



2024LS-01

京都大学防災研究所

Disaster Prevention Research Institute
Kyoto University

山岳地形の発達における間欠的地形プロセスの役割:
日本アルプスで構築したデータベースの再解析と新しい
宇宙線生成核種分析の試み

**The role of episodic geomorphic processes in mountainous
landscape evolution: Re-examination of established
database and challenges for novel cosmogenic nuclide
analysis in the Japanese Alps**

Principal Investigator:
Affiliation:
DPRI Contact Person:

Dr. Alexandru T. Codilean
University of Wollongong, Australia
Prof. Yuki Matsushi

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 July-August 2024 had two principal objectives: (1) reinforcing the longstanding research collaboration between Codilean and Matsushi, initiated in 2013 and previously supported by DPRI Research Visit grants, and (2) conducting fieldwork in Nagano Prefecture to resample small mountain rivers for cosmogenic nuclide analyses. Addressing the first objective, Codilean participated in a seminar series on Earth and Planetary Surface Processes, co-organized by Matsushi. Additionally, he joined a four-day field trip to the Noto Peninsula, Ishikawa Prefecture, alongside Matsushi and colleagues, including Prof. Tetsuya Kogure (DPRI), A/Prof. Hitoshi Saito (Nagoya University), Dr. Takuma Watakabe (Kansai Research Center), and graduate students Yoshimasa Ota and Arihito Kondo (both from DPRI). The fieldwork aimed to investigate coastline changes and landslides triggered by the 2024 Noto Earthquake. For the second objective, Codilean, Matsushi, Ota, and Saito undertook targeted fieldwork in Nagano Prefecture, resampling rivers previously studied during earlier visits funded by DPRI. This effort built upon a decade-long collaboration with DPRI, which has supported several research visits, generating a unique dataset comprising cosmogenic ^{10}Be , ^{26}Al , and ^{14}C measurements from river sediments in Japan's granitic mountain catchments. An initial DPRI Long-term Research Visit grant awarded in 2014 (26L-01) enabled Codilean, Matsushi, and University of Potsdam collaborators to sample river catchments in the central Japanese Alps, investigating temporal variations in denudation rates through cosmogenic ^{10}Be analyses. Subsequent funding from a 2023 DPRI Long-term Research Visit grant (2023LS-03) facilitated additional sampling in June 2023. Consequently, a globally unique dataset has been compiled, encompassing repeated sampling across 41 river catchments at intervals in August 2012, October 2014, June 2023, and July 2024. The new samples collected in 2024 were shipped to the University of Wollongong where they are undergoing preparation for analysis. Cosmogenic ^{10}Be analyses in a subset of the samples have been analysed in December 2024 and results are included in 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 in space — adjacent catchments will show a high variance in exported nuclide concentrations, and in time — 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.

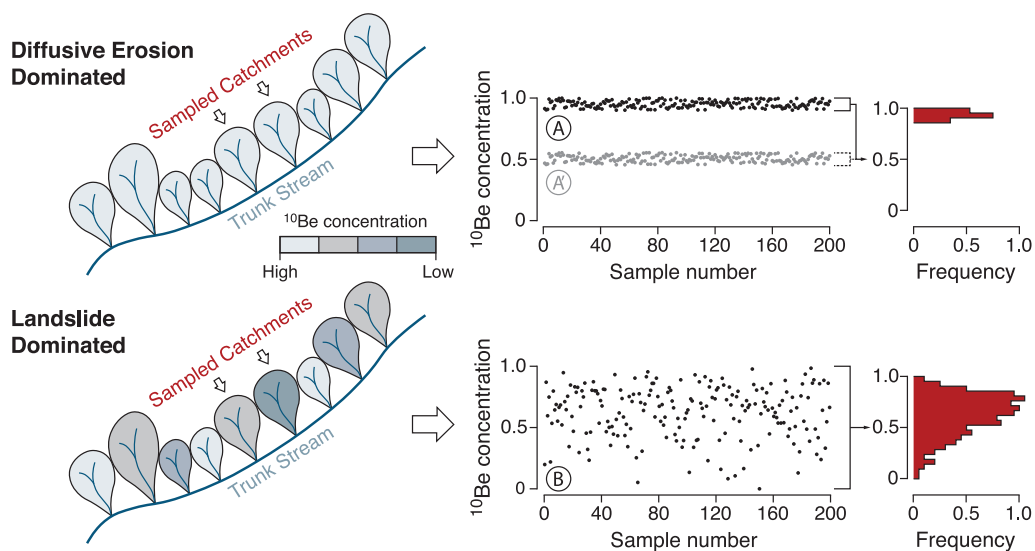


Figure 1: Adjacent catchments with no or low landslide occurrence or disturbance (A) will show a lower overall variance in ^{10}Be concentrations compared to those subjected to significant landslide disturbances (B). Plot axes are in arbitrary units.

Except for 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 $^{26}\text{Al}/^{10}\text{Be}$ and $^{14}\text{C}/^{10}\text{Be}$ 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 km², but most basins are below one km² in area. The median basin area is 0.5 km². The basins are adjacent to each other, and all occupy the same lithology – granitic rocks [25]. To date we have analysed ¹⁰Be and ²⁶Al in river sediment samples collected in August 2012 and ¹⁰Be, ²⁶Al, and ¹⁴C in samples collected in October 2014. We have also collected samples from the same basins in July 2023 and these have been processed for ¹⁰Be and ²⁶Al analyses, with analyses of ¹⁴C also planned in a selection of the samples.

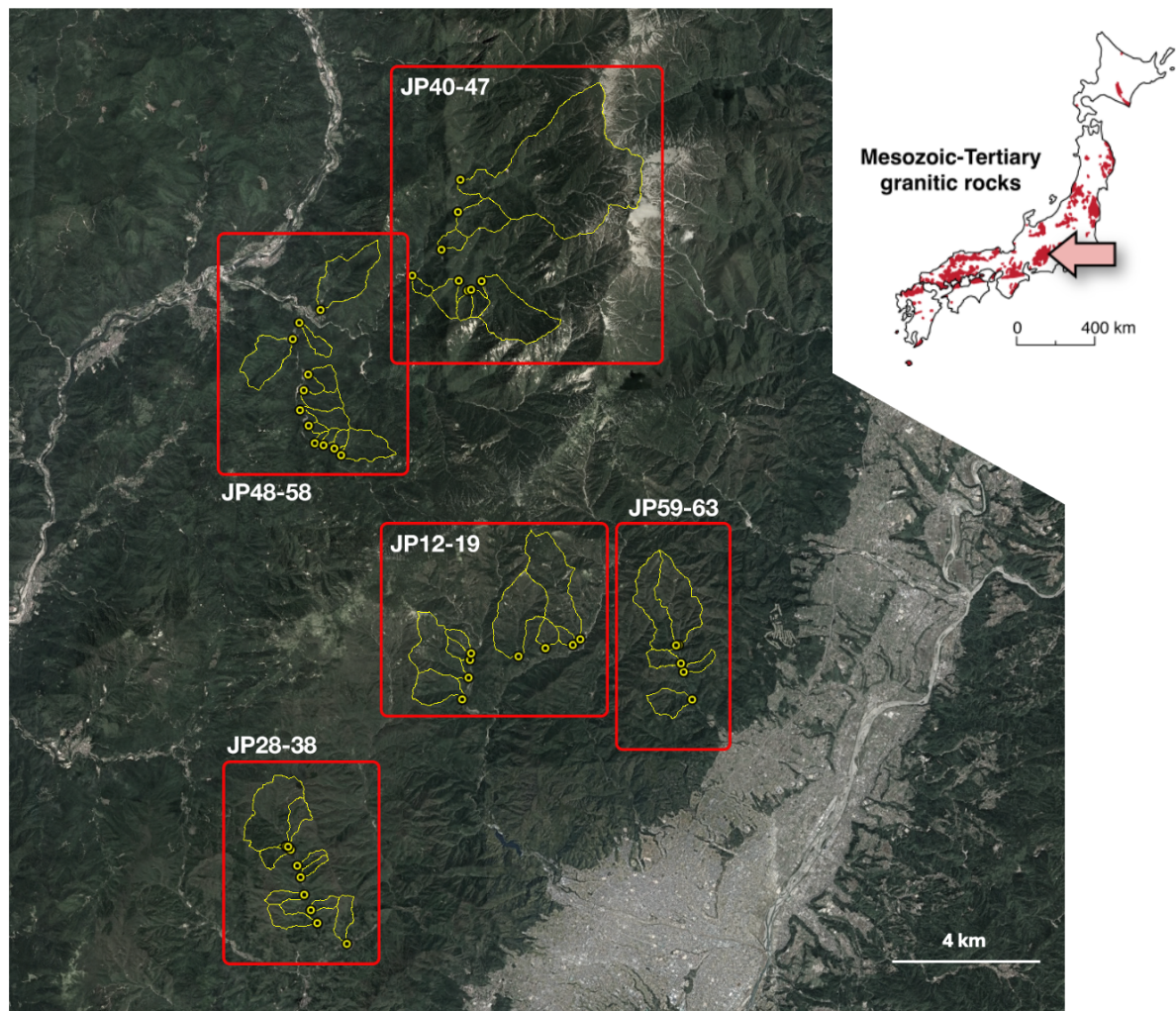


Figure 2: Location of study area. Yellow outlines show the 41 basins sampled in 2012, 2014, and 2023. Several of these basins were also resampled in 2024. Inset shows distribution of granitic rocks from Taira [25].

3. Apparent denudation rates

Figure 3 provides a summary of the apparent ¹⁰Be-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 spatial 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 ~ 3500 mm/kyr. The basins receive similar amounts of mean annual precipitation – between ~ 2000 and ~ 2600 mm.

Figure 3A shows some temporal variability in calculated denudation rates between 2012 to 2023, but the box plots do not consider the uncertainties on the calculated rates and so that makes the picture more complicated (see next section). Interestingly however, despite the variability in nuclide concentrations over time, the data show a strong correlation between ^{10}Be -derived denudation rates and mean basin gradient (Figure 3B). Similarly strong correlation is also observed for other topographic metrics (not shown).

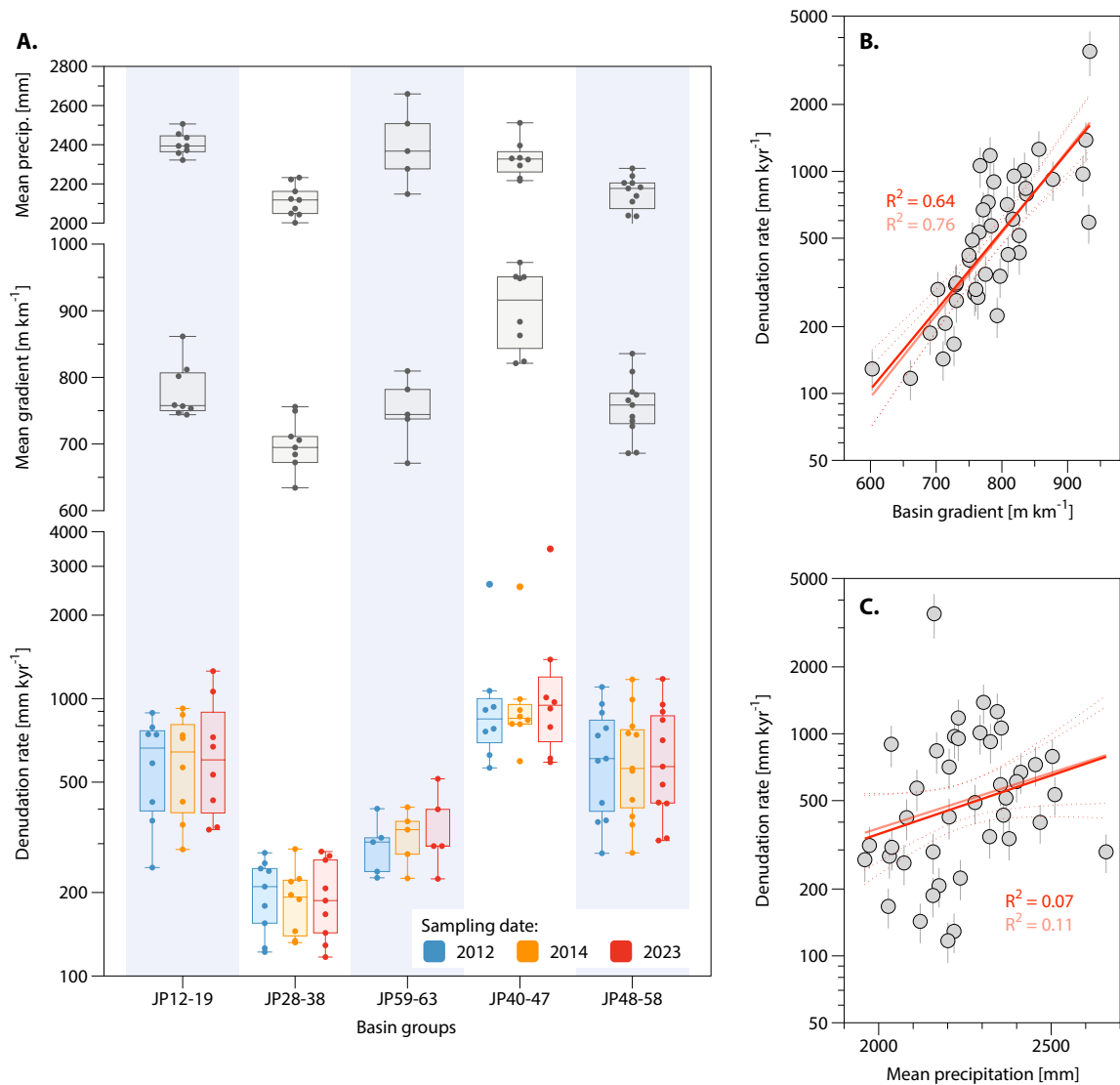


Figure 3: Summary of apparent denudation rates, mean basin gradient and mean annual precipitation values for the sampled basins. Denudation rates show a strong correlation with mean basin gradient (3B) but a weak correlation with mean annual precipitation (3C). Scatter plots in (B) and (C) show data from samples collected in 2023.

4. Rainfall intensity

We have analysed hourly rainfall data for each basin obtained from the Japan Meteorological Agency (JMA) [26] and have calculated time-series of rainfall event durations and intensities, and statistical return periods based on wider regional rainfall data. As expected, given the relatively small scale of the study area and the proximity of the sampled basins, rainfall patterns are largely similar across all basins (Figure 4).

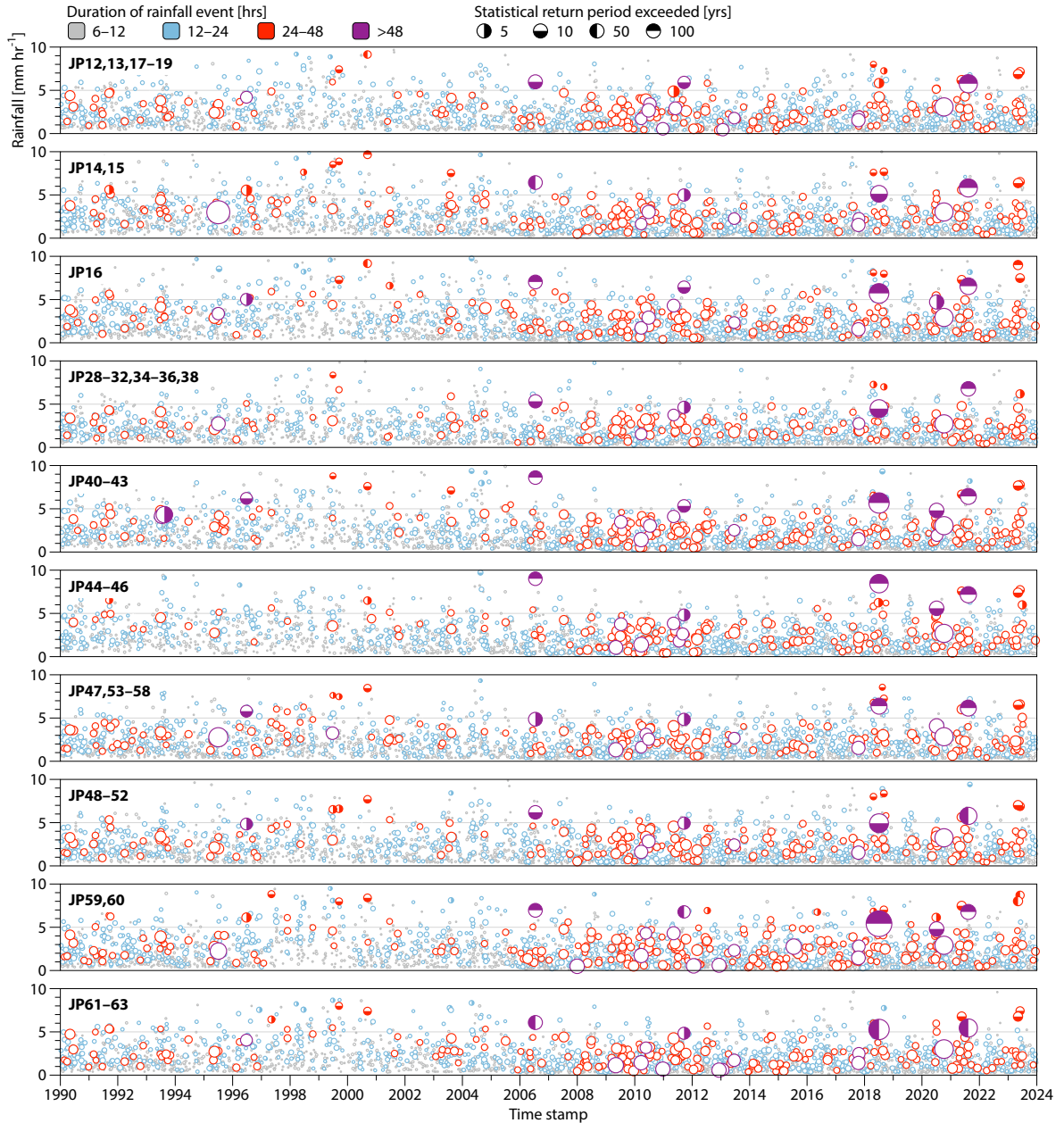


Figure 4: Duration (hours) and intensity (mm.hr^{-1}) of rainfall events for the study area for the period 1990 and 2024. The plot only show rainfall events that exceeded 6 hours in duration. The colour and size of the circles indicates duration of each rainfall event. Rainfall events exceeding statistical return periods of 5, 10, 50, and 100 years are highlighted.

Two observations regarding the rainfall data in Figure 4 are noteworthy: (1) we observe longer rainfall events after 2008 than before, and (2) basins have experienced several rainfall events that exceeded the 50- and 100-year statistical return periods between the 2014 and 2023 sampling periods. Although Figure 4 shows only a preliminary analysis of our rainfall data, in terms of forcing, it is clear that the study area has experienced extreme rainfall events that have likely triggered shallow landslides in between our sampling periods.

5. Temporal variation in measured ^{10}Be concentrations

As anticipated, variations in ^{10}Be abundances are observed across both high-concentration and low-concentration samples, occurring in both increasing and decreasing directions (Figures 5 and 6). For instance, in certain basins, the ^{10}Be concentration has steadily decreased (e.g., JP12, 17, 18, 42, 45), indicating a recent disturbance. Conversely, in other basins, the concentration has steadily increased (e.g., JP40 and 41), suggesting that the fluvial system is recovering toward an equilibrium state, with landslide-derived debris largely removed from the basin. Notably, we have identified several adjacent basins with identical geomorphic properties but opposing ^{10}Be trends (for example basins JP41 and 42; Figure 6).

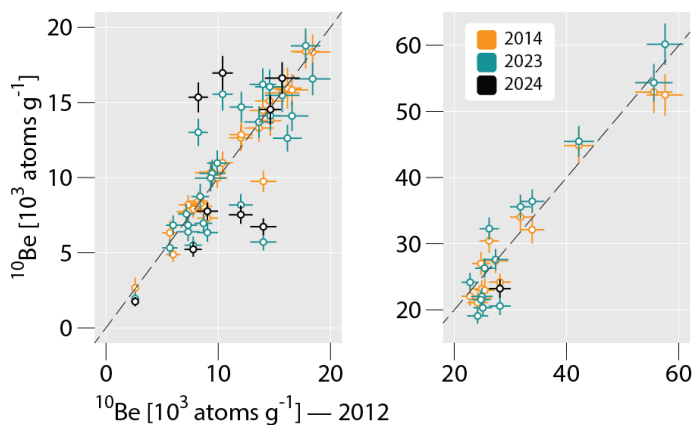


Figure 5: Comparison of ^{10}Be concentrations measured in samples collected in 2012 versus those collected in 2014, 2023, and 2024. Uncertainties are shown at 2-sigma level. Dashed line represents 1:1 line. Note how variations in ^{10}Be are observed across both high-concentration and low-concentration samples, occurring in both increasing and decreasing directions

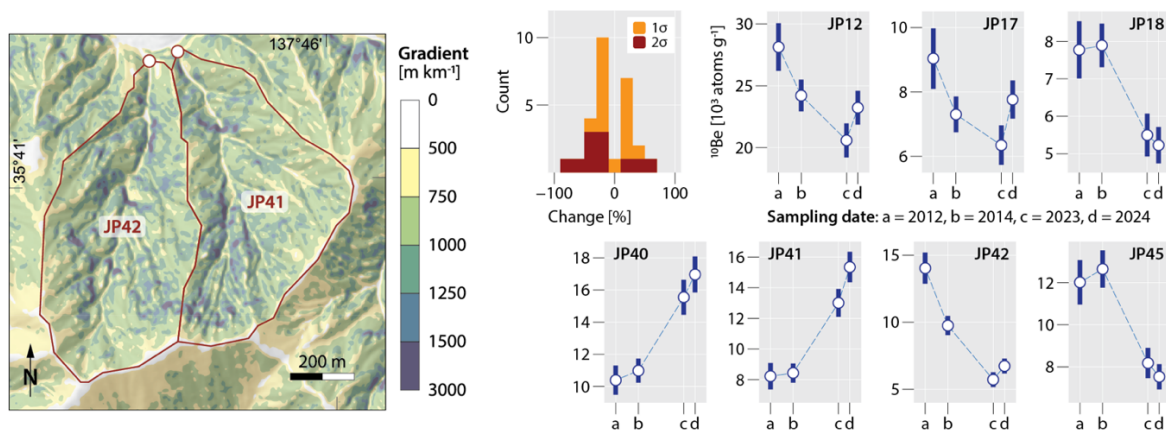


Figure 6: Topographic gradient in basins JP41 & JP42 (left), and cosmogenic ^{10}Be trends observed between 2012 and 2024 in selected basins (right). Note the opposing trends in the JP41 and JP42 samples. Uncertainties are shown at 2-sigma level.

Considering the entire dataset, the scale of change seems to correlate with topography (Figure 7), namely basins with steeper topographic gradients also tend to show the largest relative variance in ^{10}Be concentrations over the past 12 years. There is a strong correlation between maximum relative change in ^{10}Be and the gradient of zero-order channels (i.e., colluvial bedrock hollows) but no obvious correlation between maximum relative change in ^{10}Be and basin area – although the largest change is observed in the smallest basins.

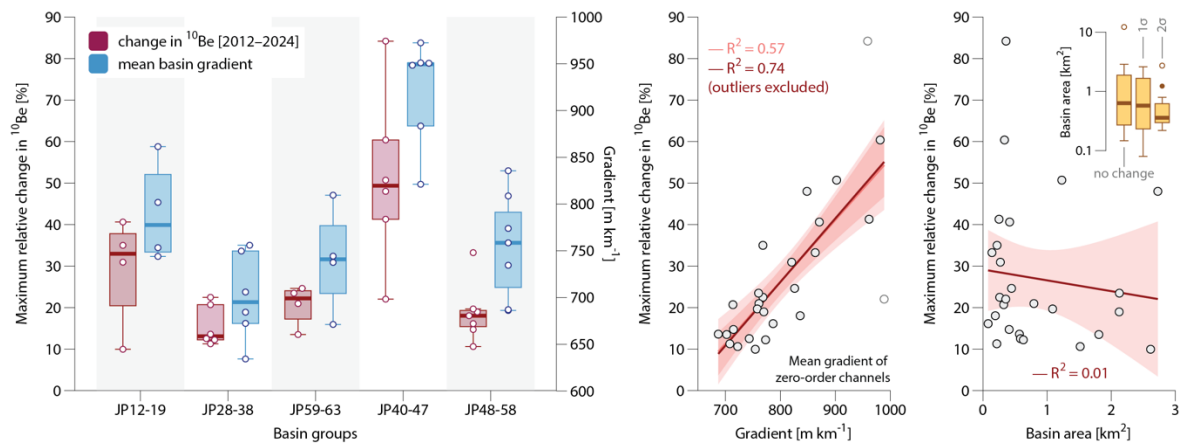


Figure 7: Relationship between maximum relative change in ^{10}Be , topographic gradient, and basin area. Note how the basins with the steepest topography also exhibit the larger relative variance in exported ^{10}Be concentrations.

6. $^{26}\text{Al}/^{10}\text{Be}$ and $^{14}\text{C}/^{10}\text{Be}$ ratios

$^{26}\text{Al}/^{10}\text{Be}$ ratios intersect the steady-state continuous erosion curve at 2-sigma for most samples with no trends apparent for the basins where changes in concentrations were detected between 2012 and 2023 (Figure 8). In-situ $^{14}\text{C}/^{10}\text{Be}$ ratios, paint a different picture, however, with all samples analysed plotting below the steady-state erosion curve (Figure 9).

There are two ways such depressed $^{14}\text{C}/^{10}\text{Be}$ ratios have been interpreted elsewhere. In a recent study from the Argentinian Andes by Slosson et al [27], depressed $^{14}\text{C}/^{10}\text{Be}$ ratios are interpreted as indicating transient storage in dynamic talus slopes in the steep topography of the High Andes. A similar interpretation was provided by Kober et al's [19] study looking at debris-flow-induced changes in ^{14}C and ^{10}Be in the Swiss Alps, their samples also deviating from the steady state erosion line. 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.

To explore sediment storage as a potential explanation for the depressed $^{14}\text{C}/^{10}\text{Be}$ ratios, we have run the numerical model CIDRE [28] that tracks grains through an evolving landscape and the evolution of their cosmogenic nuclide concentrations. Although the modeling exercises are still preliminary (Figure 10), they indicate clearly that although sediment grains with depressed $^{14}\text{C}/^{10}\text{Be}$ ratios may exist in the basin, the exported sediment mix sampled at the outlet of the basins needs to be dominated by the stored material for this to yield depressed $^{14}\text{C}/^{10}\text{Be}$ ratios (see red/blue circles in Figure 10; orange/red circles in Figure 11).

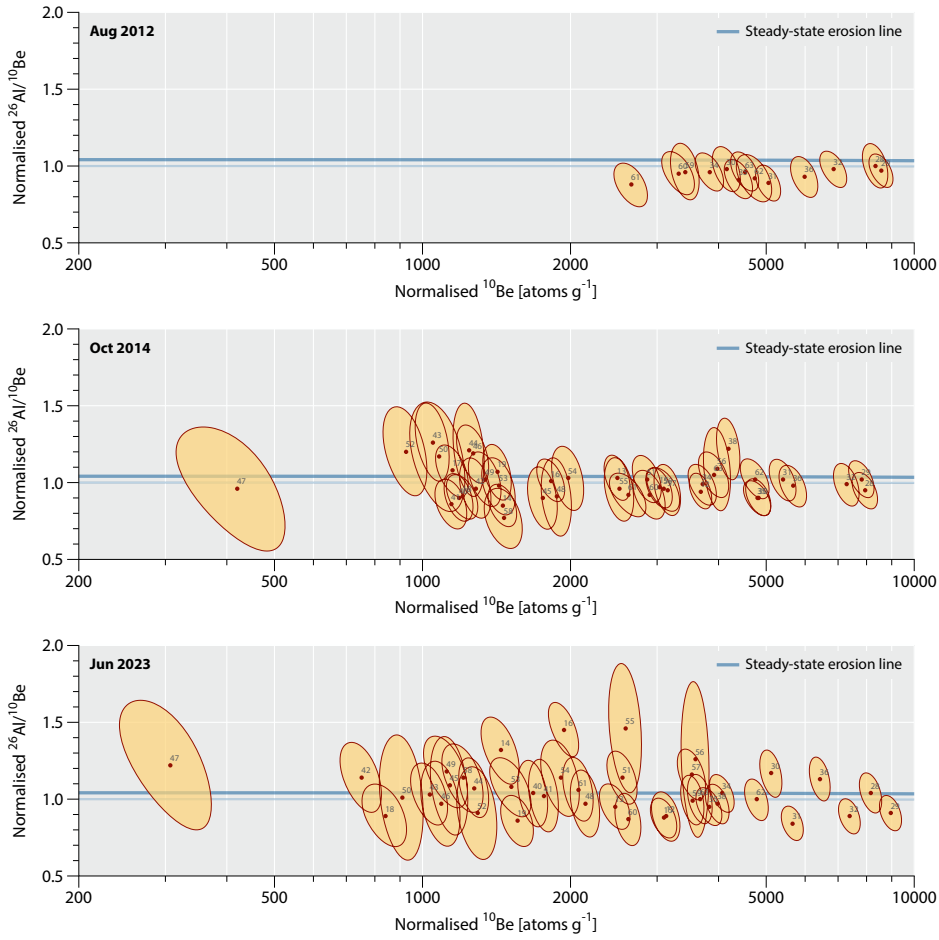


Figure 8: Normalised $^{26}\text{Al}/^{10}\text{Be}$ ratios vs normalized ^{10}Be concentrations.

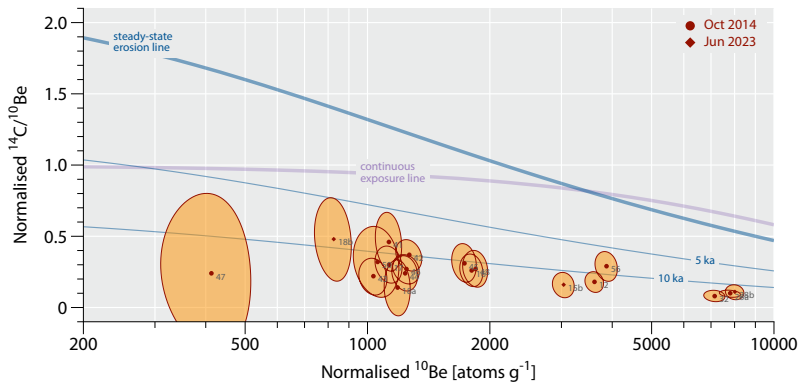


Figure 9: Normalised $^{14}\text{C}/^{10}\text{Be}$ ratios vs normalized ^{10}Be concentrations.

An alternative way to interpret depressed $^{14}\text{C}/^{10}\text{Be}$ ratios is via landscape transience, as has been suggested by recent numerical modelling studies [e.g., ^{29,30}]. The latter show that instantaneous removal of material from a hillslope – such as by a landslide – can theoretically result in depressed $^{14}\text{C}/^{10}\text{Be}$ ratios. The models considered by Mudd [²⁹] and Skov et al [³⁰] 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 likely higher, and disturbances are happening continuously.

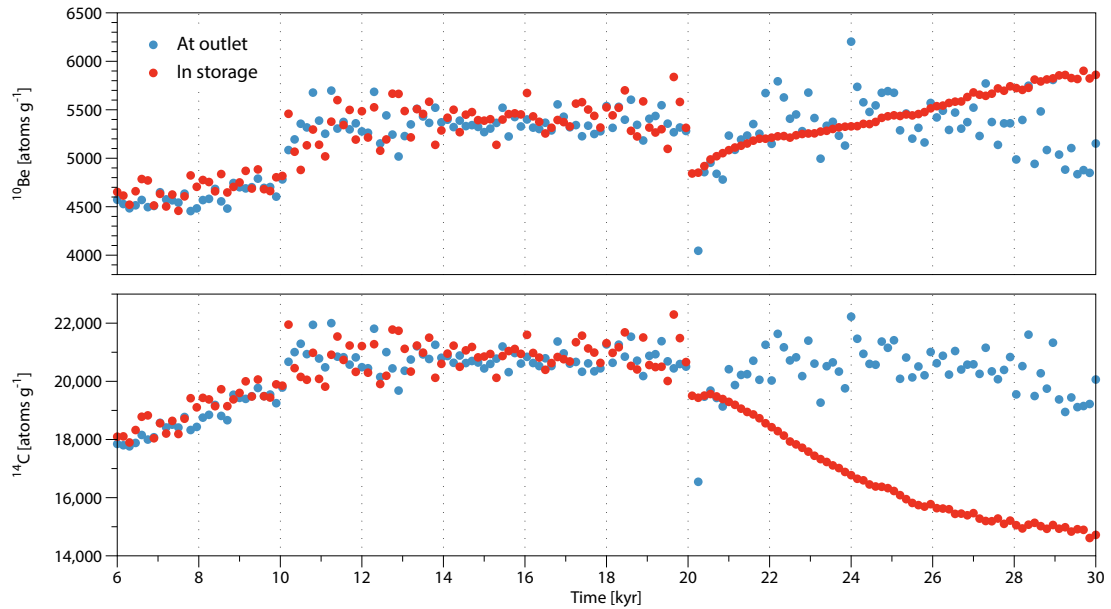


Figure 10: Temporal evolution of the average ^{10}Be and ^{14}C concentrations for a model simulation using the numerical model CIDRE [28]. The landscape domain is one drainage basin with an area of 1 square km and erosion rates and mean precipitation like that of our study area. The model is allowed to reach steady state and then it is perturbed at 10 kyr BP by large mass wasting event filling the valleys with sediment.

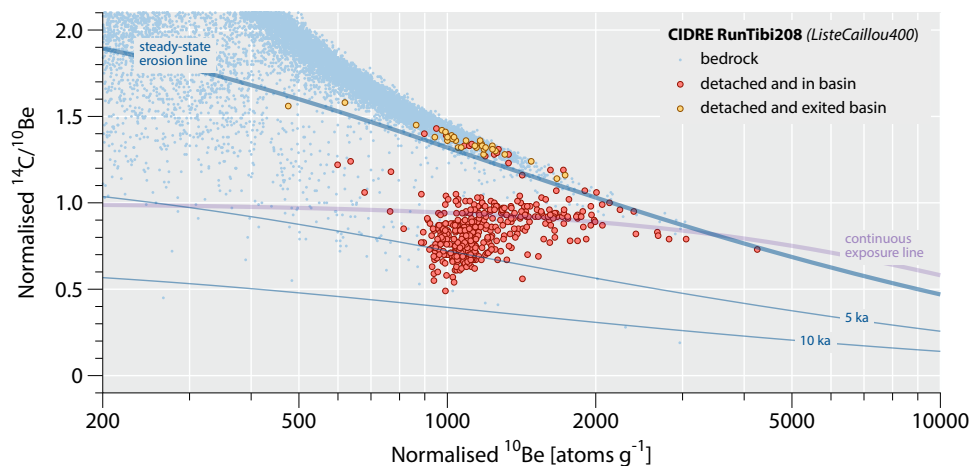


Figure 11: Normalised $^{14}\text{C}/^{10}\text{Be}$ ratios vs normalized ^{10}Be concentrations for the final timestep of the CIDRE [28] model simulation shown in Figure 10.

Lowering of $^{14}\text{C}/^{10}\text{Be}$ ratios in exported sediment is also possible via mixing of material originating from areas with contrasting erosion rates. This may be possible in situations where relict hillslope material is present in a basin and gets mobilized and delivered to the channel by processes such as shallow landsliding. Alternatively, continuous mixing of soils, may also result in depressed $^{14}\text{C}/^{10}\text{Be}$ ratios [31], however, extreme soil mixing scenarios would be required to yield $^{14}\text{C}/^{10}\text{Be}$ ratios as low as those obtained in our samples (see Figure 12).

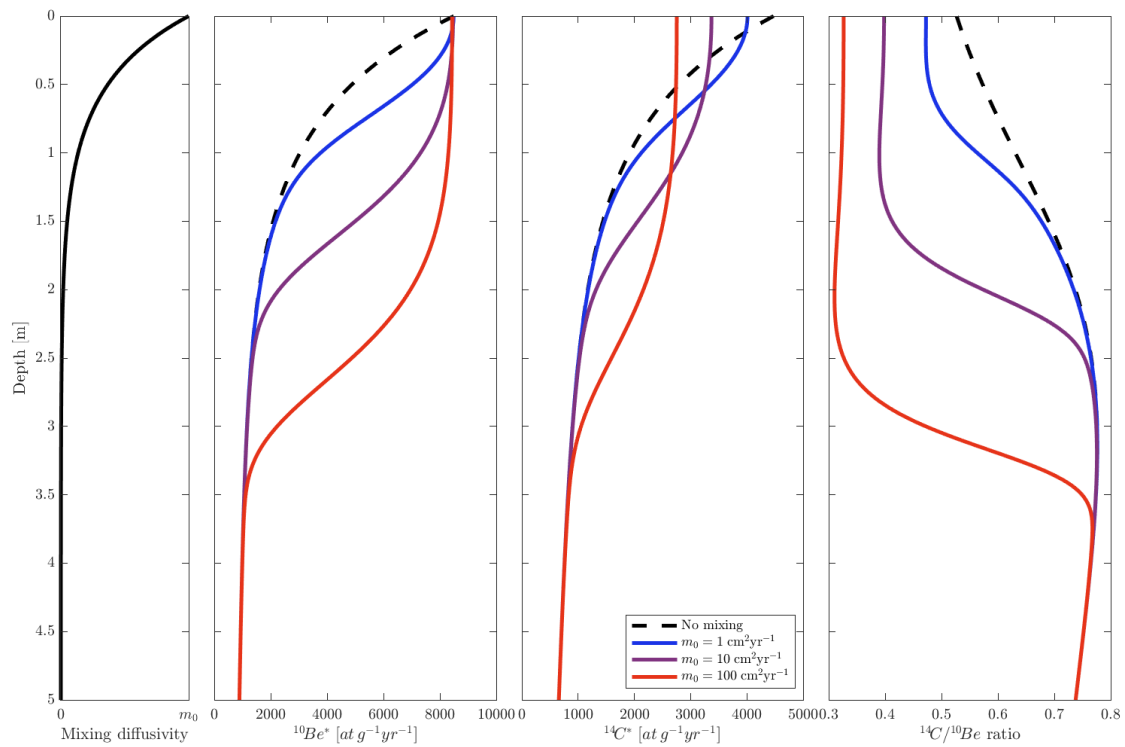


Figure 12: Results from a numerical model simulating non-uniform vertical mixing of soils with exponentially decreasing mixing intensities. The model assumes an erosion rate of 100 mm.kyr^{-1} and a soil mixing depth of 0.5 m . Surface mixing intensities are varied between 1 and $100 \text{ cm}^2.\text{yr}^{-1}$. For more detail about the model see Knudsen et al. 2019 [31].

7. Future work

This study is work in progress and we are yet to produce a satisfactory explanation for our $^{14}\text{C}/^{10}\text{Be}$ ratio data. In fact, deciding on which scenario is more likely (i.e., storage, mixing of sediment, vertical mixing of soils, landscape transience) requires further detailed fieldwork. To this end Codilean and Matsushi have obtained funding from DPRI (Grant 2025LS-01) for a research visit by Codilean and one PhD student from the University of Wollongong in June-July 2025. As part of the visit, we aim to also conduct field work in basins JP41 and JP42 (adjacent basins with identical geomorphic properties but opposing ^{10}Be trends; Figure 6), to collect soil samples from bedrock hollows and ridgelines for quantifying soil production rates and sediment residence times, thereby providing insights into the mechanisms driving the observed ^{10}Be trends and $^{14}\text{C}/^{10}\text{Be}$ ratios.

Acknowledgements

This is collaborative research, and several colleagues have made important contributions that we wish to acknowledge here. First, we acknowledge Drs. Reka-H. Fulop and Klaus Wilcken from the Australian Nuclear Science and Technology Organization for ^{10}Be , ^{26}Al , in-situ ^{14}C sample preparation and AMS measurement, A/Prof. Hitoshi Saito from Nagoya University for joining us in the field and analyzing the rainfall data, Dr. Sebastien Carretier from Géosciences Environnement Toulouse for adapting and running the CIDRE numerical model, and DPRI graduate students Yoshimasa Ota and Arihito Kondo for their support in the field. We also thank Prof David Egholm from Aarhus University for sharing the soil mixing model code.

References

1. Milliman, J. D. & Farnsworth, K. L. *River Discharge to the Coastal Ocean*. (Cambridge University Press, 2011). doi:10.1017/cbo9780511781247
2. Kumar, N., Anderson, R. F., Mortlock, R. A. & Froelich, P. N. Increased biological productivity and export production in the glacial Southern Ocean. *Nature* **378**, 675–680 (1995).
3. Jickells, T., An, Z. S., Andersen, K., Baker, A., Bergametti, G., Brooks, N., Cao, J., Boyd, P., Duce, R., Hunter, K., Kawahata, H., Kubilay, N., laRoche, J., Liss, P., Mahowald, N., Prospero, J., Ridgwell, A., Tegen, I. & Torres, R. Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science* **308**, 67–71 (2005).
4. Molnar, P. & England, P. Late Cenozoic Uplift of Mountain-Ranges and Global Climate Change - Chicken or Egg. *Nature* **346**, 29–34 (1990).
5. Raymo, M. E. & Ruddiman, W. F. Tectonic Forcing of Late Cenozoic Climate. *Nature* **359**, 117–122 (1992).
6. Whipple, K. X. The influence of climate on the tectonic evolution of mountain belts. *Nature Geoscience* **2**, 97–104 (2009).
7. Allen, P. A. From landscapes into geological history. *Nature* **451**, 274–276 (2008).
8. Romans, B. W., Castelltort, S., Covault, J. A., Fildani, A. & Walsh, J. P. Environmental signal propagation in sedimentary systems across timescales. *Earth-Science Reviews* **153**, 7–29 (2016).
9. Foster, G. L. & Vance, D. Negligible glacial–interglacial variation in continental chemical weathering rates. *Nature* **444**, 918–921 (2006).
10. Vance, D., Teagle, D. A. H. & Foster, G. L. Variable Quaternary chemical weathering fluxes and imbalances in marine geochemical budgets. *Nature* **458**, 493–496 (2009).
11. Zhang, P. Z., Molnar, P. & Downs, W. Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates. *Nature* **410**, 891–897 (2001).
12. Wittmann, H., Blanckenburg, F. von, Maurice, L., Guyot, J. L. & Kubik, P. W. Recycling of Amazon floodplain sediment quantified by cosmogenic ^{26}Al and ^{10}Be . *Geology* **39**, 467–470 (2011).
13. Fülöp, R.-H., Codilean, A. T., Wilcken, K. M., Cohen, T. J., Fink, D., Smith, A. M., Yang, B., Levchenko, V. A., Wacker, L., Marx, S. K., Stromsoe, N., Fujioka, T. & Dunai, T. J. Million-year lag times in a post-orogenic sediment conveyor. *Sci Adv* **6**, eaaz8845 (2020).
14. Jerolmack, D. J. & Paola, C. Shredding of environmental signals by sediment transport. *Geophysical Research Letters* **37** (2010).
15. Armitage, J. J., Duller, R. A., Whittaker, A. C. & Allen, P. A. Transformation of tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience* **4**, 231–235 (2011).
16. Blöthe, J. H. & Korup, O. Millennial lag times in the Himalayan sediment routing system. *Earth and Planetary Science Letters* **382**, 38–46 (2013).
17. Sklar, L. S. & Dietrich, W. E. A mechanistic model for river incision into bedrock by saltating bed load. *Water Resources Research* **40**, W06301 (2004).
18. Egholm, D. L., Knudsen, M. F. & Sandiford, M. Lifespan of mountain ranges scaled by feedbacks between landsliding and erosion by rivers. *Nature* **498**, 475–478 (2013).
19. Kober, F., Hippe, K., Salcher, B., Ivy-Ochs, S., Kubik, P. W., Wacker, L. & Hähnen, N. Debris-flow–dependent variation of cosmogenically derived catchment-wide denudation rates. *Geology* **40**, 935–938 (2012).
20. Foster, M. A. & Anderson, R. S. Assessing the effect of a major storm on ^{10}Be concentrations and inferred basin-averaged denudation rates. *Quaternary Geochronology* **34**, 58–68 (2016).
21. Gonzalez, V. S., Schmidt, A. H., Bierman, P. R. & Rood, D. H. Spatial and temporal replicability of meteoric and in situ ^{10}Be concentrations in fluvial sediment. *Earth Surf. Process. Landforms* **42**, 2570–2584 (2017).

22. Grande, A., Schmidt, A. H., Bierman, P. R., Corbett, L. B., López-Lloreda, C., Willenbring, J., McDowell, W. H. & Caffee, M. W. Landslides, hurricanes, and sediment sourcing impact basin-scale erosion estimates in Luquillo, Puerto Rico. *Earth Planet Sc Lett* **562**, 116821 (2021).
23. Knudsen, M. F. & Egholm, D. L. Constraining Quaternary ice covers and erosion rates using cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ nuclide concentrations. *Quaternary Sci Rev* **181**, 65–75 (2018).
24. Godard, V., Salgado, A., Siame, L., Fleury, J. & Team, A. Transient hillslope erosion in slow evolution landscapes. *Earth Surf Processes* **46**, 2485–2500 (2021).
25. Taira, A. Tectonic evolution of the Japanese island arc system. *Annual Review of Earth and Planetary Sciences* **29**, 109–134 (2001).
26. Makihara, Y. A method for improving radar estimates of precipitation by comparing data from radars and raingauges. *Journal of the Meteorological Society of Japan* **74**, 459–480 (1996).
27. Slosson, J. R., Hoke, G. D. & Lifton, N. Non-Steady-State ^{14}C - ^{10}Be and Transient Hillslope Dynamics in Steep High Mountain Catchments. *Geophys. Res. Lett.* **49**, (2022).
28. Carretier, S., Regard, V., Abdelhafiz, Y., & Plazolles, B. Modelling detrital cosmogenic nuclide concentrations during landscape evolution in Cidre v2.0. *Geoscientific Model Development*, **16(22)**, 6741–6755 (2023).
29. Mudd, S. M. Detection of transience in eroding landscapes. *Earth Surface Processes and Landforms* **42**, 24–41 (2016).
30. Skov, D. S., Egholm, D. L., Jansen, J. D., Sandiford, M. & Knudsen, M. F. Detecting landscape transience with in situ cosmogenic ^{14}C and ^{10}Be . *Quaternary Geochronology* **54**, 101008 (2019).
31. Knudsen, M. F., Egholm, D. L., & Jansen, J. D. Time-integrating cosmogenic nuclide inventories under the influence of variable erosion, exposure, and sediment mixing. *Quaternary Geochronology*, **51**, 110–119 (2019).