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Disaster Prevention Research Institute
Kyoto University

The role of episodic geomorphic processes in the erosion and uplift of the Japanese Alps

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1. Aims of research project and summary of visit to DPRI

This long-term collaborative research aims to determine the impact of episodic geomorphic processes, such as landsliding, on rates of erosion and sediment fluxes in steep mountain landscapes by establishing the first long-term time-series database of cosmogenic nuclide concentrations exported by small mountain rivers. The work anticipates developing a new approach for more accurate quantification of denudation rates in tectonically active mountain belts and lead to a deeper understanding of the processes that control the production and transport of sediment in these landscapes. The objectives of the proposed research can only be achieved through collaboration and joint usage of DPRI and University of Wollongong facilities and this presents opportunities in shared training of graduate students and early career researchers, as well as the co-development of new laboratory procedures that benefit both parties.

The research visit to DPRI in June/July 2023 had two main objectives: (1) to rekindle the partnership between Codilean and Matsushi that started in 2013 (and was facilitated by previous DPRI Research Visit grants), and that stalled during the interruptions due to the COVID-19 pandemic; and (2) undertake fieldwork in the Nagano Prefecture for re-sampling small mountain rivers for cosmogenic nuclide concentration analyses. As part of the first objective, Codilean and Matsushi took part in a full-day workshop on cosmogenic nuclide applications, with presentations from the above and both current and past DPRI graduate students of Matsushi. We also visited the MALT Accelerator Mass Spectrometry facility at the University of Tokyo holding discussions with Prof. Hiroyuki Matsuzaki about recent developments at MALT. The discussions at MALT were also joined by Dr. Réka Fülöp from the Australian Nuclear Science and Technology Organization (ANSTO). As part of the second objective, Codilean, Matsushi, along with two DPRI graduate students (Yoshimasa Ota and Arihito Kondo) and Dr. Hitoshi Saito from Nagoya University, collected river sediment samples from 41 adjacent first order catchments from the southern Japanese Alps. The same rivers were sampled previously in 2012 and 2014. The new samples were shipped to the University of Wollongong where they were prepared for analysis. Cosmogenic ^{26}Al analyses were conducted in April 2024 and ^{10}Be analyses are scheduled to start on the 17th of June 2024, past the deadline for this report.

2. Project background

Rivers are the world's large sediment conveyor belts delivering over 40 billion tonnes of particulate and dissolved sediment to the global ocean every year [1,2,3]. The primary source of the sediment are the mountains where the continuous interplay between tectonic forces, climate, and surface processes break the rocks down converting it to dirt and soil [4,5,6]. Changes in climate or tectonic forcing will result in changes in the sediment flux, and the response of the landscape to these environmental forcings will be recorded permanently by mineralogical, textural, or geochemical proxies. Thus, each parcel of sediment carries information about the geology, geomorphology, and the climate of the contributing upland areas, information that builds the narrative of Earth's geological history [7,8]. Quantifying the dynamics of sediment routing systems is essential to understanding the mass fluxes associated with the physical, biological, and chemical processes acting across the landscape [9,10], just as it is central to how we read and interpret the global record of Earth history [11].

Research on understanding the workings of the sedimentary source to sink continuum has to date largely focused on large river systems — such as the Amazon [12] or the Murray-Darling [13] — as the potential for storage and sediment reworking that may buffer and distort environmental signals carried by sediments is greatest here [14,15]. However, it has been suggested that the potential for considerable buffering and distorting of environmental signals is also high in the smaller river systems that characterise tectonically active mountain belts [16].

Feedbacks between hillslope processes such as landsliding and river incision — both prevalent in small mountain basins — suggest several modes may dictate natural erosion rates at different times and spatial scales that will leave diagnostic fingerprints in the geological record. At the long timescales, tectonic activity is important in providing the forcing that keeps slopes at or near landslide threshold conditions, but at shorter timescales, feedbacks can lead to both accelerated incision, and, in the case of excessive landsliding, valley alluviation [17,18]. Assessing such modality is crucial to correctly interpreting both the geomorphic record preserved within mountain systems, and quantitative measures of erosion rates such as provided by cosmogenic nuclide abundances in discharged sediment. For example, at short timescales, such feedbacks may lead to highly variable process rates at catchment scale [18]. Thus, to obtain meaningful estimates of mountain erosion, we need to better understand the frequency-magnitude characteristics of episodic erosional processes, and how these impact time-averaged estimates of erosion derived from measures such as cosmogenic isotope abundances. This is where the proposed study will make a substantial contribution.

Catastrophic geomorphic events perturb the erosion rate signal and introduce noise in the population of cosmogenic nuclide concentrations obtained from rivers draining a mountain range. This noise will be expressed both **<u>in space</u>** — adjacent catchments will show a high variance in exported nuclide concentrations, and **<u>in time</u>** — the nuclide concentrations exported from each catchment will change through time depending on the return interval of landslides and the amount of time elapsed since a landsliding event (Figure 1). Episodic processes such as landsliding, remove discrete blocks of material from greater depths truncating the exponential cosmogenic nuclide depth profile. This truncation leads to overall lower cosmogenic nuclide abundances in the exported sediment, and if all catchments are affected by landslides of the same magnitude, occurring at the same time, the nuclide concentrations measured in the exported sediment will be lower than in the diffusive erosion dominated case, but will have the same low variance and approximate a uniform probability distribution (Figure 1A’). However, landslides have variable magnitudes and recurrence intervals. It follows that, in each catchment the cosmogenic nuclide abundance in the sediment will be lowered with respect to the diffusive erosion benchmark in proportion to the area of the catchment affected by landsliding and the amount of time elapsed since the landsliding event (Figure 1B).

Previous studies have attempted to quantify the temporal change in the cosmogenic ^{10}Be concentration exported from a river basin. For example Kober et al [19] have measured cosmogenic ^{10}Be and ^{14}C concentrations in debris-flow-derived sediment from a basin in the Swiss Alps with measurements over a period of 3 years. To obtain a longer time window between measurements, other studies [e.g., 20,21] relied on published data from basins that they resampled. More recently, a recent study by Grande et al [22] measured ^{10}Be in two small basins in Puerto Rico at different intervals over a 2-year period following Hurricane Maria, and managed to actually capture the return of the ^{10}Be signal in the sediment to pre-disturbance levels in one of the basins.

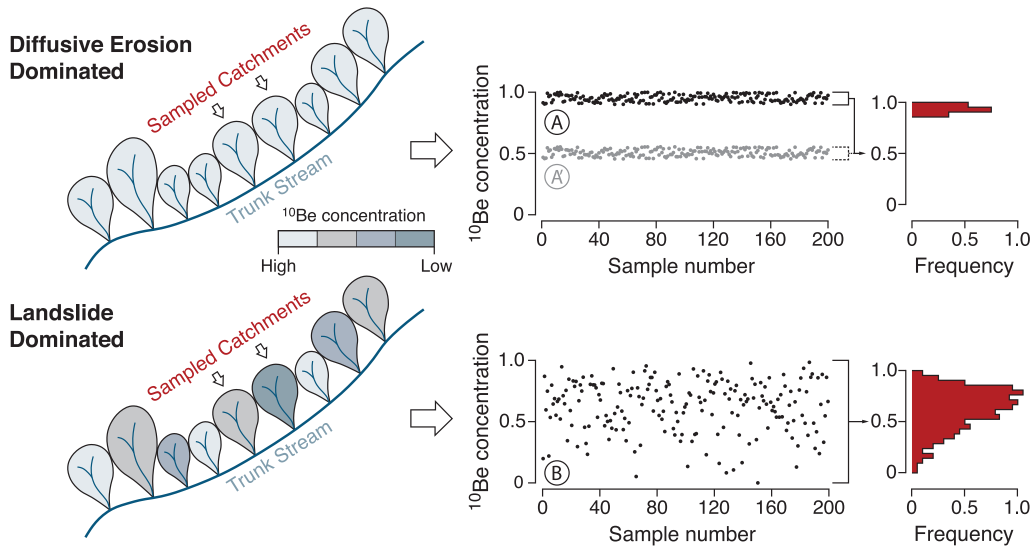

Figure 1: *Adjacent catchments with no or low landslide occurrence or disturbance (A) will show a lower overall variance in ^{10}Be concentrations compared to those subjected to significant landslide disturbances (B). Plot axes are in arbitrary units.*

With the exception of Kober et al [19], who analysed two cosmogenic nuclides, namely ^{10}Be and ^{14}C, all the other studies mentioned above considered only ^{10}Be. Studies have shown that deep sediment excavation from hillslopes because of landsliding may also export sediment with $^{26}Al/^{10}Be$ and $^{14}C/^{10}Be$ ratios deviating from steady-state values [23,24], and so, there is merit in measuring multiple cosmogenic nuclides with differing half-lives when studying basins, such as ours in the Japanese Alps, potentially affected by landsliding.

Our study is the first to systematically and rigorously quantify the temporal variance of cosmogenic nuclide concentrations in rivers draining a mountain range. The Puerto Rican study by Grande et al [22] considers disturbance after an extreme event (Hurricane Maria), however, what happens under non-extreme conditions? Is the exported cosmogenic nuclide signal constant in time or is there a natural range within which nuclide concentrations will fluctuate. To try to explore these questions, we collected sediment samples from 41 small basin in the Japanese Alps (Figure 2) at three different time intervals. The largest basin is 12 km^2, but most basins are below one km^2 in area. The median basin area is 0.5 km^2. The basins are adjacent to each other, and all occupy the same lithology – granitic rocks [25]. To date we have analysed ^{10}Be and ^{26}Al in river sediment samples collected in August 2012 and ^{10}Be, ^{26}Al, and ^{14}C in samples collected in October 2014. We have also collected samples from the same basins in July 2023 and these have been processed for ^{10}Be and ^{26}Al analyses, with analyses of ^{14}C also planned in a selection of the samples.

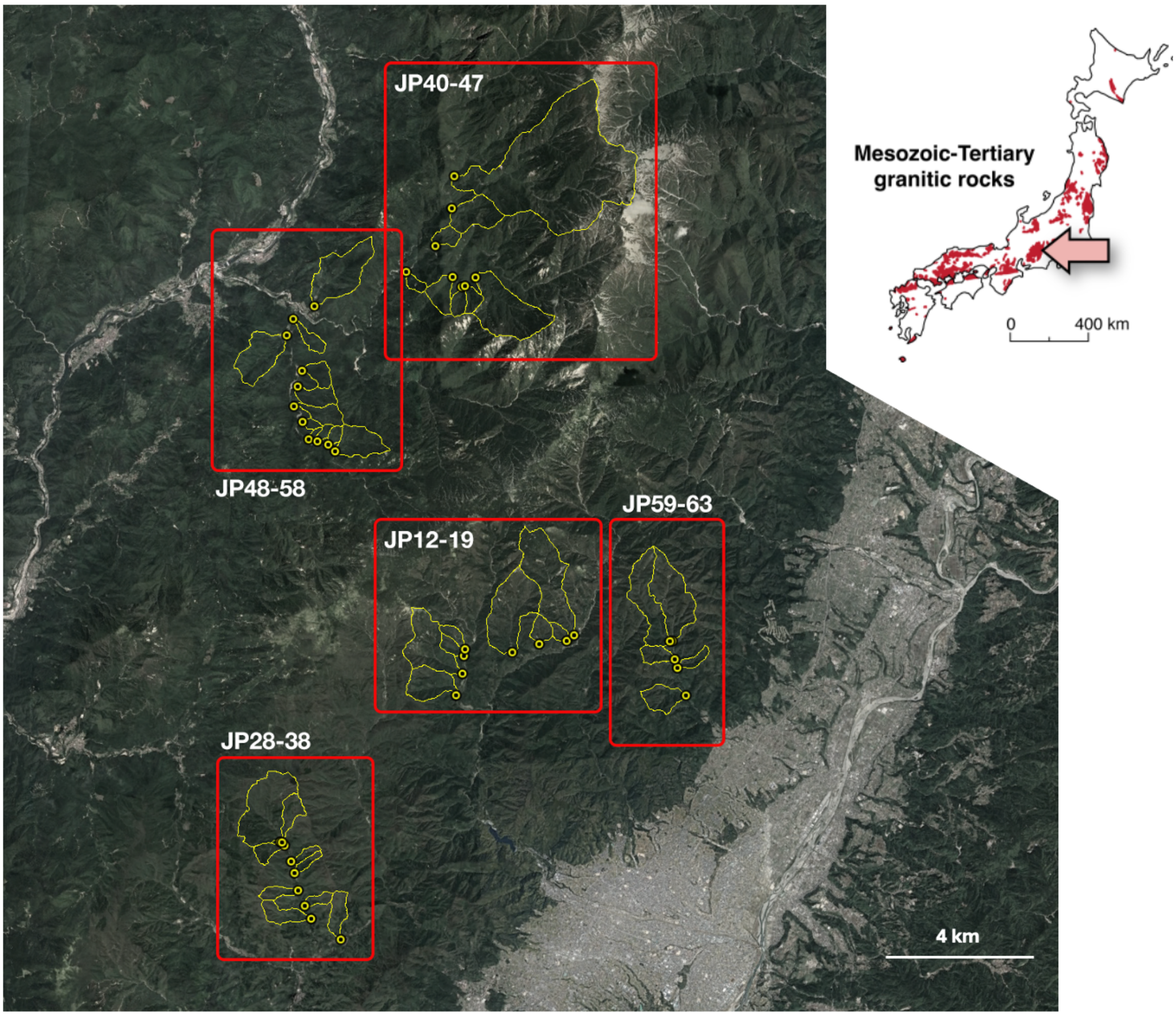

Figure 2: *Location of study area. Yellow outlines show the 41 basins sampled in 2012, 2014, and 2023. Inset shows distribution of granitic rocks from Taira [25].*

3. Apparent denudation rates

Figure 3 provides a summary of the apparent ^{10}Be-derived denudation rates and mean basin gradient and mean basin precipitation in the study area. For ease of comparison, we have grouped the sampled basins into five semi-arbitrary groups, based on proximity to each other and the trunk stream that they are connected to. As shown, there is variation in the apparent denudation rates in the five groups that to a very large extent mirrors the topography of the basins. Apparent denudation rates vary between ~120 and ~2600 mm/kyr. The basins receive similar amounts of mean annual precipitation – between ~2000 and ~2600 mm.

Figure 3A shows some variability in calculated denudation rates between 2012 and 2014, but this box plot does not consider the uncertainties on the calculated rates and so that makes the picture more complicated (see below). What is interesting is that basin 47 with the highest denudation rate yields the same nuclide concentration in 2012, 2014, and based on the ^{26}Al data, also in 2023.

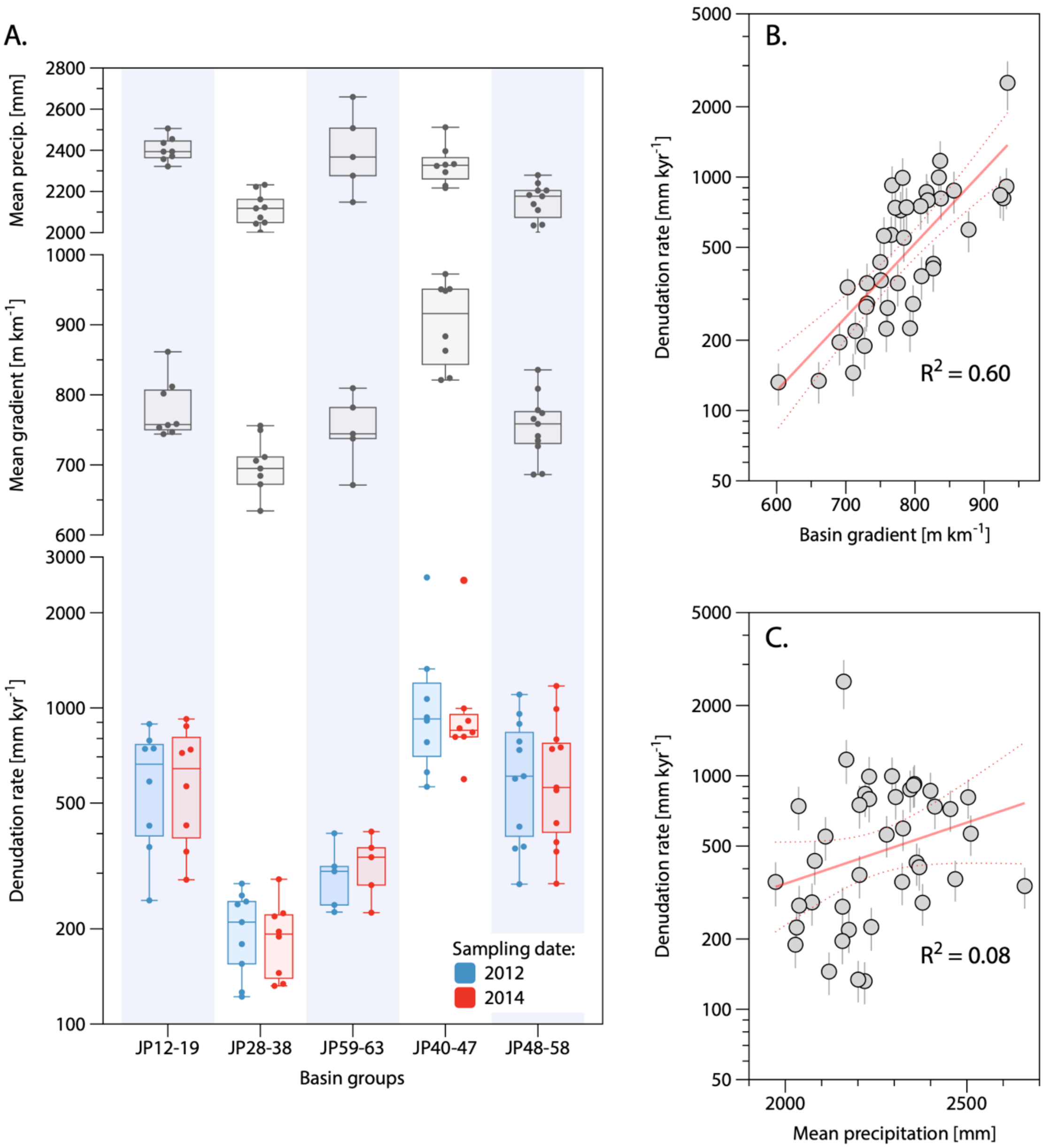

Figure 3: *Summary of apparent denudation rates, mean basin gradient and mean annual precipitation values for the sampled basins. Denudation rates show a strong correlation with mean basin gradient (3B) but a weak correlation with mean annual precipitation (3C).*

4. Temporal variation in measured ^{10}Be and ^{26}Al concentrations

Of the samples collected in 2012 and 2014, 14 have different ^{10}Be concentrations between the two sampling intervals at 1-sigma level and 6 at the 2-sigma level (average nuclide concentration uncertainties range between 3-4% for ^{10}Be and 6-8% for ^{26}Al). Of the 6 samples, one shows a difference in ^{10}Be concentrations at the 3-sigma level (Figure 4). Interestingly, the change in ^{10}Be concentrations is occurring in both directions: in some basins the ^{10}Be concentration has decreased, suggesting a recent disturbance whereas in others, the ^{10}Be concentration has increased, suggesting that the fluvial system is returning to an equilibrium state and landslide derived debris may have largely been removed from the basin.

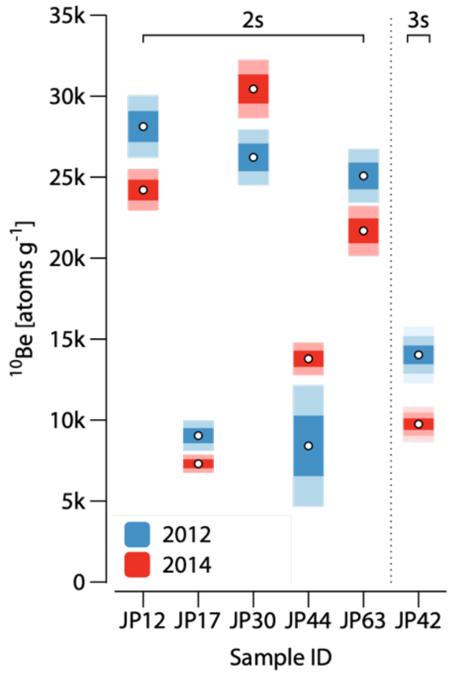

Figure 4: *Change in ^{10}Be concentrations between samples collected in August 2012 (blue) and October 2014 (red). Shades of blue and red indicate uncertainty levels (1- to 3-sigma), from dark to light going from 1-sigma to 3-sigma. Samples with no detectable change in ^{10}Be concentration between 2012 and 2014 or samples with differences at 1-sigma level only, are not shown.*

As mentioned above, we do not yet have ^{10}Be results for the samples collected in July 2023. A comparison of ^{26}Al results between 2014 and 2023 is shown in Figure 5, below. Given that ^{26}Al measurements typically have larger uncertainties than ^{10}Be (e.g., 6-8% vs. 3-4%), differences in ^{26}Al between 2014 and 2023 at the 1-sigma level will potentially materialise in differences between ^{10}Be at the 2-sigma level. For this reason, in Figure 5 we also include those samples where differences are at 1-sigma level.

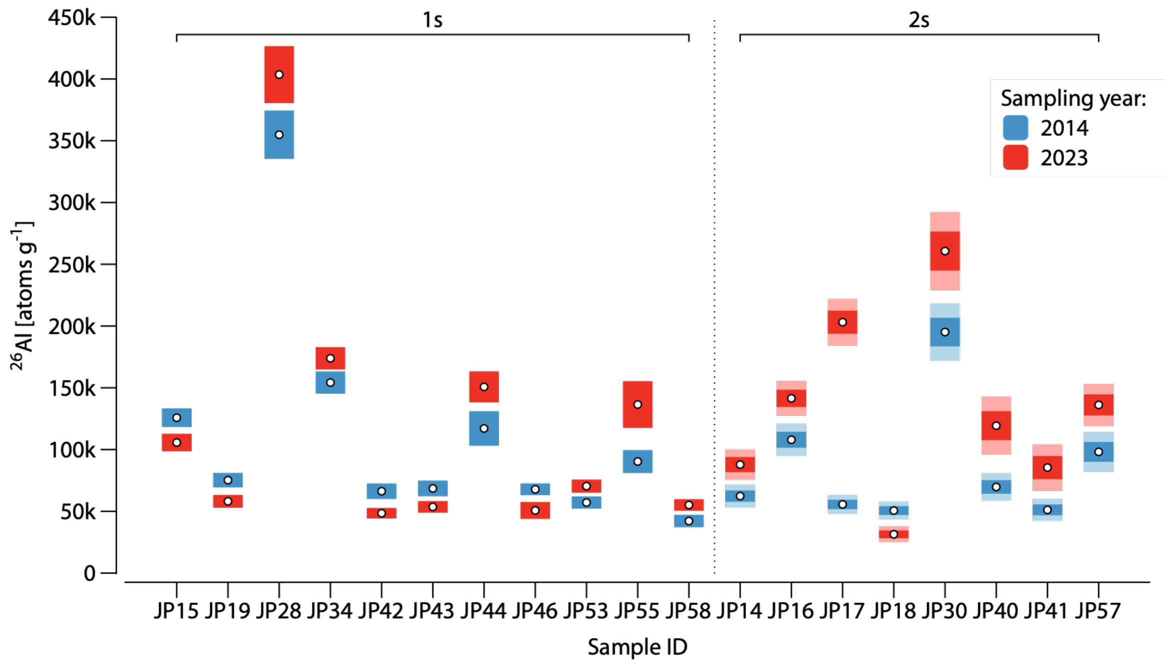

Figure 5: *Change in ^{26}Al concentration between samples collected in October 2014 (blue) and July 2023 (red). Shades of blue and red indicate uncertainty levels (1- to 2-sigma), from dark to light going from 1-sigma to 2-sigma.*

Regarding ^{26}Al, we see changes in 19 basins, with eight at 2-sigma. In 11 of the basins, concentrations have increased. In one basin (basin 17) the ^{26}Al concentration has increased 3.5-fold.

5. $^{26}Al/^{10}Be$ and $^{14}C/^{10}Be$ ratios

$^{26}Al/^{10}Be$ ratios intersect the steady-state continuous erosion curve at 1-sigma for most samples, and at 2-sigma for all samples with no trends apparent for the basins where changes in concentrations were detected between 2012 and 2014 (Figure 6). In-situ $^{14}C/^{10}Be$ ratios, paint a different picture, however, with all samples analysed plotting below the steady-state erosion curve (Figure 7). The latter is an interesting finding and one worth further investigation.

There are two ways such depressed $^{14}C/^{10}Be$ ratios have been interpreted elsewhere. In a recent study from the Argentinian Andes by Slosson et al [26], depressed $^{14}C/^{10}Be$ ratios are interpreted as indicating transient storage in dynamic talus slopes in the steep topography of the High Andes. Applying the same interpretation to the Japanese samples would imply that there is some buffering of sediment and the response of the various basins to forcing (rainfall, earthquakes) may be delayed in some instances. The other way to interpret depressed $^{14}C/^{10}Be$ ratios is via landscape transience, as has been suggested by numerical modelling studies [e.g., 27,28]. The latter show that instantaneous removal of material from a hillslope – such as by a landslide – can theoretically result in depressed $^{14}C/^{10}Be$ ratios. The models considered by Mudd [27] and Skov et al [28] are both looking at scenarios where the background erosion rate is relatively low (10 mm/kyr) and the jump in rate is relatively large. Also, in both studies, the disturbance occurred a few thousand years in the past. In our case in the Japanese Alps, background rates are higher, and disturbances are happening continuously, and it will be interesting to model this behavior and see its effects on ^{14}C and ^{10}Be concentrations. What is interesting, however, is that in Kober et al's [19] study looking at debris-flow-induced changes in ^{14}C and ^{10}Be, their samples also deviate from the steady state erosion line. They also invoke storage of colluvium as a likely cause but again their setting is similar to ours in Japan. Thus, it may be that depressed $^{14}C/^{10}Be$ ratios are the norm in landscapes where the sediment flux and erosion rates are not constant in time.

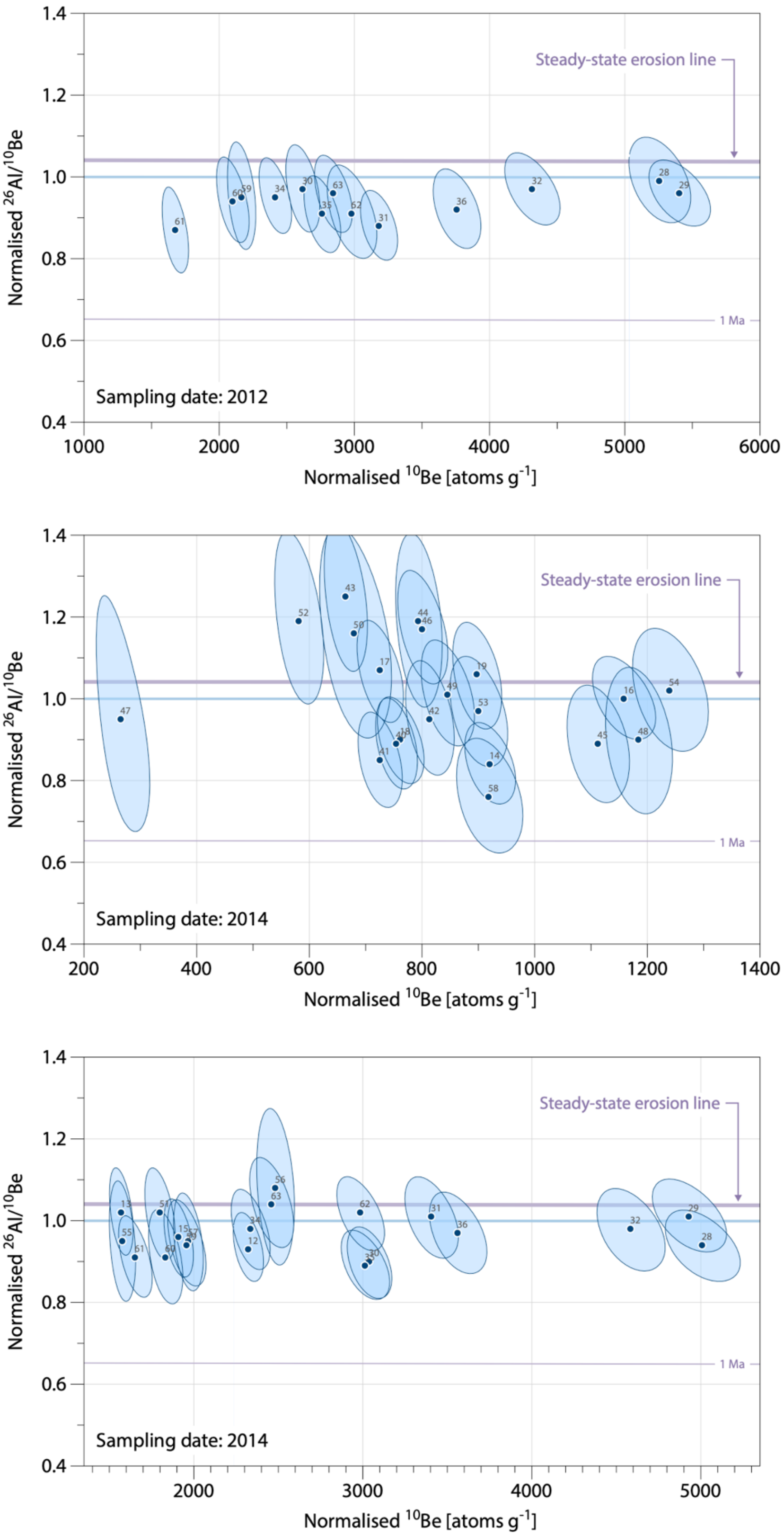

Figure 6: *Normalised $^{26}Al/^{10}Be$ ratios vs normalized ^{10}Be concentrations.*

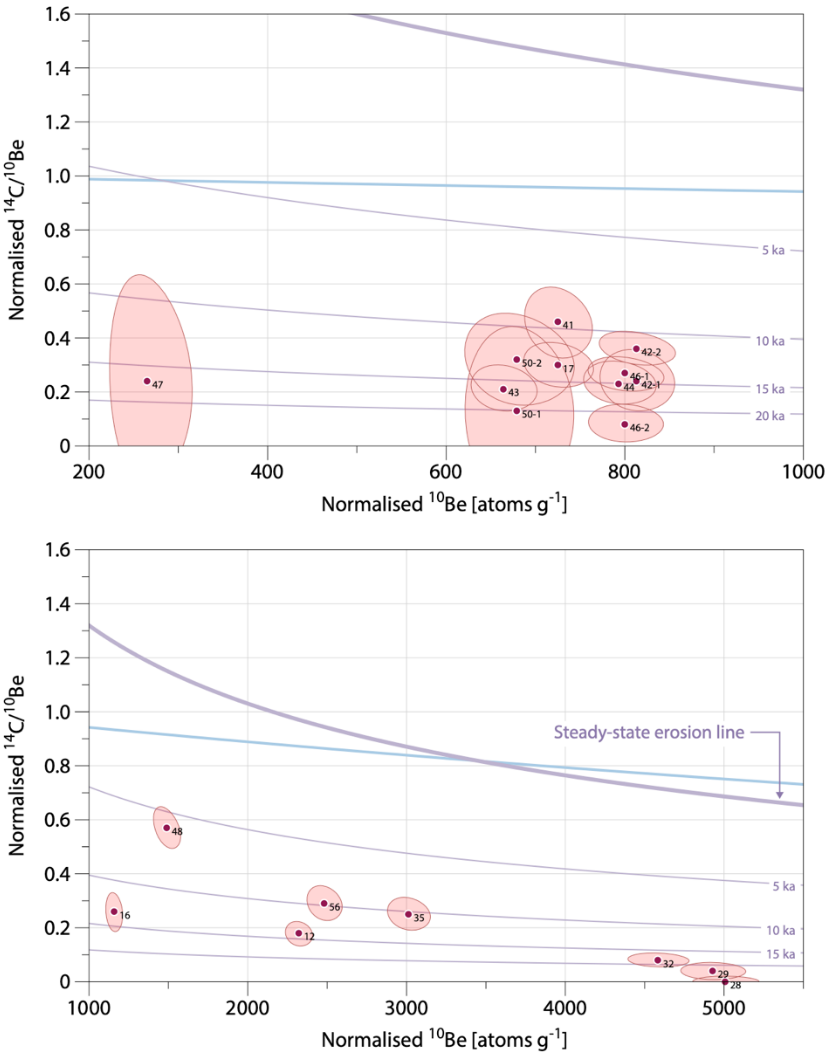

Figure 7: *Normalised $^{14}C/^{10}Be$ ratios vs normalized ^{10}Be concentrations.*

1. Future work

This study is work in progress and we anticipate that the results from the samples collected in 2023 (namely the ^{10}Be results) will contribute more to understanding transient storage dynamics and the buffering of nuclide concentrations in discharged sediment from these small mountain basins. Regarding the ^{14}C data, our next step is to undertake some numerical modelling work similar to that done by Simon Mudd and Skov et al [27,28] and investigate the degree to which landscape transience is responsible for our observed $^{14}C/^{10}Be$ ratios.

Further, Codilean and Matsushi have been awarded a **DRPI Long/Short-term Research Visit for 2024 (2024LS-01)** and this will be utilised to undertake more fieldwork in the study area in July 2024, this time targeting specific basins – based on information from the 2023 sample results – and aiming to collect sediment for other cosmogenic nuclide analyses – such as ^{36}Cl in magnetite and also meteoric ^{10}Be.

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