitation forcings are derived from a pollen profile that spans the last 47,000 years (Nakagawa et al., 2002). The best modern analogue method was used to produce the climate reconstructions. These climate reconstructions are similar to the temperature estimates based on nearby stalagmite records (Kigoshi et al., 2014; Uemura et al., 2016; Mori et al., 2018).
* The *Lake Biwa* temperature and precipitation forcings are derived from a pollen profile that spans the last 430,000 years (Tarasov et al., 2011). The modern analogue pollen and climate data were used to create transfer functions that were then applied to the pollen record derived from the Lake Biwa sediments.
* The *Lake Nojiri/ Takano formation* temperature and precipitation forcings span the last 158,000 years (Kigoshi et al., 2017) and are based on pollen composition data in lake sediments.

Because there are no modern ELAs in the area that can be used to tune the snow meltfactor (as done by Anderson et al, 2019) each ELA simulation is made relative to the LGM ELA estimates from Ono et al. (2005) in the Kuranosuke valley of Tateyama, which is ~10 km southwest from the study area.

6.2 Model results

The modelling results indicate that ice was present in the Tateyama region of the Hida Range within the past 100,000 years, which is consistent with the presence of relict cirque basins. In contrast, at Kurobe the model predicts that the ELA was above the maximum elevation of the sample area, showing that Kurobe was ice-free throughout the past 100 ka. (Fig. S.31).

**Table S.1**: Sample names, locations, altitudes and ages. ZHe – zircon (U-Th)/He, this study; ZFT – zircon fission track, Yamada, (1999); ZUPb – U-Pb in zircon, Ito et al. (2013; 2017); IRSL50/100/150/225 – infra-red stimulated luminescence, this study and King et al. (2020); ESR-Ti/Al – electron spin resonance Ti/Al centre, King et al. (2020).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sample code** | **Longitude** | **Latitude** | **Altitude (m)** | **ZHe (Ma)** | | **ZFT (Ma)** | | **ZUPb (Ma)** | | **IRSL50 (Ma)** | | **IRSL100 (Ma)** | | **IRSL150 (Ma)** | | **IRSL225 (Ma)** | | **ESR-Ti (Ma)** | | **ESR-Al (Ma)** | |
| **92910-4** | 137.7625 | 36.6819 | 2615 | 2.2 | ± 0.1 | 2.68 | ± 0.97 | 5.27 | ± 0.15 |  | - |  | - |  | - |  | - |  | - |  | - |
| **92913-3** | 137.7500 | 36.6214 | 2889 | 3.5 | ± 0.4 | 1.90 | ± 0.90 | 1.98 | ± 0.20 |  | - |  | - |  | - |  | - |  | - |  | - |
| **KRG-15** | 137.6409 | 36.6389 | 2065 | 2.5 | ± 1.7 | 2.60 | ± 1.25 | 10.00 | ± 3.40 |  | - |  | - |  | - |  | - |  | - |  | - |
| **KRG-2** | 137.6614 | 36.6523 | 1420 | 0.4 | ± 0.1 | 1.83 | ± 0.52 | 5.50 | ± 0.30 |  | - |  | - |  | - |  | - |  | - |  | - |
| **KRG01** | 137.6750 | 36.6528 | 1140 | 0.4 | ± 0.1 | 0.74 | ± 0.27 | 4.00 | ± 0.10 | 0.107 | ± 0.045 | 0.054 | ± 0.037 | 0.058 | ± 0.033 | 0.062 | ± 0.032 |  | - |  | - |
| **KRG03** | 137.6835 | 36.6517 | 965 | 0.3 | ± 0.2 | 0.77 | ± 0.35 | 0.76 | ± 0.09 | 0.039 | ± 0.006 | 0.016 | ± 0.003 | 0.017 | ± 0.001 | 0.018 | ± 0.003 |  | - |  | - |
| **KRG04** | 137.6835 | 36.6459 | 903 | 0.1 | ± 0.01 | 1.30 | ± 0.61 | 5.50 | ± 0.10 |  | - |  | - |  | - |  | - |  | - |  | - |
| **KRG05\*** | 137.6473 | 36.6349 | 2134 | 1.6 | ± 0.01 | 6.93 | ± 1.13 | 9.50 | ± 0.30 | 0.405 | ± 0.159 | 0.243 | ± 0.223 | 0.237 | ± 0.397 | 0.158 | ± 0.046 | 0.291 | ± 0.013 | 0.175 | ± 0.009 |
| **KRG06\*** | 137.6510 | 36.6402 | 1884 | 1.0 | ± 0.4 | 4.62 | ± 0.67 | 7.80 | ± 0.10 | 0.121 | ± 0.050 | 0.067 | ± 0.019 | 0.045 | ± 0.009 | 0.052 | ± 0.009 | 0.076 | ± 0.007 | 0.074 | ± 0.014 |
| **KRG07** | 137.6544 | 36.6443 | 1695 | 1.2 | ± 0.7 | 4.02 | ± 1.00 | 5.60 | ± 0.10 | 0.112 | ± 0.002 | 0.045 | ± 0.005 | 0.046 | ± 0.008 | 0.052 | ± 0.002 |  | - |  | - |
| **KRG08** | 137.6924 | 36.6407 | 1337 | 0.6 | ± 0.2 | 0.99 | ± 0.39 | 0.76 | ± 0.09 | 0.211 | ± 0.010 | 0.093 | ± 0.009 | 0.060 | ± 0.005 | 0.094 | ± 0.004 |  | - |  | - |
| **KRG10** | 137.6861 | 36.6520 | 795 |  | - |  | - |  | - | 0.015 | ± 0.009 | 0.008 | ± 0.004 | 0.009 | ± 0.004 | 0.020 | ± 0.009 |  | - |  | - |
| **KRG13** | 137.6501 | 36.6378 | 1992 | 1.7 | ± 1.1 | 5.36 | ± 0.82 | 9.10 | ± 0.20 | 0.177 | ± 0.232 | 0.133 | ± 0.054 | 0.141 | ± 0.026 | 0.151 | ± 0.030 |  | - |  | - |
| **KRG100** | 137.7596 | 36.6852 | 2632 |  | - |  | - |  | - | 0.144 | ± 0.050 | 0.052 | ± 0.007 | 0.104 | ± 0.134 | 0.075 | ± 0.025 |  | - |  | - |
| **KRG101\*** | 137.6624 | 36.6469 | 1605 |  | - |  | - |  | - | 0.218 | ± 0.058 | 0.072 | ± 0.008 | 0.062 | ± 0.004 | 0.051 | ± 0.003 | 0.037 | ± 0.002 | 0.036 | ± 0.003 |
| **KRG102** | 137.6693 | 36.6492 | 1438 |  | - |  | - |  | - | 0.076 | ± 0.003 | 0.046 | ± 0.008 | 0.060 | ± 0.009 | 0.074 | ± 0.011 |  | - |  | - |
| **KRG103** | 137.6724 | 36.6491 | 1326 |  | - |  | - |  | - | 0.077 | ± 0.010 | 0.058 | ± 0.012 | 0.056 | ± 0.008 | 0.053 | ± 0.006 |  | - |  | - |
| **KRG104\*** | 137.6750 | 36.6484 | 1194 |  | - |  | - |  | - | 0.080 | ± 0.030 | 0.058 | ± 0.040 | 0.057 | ± 0.032 | 0.063 | ± 0.033 | 0.076 | ± 0.004 | 0.069 | ± 0.004 |
| **KRG111\*** | 137.6820 | 36.6510 | 914 |  | - |  | - |  | - | 0.001 | ± 0.000 | 0.001 | ± 0.000 | 0.001 | ± 0.000 | 0.001 | ± 0.001 | 0.005 | ± 0.011 | 0.168 | ± 0.251 |
| **KRG112\*** | 137.6795 | 36.6525 | 914 |  | - |  | - |  | - | 0.000 | ± 0.000 | 0.000 | ± 0.000 | 0.000 | ± 0.000 | 0.000 | ± 0.000 |  | - |  | - |
| **KRG113** | 137.0000 | 36.0000 | 914 |  | - |  | - |  | - | 0.000 | ± 0.000 | 0.000 | ± 0.000 | 0.000 | ± 0.000 | 0.000 | ± 0.000 |  | - |  | - |
| **KRG115** | 137.6817 | 36.6548 | 979 |  | - |  | - |  | - | 0.029 | ± 0.003 | 0.020 | ± 0.002 | 0.022 | ± 0.002 | 0.021 | ± 0.003 |  | - |  | - |

\*IRSL and ESR measurements reported in King et al. (2020).

**Table S.2**: Radioisotope concentrations and calculated total feldspar environmental dose rate (. See text for calculation details.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **U (ppm)** | **Th (ppm)** | **K (%)** | **Rb (ppm)** | **Grain size range** | **(Gy/ka)** |
| **KRG01** | 2.50 ± 0.03 | 13.20 ± 0.53 | 3.15 ± 0.03 | 139 ± 1.39 | 180-720 | 6.18 ± 1.048 |
| **KRG03** | 2.40 ± 0.02 | 11.60 ± 0.46 | 3.15 ± 0.03 | 122 ± 1.22 | 180-1000 | 6.36 ± 1.528 |
| **KRG05** | 6.70 ± 0.07 | 19.90 ± 0.80 | 4.06 ± 0.04 | 174 ± 1.74 | 180-750 | 8.53 ± 1.137 |
| **KRG06** | 3.10 ± 0.03 | 9.40 ± 0.38 | 3.13 ± 0.03 | 108 ± 1.08 | 750-1000 | 7.02 ± 0.453 |
| **KRG07** | 3.40 ± 0.03 | 12.70 ± 0.51 | 2.92 ± 0.03 | 105 ± 1.05 | 180-1000 | 6.48 ± 1.526 |
| **KRG08** | 2.40 ± 0.02 | 11.40 ± 0.46 | 3.00 ± 0.03 | 115 ± 1.15 | 180-1000 | 6.22 ± 1.524 |
| **KRG10** | 2.80 ± 0.03 | 11.70 ± 0.47 | 3.16 ± 0.03 | 114 ± 1.14 | 180-700 | 6.12 ± 1.012 |
| **KRG13** | 4.10 ± 0.04 | 14.90 ± 0.60 | 3.10 ± 0.03 | 135 ± 1.35 | 180-400 | 6.27 ± 0.45 |
| **KRG100** | 6.20 ± 0.06 | 24.50 ± 0.98 | 3.71 ± 0.04 | 134 ± 1.34 | 180-900 | 8.57 ± 1.39 |
| **KRG101** | 3.10 ± 0.03 | 14.00 ± 0.56 | 2.86 ± 0.03 | 106 ± 1.06 | 250-1000 | 6.51 ± 1.383 |
| **KRG102** | 2.60 ± 0.03 | 11.30 ± 0.46 | 3.27 ± 0.03 | 140 ± 1.40 | 180-600 | 6.02 ± 0.829 |
| **KRG103** | 2.50 ± 0.03 | 11.80 ± 0.47 | 3.38 ± 0.03 | 135 ± 1.35 | 180-400 | 5.90 ± 0.449 |
| **KRG104** | 3.10 ± 0.03 | 12.30 ± 0.49 | 3.21 ± 0.03 | 131 ± 1.31 | 180-600 | 6.16 ± 0.829 |
| **KRG111** | 3.30 ± 0.03 | 13.90 ± 0.56 | 3.43 ± 0.03 | 135 ± 1.35 | 180-1000 | 6.98 ± 1.538 |
| **KRG112** | 4.10 ± 0.04 | 13.20 ± 0.53 | 3.36 ± 0.03 | 165 ± 1.65 | 180-1000 | 7.06 ± 1.537 |
| **KRG113** | 5.60 ± 0.06 | 13.30 ± 0.53 | 3.07 ± 0.03 | 152 ± 1.52 | 180-1000 | 7.18 ± 1.532 |
| **KRG115** | 2.60 ± 0.03 | 11.00 ± 0.44 | 3.10 ± 0.03 | 120 ± 1.20 | 180-760 | 6.04 ± 1.118 |

Table S.3: Kinetic parameters and ages for luminescence samples analysed in this study and King et al. (2020).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Signal** | **Et (eV)** | **Eu (eV)** | **log10(s) (s-1)** | **log10(*ρ*)** | **g2days (%/decade)** | **D0 (Gy)** | **Age (ka)** | **+∂(Age)** | **-∂(Age)** |
| **KRG01** | 50 | 1.32 ± 0.02 | 0.08 ± 0.01 | 9.04 ± 0.21 | -5.12 ± 0.02 | 9.86 ± 0.48 | 803 ± 35 | 107.15 | 20.46 | 24.85 |
|  | 100 | 1.37 ± 0.02 | 0.09 ± 0.01 | 8.92 ± 0.20 | -5.49 ± 0.10 | 4.38 ± 1.02 | 704 ± 29 | 53.78 | 16.90 | 20.02 |
|  | 150 | 1.36 ± 0.03 | 0.08 ± 0.01 | 8.55 ± 0.26 | -5.56 ± 0.11 | 3.85 ± 1.00 | 779 ± 31 | 57.78 | 15.20 | 17.39 |
|  | 225 | 1.35 ± 0.04 | 0.12 ± 0.01 | 7.73 ± 0.32 | -5.67 ± 0.13 | 3.06 ± 0.94 | 708 ± 30 | 62.02 | 14.98 | 17.31 |
| **KRG03** | 50 | 1.35 ± 0.02 | 0.08 ± 0.00 | 9.30 ± 0.16 | -5.15 ± 0.01 | 9.08 ± 0.30 | 886 ± 46 | 38.95 | 2.83 | 2.89 |
|  | 100 | 1.35 ± 0.02 | 0.09 ± 0.00 | 8.63 ± 0.18 | -5.60 ± 0.07 | 3.37 ± 0.52 | 950 ± 38 | 15.80 | 1.54 | 1.55 |
|  | 150 | 1.32 ± 0.03 | 0.09 ± 0.01 | 7.91 ± 0.26 | -5.73 ± 0.11 | 2.52 ± 0.67 | 991 ± 39 | 16.54 | 0.65 | 0.65 |
|  | 225 | 1.21 ± 0.04 | 0.13 ± 0.01 | 6.35 ± 0.33 | -5.94 ± 0.17 | 1.60 ± 0.62 | 710 ± 29 | 17.61 | 1.58 | 1.60 |
| **KRG05** | 50 | 1.33 ± 0.02 | 0.07 ± 0.01 | 9.31 ± 0.21 | -5.27 ± 0.08 | 6.96 ± 1.24 | 848 ± 29 | 404.62 | 251.75 | -93.11 |
|  | 100 | 1.38 ± 0.03 | 0.07 ± 0.01 | 9.09 ± 0.24 | -5.45 ± 0.06 | 4.95 ± 0.65 | 817 ± 20 | 243.05 | 116.42 | 106.60 |
|  | 150 | 1.32 ± 0.04 | 0.09 ± 0.01 | 8.02 ± 0.34 | -5.73 ± 0.10 | 2.75 ± 0.65 | 837 ± 21 | 236.51 | 70.10 | 326.66 |
|  | 225 | 1.34 ± 0.05 | 0.13 ± 0.01 | 7.53 ± 0.43 | -5.98 ± 0.06 | 1.54 ± 0.23 | 701 ± 21 | 157.96 | 19.67 | 26.03 |
| **KRG06** | 50 | 1.36 ± 0.03 | 0.06 ± 0.01 | 9.57 ± 0.25 | -5.04 ± 0.04 | 11.07 ± 0.82 | 829 ± 39 | 121.37 | 21.99 | 28.00 |
|  | 100 | 1.41 ± 0.03 | 0.07 ± 0.01 | 9.41 ± 0.28 | -5.18 ± 0.05 | 9.14 ± 0.85 | 1002 ± 39 | 67.40 | 9.24 | 9.96 |
|  | 150 | 1.35 ± 0.04 | 0.08 ± 0.01 | 8.28 ± 0.37 | -5.45 ± 0.05 | 5.14 ± 0.54 | 980 ± 36 | 44.75 | 4.22 | 4.36 |
|  | 225 | 1.41 ± 0.06 | 0.13 ± 0.01 | 8.12 ± 0.47 | -5.54 ± 0.04 | 4.36 ± 0.44 | 791 ± 32 | 52.31 | 4.20 | 4.37 |
| **KRG07** | 50 | 1.34 ± 0.02 | 0.07 ± 0.00 | 9.30 ± 0.18 | -5.13 ± 0.02 | 9.71 ± 0.38 | 825 ± 44 | 112.44 | 0.97 | 0.98 |
|  | 100 | 1.33 ± 0.02 | 0.09 ± 0.00 | 8.62 ± 0.18 | -5.50 ± 0.05 | 4.36 ± 0.49 | 916 ± 36 | 44.97 | 2.72 | 2.78 |
|  | 150 | 1.34 ± 0.03 | 0.09 ± 0.01 | 8.22 ± 0.24 | -5.69 ± 0.08 | 2.82 ± 0.51 | 956 ± 38 | 46.46 | 3.89 | 3.99 |
|  | 225 | 1.35 ± 0.04 | 0.12 ± 0.01 | 7.67 ± 0.33 | -5.88 ± 0.12 | 1.88 ± 0.53 | 741 ± 34 | 51.69 | 1.05 | 1.06 |
| **KRG08** | 50 | 1.46 ± 0.02 | 0.07 ± 0.00 | 10.58 ± 0.15 | -5.19 ± 0.04 | 8.38 ± 0.74 | 641 ± 35 | 211.38 | 5.09 | 5.38 |
|  | 100 | 1.58 ± 0.04 | 0.09 ± 0.01 | 10.88 ± 0.30 | -5.39 ± 0.09 | 5.49 ± 1.09 | 813 ± 39 | 92.62 | 4.41 | 4.57 |
|  | 150 | 1.58 ± 0.07 | 0.13 ± 0.01 | 10.21 ± 0.59 | -5.85 ± 0.28 | 1.93 ± 1.22 | 846 ± 39 | 60.39 | 2.32 | 2.36 |
|  | 225 | 1.36 ± 0.12 | 0.15 ± 0.02 | 7.48 ± 1.02 | -5.58 ± 0.16 | 3.64 ± 1.35 | 707 ± 32 | 93.88 | 1.92 | 1.96 |
| **KRG10** | 50 | 1.36 ± 0.02 | 0.08 ± 0.01 | 9.43 ± 0.21 | -5.02 ± 0.02 | 12.21 ± 0.59 | 937 ± 38 | 15.18 | 4.51 | 4.66 |
|  | 100 | 1.35 ± 0.04 | 0.06 ± 0.01 | 8.90 ± 0.38 | -5.29 ± 0.06 | 6.89 ± 0.99 | 1039 ± 31 | 8.45 | 2.11 | 2.14 |
|  | 150 | 1.27 ± 0.03 | 0.08 ± 0.01 | 7.61 ± 0.52 | -5.77 ± 0.22 | 2.42 ± 1.24 | 1044 ± 36 | 9.11 | 2.21 | 2.24 |
|  | 225 | 1.17 ± 0.08 | 0.13 ± 0.01 | 5.88 ± 0.69 | -5.48 ± 0.15 | 4.87 ± 1.68 | 831 ± 35 | 19.82 | 4.55 | 4.72 |
| **KRG13** | 50 | 1.31 ± 0.02 | 0.07 ± 0.01 | 9.24 ± 0.21 | -5.23 ± 0.03 | 7.74 ± 0.48 | 805 ± 24 | 177.26 | 66.27 | 165.46 |
|  | 100 | 1.36 ± 0.02 | 0.08 ± 0.00 | 9.15 ± 0.19 | -5.65 ± 0.06 | 3.10 ± 0.45 | 807 ± 21 | 132.61 | 23.96 | 29.69 |
|  | 150 | 1.38 ± 0.03 | 0.09 ± 0.01 | 8.78 ± 0.25 | -5.88 ± 0.16 | 1.87 ± 0.69 | 912 ± 30 | 141.12 | 12.59 | 13.81 |
|  | 225 | 1.37 ± 0.04 | 0.12 ± 0.01 | 7.98 ± 0.34 | -6.02 ± 0.20 | 1.37 ± 0.61 | 776 ± 28 | 150.67 | 13.98 | 15.79 |
| **KRG100** | 50 | 1.37 ± 0.02 | 0.07 ± 0.00 | 9.45 ± 0.18 | -5.80 ± 0.06 | 2.24 ± 0.31 | 309 ± 8 | 144.46 | 74.71 | -24.93 |
|  | 100 | 1.39 ± 0.02 | 0.07 ± 0.00 | 9.33 ± 0.18 | -7.00 ± 2.95 | 0.07 ± 0.43 | 279 ± 7 | 51.66 | 3.43 | 3.83 |
|  | 150 | 1.43 ± 0.02 | 0.07 ± 0.00 | 9.34 ± 0.20 | -6.14 ± 0.26 | 1.00 ± 0.60 | 330 ± 10 | 103.81 | 25.32 | 108.28 |
|  | 225 | 1.47 ± 0.04 | 0.09 ± 0.01 | 9.03 ± 0.35 | -7.00 ± 5.45 | 0.05 ± 0.50 | 318 ± 11 | 75.29 | 10.53 | 14.76 |
| **KRG101** | 50 | 1.52 ± 0.03 | 0.07 ± 0.00 | 11.06 ± 0.24 | -5.05 ± 0.04 | 11.01 ± 0.81 | 910 ± 46 | 217.99 | 25.78 | 32.72 |
|  | 100 | 1.39 ± 0.03 | 0.08 ± 0.01 | 9.29 ± 0.27 | -5.33 ± 0.03 | 6.46 ± 0.50 | 1029 ± 44 | 71.51 | 3.88 | 3.98 |
|  | 150 | 1.40 ± 0.03 | 0.08 ± 0.01 | 8.77 ± 0.25 | -5.49 ± 0.05 | 4.64 ± 0.55 | 1105 ± 45 | 61.60 | 1.90 | 1.92 |
|  | 225 | 1.29 ± 0.04 | 0.12 ± 0.01 | 7.14 ± 0.36 | -5.77 ± 0.07 | 2.69 ± 0.39 | 892 ± 37 | 50.73 | 1.36 | 1.37 |
| **KRG102** | 50 | 1.30 ± 0.02 | 0.07 ± 0.01 | 8.91 ± 0.22 | -5.20 ± 0.02 | 8.27 ± 0.33 | 686 ± 23 | 76.43 | 1.35 | 1.36 |
|  | 100 | 1.34 ± 0.03 | 0.07 ± 0.01 | 8.81 ± 0.29 | -5.77 ± 0.17 | 2.41 ± 0.93 | 779 ± 28 | 45.65 | 3.77 | 3.88 |
|  | 150 | 1.39 ± 0.04 | 0.07 ± 0.01 | 8.89 ± 0.35 | -5.76 ± 0.10 | 2.38 ± 0.55 | 888 ± 32 | 60.04 | 4.27 | 4.40 |
|  | 225 | 1.50 ± 0.07 | 0.11 ± 0.01 | 9.09 ± 0.60 | -5.76 ± 0.15 | 2.46 ± 0.84 | 754 ± 34 | 73.84 | 5.57 | 5.84 |
| **KRG103** | 50 | 1.35 ± 0.02 | 0.08 ± 0.00 | 9.22 ± 0.18 | -5.24 ± 0.02 | 7.52 ± 0.28 | 749 ± 27 | 77.50 | 5.10 | 5.33 |
|  | 100 | 1.43 ± 0.04 | 0.07 ± 0.01 | 9.48 ± 0.31 | -5.62 ± 0.08 | 3.31 ± 0.59 | 790 ± 29 | 57.91 | 5.74 | 6.01 |
|  | 150 | 1.49 ± 0.06 | 0.08 ± 0.01 | 9.53 ± 0.48 | -5.86 ± 0.12 | 1.92 ± 0.55 | 836 ± 33 | 56.47 | 3.74 | 3.84 |
|  | 225 | 1.51 ± 0.08 | 0.12 ± 0.01 | 8.91 ± 0.66 | -7.00 ± 1.10 | 0.35 ± 0.85 | 692 ± 29 | 52.63 | 2.97 | 3.05 |
| **KRG104** | 50 | 1.33 ± 0.03 | 0.08 ± 0.01 | 9.14 ± 0.22 | -5.19 ± 0.01 | 8.28 ± 0.22 | 784 ± 34 | 80.15 | 13.84 | 15.72 |
|  | 100 | 1.37 ± 0.02 | 0.09 ± 0.01 | 8.88 ± 0.21 | -5.45 ± 0.03 | 4.91 ± 0.33 | 709 ± 29 | 57.57 | 18.31 | 22.00 |
|  | 150 | 1.41 ± 0.03 | 0.09 ± 0.01 | 8.93 ± 0.27 | -5.57 ± 0.04 | 3.89 ± 0.41 | 777 ± 31 | 56.76 | 14.88 | 16.97 |
|  | 225 | 1.39 ± 0.04 | 0.13 ± 0.01 | 8.12 ± 034 | -5.65 ± 0.07 | 3.26 ± 0.48 | 709 ± 31 | 63.32 | 15.35 | 17.81 |
| **KRG111** | 50 | 1.38 ± 0.02 | 0.08 ± 0.01 | 9.47 ± 0.19 | -5.29 ± 0.02 | 6.71 ± 0.38 | 615 ± 32 | 0.64 | 0.06 | 0.06 |
|  | 100 | 1.30 ± 0.04 | 0.09 ± 0.01 | 8.12 ± 0.33 | -5.63 ± 0.14 | 3.32 ± 1.04 | 871 ± 43 | 0.99 | 0.04 | 0.04 |
|  | 150 | 1.32 ± 0.07 | 0.09 ± 0.01 | 7.85 ± 0.56 | -5.81 ± 0.22 | 2.28 ± 1.15 | 932 ± 39 | 1.16 | 0.18 | 0.18 |
|  | 225 | 1.22 ± 0.06 | 0.12 ± 0.01 | 6.46 ± 0.52 | -5.86 ± 0.17 | 1.93 ± 0.77 | 748 ± 33 | 1.39 | 0.32 | 0.32 |
| **KRG112** | 50 | 1.38 ± 0.02 | 0.08 ± 0.00 | 9.58 ± 0.18 | -5.32 ± 0.01 | 6.13 ± 0.21 | 572 ± 31 | 0.27 | 0.02 | 0.02 |
|  | 100 | 1.38 ± 0.02 | 0.09 ± 0.01 | 9.03 ± 0.21 | -5.62 ± 0.10 | 3.21 ± 0.71 | 807 ± 37 | 0.32 | 0.08 | 0.08 |
|  | 150 | 1.40 ± 0.04 | 0.10 ± 0.01 | 8.71 ± 0.31 | -5.92 ± 0.32 | 1.61 ± 1.18 | 847 ± 32 | 0.36 | 0.12 | 0.12 |
|  | 225 | 1.34 ± 0.05 | 0.12 ± 0.01 | 7.52 ± 0.40 | -6.04 ± 0.24 | 1.28 ± 0.70 | 768 ± 35 | 0.44 | 0.08 | 0.08 |
| **KRG113** | 50 | 1.35 ± 0.02 | 0.08 ± 0.00 | 9.32 ± 0.16 | -5.11 ± 0.02 | 10.06 ± 0.58 | 863 ± 40 | 0.28 | 0.03 | 0.03 |
|  | 100 | 1.34 ± 0.02 | 0.08 ± 0.00 | 8.63 ± 0.18 | -5.41 ± 0.05 | 5.26 ± 0.62 | 976 ± 37 | 0.16 | 0.04 | 0.04 |
|  | 150 | 1.37 ± 0.03 | 0.09 ± 0.01 | 8.31 ± 0.28 | -5.58 ± 0.07 | 3.58 ± 0.55 | 977 ± 38 | 0.10 | 0.04 | 0.04 |
|  | 225 | 1.30 ± 0.04 | 0.12 ± 0.01 | 7.06 ± 0.36 | -5.72 ± 0.12 | 2.67 ± 0.73 | 765 ± 29 | 0.50 | 0.02 | 0.02 |
| **KRG115** | 50 | 1.32 ± 0.02 | 0.08 ± 0.00 | 9.12 ± 0.15 | -5.22 ± 0.02 | 7.81 ± 0.28 | 772 ± 34 | 29.49 | 1.42 | 1.44 |
|  | 100 | 1.34 ± 0.02 | 0.09 ± 0.00 | 8.50 ± 0.19 | -5.59 ± 0.04 | 3.48 ± 0.35 | 985 ± 36 | 19.75 | 1.02 | 1.03 |
|  | 150 | 1.40 ± 0.04 | 0.10 ± 0.01 | 8.41 ± 0.31 | -5.65 ± 0.06 | 3.05 ± 0.42 | 1011 ± 33 | 21.51 | 0.84 | 0.84 |
|  | 225 | 1.28 ± 0.04 | 0.14 ± 0.01 | 6.79 ± 0.36 | -5.83 ± 0.07 | 2.02 ± 0.35 | 754 ± 28 | 21.37 | 1.28 | 1.29 |

Table S.4: Zircon (U-Th)/He data

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sample** | **FT** | **Rs** (mg) | **Weight** (mg) | **He** (mol) | **± s** | **U** (ng) | **Th** (ng) | **He** (pmol/g) | **± s** | **U** (ppm) | **Th** (ppm) | **eU** | **Th/U** | **Unc.**  **Age** (Ma) | **Corr**  **Age** (Ma) | **± s** | **Mean**  **Age** (Ma) | **σ** |
| *KRG-1-A* | *0.76* | *43* | *3.4* | *1.5E-14* | *1.5E-16* | *1.3* | *1.1* | *4568* | *46* | *382* | *339* | *463* | *0.9* | *1.8* | *2.4* | *0.24* |  |  |
| KRG-1-B | 0.74 | 38 | 2.1 | 3.4E-15 | 3.4E-17 | 1.6 | 0.5 | 1593 | 16 | 778 | 232 | 834 | 0.3 | 0.4 | 0.5 | 0.05 |  |  |
| KRG-1-C | 0.79 | 48 | 4.1 | 3.3E-15 | 3.3E-17 | 2.7 | 0.4 | 815 | 8 | 662 | 91 | 684 | 0.1 | 0.2 | 0.3 | 0.03 |  |  |
| KRG-1-D | 0.77 | 46 | 4.4 | 2.3E-14 | 2.3E-16 | 11.0 | 3.0 | 5306 | 53 | 2479 | 676 | 2642 | 0.3 | 0.4 | 0.5 | 0.05 |  |  |
| KRG-1-F | 0.82 | 65 | 5.6 | 2.3E-15 | 2.3E-17 | 1.5 | 0.9 | 420 | 4 | 277 | 152 | 314 | 0.6 | 0.2 | 0.3 | 0.03 |  |  |
| KRG-1-H | 0.74 | 44 | 2.9 | 3.2E-15 | 3.2E-17 | 1.5 | 0.8 | 1135 | 11 | 518 | 264 | 581 | 0.5 | 0.4 | 0.5 | 0.05 |  |  |
| KRG-1-I | 0.80 | 57 | 7.4 | 3.6E-15 | 3.6E-17 | 3.1 | 1.0 | 492 | 5 | 423 | 131 | 455 | 0.3 | 0.2 | 0.3 | 0.03 | 0.4 | 0.1 |
| KRG-2-A | 0.84 | 73 | 12.2 | 1.4E-14 | 1.4E-16 | 7.2 | 3.1 | 1149 | 11 | 588 | 251 | 649 | 0.4 | 0.3 | 0.4 | 0.04 |  |  |
| KRG-2-B | 0.89 | 92 | 26.5 | 2.3E-14 | 2.3E-16 | 10.7 | 4.9 | 856 | 9 | 402 | 185 | 446 | 0.5 | 0.4 | 0.4 | 0.04 |  |  |
| KRG-2-C | 0.80 | 58 | 5.5 | 5.5E-15 | 5.5E-17 | 5.1 | 1.4 | 995 | 10 | 923 | 252 | 983 | 0.3 | 0.2 | 0.2 | 0.02 |  |  |
| *KRG-2-D* | *0.84* | *72* | *11.0* | *1.7E-14* | *1.7E-16* | *2.6* | *1.3* | *1559* | *16* | *238* | *119* | *267* | *0.5* | *1.1* | *1.3* | *0.13* |  |  |
| KRG-2-E | 0.83 | 67 | 9.6 | 3.0E-15 | 3.0E-17 | 2.0 | 1.0 | 308 | 3 | 209 | 100 | 233 | 0.5 | 0.2 | 0.3 | 0.03 |  |  |
| KRG-2-F | 0.81 | 62 | 7.6 | 2.0E-15 | 2.0E-17 | 1.4 | 0.8 | 270 | 3 | 185 | 100 | 209 | 0.5 | 0.2 | 0.3 | 0.03 |  |  |
| KRG-2-I | 0.80 | 57 | 5.1 | 3.5E-15 | 3.5E-17 | 1.7 | 0.9 | 692 | 7 | 343 | 168 | 383 | 0.5 | 0.3 | 0.5 | 0.05 | 0.4 | 0.1 |
| KRG-3-B$ | 0.83 | 66 | 8.7 | 2.4E-15 | 2.4E-17 | 4.2 | 2.3 | 279 | 3 | 483 | 265 | 546 | 0.5 | 0.1 | 0.1 | 0.01 |  |  |
| KRG-3-C$ | 0.83 | 63 | 11.5 | 2.1E-15 | 2.1E-17 | 4.5 | 2.7 | 187 | 2 | 393 | 231 | 449 | 0.6 | 0.1 | 0.1 | 0.01 |  |  |
| KRG-3-D$ | 0.82 | 63 | 9.1 | 7.5E-15 | 7.5E-17 | 5.5 | 2.8 | 824 | 8 | 607 | 307 | 681 | 0.5 | 0.2 | 0.3 | 0.03 |  |  |
| KRG-3-E$ | 0.80 | 58 | 7.3 | 2.0E-15 | 2.0E-17 | 2.2 | 1.3 | 282 | 3 | 297 | 174 | 338 | 0.6 | 0.2 | 0.2 | 0.02 |  |  |
| KRG-3-F$ | 0.79 | 55 | 5.3 | 3.4E-15 | 3.4E-17 | 2.4 | 1.3 | 639 | 6 | 451 | 240 | 508 | 0.5 | 0.3 | 0.3 | 0.03 |  |  |
| KRG-3-G$ | 0.82 | 62 | 5.8 | 2.3E-15 | 2.3E-17 | 0.9 | 0.7 | 390 | 4 | 162 | 119 | 191 | 0.7 | 0.4 | 0.6 | 0.05 | 0.3 | 0.2 |
| KRG-4-2 | 0.82 | 63 | 8.1 | 2.2E-15 | 2.2E-17 | 2.0 | 1.6 | 272 | 3 | 246 | 205 | 295 | 0.8 | 0.2 | 0.2 | 0.02 |  |  |
| KRG-4-3 | 0.77 | 50 | 3.7 | 5.1E-16 | 5.1E-18 | 1.6 | 1.0 | 136 | 1 | 436 | 256 | 498 | 0.6 | 0.1 | 0.1 | 0.01 | 0.1 | 0.1 |
| KRG-5-A | 0.80 | 49 | 4.3 | 1.2E-13 | 1.2E-15 | 15.1 | 9.9 | 27847 | 278 | 3534 | 2335 | 4095 | 0.7 | 1.3 | 1.6 | 0.16 |  |  |
| KRG-5-B | 0.83 | 57 | 6.1 | 2.8E-14 | 2.8E-16 | 5.2 | 2.9 | 4524 | 45 | 857 | 477 | 972 | 0.6 | 0.9 | 1.0 | 0.10 |  |  |
| *KRG-5-C* | *0.80* | *47* | *3.4* | *2.7E-13* | *2.7E-15* | *14.9* | *8.0* | 78479 | 785 | *4358* | *2340* | *4919* | *0.5* | *3.0* | *3.7* | *0.37* |  |  |
| KRG-5-E\* | 0.76 | 52 | 3.1 | 2.0E-14 | 9.1E-17 | 3.2 | 1.4 | 6491 | 100 | 1046 | 461 | 1157 | 0.5 | 1.0 | 1.4 | 0.02 |  |  |
| KRG-5-F\* | 0.78 | 55 | 5.0 | 7.8E-14 | 1.3E-16 | 7.7 | 3.3 | 15704 | 234 | 3240 | 669 | 3401 | 0.4 | 1.7 | 2.2 | 0.03 |  |  |
| KRG-5-G\* | 0.78 | 57 | 6.5 | 1.7E-13 | 5.3E-16 | 21.1 | 9.8 | 26411 | 412 | 3240 | 1496 | 3599 | 0.5 | 1.4 | 1.7 | 0.02 |  |  |
| KRG-5-H\* | 0.77 | 52 | 4.3 | 6.8E-14 | 2.3E-16 | 9.3 | 3.8 | 15851 | 236 | 2180 | 883 | 2392 | 0.4 | 1.2 | 1.6 | 0.02 | 1.6 | 0.4 |
| KRG-6-1 | 0.76 | 46 | 2.8 | 8.1E-15 | 8.1E-17 | 2.9 | 3.8 | 2927 | 29 | 1031 | 1381 | 1362 | 1.3 | 0.4 | 0.5 | 0.05 |  |  |
| KRG-6-A | 0.85 | 59 | 8.1 | 1.6E-14 | 1.6E-16 | 2.9 | 1.1 | 2022 | 20 | 354 | 130 | 385 | 0.4 | 1.0 | 1.1 | 0.11 |  |  |
| KRG-6-C | 0.85 | 63 | 8.3 | 2.8E-14 | 2.8E-16 | 7.4 | 2.5 | 3447 | 34 | 899 | 308 | 973 | 0.3 | 0.7 | 0.8 | 0.08 |  |  |
| KRG-6-D | 0.87 | 67 | 12.4 | 5.5E-14 | 5.5E-16 | 7.0 | 1.4 | 4463 | 45 | 568 | 112 | 595 | 0.2 | 1.4 | 1.6 | 0.16 |  |  |
| KRG-6-E | 0.85 | 77 | 15.5 | 5.4E-14 | 5.4E-16 | 13.3 | 5.3 | 3452 | 35 | 855 | 343 | 937 | 0.4 | 0.7 | 0.8 | 0.08 | 1.0 | 0.4 |
| KRG-7-A | 0.84 | 72 | 10.7 | 2.8E-14 | 2.8E-16 | 2.7 | 2.0 | 2622 | 26 | 256 | 189 | 302 | 0.7 | 1.6 | 1.9 | 0.19 |  |  |
| KRG-7-B | 0.80 | 59 | 5.7 | 3.0E-14 | 3.0E-16 | 9.8 | 5.1 | 5281 | 53 | 1722 | 901 | 1938 | 0.5 | 0.5 | 0.6 | 0.06 |  |  |
| KRG-7-C | 0.81 | 60 | 6.3 | 9.6E-15 | 9.6E-17 | 1.8 | 0.8 | 1529 | 15 | 281 | 128 | 312 | 0.5 | 0.9 | 1.1 | 0.11 | 1.2 | 0.7 |
| KRG-8-1$ | 0.83 | 68 | 7.5 | 6.8E-15 | 6.8E-17 | 3.2 | 2.6 | 902 | 9 | 432 | 347 | 516 | 0.8 | 0.3 | 0.4 | 0.04 |  |  |
| KRG-8-2$ | 0.74 | 44 | 2.8 | 3.2E-15 | 3.2E-17 | 0.8 | 0.8 | 1175 | 12 | 278 | 291 | 347 | 1.0 | 0.7 | 0.9 | 0.09 |  |  |
| KRG-8-3$ | 0.81 | 58 | 8.4 | 5.0E-15 | 5.0E-17 | 1.3 | 0.9 | 601 | 6 | 157 | 108 | 182 | 0.7 | 0.6 | 0.8 | 0.08 |  |  |
| KRG-8-4$ | 0.81 | 60 | 8.6 | 5.5E-15 | 5.5E-17 | 1.7 | 1.3 | 642 | 6 | 194 | 153 | 231 | 0.8 | 0.5 | 0.7 | 0.07 |  |  |
| KRG-8-A$ | 0.83 | 68 | 10.9 | 2.1E-14 | 2.1E-16 | 8.6 | 4.1 | 1953 | 20 | 792 | 372 | 881 | 0.5 | 0.4 | 0.5 | 0.05 |  |  |
| KRG-8-B$ | 0.86 | 70 | 15.9 | 1.7E-14 | 1.7E-16 | 5.7 | 3.1 | 1085 | 11 | 361 | 198 | 408 | 0.5 | 0.5 | 0.6 | 0.06 |  |  |
| KRG-8-C$ | 0.83 | 63 | 10.4 | 1.5E-14 | 1.5E-16 | 4.6 | 2.6 | 1447 | 14 | 438 | 253 | 499 | 0.6 | 0.6 | 0.7 | 0.07 |  |  |
| KRG-8-D$ | 0.82 | 66 | 9.8 | 8.8E-15 | 8.8E-17 | 4.9 | 2.1 | 890 | 9 | 497 | 211 | 548 | 0.4 | 0.3 | 0.4 | 0.04 | 0.6 | 0.2 |
| KRG-13-A | 0.83 | 61 | 9.6 | 4.1E-14 | 4.1E-16 | 6.6 | 3.0 | 4285 | 43 | 685 | 307 | 758 | 0.4 | 1.0 | 1.3 | 0.13 |  |  |
| KRG-13-B | 0.83 | 63 | 10.5 | 1.2E-13 | 1.2E-15 | 12.7 | 5.5 | 11023 | 110 | 1211 | 530 | 1339 | 0.4 | 1.5 | 1.8 | 0.18 |  |  |
| KRG-13-C | 0.80 | 52 | 5.1 | 6.7E-14 | 6.7E-16 | 12.6 | 6.8 | 13137 | 131 | 2484 | 1345 | 2807 | 0.5 | 0.9 | 1.1 | 0.11 |  |  |
| KRG-13-D | 0.77 | 44 | 3.8 | 3.4E-14 | 3.4E-16 | 3.4 | 1.0 | 8962 | 90 | 903 | 275 | 969 | 0.3 | 1.7 | 2.2 | 0.22 |  |  |
| KRG-13-G | 0.79 | 53 | 3.0 | 8.6E-15 | 8.6E-17 | 6.5 | 3.5 | 2849 | 28 | 2141 | 1171 | 2422 | 0.5 | 0.2 | 0.3 | 0.03 |  |  |
| KRG-13-H | 0.76 | 48 | 4.9 | 2.8E-14 | 2.8E-16 | 1.9 | 1.0 | 5715 | 57 | 383 | 202 | 432 | 0.5 | 2.5 | 3.6 | 0.35 | 1.7 | 1.1 |
| KRG-15-A | 0.86 | 73 | 15.3 | 1.7E-13 | 1.7E-15 | 9.2 | 2.6 | 10904 | 109 | 603 | 170 | 643 | 0.3 | 3.1 | 3.7 | 0.37 |  |  |
| KRG-15-B | 0.84 | 58 | 8.2 | 3.2E-14 | 3.2E-16 | 5.1 | 1.4 | 3932 | 39 | 613 | 169 | 654 | 0.3 | 1.1 | 1.3 | 0.13 | 2.5 | 1.7 |
| 92910-4B | 0.80 | 57 | 5.4 | 3.8E-14 | 3.8E-16 | 3.8 | 1.6 | 7049 | 70 | 698 | 302 | 770 | 0.4 | 1.7 | 2.1 | 0.21 |  |  |
| 92910-4C | 0.82 | 49 | 4.8 | 8.5E-15 | 8.5E-17 | 0.4 | 0.2 | 1777 | 18 | 87 | 45 | 98 | 0.5 | 3.4 | 4.1 | 0.41 |  |  |
| 92910-4D | 0.75 | 46 | 3.3 | 1.3E-13 | 1.3E-15 | 12.0 | 7.2 | 38181 | 382 | 3664 | 2181 | 4188 | 0.6 | 1.7 | 2.2 | 0.22 | 2.2 | 0.1 |
| 92913-3C | 0.77 | 49 | 3.8 | 3.7E-14 | 3.7E-16 | 2.3 | 1.0 | 9701 | 97 | 610 | 251 | 670 | 0.4 | 2.7 | 3.5 | 0.35 | 3.5 | 0.0 |
| *KRG-1-A* data ignored to perform the mean age calculation | | | | | | | | | | | | | | | | | | |
| $ ZHe age of this aliquot has been corrected by 5% associated to U-Th decay disequilibrium | | | | | | | | | | | | | | | | | | |

|  |
| --- |
|  |
| **Fig S.1**: Measured and modeled luminescence data for sample KRG01. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.2**: Measured and modeled luminescence data for sample KRG03. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.3**: Measured and modeled luminescence data for sample KRG05 (King et al., 2020). (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.4**: Measured and modeled luminescence data for sample KRG06 (King et al., 2020). (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.5**: Measured and modeled luminescence data for sample KRG07. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.6**: Measured and modeled luminescence data for sample KRG08. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.7**: Measured and modeled luminescence data for sample KRG10. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.8**: Measured and modeled luminescence data for sample KRG13. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.9**: Measured and modeled luminescence data for sample KRG100. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.10**: Measured and modeled luminescence data for sample KRG101 (King et al., 2020). (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.11**: Measured and modeled luminescence data for sample KRG102. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.12**: Measured and modeled luminescence data for sample KRG103. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.13**: Measured and modeled luminescence data for sample KRG104 (King et al., 2020). (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.14**: Measured and modeled luminescence data for sample KRG111 (King et al., 2020). (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.15**: Measured and modeled luminescence data for sample KRG112 (King et al., 2020). (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.16**: Measured and modeled luminescence data for sample KRG113. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |

|  |
| --- |
|  |
| **Fig S.17**: Measured and modeled luminescence data for sample KRG115. (a) Luminescence athermal decay (b) constraint of the fraction of saturation and (c) measurement of luminescence isothermal decay. |



**Fig. S.18**: Dose recovery experiment results. Blue data points are the response of individual aliquots with uncertainty calculated from counting statistics. Red data points are the average of all of the data measured for that particular temperature with 1σ uncertainty.



**Fig. S.19**: Screening samples for a thermal signal. Comparison of (n/N)nat with (n/N­)ss for the different signals of the different samples. Samples that plot on the 1:1 line, or within the 15% bounds are in athermal steady state, and can only be used to determine the minimum exhumation rate.

|  |
| --- |
|  |
|  |
|  |
|  |
| **Fig. S.20:** Results of forward model inversions for sample NB123 (King et al., 2016) for models 1-8 (by row). Left panels, time-depth plots shaded according to the density of accepted paths. The thin black lines are the 2σ uncertainty bounds, the thin green lines are the 1σ uncertainty bounds, whilst the red line is median model. The thick black line is the forward model time-depth path. Right panel, comparison between and for the accepted models. Closed symbols are values for the sample. |
|  |
|  |
|  |
| **Fig. S.20 cont.:** Results of forward model inversions for sample NB123 (King et al., 2016) for models 9-14 (by row). Left panels, time-depth plots shaded according to the density of accepted paths. The thin black lines are the 2σ uncertainty bounds, the thin green lines are the 1σ uncertainty bounds, whilst the red line is median model. The thick black line is the forward model time-depth path. Right panels, comparison between and for the accepted models. Closed symbols are values for the sample. |

|  |
| --- |
|  |
| **Fig. S21:** Exhumation rates inverted from forward modelling of sample NB123 (King et al., 2016) for models 1-14 (by row). Dark grey shading is the 2σ uncertainty bound, light grey shading the 1σ uncertainty bound, the red line is the median exhumation rate and the black line is the exhumation rate imposed in the forward model. |

|  |
| --- |
|  |
| **Fig S.22:** Results of forward model inversions for sample KRG104 (King et al., 2020) for models 1-8 (by row). Left panels, time-depth plots shaded according to the density of accepted paths. The thin black lines are the 2σ uncertainty bounds, the thin green lines are the 1σ uncertainty bounds, whilst the red line is median model. The thick black line is the forward model time-depth path. Right panel, comparison between and for the accepted models. Closed symbols are values for the sample. |

|  |
| --- |
|  |
| **Fig S.22 cont.:** Results of forward model inversions for sample KRG104 (King et al., 2020) for models 9-14 (by row). Left panels, time-depth plots shaded according to the density of accepted paths. The thin black lines are the 2σ uncertainty bounds, the thin green lines are the 1σ uncertainty bounds, whilst the red line is median model. The thick black line is the forward model time-depth path. Right panel, comparison between and for the accepted models. Closed symbols are values for the sample. |

|  |
| --- |
|  |
| **Fig. S23:** Exhumation rates inverted from forward modelling of sample KRG104 (King et al., 2020) for models 1-14 (by row). Dark grey shading is the 2σ uncertainty bound, light grey shading the 1σ uncertainty bound, the red line is the median exhumation rate and the black line is the exhumation rate imposed in the forward model. |
|  |
|  |
|  |
|  |
| **Fig. S.24:** Depth-time histories for inversion of the luminescence data of samples KRG01, KRG03, KRG05, KRG06, KRG07, KRG08, KRG10 and KRG13 inverted using only the IRSL100, IRSL150 and IRSL225 signals. Left panels show a probability density function of the accepted paths, the black lines are 2σ confidence intervals, the green lines are 1σ confidence intervals and the red line is the median model. Right panels show the misfit between the measured (open symbols) and modelled values for the IRSL50,IRSL100, IRSL150 and IRSL225 signals. Closed symbols are the field saturation values computed for each specific luminescence signal. |
|  |
|  |
|  |
| **Fig. S.24** **cont.**: Depth-time histories for inversion of the luminescence data of samples KRG100, KRG101, KRG102, KRG103, KRG104 and KRG115 inverted using only the IRSL100, IRSL150 and IRSL225 signals. Left panels show a probability density function of the accepted paths, the black lines are 2σ confidence intervals, the green lines are 1σ confidence intervals and the red line is the median model. Right panels show the misfit between the measured (open symbols) and modelled values for the IRSL50,IRSL100, IRSL150 and IRSL225 signals. Closed symbols are the field saturation values computed for each specific luminescence signal. The very large uncertainites for the IRSL100 and IRSL225 signals of sample KRG100 reflect that these signals exhibit very low (zero) anomalous fading. |

|  |
| --- |
|  |
|  |
|  |
|  |
| **Fig. S.25**: Depth-time histories for inversion of the ESR and luminescence data of sampe KRG05, KRG06, KRG101 and KRG104. The left panel shows a probability density function of the accepted paths, the black lines are 2σ confidence intervals, the green lines are 1σ confidence intervals and the red line is the median model. The central panel shows the misfit between the measured (open symbols) and modelled values for the IRSL100, IRSL150 and IRSL225 luminescence signals. Closed symbols are the field saturation values computed for each specific luminescence signal. The right panel shows the misfit between the measured and modelled ESR ages. Note that for sample KRG06 it was only possible to fit both the ESR and OSL data where fits that were within 15% and 10% of the measured values respectively were accepted. |

|  |
| --- |
|  |
|  |
|  |
|  |

**Fig. S.26:** Depth-time histories for inversion of the ZHe (this study) and ZFT (Yamada, 1999) data of samples KRG01, KRG02, KRG03, KRG04, KRG05, KRG06, KRG07 and KRG08. Left panels show a probability density function of the accepted paths, the black lines are 2σ confidence intervals, the green lines are 1σ confidence intervals and the red line is the median model. Right panels show the misfit between the measured ages (open symbols) and modelled ages.

|  |
| --- |
|  |
|  |

**Fig. S.26 cont.**: Depth-time histories for inversion of the ZHe (this study) and ZFT (Yamada, 1999) data of samples KRG13, KRG15, S92910-4 and S92913-3. Left panels show a probability density function of the accepted paths, the black lines are 2σ confidence intervals, the green lines are 1σ confidence intervals and the red line is the median model. Right panels show the misfit between the measured ages (open symbols) and modelled ages.

|  |
| --- |
|  |
|  |
|  |
|  |
|  |

**Fig. S.27:** Exhumation rates inverted from samples KRG01, KRG03, KRG07, KRG08, KRG10, KRG13, KRG100, KRG102, KRG103 and KRG115 from this study and KRG05, KRG06 and KRG101 from King et al. (2020). Dark grey shading is the 2σ uncertainty bound, light grey shading the 1σ uncertainty bound, the red line is the median exhumation rate and the black line is the exhumation rate imposed in the forward model. Yellow stars show luminescence ages. The black stars for sample KRG100 are the modelled maximum ages for this sample, showing that the sample is in field saturation.

|  |
| --- |
|  |

**Fig. S.27 cont.:** Exhumation rates inverted from sample KRG115 from this study and from KRG104 from King et al. (2020). Dark grey shading is the 2σ uncertainty bound, light grey shading the 1σ uncertainty bound, the red line is the median exhumation rate and the black line is the exhumation rate imposed in the forward model. Yellow stars show luminescence ages.

|  |
| --- |
|  |

**Fig. S.28:** Exhumation rates inverted from the luminescence and ESR data of samples KRG05, KRG06, KRG101 and KRG104 (King et al., 2020). Dark grey shading is the 2σ uncertainty bound, light grey shading the 1σ uncertainty bound, the red line is the median exhumation rate and the black line is the exhumation rate imposed in the forward model. Yellow stars show luminescence ages and red stars ESR ages.

|  |
| --- |
|  |
| **Fig. S.29:** (a) Chi-plot of the Kurobe River and major tributaries. (b) Stream-profile showing knickpoints along the Kurobe River and major tributaries (see text for details). Note that some “knickpoints” are coincident with dams e.g. at the Kurobe dam 65 km upstream. |



**Fig. S.30:** Knickpoint retreat rates calculated using the basin-wide modelling approach of Crosby and Whipple (2006) assuming an age for the knickpoint coincident with the Kurobe dam 65 km upstream of 20 and 65 ka.

|  |
| --- |
| **Chart, line chart  Description automatically generated**  **Chart  Description automatically generated**  **Histogram  Description automatically generated with low confidence** |

**Fig. S.31:** Results of ELA modelling using three different climatic records over the past 100 ka. The predicted ELA elevations exceed the elevation of the highest local topography at Kurobe, showing that the region was ice-free over this time period.

**References**

Anderson, L. S., Geirsdóttir, Á., Flowers, G. E., Wickert, A. D., Aðalgeirsdóttir, G., and Thorsteinsson, T, 2019. Controls on the lifespans of Icelandic ice caps, 527, 115780, https://doi.org/10.1016/j.epsl.2019.115780.

Auclair, M., Lamothe, M. and Huot, S., 2003. Measurement of anomalous fading for feldspar IRSL using SAR. *Radiation measurements*, *37*(4-5), pp.487-492.

Balescu, S. and Lamothe, M., 1992. The blue emission of K-feldspar coarse grains and its potential for overcoming TL age underestimation. *Quaternary Science Reviews* *11*, 45–51.

Bell, W.T., 1980. Alpha dose attenuation in quartz grains for thermoluminescence dating. *Ancient Tl*, *12*(4), p.8.

Berlin, M.M. and Anderson, R.S., 2007. Modeling of knickpoint retreat on the Roan Plateau, western Colorado. *Journal of Geophysical Research: Earth Surface*, *112*(F3).

Biswas, R.H., Herman, F., King, G.E. and Braun, J., 2018. Thermoluminescence of feldspar as a multi-thermochronometer to constrain the temporal variation of rock exhumation in the recent past. *Earth and Planetary Science Letters*, *495*, pp.56-68.

Buscombe, D., 2013. Transferable wavelet method for grain‐size distribution from images of sediment surfaces and thin sections, and other natural granular patterns. *Sedimentology*, *60*(7), pp.1709-1732.

Braun, J., Van der Beek, P. and Batt, G., 2006. *Quantitative thermochronology: numerical methods for the interpretation of thermochronological data*. Cambridge University Press.

Cook, K.L., Turowski, J.M. and Hovius, N., 2013. A demonstration of the importance of bedload transport for fluvial bedrock erosion and knickpoint propagation. *Earth Surface Processes and Landforms*, *38*(7), pp.683-695.

Cooperdock, E.H., Ketcham, R.A. and Stockli, D.F., 2019. Resolving the effects of 2D versus 3D grain measurements on (U-Th)/He age data and reproducibility. *Geochronology*.1, 17-41.

Crosby, B.T. and Whipple, K.X., 2006. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand. *Geomorphology*, *82*(1-2), pp.16-38.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.

Durcan, J.A., King, G.E. and Duller, G.A., 2015. DRAC: Dose Rate and Age Calculator for trapped charge dating. *Quaternary Geochronology*, *28*, pp.54-61.

Gautheron, C., Djimbi, D.M., Roques, J., Balout, H., Ketcham, R.A., Simoni, E., Pik, R., Seydoux-Guillaume, A.M. and Tassan-Got, L., 2020. A multi-method, multi-scale theoretical study of He and Ne diffusion in zircon. *Geochim. Cosmoch. Acta* 268, 348-367.

Gautheron, C., Pinna Jamme, R., Derycke, A., Ahadi, F., Sanchez, C., Haurine, F., Monvoisin, G., Barbosa, D., Delpech, G., Maltese, J., Sarda, P. and Tassan-Got, L., 2021. Technical note: Analytical protocols and performance for apatite and zircon (U–Th) = He analysis on quadrupole and magnetic sector mass spectrometer systems between 2007 and 2020. *Geochronology* 3, pp.351-370.

Guenthner, W., Reiners, P.W., Ketcham, R., Nasdala, L. and Giester, G., 2013. Helium diffusion in natural zircon: radiation damage, anisotropy, and the interpretation of zircon (U-Th)/He thermochronology. *American Journal of Science* 313, 145-198.

Guérin, G., Mercier, N. and Adamiec, G., 2011. Dose-rate conversion factors: update. *Ancient TL*, *29*(1), pp.5-8.

Guérin, G., Mercier, N., Nathan, R., Adamiec, G. and Lefrais, Y., 2012. On the use of the infinite matrix assumption and associated concepts: a critical review. *Radiation Measurements*, *47*(9), pp.778-785.

Guralnik, B., Jain, M., Herman, F., Ankjærgaard, C., Murray, A.S., Valla, P.G., Preusser, F., King, G.E., Chen, R., Lowick, S.E. and Kook, M., 2015. OSL-thermochronometry of feldspar from the KTB borehole, Germany. *Earth and Planetary Science Letters*, *423*, pp.232-243.

Huntley, D.J. and Baril, M.R., 1997. The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating. Ancient Tl, 15(1), pp.11-13.

Huntley, D.J., 2006. An explanation of the power-law decay of luminescence. *Journal of Physics: Condensed Matter*, *18*(4), p.1359.

Ito, H., Yamada, R., Tamura, A., Arai, S., Horie, K. and Hokada, T., 2013. Earth's youngest exposed granite and its tectonic implications: the 10–0.8 Ma Kurobegawa Granite. *Scientific reports*, *3*(1), pp.1-5.

Kamiguchi, K., Arakawa, O., Kitoh, A., Yatagai, A., Hamada, A., and Yasutomi, N., 2010. Development of APHRO\_JP, the first Japanese high-resolution daily precipitation product for more than 100 years, 4, 60–64.

Kars, R.H., Wallinga, J. and Cohen, K.M., 2008. A new approach towards anomalous fading correction for feldspar IRSL dating—tests on samples in field saturation. *Radiation Measurements*, *43*(2-6), pp.786-790.

Ketcham, R.A., Gautheron, C. and Tassan-Got, L., 2011. Accounting for long alpha-particle stopping distances in (U-Th-Sm)/He geochronology: refinement of the baseline case. *Geochimica et Cosmochimica Acta* 75, pp. 7779-7791.

Kigoshi, T., Kumon, F., Hayashi, R., Kuriyama, M., Yamada, K., and Takemura, K., 2014. Climate changes for the past 52 ka clarified by total organic carbon concentrations and pollen composition in Lake Biwa, Japan, Quaternary International, 333, 2–12, https://doi.org/10.1016/j.quaint.2014.04.028.

Kigoshi, T., Kumon, F., Kawai, S., and Kanauchi, A., 2017. Quantitative reconstruction of paleoclimate in central Japan for the past 158,000 years based on a modern analogue technique of pollen composition, 455, 126–140.

King, G.E., Herman, F., Lambert, R., Valla, P.G. and Guralnik, B., 2016. Multi-OSL-thermochronometry of feldspar. *Quaternary Geochronology*, *33*, pp.76-87.

King, G.E., Burow, C., Roberts, H.M. and Pearce, N.J., 2018. Age determination using feldspar: Evaluating fading-correction model performance. *Radiation Measurements*, *119*, pp.58-73.

King, G.E., Tsukamoto, S., Herman, F., Biswas, R.H., Sueoka, S. and Tagami, T., 2020. Electron spin resonance (ESR) thermochronometry of the Hida range of the Japanese Alps: validation and future potential. *Geochronology*, *2*(1), pp.1-1.

Li, B. and Li, S.H., 2011. Luminescence dating of K-feldspar from sediments: a protocol without anomalous fading correction. *Quaternary Geochronology*, *6*(5), pp.468-479.

Loget, N. and Van Den Driessche, J., 2009. Wave train model for knickpoint migration. *Geomorphology*, *106*(3-4), pp.376-382.

Mori, T., Kashiwagi, K., Amekawa, S., Kato, H., Okumura, T., Takashima, C., Wu, C.-C., Shen, C.-C., Quade, J., and Kano, A., 2018. Temperature and seawater isotopic controls on two stalagmite records since 83 ka from maritime Japan, Quaternary Science Reviews, 192, 47–58, <https://doi.org/10.1016/j.quascirev.2018.05.024>.

Mudd, S.M., Clubb, F.J., Gailleton, B. and Hurst, M.D., 2018. How concave are river channels?. *Earth Surface Dynamics*, *6*(2), pp.505-523.

Nakagawa, T., Tarasov, P. E., Nishida, K., Gotanda, K., and Yasuda, Y., 2002. Quantitative pollen-based climate reconstruction in central Japan: application to surface and Late Quaternary spectra, Quaternary Science Reviews, 21, 2099–2113, https://doi.org/10.1016/S0277-3791(02)00014-8.

Ono, Y., Aoki, T., Hasegawa, H., and Dali, L., 2005. Mountain glaciation in Japan and Taiwan at the global Last Glacial Maximum, Quaternary International, 138–139, 79–92, https://doi.org/10.1016/j.quaint.2005.02.007.

Perron, J.T. and Royden, L., 2013. An integral approach to bedrock river profile analysis. *Earth Surface Processes and Landforms*, *38*(6), pp.570-576.

Reiners, P.W. and Brandon, M.T., 2006. Using thermochronology to understand orogenic erosion. *Annu. Rev. Earth Planet. Sci.*, **34**, 419.

Rosenbloom, N.A. and Anderson, R.S., 1994. Hillslope and channel evolution in a marine terraced landscape, Santa Cruz, California. *Journal of Geophysical Research: Solid Earth*, *99*(B7), pp.14013-14029.

Sato, A., Takahashi, S., Naruse, R., and Wakahama, G., 1984. Ablation and heat balance of-the Yukikabe snow patch in-the Daisetsu Mountains, Hokkaido, Japan, 5, 122–226.

Schwanghart, W. and Scherler, D., 2014. TopoToolbox 2–MATLAB-based software for topographic analysis and modeling in Earth surface sciences. *Earth Surface Dynamics*, *2*(1), pp.1-7.

Tarasov, P. E., Nakagawa, T., Demske, D., Österle, H., Igarashi, Y., Kitagawa, J., Mokhova, L., Bazarova, V., Okuda, M., Gotanda, K., Miyoshi, N., Fujiki, T., Takemura, K., Yonenobu, H., and Fleck, A., 2011. Progress in the reconstruction of Quaternary climate dynamics in the Northwest Pacific: A new modern analogue reference dataset and its application to the 430-kyr pollen record from Lake Biwa, Earth-Science Reviews, 108, 64–79, https://doi.org/10.1016/j.earscirev.2011.06.002.

Uemura, R., Nakamoto, M., Asami, R., Mishima, S., Gibo, M., Masaka, K., Jin-Ping, C., Wu, C.-C., Chang, Y.-W., and Shen, C.-C., 2016. Precise oxygen and hydrogen isotope determination in nanoliter quantities of speleothem inclusion water by cavity ring-down spectroscopic techniques, Geochimica et Cosmochimica Acta, 172, 159–176, https://doi.org/10.1016/j.gca.2015.09.017.

Valla, P.G., Lowick, S.E., Herman, F., Champagnac, J.D., Steer, P. and Guralnik, B., 2016. Exploring IRSL50 fading variability in bedrock feldspars and implications for OSL thermochronometry. *Quaternary Geochronology*, *36*, pp.55-66.

Wheelock, B., Constable, S., Key, K., 2015. The advantages of logarithmically scaled data for electromagnetic inversion. Geophysical Journal International 201, 1765-1780.

Whipple, K.X. and Tucker, G.E., 1999. Dynamics of the stream‐power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. *Journal of Geophysical Research: Solid Earth*, *104*(B8), pp.17661-17674.

Yamada, R., 1999. Cooling history analysis of granitic rock in the Northern Alps, central Japan. The Earth Monthly, 21, 803–810 (in Japanese).

Yuhara, K. and Yamamoto, T., 1983. Thermal Effect of Water Flowing through Fractures on the Cooling of Kurobe Jobu Railway Tunnel (Hot Tunnel), Central Japan. Journal of the Geothermal Research Society of Japan, 5(4), pp.259-276.