COSMO
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SCOTLAND

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We appreciate Zsófia Ruszkiczay-Rüdiger for helping on the science committee. Thanks to everyone at SUERC who helped with the tours!

Workshop Sponsors

BSG Conference Grant BSG-2020-15

Welcome to the continuation of the Nordic Cosmo Conferences – dipping slightly further south to Edinburgh!

Venue:
The workshop will be held in the Edinburgh Climate Change Institute (ECCI) on the University of Edinburgh campus. The building is located at High School Yards, Edinburgh EH1 1LZ (directions here: https://edinburghcentre.org/contact/how-to-get-here).

Format:
We have a variety of keynote talks alongside posters & talks from participants, with plenty of time for somewhat organised discussions on requested topics and informal chats.

SUERC Tour:
This is an optional tour on Monday, 6 June 2022 at 11:00, where you will get to see the AMS, laboratories, and discuss details of sample prep and measurement. Lunch will be provided.

Main Programme:
In general, we will have sessions from Tuesday morning until Thursday afternoon. However, each day is slightly different because we have amended the schedule to include a late start after the conference dinner and an early finish on the last day to accommodate travel home, so please check the conference schedule.

Conference Dinner:
We have a conference dinner on Wednesday night (included with your registration) which will be held at the Ghillie Dhu (https://ghillie-dhu.co.uk/, 2 Rutland Place, Edinburgh, EH1 2AD). Doors open at 6pm for socialising, dinner starts at 7pm, and the band starts at 9pm. The evening includes a 3-course meal featuring classic Scottish fare, followed by a ceilidh (pronounced kay-lee). This is a fun dance for all with a caller to provide instructions. We'll be there to help you out, but it's easy to pick up and fun for everyone! You can get an idea on this website: https://www.inlingua-edinburgh.co.uk/what-is-the-scottish-ceilidh-and-ceilidh-dancing/

Field Trip:
The optional field trip will be held on the 10th June, departing the ECCI at 8am. We will travel by coach to Rannoch Moor, western Scotland. On the way you will get a flavour of the Scottish Highlands and view areas of hummocky moraine, a classic Scottish glacial landform.
Schedule:
08:00 – depart from ECCI, Edinburgh
10:15 – comfort stop at The Green Wellie, Tyndrum (10:30)
11:00 – start walk to Ralston Cairn for the view and discussion about sampling
12:30 – Lunch near Kingshouse Hotel
13:30 – Discussion about production rates
17:00 – Return to ECCI
The walks are on well-made paths except for 200 metres cross country (includes boulder hopping across a stream). So far everyone I have seen going across has stayed dry.

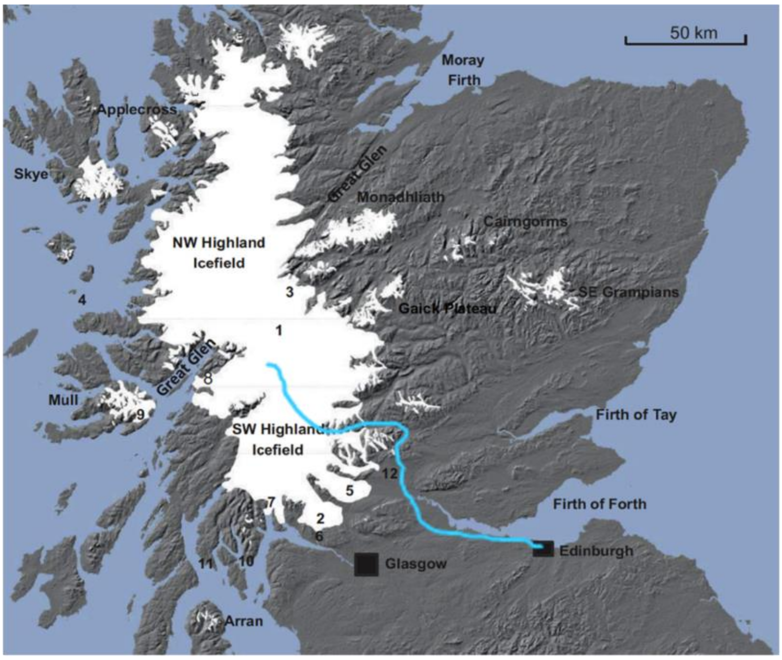

Fig. 1 The maximal glacial limits of the Loch Lomond ('Younger Dryas') Readvance in mainland Scotland and the Inner Hebrides (after Lowe et al. 2019).

The deglaciation age of Rannoch Moor has recently been debated (Bromley et al. 2014; Small and Fabel, 2016a, 2016b; Bromley et al 2016) because of the interpretation of radiocarbon ages published in Bromley et al. 2014. Putnam et al. (2019) used the controversial independent age control to establish a new ^{10}Be production rate calibration data set. Lowe et al (2019) collected more cores from Rannoch Moor and present radiocarbon ages which support the previous understanding of the deglaciation age, while Palmer et al. (2020) tie the deglaciation history to the Lochaber Master Varve Chronology 2019. There will be plenty to discuss…

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Bickerdike, H.L., Evans, D.J.A., Stokes, C.R., O Cofaigh, C., 2018. The glacial geomorphology of the Loch Lomond (Younger Dryas) Stadial in Britain: a review. J. Quaternary Sci 33, 1–54. https://doi.org/10.1002/jqs.3010

Bromley, G.R.M., Putnam, A.E., Lowell, T.V., Hall, B.L., Schaefer, J.M., 2016. Comment on "Was Scotland deglaciated during the Younger Dryas?" by Small and Fabel (2016). Quaternary Sci Rev 152, 203–206. https://doi.org/10.1016/j.quascirev.2016.09.025

Lowe, J., Matthews, I., Mayfield, R., Lincoln, P., Palmer, A., Staff, R., Timms, R., 2019. On the timing of retreat of the Loch Lomond ('Younger Dryas') Readvance icefield in the SW Scottish Highlands and its wider significance. Quaternary Science Reviews 219, 171–186. https://doi.org/10.1016/j.quascirev.2019.06.034

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COSMO 2022 SCOTLAND

Workshop Programme
ECCI, Edinburgh 7-9 June 2022

Tuesday, 7 June 2022

09:00 – 09:40	Registration & Welcome	
Session 1: Scaling		[Chair: Shasta Marrero]
09:45 - 10:30	**Keynote: Nat Lifton**	**Advances in cosmogenic nuclide production rate scaling: how we got here and potential opportunities ahead**
10:30 - 11:40	Poster Kickoff & Coffee	[Authors & titles at end]
11:40 - 12:30	**Discussion:** Scaling, 14C	
12:30 - 13:30	*Lunch & Posters*	
Session 2: Glacial Landscape Evolution		[Chair: Andy Hein]
13:30 - 14:15	**Keynote: Irene Schimmelpfennig**	**Holocene glacier advance and retreat chronologies: novel contributions involving 36Cl and 14C**
14:20 - 14:40	Annina Margreth	EVOLUTION OF GLACIATED LANDSCAPES – GLACIAL EROSION VS. WEATHERING
14:40 - 15:00	Tancrède Leger	Geomorphology and 10Be chronology of the Last Glacial Maximum and deglaciation in northeastern Patagonia, 43°S-71°W
15:00 - 15:30	*Coffee and Posters*	
15:30 - 15:50	Maria Paz Lira	Evolution of the Seno Skyring ice lobe (52°S) during the last glacial cycle, Southernmost Patagonia
15:50 - 16:10	Sophie Norris	Rapid retreat of the southwestern Laurentide Ice-Sheet during the Bølling-Allerød interval
16:10 - 16:50	**Discussion:** Multi-nuclide	

Wednesday, 8 June 2022

Session 3: Denudation rates, incision and uplift		[Chair: Martin Hurst]
09:00 - 09:45	**Keynote: Simon Mudd**	**Tracing transient landscapes with the 14C/10Be pair**
09:50 - 10:10	Clement Desormeaux	Using 10Be-derived denudation rates to test river incision models across a Climatic and Morphological gradient
10:15 - 11:00	*Coffee and Posters*	
11:00 - 11:20	Duna Roda-Boluda	IMPORTANCE OF PERIGLACIAL AND PARAGLACIAL EROSION IN THE WESTERN SOUTHERN ALPS OF NEW ZEALAND
11:20 - 11:40	Aidan McLean	A LATE-HOLOCENE RECORD OF MARINE TERRACE UPLIFT AT NEEDLES PT, MARLBOROUGH, FROM COSMOGENIC 10BE, INDICATES REVISED HOLOCENE EARTHQUAKE INTENSITY FOR NORTHEAST SOUTH ISLAND, NEW ZEALAND
11:40 - 12:00	Gerald Raab	Determining relief evolution in the Alps with muon paleotopometry
12:30 - 13:30	*Lunch & Posters*	

Wednesday, 8 June 2022 (cont)

Session 4: Noble Gas		[Chair: Derek Fabel]
13:30 - 14:15	**Keynote: Tibor Dunai**	**In situ-produced cosmogenic krypton in zircon: a valuable addition to the terrestrial cosmogenic tool box**
14:20 - 14:40	Finlay Stuart:	Cosmogenic Ne provides first constraints on the complex burial history of lunar regolith from Apollo 12 basaltic soil grains
14:40 - 15:00	Isaac Larsen	DATING THE CHANNELED SCABLAND: INSIGHTS ON 3He PRODUCTION SYSTEMATICS FROM MEASUREMENTS ON FINE-GRAINED MINERALS IN OLD BASALT
15:00 - 15:30	*Coffee and Posters*	
15:30 - 15:50	Luigia Di Nicola:	High precision cosmogenic Ne measurements on small samples using Thermo Fisher ARGUS VI
15:50 - 16:10	Ana Carracedo-Plumed:	Long-term survival of detrital gold in glaciated landscape based on cosmogenic 3 He in detrital grains from Scotland
16:10 - 16:30	**Discussion:** Noble Gas	
18:00 - ????	**CONFERENCE DINNER & CEILIDH**	**[**Ghillie Dhu]

Thursday, 9 June 2022

Session 5: Burial dating and isochrons		[Chair: Angel Rodés]
10:30 - 11:00	*Coffee and Posters*	
11:00 - 11:20	Catharina Dieleman:	Constraining the timing of gravel accumulation in glaciated landscapes: Insights from the Swiss northern Alpine Foreland
11:20 - 11:40	Zsófia Ruszkiczay-Rüdiger:	COMPARISON OF THREE COSMOGENIC RADIONUCLIDE METHODS OF SEDIMENT BURIAL DATING
11:40 - 12:30	**Discussion:** Data analysis	
12:30 - 13:30	*Lunch & Posters*	

Session 6: Meteoric/authigenic		[Chair: Zsofia Ruszkiczay-R.]
13:30 - 14:15	Joseph Graly	Meteoric 10Be speciation in Antarctic subglacial sediments as a chemical and chronological tracer
14:20 - 14:40	Kishan Aherwar	DATING THE EXISTENCE DURATION AND REGRESION OF THE TURIEC LAKE IN WESTERN CARPATHIANS, SLOVAKIA, WITH AUTHIGENIC 10BE/9BE DATING METHOD
14:40 - 15:00	Michal Sujan	VARIABILITY OF THE AUTHIGENIC 10BE/9BE IN OFFSHORE TO DELTAIC SEDIMENTS IN EPICONTINENTAL BASIN SEQUENCES AND ITS RELEVANCE FOR GEOCHRONOLOGY
15:00 - 15:30	Organising Committee	Discussion and closing remarks

Posters [Available for the entire workshop]

Jane Lund Andersen	LONG-TERM EAST ANTARCTIC NUNATAK EXPOSURE AND EROSION CONSTRAINED BY INVERSE MODELLING OF COSMOGENIC MULTI-NUCLIDE INVENTORIES (36Cl, 26Al, 10Be, 21Ne) IN BEDROCK
Ariane (Steve) Binnie	Drivers of river incision in the Atacama Desert
Ewelina Bros	ISOCHRON-BURIAL DATING OF THE OLDEST GLACIOFLUVIAL SEDIMEMTS IN THE NORTHERN ALPINE FORELAND
Liesa Brosens	The slow downwearing of an island: inferring patterns and controls on long-term basin-averaged erosion rates from in situ 10Be in Madagascar
François Clapuyt	To what extent landslides affect 10Be-derived catchment-averaged denudation rates?
Felix Hofmann	CHRONOLOGY OF THE LATE PLEISTOCENE GLACIATION OF THE SOUTHERN BLACK FOREST, GERMANY: 10BE COSMIC-RAY EXPOSURE DATING OF MORAINES
Angus Moore	Unique altitude scaling of cosmogenic 36Cl production on Fe
Jesper Nørgaard	P-PINI: A cosmogenic nuclide burial dating method for landscapes undergoing non-steady erosion
Kevin Norton	DILUTION OF 10BE IN FLUVIAL SEDIMENT OF MULTIPLE GRAIN SIZES FROM THE 2016 KAIKōURA, NEW ZEALAND M7.8 EARTHQUAKE ITS INSIGHTS INTO LANDSLIDE SEDIMENT DYNAMICS
Rose Paque	USING METEORIC 10BE TO ASSESS SOIL EROSION RATES IN VOLCANIC ECOSYSTEMS (GALAPAGOS, ECUADOR)
Duna Roda-Boluda	TRACK & TRACE: TRACKING LANDSLIDE RECURRENCE INTERVALS AND TRACING LANDSLIDE-SOURCED SEDIMENT WITH IN-SITU 10Be AND 14C
Zsofia Ruszkiczay-R.	INHERITED COSMOGENIC NUCLIDE INVENTORY IN THE CIRQUE AREA OF FORMERLY GLACIATED MOUNTAIN RANGES OF SOUTHEASTERN EUROPE
Anne Sofie Søndergaard	Developing the first North Greenland in-situ 14C chronology
Arjen Stroeven	PALEOEARTHQUAKE RECONSTRUCTION ON AN IMPURE LIMESTONE FAULT SCARP
Michal Sujan	REDEPOSITION OF MUD DURING RIVER INCISION AFFECTS THE AUTHIGENIC 10BE/9BE DATING: MAMMAL FOSSIL-BEARING SITE NOVÁ VIESKA, WESTERN SLOVAKIA
Sheng Xu	High 26Al/10Be ratios in granitic regolith and their implications

DATING THE EXISTENCE DURATION AND REGRESION OF THE TURIEC LAKE IN WESTERN CARPATHIANS, SLOVAKIA, WITH AUTHIGENIC ^{10}BE/^{9}BE DATING METHOD.

Kishan Aherwar[1], Michal Šujan[1], Rastislav Vojtko[1], Régis Braucher[2], Andrej Chyba[3], Jozef Hók[1], Barbara Rózsová[1], Aster Team[2]

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The principle of authigenic ^{10}Be/^{9}Be dating method is similar to any other radiometric dating method which utilizes the equation $N=N_0\ e^{-\lambda t}$. However, the different source of the isotopes ^{9}Be (from weathering of rock massifs) and ^{10}Be (from atmosphere, through spallation reaction) brings some difficulties in direct application of the authigenic ^{10}Be/^{9}Be dating method. The different sources of both isotopes make determination of the initial ratio important to obtain reliable depositional ages.

According to previous studies the Turiec Lake existed from Late Middle Miocene to Pliocene in the heart of the Western Carpathians in the Turiec Basin. The authigenic ^{10}Be/^{9}Be dating method was applied to determine the existence duration and regression of the long-lived Lake Turiec. Altogether 35 samples were collected from 11 different localities of the basin representing different sedimentary environment such as lacustrine, fan delta, alluvial fan and braided river. Four different localities, Late Pleistocene alluvial fans Veľký Čepčín and Malý Čepčín, Holocene river floodplains Košťany and Kalamová were considered for determining the initial ratio. The weighted mean initial ratios from Malý Čepčín and Kalamová were ~5.20 × 10^{-9} and ~6.32 × 10^{-9} respectively. The initial ratio from Veľký Čepčín has weighted mean value of ~1.43 × 10^{-9} and from Košťany was ~10.07 × 10^{-9}. We hypothesize that this difference in initial ratio of samples from these different localities is attributed to the reasons such as: (i) Veľký Čepčín and Malý Čepčín successions were deposited in a glacial period while Košťany and Kalamová were deposited in interglacial, (ii) Veľký Čepčín was deposited in higher sedimentation rate settings and is topographically elevated, while Koštany and Kalamová were deposited with low sedimentation rate and might potentially be affected by post-depositional processes related to the presence of groundwater in low topography settings. The relative position of the Malý Čepčín succession is less elevated than Veľký Čepčín and implies also likely influence of groundwater.

Weighted mean depositional ages calculated using N_0 from Veľký Čepčín imply that the Lake Turiec existed from ~9.96 Ma for more than 3.25 Myr and regression of the lake begun nearly ~6.71 Ma. The initial ratio from the Veľký Čepčín alluvial fan was used for all other localities representing lacustrine, fan delta, alluvial fan and braided river to determine ages, because it is the only N_0 in agreement with the independent age proxies indicating that the lacustrine deposits cannot be older than 11.6 Ma. Ongoing analyses of paleoenvironmental conditions are aimed to provide more robust argumentation for N_0 selection.

The presented application of authigenic ^{10}Be/^{9}Be yielded a first radiometric age of long-lived Lake Turiec as compared to roughly estimated age described in previous studies of the Turiec Basin. This novel method also appeared as a promising dating tool to determine the beginning of regression of the lake in an intermontane settings with complicated tectonic and sedimentary history.

The study was supported by the Slovak Research and Development Agency under contract APVV-20-0120.

LONG-TERM EAST ANTARCTIC NUNATAK EXPOSURE AND EROSION CONSTRAINED BY INVERSE MODELLING OF COSMOGENIC MULTI-NUCLIDE INVENTORIES (^{36}Cl, ^{26}Al, ^{10}Be, ^{21}Ne) IN BEDROCK

Jane Lund Andersen[1,2], Jennifer C.H. Newall[2,3,4], Ola Fredin[5], Neil F. Glasser[6], Nathaniel A. Lifton[4,7], Alexandria Koester[4], Derek Fabel[8], Fin Stuart[8], Marc W. Caffee[4,7], Vivi K. Pedersen[1], David L. Egholm[1], Yusuke Suganuma[9,10], Jonathan M. Harbor[2,4,11], Arjen P. Stroeven[2,3]

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The impact of late Cenozoic climatic changes on the configuration of the East Antarctic Ice Sheet (EAIS) is uncertain. While the EAIS margins likely extended close to the continental shelf edge along most of the perimeter during phases of Pleistocene global cooling, the interior ice sheet thinned due to moisture starvation from a cooler and more distal Southern Ocean. Yet, the spatial pattern of relative thinning and thickening remains sparsely constrained, impairing the reconstruction of past global sea-level budgets. The low erosion rates associated with the hyper arid polar climate in East Antarctica present a challenge for dating the last ice retreat, owing to inheritance of cosmogenic nuclides accumulated during previous exposure periods. However, the low erosion rates simultaneously provide an opportunity to explore the long-term ice-sheet history, because inherited cosmogenic nuclides retain a memory of past exposure, burial, and erosion. We apply Markov Chain Monte Carlo (MCMC) inverse modelling of cosmogenic ^{36}Cl, ^{26}Al, ^{10}Be, and ^{21}Ne in bedrock to quantify the long-term erosion and ice-cover histories of mountains protruding the EAIS along the Jutulstraumen Ice Stream and in Heimefrontfjella in western Dronning Maud Land (Fig. 1). Our findings demonstrate that during the last 1 Myr the EAIS experienced only brief episodes of thicker-than-present ice in Heimefrontfjella, while the EAIS covered sample sites along Jutulstraumen for up to 90% of the time as it thickened ~300 m above the present-day ice sheet. For both regions, samples collected above c. 1.7 km a.s.l. have resided within 1 m of the present-day surface since the Late Miocene or Pliocene, with low erosion (<20 cm) and limited ice-cover duration (<20 %) during the last 1 Myr.

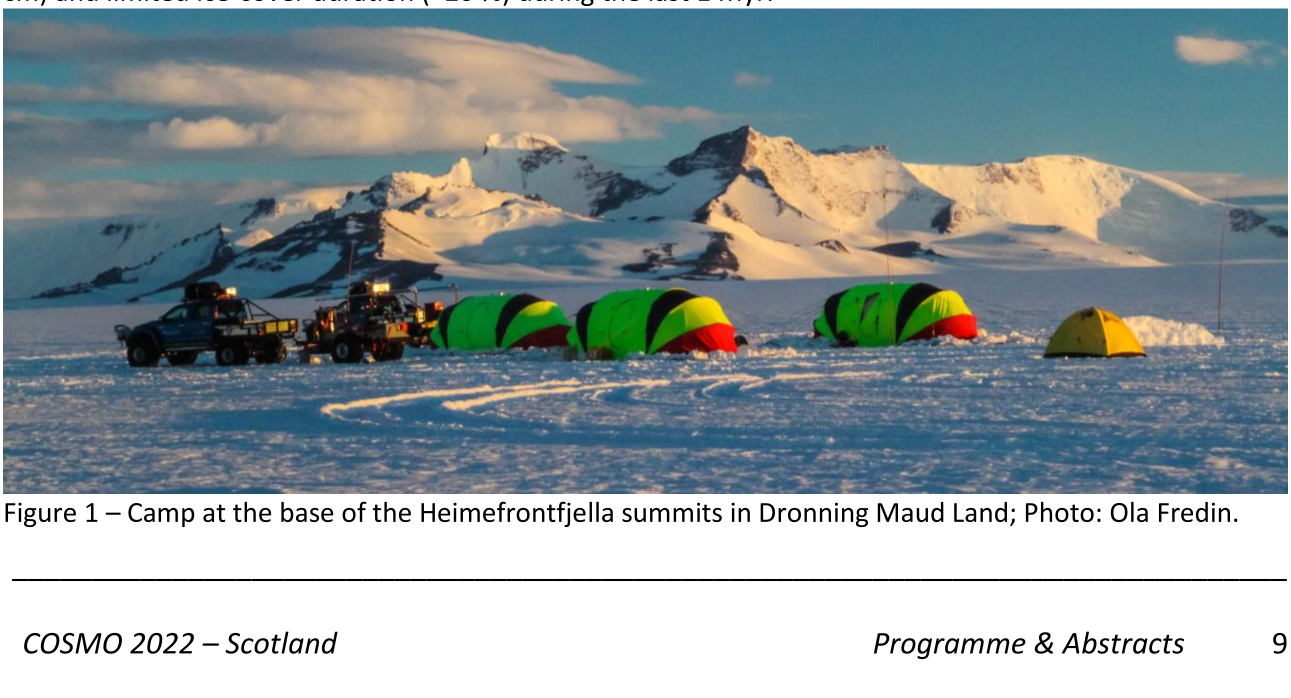

Figure 1 – Camp at the base of the Heimefrontfjella summits in Dronning Maud Land; Photo: Ola Fredin.

Drivers of river incision in the Atacama Desert

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The Atacama Desert in northern Chile is considered to be the driest, oldest desert on Earth. None-the-less, even the hyperarid core of this desert is host to several deeply incised, fluvially active river canyons. The rivers that are running though these canyons source their discharge from the high Andes and Precordillera and flow west through the hyperarid Atacama. While many rivers have managed to cut through the intervening Coastal Cordillera on their way to the Pacific Ocean, others are endorheic, terminating in the Central Depression, a foreland basin lying between the Andes and the coastal mountain range. The history of these drainages is tied to the tectonic and climatic evolution of the region, however, the timing and hence the mechanisms driving canyon formation are poorly constrained.

We have used cosmogenic ^{10}Be exposure ages to define the Quaternary incision history for the southern tributary of the Tiliviche River, which exits to the Pacific approximately 19.5°S. Ages from flights of fluvial fill-cut terraces at two separate locations are consistent and suggest this branch of the river formed shortly after 2 Myr ago by relatively slow fluvial incision. This slow incision persisted until around 300-400 kyr ago, whereupon rates of downcutting increased by around an order of magnitude and have remained more rapid until the present day.

In this contribution, we discuss how the timing of the Tiliviche River incision rate increase may relate to tectonic mechanisms, both local faulting and with regards to proposed increases in regional scale crustal uplift. There is evidence for blocking of the river and ponding episodes downstream of our sample sites, and we consider the timing and links to other nearby ponding events in the Atacama Desert, plus the role this process could have played in the formation of the terraces. Additionally, we have measured cosmogenic ^{10}Be derived exposure ages from several proximal sites in order to constrain the timing of nearby drainage diversions and we find potential linkages between these events and the Tiliviche River evolution. Lastly, our project aims to compare the results from cosmogenic nuclide dating with fluvial histories derived from the timing of amphipod speciation. Our initial results show that there is much potential in combining cosmogenic nuclide approaches with molecular clock dating and implies river evolution in this area is controlled by a common, regional-scale process.

ISOCHRON-BURIAL DATING OF THE OLDEST GLACIOFLUVIAL SEDIMEMTS IN THE NORTHERN ALPINE FORELAND

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During the Middle and Early Pleistocene, the northern Alpine foreland witnessed several phases of alternating deposition and incision, shaping the landscape that can be seen today. High elevated plateaus separated by deeply incised overdeepened valleys, create a topography with relief of several hundreds of meters. On top of these plateaus can be found the oldest glaciofluvial sediments in Switzerland called Deckenschotter (DS). These Deckenschotter deposits consist mainly of glaciofluvial sediments intercalated with glacial sediments. The DS have traditionally been divided into two morphostratigraphic units, the Higher (older; HDS) and the Lower (younger; TDS) Deckenschotter. Both, HDS and TDS, form gravel terraces located up to about 250 m above the modern valley bottom. The elevation difference between HDS and TDS deposits is approximately 100-150 m. Their exact time of deposition is important for understanding long-term landscape evolution scenarios of the northern Foreland during the Middle and Early Pleistocene and was addressed recently in few studies in the Northern Alpine Foreland (Akçar et al. 2017, Claude et al. 2019, Grischott et al. 2020, Knudsen et al. 2020, Dieleman et al. 2022).
In this study we implement the isochron-burial dating technique with a pair of cosmogenic nuclides ^{26}Al and ^{10}Be, to further examine and refine the question of the age of the Deckenschotter. We aim to reconstruct the chronology of the alternating deposition and incision of the gravel units in the Northern Alpine Foreland. Our focus is placed on similar and complementary Deckenschotter deposits outcropping in several sites across the Northern Alpine Foreland. Our first preliminary age estimates point to deposition in the latter part of the Early Pleistocene. With the aim to determine the age of these oldest glaciofluvial sediments, our results will also complement the knowledge about their sedimentology, as well as inform our understanding of landscape change during and after Deckenschotter times.

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The slow downwearing of an island: inferring patterns and controls on long-term basin-averaged erosion rates from in situ ^{10}Be in Madagascar

Liesa Brosens[1], Rónadh Cox[2], Benjamin Campforts[3], Liesbet Jacobs[4], Veerle Vanacker[5], Paul Bierman[6], Vao Fenotiana Razanamahandry[1], Steven Bouillon[1], Amos Fety Michel Rakotondrazafy[7], Tantely Razafimbelo[8], Tovonarivo Rafolisy[8] and Gerard Govers[1]

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Cosmogenic nuclide analysis of river sediment provides insight into catchment-wide erosion rates and dynamics. Studies on factors controlling variations in long-term erosion rates have often been focussed on active mountainous and temperate areas, where strong linkages with topographic variables like catchment gradient and normalized river steepness have been found. Less is known about these rates and controls in regolith-covered and tropical areas that are often intensively used by humans. Information on long-term erosion rates is therefore crucial if human impact on landscape dynamics is to be understood in these areas. Here, we investigate spatial patterns and controls on ^{10}Be-inferred erosion rates in Madagascar, a seismically active island surrounded by passive margins where relief can be as dramatic as in New Zealand and climate varies from humid tropical to semi-arid. We do so based on a compiled dataset of 99 detrital ^{10}Be measurements from a wide range of catchments, covering more than 30% of the country.

Overall, ^{10}Be erosion rates are low (2.4 - 51.1 mm kyr^{-1}), but we find clear differences between different geomorphic regions. The lowest rates are measured on the plateau (7.8 ± 2.8 mm kyr^{-1}, N = 27), in the Alaotra-Ankay graben (10.8 ± 4.0 mm kyr^{-1}, N = 12), and in large north-central catchments (10.7 ± 1.1 mm kyr^{-1}, N = 4). Higher ^{10}Be erosion rates are found on the steep eastern escarpment (20.0 ± 9.2 mm kyr^{-1} N = 32), in the northwest (31.0 ± 12.2 mm kyr^{-1}, N = 5), and in the southwest (28.9 ± 12.4 mm kyr^{-1}, N = 11).

Factor, correlation, and stepwise linear regression analysis on the full dataset shows that 27% of the observed variation in ^{10}Be erosion rates is explained by elevation (lower rates for higher catchments), where an additional 18% of the variation can be explained by river concavity, seismicity, and lithological erodibility (higher rates for more convex, seismically active and more erodible catchments). Random within-between models (REWB) indicate that the main variations in ^{10}Be-inferred rates between different geomorphic zones are explained by differences in river concavity, seismic events and gully densities, where additional variation within the geomorphic zones is linked with seismicity. The use of a REWB model considerably increased the explanatory power to 73%. We find no correlation between catchment or river steepness and ^{10}Be-inferred rates of landscape change.

Our results indicate that in Madagascar, where there is great variation in both geomorphology and climate, simple topography-based models do not explain rates of landscape change inferred from the concentration of ^{10}Be in river sediment. We demonstrate that identifying different geomorphic zones aids in inferring spatial patterns of erosion rates, and that random within-between models can be a powerful tool in deciphering environmental controls on ^{10}Be erosion rates. While ^{10}Be concentrations suggest that rates of landscape change in Madagascar are low, river water chemistry along with the ubiquitous presence of deep regolith suggests that chemical weathering occurs below the depth of most ^{10}Be production. These observations suggest that rates of landscape mass loss likely exceed those inferred from ^{10}Be concentration in sediment in Madagascar.

Long-term survival of detrital gold in glaciated landscape based on Cosmogenic ^3He in detrital grains from Scotland

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Cosmogenic ^3He can be measured from individual detrital mineral grains [1] and provides the potential to tease out details of sediment storage and transport that are unavailable from bulk sample analysis, and may, for instance, shed light on the longevity of the landscape. While extremely long exposure histories have been measured in detrital grains from unglaciated regions [1], the effect of repeated glacial cycles in removing detrital minerals is unknown. Here we report the cosmogenic 3He content of 36 (2-50 mg) native gold grains from the beds of 8 streams in the ScottishHighlands to determine their ability to survive glaciation.

Measured 4He concentrations vary from 4 to 299 x 1013 atoms/g these variation on the ^4He concentrations may be related to the presence of U and Th in the mineral lattice or U- and Th-rich mineral inclusions. Based on measured Li contents (<1 ppb) the nucleogenic ^3He contribution in all samples is negligible. Using theoretical production rate of 25 atoms/g/year [1] and assuming no shielding the samples yielded minimum surface residence times that range from 0.02 to 3.95 Ma. These residence times are all in excess of Last Glacial Maximum (i.e > 20 Ka) suggesting long-term storage and thus constraining the ability of valley glaciers to erode. Since the alluvial gold in Scottish streams is localized, implying minimal transportation lengths, it seems likely that the long surface residence times reflect Tertiary weathering and may have the potential to trace landscape preservation.

[1] O. Yakubovich, F.M. Stuart, A. Nesterenok & A.P. Carracedo (2019). Chemical Geology 517, 22-33.

TO WHAT EXTENT LANDSLIDES AFFECT ^{10}BE-DERIVED CATCHMENT-AVERAGED DENUDATION RATES ?

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Cosmogenic radionuclides (CRN), such as in-situ produced ^{10}Be nuclides, are now commonly used to constrain denudation rates of tectonically active regions. Such radionuclide concentrations are often determined in fluvial sediments that are supplied to the river network by e.g. shallow and deep-seated landslides. Stochastically occurring landslides can exhumate deep-seated hillslope material that is shielded from cosmic rays by their overburden. Sediment supply by landsliding are stochastic discrete disturbances that potentially introduce deeply shielded (lower ^{10}Be concentration) material into the sediment cascade. Depending on the sediment connectivity, it is in turn expected that landslide material will alter proper sediment mixing and dilute the overall ^{10}Be concentration of fluvial sediments.

In this contribution, we aim to assess the potential variability in ^{10}Be concentrations and CRN-derived denudation rates using a 2D numerical model. Building on existing frameworks to simulate the ^{10}Be concentration evolution over time in landslide-affected landscapes, we replicated hundreds of independent numerical simulations to account for the stochastic impact of landslides on CRN-derived denudation rates. The simulations were realised for different scenarios of landscape evolution defined by a combination of catchment area, background erosion and landslide mobilization rates.

We modelled more than 700 scenarios of landscape evolution for a wide range of background erosion and landslide mobilisation rates, and for catchment areas up to 100 km². Our results show that the overestimation of CRN-derived denudation rates with respect to volumetrically-derived erosion rates becomes negligible for catchments larger than 50 km². The sediment mixing capacity of larger rivers permits to dampen the effects of deep-seated landslides on ^{10}Be concentrations. For smaller catchments affected by landslides, our modelling framework provides a useful tool to assess potential bias on ^{10}Be-derived measurements, to guide the design of field campaigns and the interpretation of associated denudation rates.

Using 10Be-derived denudation rates to test river incision models across a Climatic and Morphological gradient

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Investigating landscapes evolution and their responses to tectonic or climatic perturbation requires accurate representations and models of surfaces processes. Rivers are keys agents of the transmission of external forcing through landscapes and the main drivers of continental denudation. For these reasons the mechanisms of fluvial incision have been a key focus of geomorphological research over the last decades.

Long-term river incision is usually modeled with the Stream Power Model (Howard et al., 1997; Whipple and Tucker, 1999) based on the along-stream evolution of drainage area and channel elevation gradient. More complex developments of the SPM (Tucker and Bras, 2000; Tucker, 2004; Lague et al., 2005) combine instantaneous river incision with the probability for discharge occurrence and take into account discharge variability and incision threshold. These models have been confronted with field data in a limited number of cases (DiBiase et al., 2011; Carretier et al., 2013; Scherler et al., 2017, Campforts et al., 2020).

Our objective is to investigate the behavior of stochastic-threshold incision models across the southeastern margin of the Massif Central (France) where strong climatic and morphological gradient are reported. We present a new dataset combining measurements of denudation rates on 34 basins from 10Be concentrations, discharge variability from gauging stations, morphometric parameters from river long-profile analysis, bedloadsize and channel width from fields measurments and database.

Our results show a contrasted variation of 10Be denudation rates across our study area with a clear co-variation with precipitation/runoff. Such correlation is partly due to a pronounced orographic effect with higher rainfall focused on the steep and high-relief areas. Results show a complex relationship between 10Be denudation rates and river steepness which cannot be explain only by the regional discharge variability gradient (Fig1). When compared with measured erosion rates, we observe that the predictions of a stochastic-threshold incision model are not better than simpler versions of the SPM and require to take into account spatial variations in incision thresholds. When compared with measured erosion rates, we observe that the predictions of a simple version of the Stream Power Model, accounting for the distribution of precipitation, perform better at reproducing observed denudation rates when compared to the more elaborate Stochastic-Threshold SPM. The performances of such ST-SPM are critically impacted by the definition and parameterization of the incision threshold. These results raise questions about the reliability of the assumptions usually made on bedload properties in such models and the signification of their estimate from field observations (Fig2), both in terms of underlying spatial variations and time integration of drastic changes in surface processes over the Late Pleistocene.

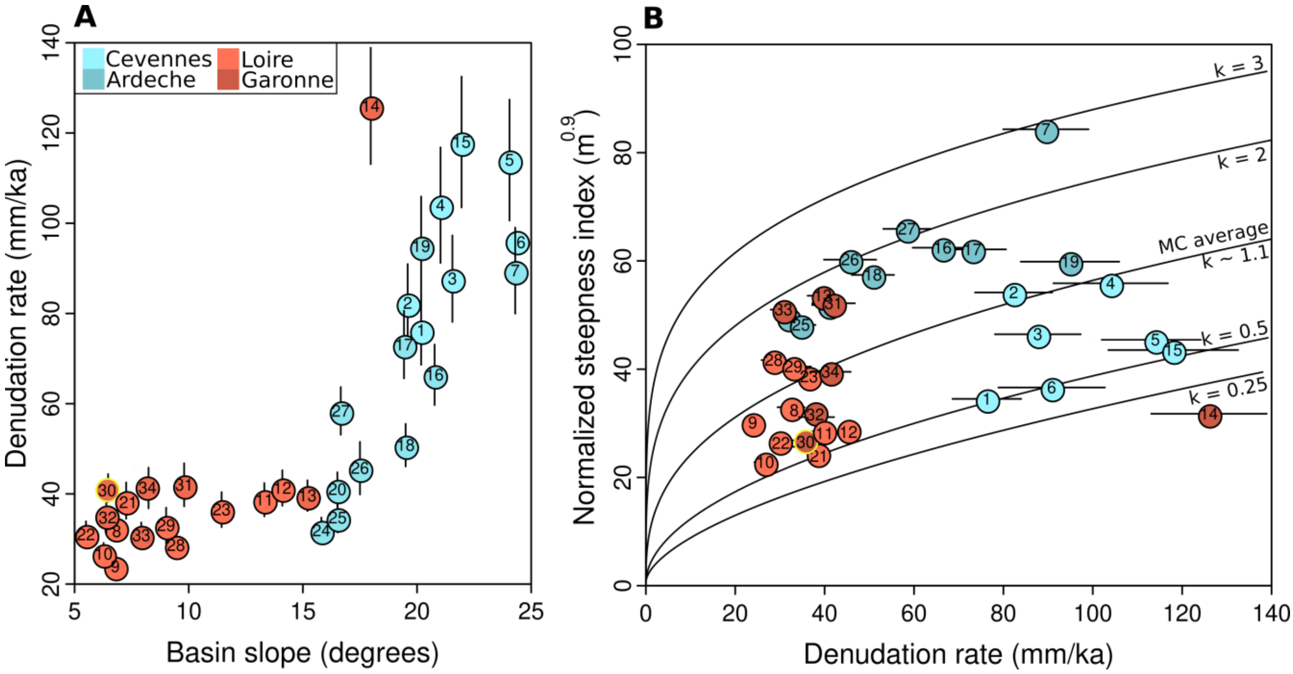

Fig1: (A) Comparison between erosion rate and basin slope. Symbols are colored according to the location of the measurements. B) Comparison between normalized channel steepness index and denudation rates. Black lines correspond to the theoretical relationship between denudation rate and steepness index for various values of the discharge variability parameter k.

Fig2: Abrasion figures along the “Gardon de Mialet” bedrock river

Constraining the timing of gravel accumulation in glaciated landscapes: Insights from the Swiss northern Alpine Foreland

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Isochron-burial dating with cosmogenic ^{10}Be and ^{26}Al has been successfully applied for dating the fluvial deposits. However, its application to the gravel accumulations in glaciated landscapes is challenging as cosmogenic nuclides concentrations are generally low due the repeated glaciations. Furthermore, the initial $^{26}Al/^{10}Be$ ratio at the time of deposition is apparently >6.75 due to the deep glacial erosion, because the clasts are completely shielded from cosmic rays when they are *first* eroded by a glacier at the source from the bedrock at depth (deep glacial erosion), *second* transported either englacially or subglacially, and *third* later embedded and deeply buried in a glacial or a glaciofluvial deposit.

Alpine glaciers advanced and reached the northern Alpine Foreland at least 13 times during the Quaternary. These advances are recognized within four distinct units, which are differentiated by their topographical position and morphostratigraphy. The topographically higher units are older than the lower ones. These are, from the oldest to youngest, Höhere Deckenschotter (HDS – Higher Cover Gravels), Tiefere Deckenschotter (TDS – Lower Cover Gravels), Hochterrasse (HT – Higher Terrace) and Niederterrasse (NT – Lower Terrace). For a long time, the Quaternary stratigraphy of the northern Alpine Foreland had been correlated to that of southern Germany where the four units are attributed to the Günz, Mindel, Riss and Würm glaciations of Penck and Brückner. According to this correlation, HDS was correlated with Günz, TDS with Mindel, HT with Riss and NT with Würm, respectively. The Swiss Deckenschotter are the oldest Quaternary units in the northern Swiss Alpine Foreland. They are a succession of glaciofluvial gravel beds with intercalated glacial and/or overbank deposits. This lithostratigraphic sequence is called Deckenschotter because it "covers" Molasse or Mesozoic bedrock and forms mesa-type hill-tops. Deckenschotter occur both within and beyond the extent of the Last Glacial Maximum. Swiss Deckenschotter deposits have been categorized in two units: HDS and TDS, which are separated by a significant phase of incision.

In this study, we present the landscape evolution of the Swiss northern Alpine Foreland during the Pleistocene using the isochron-burial chronology that was reconstructed at eighteen sites based on more than hundred successfully analysed samples during the last decade. This chronology allowed us to establish the timing of five Pleistocene glacier advances between 2.5 Ma and ca. 250 ka. Three glaciations occurred during the Early Pleistocene prior to the Mid-Pleistocene Revolution (MPR) and two during the Middle Pleistocene. Today, records of these three Early Pleistocene glacier advances are located at the same topographic elevation and therefore are considered to represent a cut-and-fill architecture as a result of glacially induced changes in bedload and stream power. In addition, this cut-and-fill architecture challenges the existing morphostratigraphy, which indicates that the stratigraphy of these deposits seems to be more complex that thought so far. Based on the cosmogenic nuclide chronology, we suggest that the regional base level was relatively constant between 2.5 Ma and 1 Ma and that a significant phase of erosion took place afterwards, likely induced by the MPR.

High precision cosmogenic Ne measurements on small samples using Thermo Fisher ARGUS VI

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Cosmogenic Ne isotopes are now routinely used for constraining the timing and rates of surface processes on Earth, successfully applied to determining long-term landscape development in low erosion rate regions like Atacama, Namibia, and deglaciation timescales in cold arid regions such as Antarctica and Tibet. In extraterrestrial rocks cosmogenic Ne are the go-to method for determining the exposure history of meteorites in space and determining the impact histories of lunar surface.

Neon isotope determinations have become more precise in the last ten years largely due to developments in mass spectrometry and electronics. Here, we present new data obtained using an ARGUS VI mass spectrometer tuned for cosmogenic Ne determinations by changing the magnet position and the detector deflection plate voltages used for multi-collector Ar isotope analysis. The instrument has several advantages over existing off-the-shelf options for Ne isotope determinations. The low static volume and source design generate high sensitivity permitting the analysis of samples that are considerably smaller than previous generations of mass spectrometers. The stable electronics and multi-collection capability result in improved precision of isotope ratio determinations. Automatic liquid nitrogen-cooled charcoal traps developed in-house allow non-stop operation for up to 80 hours, and the remote control of gas extraction (using diode laser), purification and analysis has increased sample throughput and improved data confidence due to the increased calibration and blank measurements.

Material with high Ne concentrations, for instance meteorites and lunar basalts, are analysed using multi-collection Faraday detectors. Multiple temperature steps of ~5 mg Winchcombe CM2 meteorite has allowed the resolution of both implanted solar wind and pre-solar Ne components as well as determination of the short space exposure time using cosmogenic ^{21}Ne. The instrument has primarily been developed for determination of cosmogenic Ne in terrestrial material. Routine analysis of cosmogenic Ne from 20-30 mg quartz requires peak jumping using the compact discrete dynode detector in the L3 position. Analysis of multiple aliquots of CREU-1 quartz standard yields repeatability of ±2% (1σ); a performance level that has required 5-10x more sample using standard instruments. We will present several examples of instrument performance using recent studies. As well as increasing sample throughput and allowing replicate analysis, the new instrument makes it possible to expand cosmogenic Ne analysis to studies where limited material is available, such as individual detrital grains from sediments and asteroid/planetary-return material. Beyond cosmogenic studies the instrument has the potential to develop (U+Th)/Ne thermochronology and geochronology of accessory minerals.

In situ-produced cosmogenic krypton in zircon: a valuable addition to the terrestrial cosmogenic tool box

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Since its discovery in the mid-60s of the last century, in situ-produced cosmogenic krypton has seen many applications in meteorite research. In terrestrial in situ applications, it was notable for its absence, being the only cosmogenic nuclide that has not yet made the transition from extraterrestrial to terrestrial applications. The availably of four stable and one long-lived radioactive isotope (^{81}Kr, $t_{½}$ 229 kyr) that are predominantly/exclusively produced by spallation (i.e. those of mass ≤ 83) make it unique amongst elements with cosmogenic nuclides, not just amongst noble gases.

A key conceptual step in utilizing in situ produced terrestrial cosmogenic Kr (Kr_{it}) is the realization that, due to the geochemical differentiation of the Earth the target elements for Kr_{it} (Rb, Sr, Y, Zr, Nd) may form discrete minerals or are enriched in some minerals. Enrichments over the concentrations in meteorites may be of the order of 10^3–10^4, similar in magnitude to the cosmic ray flux differences between space and on Earth, but in a reversed sense. The lower cosmic ray flux on Earth is thus fully compensated by the higher target-element concentrations. Hence, determination of Kr_{it} in enriched minerals may be as easily attainable as Kr_{iet} is in meteorites. Zircon ($ZrSiO_4$) has a particular appeal: it is near ubiquitous; it is extremely weathering resistant, has a simple target chemistry and is very retentive for heavy noble gases. Anticipating novel applications in Earth surface sciences Kr_{it} is developed as a new tool: with first determinations of production rates and ratios, cross-calibration/validation, and a conceptual framework to interpret results. Examples for initial applications include the long-term evolution of stable landforms and landscape transformations at major climatic transitions. Together they provide proof of principle that terrestrial Krit can be quantified and used to unravel Earth surface processes.

DILUTION OF 10BE IN FLUVIAL SEDIMENT OF MULTIPLE GRAIN SIZES FROM THE 2016 KAIKŌURA, NEW ZEALAND M7.8 EARTHQUAKE ITS INSIGHTS INTO LANDSLIDE SEDIMENT DYNAMICS

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The concentration of in situ produced cosmogenic radionuclides such as ^{10}Be in detrital quartz from river sediments is widely used to calculate catchment-wide denudation rates. Although useful for quantifying long-term catchment denudation rates, the catchment-average approach does not capture erosional processes driven by landsliding. Major landslide events can input large amounts of low-concentration ^{10}Be into the river system, biasing the concentration distribution and increasing the average denudation rate. A better understanding of how earthquake-induced landslides can influence the ^{10}Be signal, particularly in different grain size fractions, is necessary before reliably inferring denudation rates. To test how major landslide events influence the ^{10}Be concentration, we use the landsliding that occurred in the Hapuku and Kowhai catchments from the 2016 Kaikōura, New Zealand M_w7.8 earthquake. Major landslides occurred in both catchments, however the landslides in each catchment have contrasting volumes, depths, and river connectivity. We have collected and examined the concentration of ^{10}Be in sediment from three different grain sizes in both catchments for the past seven years. This is one of the first studies that contains a high-resolution time series of ^{10}Be concentration post a major earthquake event and the first to compare the concentration of multiple grain sizes to provide a detailed insight into landslide sediment dynamics. ^{10}Be concentrations have progressively decreased to extremely low concentrations since the earthquake implying transport mechanisms are dominated by landslide inputs. The results from the first two years since the earthquake show that the concentration of ^{10}Be is highly dependent on landslide connectivity and degree of sediment mixing. Due to the extremely low concentrations however, subtle trends may be obscured by the larger errors. These results will provide new insight into fluvial transport mechanisms from landslide inputs and its implications for determining denudation rates from landslide dominated catchments.

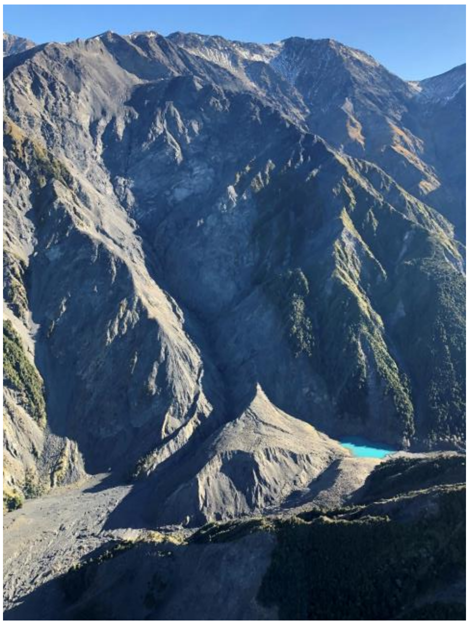

Figure 1 – The Hapuku landslide dam from the 2016 Kaikōura, NZ M_w7.8 earthquake.

PALEOEARTHQUAKE RECONSTRUCTION ON AN IMPURE LIMESTONE FAULT SCARP

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Reliable reconstructions of paleoseismicity are useful for understanding, and mitigating, seismic hazard risks. In this study, we apply ^{36}Cl exposure-age dating and concentrations of rare-earth elements and yttrium (REY) to unravelling the paleoseismic history of the Sparta fault, Greece, which is a range-bounding normal fault developed in limestone. A 464 BCE earthquake devastated Spartan society and is the last recorded earthquake on this fault. Even with high quality (low measurement error) ^{36}Cl data, two ^{36}Cl profiles sampled in 10 cm steps, one of which is located adjacent to a previously measured profile, and a known earthquake in 464 BCE, we struggle to reliably identify individual earthquakes from our ^{36}Cl data.

Either four modeled earthquakes, informed by deviations in ^{36}Cl concentrations, or three earthquakes informed by deviations in REY data, provide good fits to our ^{36}Cl data. ^{36}Cl and REY concentrations theoretically vary systematically with depth beneath the hanging wall soil surface, with those variations imprinted to some shallow depth into the fault scarp. Following scarp exhumation during an earthquake those geochemical imprints are uplifted above the hanging wall soil surface and remain preserved over time in the fault scarp. Successive earthquakes are considered to leave a staircase of such geochemical imprints. However, the apparent positions of former soil surfaces on the Sparta fault scarp vary between the ^{36}Cl and REY data, which confounds the interpretation of former earthquakes. Relying solely on the ^{36}Cl data to infer earthquakes is also hindered by equivocal interpretations of former hanging wall soil surfaces. We cannot therefore reliably infer a recurrence interval for earthquakes on this fault scarp. Whereas we cannot reliably identify individual earthquakes, we can more confidently infer a cumulative uplift rate, which appears to have increased over the past 3.2-4.2 kyr to ~1.0–1.2 mm a^{-1}, from ~0.6–0.9 mm a^{-1} over the preceding 2.7-4.4 kyr.

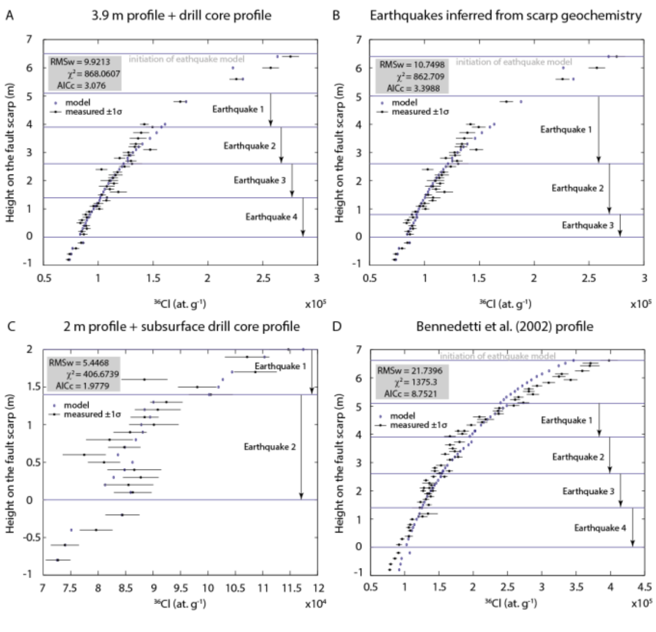

Figure 1 – Cosmogenic ^{36}Cl on the Sparta fault scarp.

The Sparta fault scarp is composed of fault breccia, which contains quartz and clay-lined pores, in addition to host rock-derived clasts of calcite and microcrystalline calcite cement. The exchange of REY between the hanging wall colluvium and the fault scarp calcite, which has been applied to the study of paleoseismicity on other limestone normal faults, is overwhelmed on this fault scarp by REYs attached to the breccia pore clays. We interpret that REY patterns along vertical transects may not reliably reflect fault slip lengths from which to infer Holocene earthquakes and their magnitudes. The complex composition of the Sparta fault breccia may also produce variations in ^{36}Cl that confound the interpretations of earthquakes.

Meteoric ^{10}Be speciation in Antarctic subglacial sediments as a chemical and chronological tracer

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Meteoric ^{10}Be is the fraction of the ^{10}Be isotope that forms in the atmosphere and subsequently remains mobile on the Earth's surface. It is far more abundant than *in situ* ^{10}Be but, due to its mobility, is less frequently employed as a chronometer. In ice sheet settings, meteoric ^{10}Be has been employed as a tracer of the solar cycle and magnetic field variability, providing detailed measurement of ^{10}Be fallout in ice in several East Antarctic locations.

Here, we examine the concentration and speciation of meteoric ^{10}Be in subglacial sediments emerging at a blue ice moraine in the Central Transantarctic Mountains. Because the concentration in ice is known, the total concentration meteoric ^{10}Be in subglacial sediment traces meltwater input. More precisely, meteoric ^{10}Be captures the volumetric ratio of meltwater to sediment over the sediment's residence time in the subglacial environment. In examining the speciation, we analyse the degree to which newly forming minerals take up meteoric ^{10}Be from the subglacial meltwater. In principle, we expect the two to be linked: that high meltwater input would allow for chemical weathering and greater incorporation of ^{10}Be into weathering products such as oxides and clays.

The first step of our sequential extraction procedure was designed to desorb meteoric ^{10}Be from the surface of mineral particles without dissolving minerals that contained meteoric ^{10}Be in the crystal lattice. Our experiments show that, at least with these sort of sediment samples, acetic acid effectively desorbs Be without dissolving clays or oxyhydroxides between pH 3.2 and 3.5. We subsequently targeted oxides and hydroxide species through a hydrochloric acid leach. The remaining particles were separated into silt and clay fractions, then totally dissolved.

Variants of this procedure were tested on sediment samples collected at Mt. Achernar Moraine. Five samples showed features of recent emergence from the subglacial environment and were collected at the ice margin. One sample was collected from the interior of the moraine with ~0.5 Ma of surface exposure. In the freshly emerging samples, total meteoric ^{10}Be ranges from $2{\cdot}10^7$ to $2.8{\cdot}10^8$ atoms g^{-1}. Despite the order of magnitude difference in concentration, speciation is broadly similar between samples, with approximately 50% of the meteoric ^{10}Be incorporated into clay lattices, 30% absorbed onto mineral surfaces, and 20% bound into HCl soluble phases. Less than 2% was found in greater than clay-sized residual particles. The surface-exposed sample has $1.2{\cdot}10^9$ atoms g^{-1} meteoric ^{10}Be and a larger proportion of HCl soluble and residual Be speciation.

The samples all contain smectite and kaolinite clays that are nearly absent from the underlying rock. The total abundance of meteoric ^{10}Be strongly correlates to the abundance of these authigenic mineral products. This suggests that the input of meltwater is causing both build-up of meteoric ^{10}Be and authigenic minerals in the subglacial sediment, but with little variability is speciation over time. Alternatively the results could represent a mixing-dilution pattern of an intensely weathered, ^{10}Be-rich subglacial source. Clays remain a primary reservoir for ^{10}Be in the surface exposed sample, strongly suggesting authigenic clay formation on the surface as well as subglacial environments. This work shows that the mobility of meteoric ^{10}Be can be used advantageously to assess authigenic mineral formation in these glacial settings. Furthermore the isotope can be used to trace the meltwater budget of the subglacial environment, and together with melt rate and mineralogical information can serve as a weathering rate chronometer.

CHRONOLOGY OF THE LATE PLEISTOCENE GLACIATION OF THE SOUTHERN BLACK FOREST, GERMANY: ^{10}BE COSMIC-RAY EXPOSURE DATING OF MORAINES

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Since pioneering work in the 19th century, multiple studies have been undertaken on the Late Pleistocene glaciation of the southern Black Forest. They conclude that an about 1000 km^2-large ice cap and its outlet glaciers temporarily covered the highest summit of the Black Forest, Feldberg (1493 m above sea-level), and the surrounding region. Multiple groups of moraines have been observed inside landforms that are interpreted to represent the Late Pleistocene maximum ice extent (Fig. 1). Previous investigators proposed that these landforms imply several phases of glacial re-advances and standstills during the last deglaciation. As moraines in the southern Black Forest have hitherto not been directly dated, the chronology of the Late Pleistocene glaciation of the southern Black Forest remains largely unknown. We aim at filling this gap by obtaining the first cosmic-ray exposure (CRE) ages for moraines.

Glacial landforms in the region around Feldberg with particular emphasis on moraines were mapped with high-resolution remote sensing data and subsequently confirmed in the field. Revisiting the area NW and NE of Feldberg revealed numerous moraines that have hitherto not been described. Some of the previously mentioned moraines have not been confirmed. ^{10}Be CRE dating was applied to sufficiently large and stable boulders on moraines. The CRE ages of moraines in one valley NW of Feldberg are consistent with the morphostratigraphy and imply two distinct periods of glacial re-advances and standstills during the deglaciation (no later than 17-16 ka and 14 ka). The CRE age of a boulder on a moraine NE of Feldberg that has previously attributed to the Late Pleistocene maximum advance falls into the final part of the Lateglacial. As CRE ages of stratigraphically much younger moraines turned out to be consistently older and since the sampled boulder was relatively small, we argue that this boulder was probably affected by post-depositional processes. CRE dating of morphostratigraphically younger moraines yielded stratigraphically consistent ages between 16 and 13 ka. They resemble those of moraines NW of Feldberg, but they do not fall into two distinct groups.

As ^{10}Be CRE dating of the Late Pleistocene glaciation maximum in the study area was so far not successful, moraines of this phase in other parts of the southern Black Forest will be exposure dated. In addition, we intend to incorporate the CRE ages of moraines in the area NE of Feldberg in a Bayesian model with chronological data from a mire inside a terminal moraine and independent stratigraphic information. CRE dating of moraines of the deglaciation outside the study area will allow for evaluating whether the glacial phases are of regional relevance. Reconstructing former glaciers and equilibrium line altitudes during moraine formation will provide valuable paleoclimatic information.

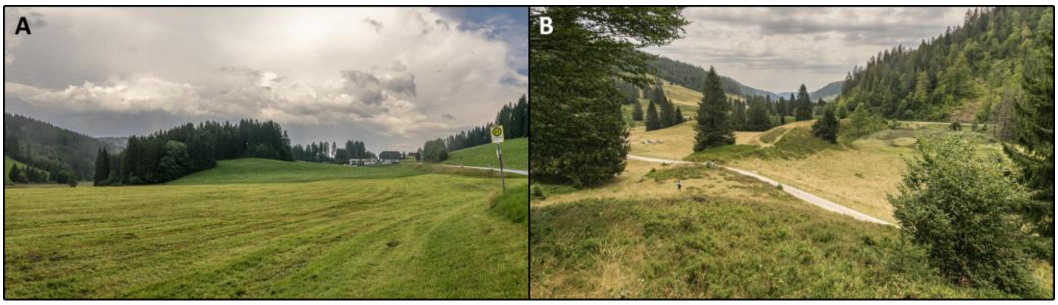

Figure 1 – A. Moraine that is interpreted to represent the Late Pleistocene maximum ice extent. B. Well-preserved moraine of the last deglaciation.

DATING THE CHANNELED SCABLAND: INSIGHTS ON ^{3}He PRODUCTION SYSTEMATICS FROM MEASUREMENTS ON FINE-GRAINED MINERALS IN OLD BASALT

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The Channeled Scabland in eastern Washington, USA is an iconic landscape carved by the largest outburst floods in Earth's history. Repeated failure of an ice dam that impounded glacial Lake Missoula generated floods that overtopped the Columbia River valley and flowed across Miocene-age flood basalt on the Columbia Plateau, where they scoured bedrock, incised deep canyons, and deposited huge bars. The chronology of the Missoula floods is known mostly from ^{14}C dated charcoal and ^{10}Be ages on ice-rafted granitic erratics, but there is limited datable material for these methods. Existing ages indicate the floods occurred during the latest Pleistocene, but prior work suggested there were older flood-scoured geomorphic surfaces ("scablands"), based on a greater degree of weathering on higher- versus lower-elevation scablands. Here, we use ^{3}He to investigate the timing of flooding on the Columbia Plateau, including two weathered, high-elevation scablands.

The Columbia River basalts lack olivine and pyroxene phenocrysts typically used for ^{3}He exposure dating, but many of the flows contain fine-grained (∼20 µm cross-section) pyroxene or ilmenite. We calibrated the ^{3}He production rate in ilmenite against the well-constrained production rate in pyroxene. The concentration ratio of ilmenite to pyroxene is 0.78 ± 0.02, yielding an apparent cosmogenic ^{3}He production rate of 93.6 ± 7.7 atom g^{-1} yr^{-1} that is 20–30% greater than expected from prior estimates for compositionally similar minerals. The production rate discrepancy arises from the high energy with which cosmic ray spallation reactions emit tritium and ^{3}He and the associated long stopping distances that cause them to redistribute within a rock. Semi-quantitative modelling supports our conclusion that fine-grained phases with low cosmogenic ^{3}He production rates, like ilmenite, will have anomalously high production rates owing to net implantation of ^{3}He from the surrounding, higher ^{3}He production rate, matrix. Our finding are relevant to ^{3}He production in other minerals, and indicate the redistribution effect is maximized when the host rock and crystals differ substantially in mean atomic number.

After calibrating the production rate, ^{3}He concentrations from the youngest scablands yielded anomalously old, inter-glacial exposure ages. Hence we measured ^{3}He in samples shielded from production from spallation from a ~300 m-deep core. ^{3}He concentrations in the core exhibit an exponential decline with depth with an *e*-folding length of 32.4 m, which corresponds to an attenuation length for ^{3}He production of 8780 g cm^{-2}. The deeply penetrating exponential is diagnostic of ^{3}He production by cosmic ray muons. Incorporating erosion, we constrain the minimum surface muonogenic production rate to be 0.45 atom g^{-1} pyroxene yr^{-1}. Our results provide the first definitive empirical evidence for ^{3}He production by muons. An important implication is that, despite the low production rates, landforms in the Channeled Scabland, have high concentrations of ^{3}He inherited from post-Miocene muon exposure. Hence ^{3}He production by muons must be considered, particularly when dating rapid erosional events in old bedrock, as samples with less than several tens of meters of shielding by overlying rock will contain cosmogenic ^{3}He unrelated to the recent exposure history.

Correcting ^{3}He concentrations for muon production indicates exposure ages of nearly all the ~60 samples we collected date to the latest Pleistocene, including one of the high, weathered scablands. The second weathered scabland has ^{3}He concentrations equivalent to 300-400 ka of exposure. However, the site geology and a 17.3 ka ^{10}Be age on a granitic erratic indicate the scabland is an exhumed Miocene unconformity that was scoured, but not deeply eroded by late Pleistocene flooding.

Overall, our results indicate: i) grain-size influences ^{3}He production when mineral and bulk rock composition differ; ii) ^{3}He is produced by muons; and iii) weathered scablands do not reflect flooding during prior glaciations, but rather differential flood erosion on high versus low elevation scablands by late Pleistocene floods.

Geomorphology and ^{10}Be chronology of the Last Glacial Maximum and deglaciation in northeastern Patagonia, 43°S-71°W

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In southern South America, well-dated glacial geomorphological records constrain the last glacial cycle across much of the former Patagonian Ice Sheet, but its northeastern sector remains comparatively understudied and unconstrained. This knowledge gap inhibits our understanding of the timing of maximum glacier extent, the duration of the glacial maximum, the onset of deglaciation, and whether asynchronies exist in the behaviour of the former ice sheet with latitude, or with location (east or west) relative to the ice divide. Robust glacial reconstructions from this region are thus required to comprehend the mechanisms driving Quaternary glaciations at the southern mid-latitudes. We here present 38 ^{10}Be surface exposure ages from five moraine sets along with Bayesian age modelling to reconstruct a detailed chronology of Last Glacial Maximum expansions of the Río Corcovado glacier, a major former ice conduit of northern Patagonia. We find that the outlet glacier reached maximum expansion of the last glacial cycle during the global Last Glacial Maximum at ~26.5-26 ka, and that at least four subsequent advances/stillstands occurred over a 2-3 ka period, at ~22.5-22 ka, ~22-21.5 ka, ~21-20.5 ka and 20-19.5 ka. The onset of local ice sheet deglaciation likely occurred between 20 and 19 ka. Contrary to several other Patagonian outlet glaciers, including from similar latitudes on the western side of the Andes, we find no evidence for MIS 3/4 advances. Exposure dating of palaeo-shoreline cobbles reconstructing the timing of proglacial lake formation and drainage shifts in the studied region indicate three glaciolacustrine phases characterised by Atlantic-directed drainage. Phase one occurred from 26.4 ± 1.4 ka, phase two between ~21 and ~19 ka and phase three between ~19 ka and ~16.3 ka. Exposure dating of ice- moulded bedrock in the interior of the cordillera indicates local disintegration of the Patagonian Ice Sheet and the Atlantic-Pacific drainage reversal had occurred by ~16.3 ka. We find that local Last Glacial Maximum glacier expansions were coeval with Antarctic and southern mid-latitude atmospheric and oceanic cooling signals, but out of phase with local summer insolation intensity. Our results indicate that local Patagonian Ice Sheet deglaciation occurred 1-2 ka earlier than northwestern, central eastern and southeastern Patagonian outlet glaciers, which could indicate high regional Patagonian Ice Sheet sensitivity to warming and drying during the Varas interstade (~22.5-19.5 ka).

Advances in cosmogenic nuclide production rate scaling: how we got here and potential opportunities ahead

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Accurate knowledge of the production rate of an *in situ* cosmogenic nuclide (CN) at a location of interest is critical for interpreting measured nuclide concentrations. Time-averaged production rates are typically determined by measuring CN concentrations in surficial rocks from key sites with independently well-constrained exposure histories. Scaling these calibrated production rates to other locations with different exposure durations, though, requires knowledge or assumptions of how temporal and spatial variations in the atmospheric secondary cosmic-ray flux have affected instantaneous production rates. Since the accuracy of these scaled production rates directly affects the accuracy of many CN applications that use them, much effort has been directed over the last 30 years to improving models of how CN production (particularly that derived from nucleon spallation) varies with the secondary cosmic-ray flux.

Models describing the spatial variation of the secondary cosmic-ray flux date to the 1950s, but only became generally accessible to a broader audience beyond cosmic-ray physicists with Devendra Lal's landmark publication in 1991 (Lal, 1991. *EPSL* **104**, 424–439). Lal (1991) presented theoretical underpinnings of key terrestrial CN applications, including polynomial fits to a spatial scaling model developed as part of his 1958 dissertation, based on atmospheric measurements of nuclear disintegrations in photographic emulsions combined with data from various neutron detectors sensitive to different portions of the secondary cosmic-ray spectrum. Over the next decade, most *in situ* CN publications used the Lal (1991) formulation (subsequently re-parameterized from altitude to atmospheric pressure by Stone (2000. *JGR* **105**, 23,753-23,759.).

However, a trio of alternative scaling models emerged in the early 2000's addressing observed discrepancies between the Lal (1991) model and measurements of atmospheric cosmic ray fluxes (e.g., Dunai, 2001. *EPSL* **193**, 197–212; Desilets and Zreda, 2003. *EPSL* **206**, 21–42; Lifton et al., 2005, *EPSL* **239**, 140–161). These were based (either largely or entirely) on global survey data from neutron monitors, which all sample similar portions of the cosmic-ray spectrum. Each of the neutron monitor-based models accommodated a time-dependent geomagnetic field, while the Lal model does not (although Balco et al., (2008. *Quat. Geochron.* **3**, 174–195) include a simplified time-dependent geomagnetic parameterization for a version of that model). Lifton et al. (2005) also includes a parameterization for the effects of solar modulation on atmospheric cosmic ray intensities. This proliferation of scaling models and accompanying debates about which should be preferred led to another decade or so characterized by cumbersome recommendations for publications to include results using the 5(!) different scaling schemes.

Lifton et al. (2014. *EPSL* **386**, 149–160) subsequently developed a scaling model based on analytical fits to Monte Carlo simulations of secondary cosmic-ray flux spectra (both of which agree well with measured particle spectra) – a significant advance that enabled identification and quantification of the biases in previously published models. Flux-based scaling predictions derived from this model (termed LSD) suggest two potential sources of bias in the previous models: different energy responses of the secondary neutron detectors used in developing the models, and different geomagnetic parameterizations. In addition, the particle flux spectra generated by the LSD model allow one to generate CN-specific scaling factors (LSDn) that reflect the influences of the flux energy distribution and the relevant spallogenic excitation functions (probability of nuclide production from a given nuclear reaction as a function of energy). Resulting CN-specific scaling factors indicate ^{3}He shows the strongest positive deviation from the flux-based scaling, while ^{14}C exhibits the strongest negative deviation.

Implemented in MATLAB for desktop use and in various online calculators, the LSDn framework thus provides an accurate and flexible foundation for exploring the implications of ongoing advances in model inputs (e.g., time-dependent models of geomagnetic field and atmospheric structure) for CNs commonly measured in surficial process and Quaternary geologic research.

Evolution of the Seno Skyring ice lobe (52°S) during the last glacial cycle, Southernmost Patagonia

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There are still many uncertainties about the climatic forcing that drove the glacier fluctuations of the Patagonian Ice Sheet (PIS, 38-55°S) during the last glacial period. A key source of uncertainty is the asynchrony of ice lobe fluctuations between the northern, central, and southern PIS. To fully understand the regional trends requires careful mapping and extensive geochronological studies. We present geomorphological and geochronological reconstructions of the glacial and deglacial landforms formed during the last glacial period at the Seno Skyring ice lobe (52°S, 71°W), located in southernmost Patagonia.

In our geomorphological mapping, we identify two moraine systems. The outer and older is named Laguna Blanca (LB) and the inner Río Verde (RV). The LB moraines were built subaerially, whereas the frontal part of the RV was deposited subaqueously under the palaeo lake Laguna Blanca. We conducted surface exposure ^{10}Be dating methods on boulder samples collected from LB and RV glacial margins. The moraine LB III and LB IV formed at 26.3 ±2.3 ka (n=5) and 24.3 ±0.9 ka (n=3), respectively. For the inner RV moraine, we obtained an age of 18.7 ±1.5 ka (n=6). The palaeo Laguna Blanca formed as soon as the ice retreated from LB moraines (24.3 ±0.9 ka). Its evolution is marked by six former shorelines and a partial drainage event. We have constrained the evolution between 22 ±3 ka and 14.8 ±1.2 ka, as based on ^{10}Be exposure dating of cobbles, ^{10}Be depth profile and OSL dating of glaciolacustrine sediments. The deglaciation from RV moraine was underway by 16.4 cal kyr BP and completed by 14.9 cal kyr BP.

Our moraine geochronology shows an asynchrony in the maximum extents and a different morpho stratigraphic pattern of ice advances between neighbouring lobes in southern Patagonia. We speculate that this may be due, at least in part, to the interaction between topography and the precipitation carried by the southern westerly wind belt. However, we observe broad synchrony of glacial readvances by ~18-19 ka, at the end of the gLGM. Some ice lobes experimented large readvances during the Antarctic Cold Reversal, but this is not obvious elsewhere, as in Seno Skyring.

EVOLUTION OF GLACIATED LANDSCAPES – GLACIAL EROSION VS. WEATHERING

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The evolution of glaciated landscapes has been a focus of research for over a century and many conceptual models have been proposed, debated, and discarded during the past decades. Some of this discussion evolve around the contrast between glacially scoured valleys and more intensely weathered upland areas. The occurrence of weathering mantles on upland plateaus has been interpreted to indicate absence of glacial coverage or protection beneath non-erosive, cold-based ice, whereas the conservation of glacial striae, chatter marks, and other signs of glacial abrasion of bedrock in ice-sculpted areas has been used to infer low post-glacial surface weathering rates. The advancement of cosmogenic nuclide chronometry has informed some of these debates in the last three decades, for example, by measuring the amount of inherited nuclides across different landscape types.

The coastal landscape in Norway is fascinating due to the remarkable difference between the deeply scoured fjords and valleys (exhibiting some of the highest relief in Scandinavia) and the narrow stretch of low-relief bedrock terrain along the outer coast known as the strandflat (Holtedahl, 1998). Several hypotheses have been presented to explain the development of the strandflat ranging from partial preservation of Mesozoic weathering remnants to formation by marine abrasion, glacial erosion, or subaerial denudation during the Quaternary. The idea that the strandflat represents an "etch-surface with inselbergs" formed by deep weathering in a tropical climate has recently been rejuvenated by K-Ar dating of saprolite remnants preserved along fracture zones (Fredin et al., 2017). The K-Ar data indicate that some of the the low-altitude basement landforms on- and offshore southwestern Scandinavia represent a rejuvenated geomorphological relic from Mesozoic times. However, abundant signs of glacial abrasion and occurrence of glacially sculpted landforms on the strandflat indicate that the landscape has, at least partially, been modified by more recent erosion processes.

The existence of weathering mantles or other bedrock weathering phenomena cannot always be used to infer long subaerial exposure or coverage by non-erosive, cold-based ice. Locally, post-glacial weathering and erosion rates can be rapid, even in cold temperate to subarctic coastal locations. Rapid post-glacial weathering has been demonstrated on three different coastal locations in Norway. Cosmogenic nuclide dating indicate that the observed weathering phenomena (i) do not indicate negligible glacial erosion, (ii) formed after the last deglaciation, and (iii) depend on lithological and environmental factors (Andersen et al., 2022).

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A LATE-HOLOCENE RECORD OF MARINE TERRACE UPLIFT AT NEEDLES PT, MARLBOROUGH, FROM COSMOGENIC ^{10}BE, INDICATES REVISED HOLOCENE EARTHQUAKE INTENSITY FOR NORTHEAST SOUTH ISLAND, NEW ZEALAND

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Rock shorelines preserve little evidence of the timing of erosion and the processes from which they formed. However, coastal landforms are often interpreted as markers of past sea level change and tectonic uplift. Paleoseismic studies typically use radiocarbon and other dating techniques on cover deposits of marine terraces to constrain the timing and magnitude of earthquakes along tectonically active coasts. However, there is potential for marine terraces to be destroyed through erosion following coseismic uplift, which can result in terrace derived chronologies being incomplete records of earthquakes. Without ways of identifying if terraces are missing or removed from a landscape, we are not able to accurately determine a regions paleoseismic history. Recent applications of cosmogenic nuclides in the dating of shore platforms demonstrate the potential for this method to reveal the complex histories of rock shorelines. Measurements of cosmogenic nuclides across a unique set of exposed bedrock marine terraces and a gravel covered shore platform at Needles Point in the north-eastern South Island, NZ, produce a new chronology of surface ages and erosion rates. This marine terrace sequence recently saw uplift of ~2.5 m in the M_W 7.8 2016 Kaikōura earthquake. ^{10}Be-derived ages for the platform surface and terrace 1 reveal their formation aligns with known surface-rupturing earthquakes on the nearby Kēkerengū fault, which also ruptured in the Kaikōura earthquake. Terraces 2 and 3 are much older surfaces, the timing of their formation does not align with any known local earthquakes. These may represent earthquakes that potentially extend the Kēkerengū fault earthquake record. Some known earthquakes on the Kēkerengū fault have not preserved terraces at Needles Point, indicating that the sequence does not represent a full record of local paleoearthquakes. As such, estimates of coseismic uplift derived from these terraces would over-estimate earthquake magnitude. Surface exposure dating and multi-nuclide approaches therefore offer the potential to quantify marine terrace preservation and destruction, potentially elucidating where terraces may be missing or removed from a sequence.

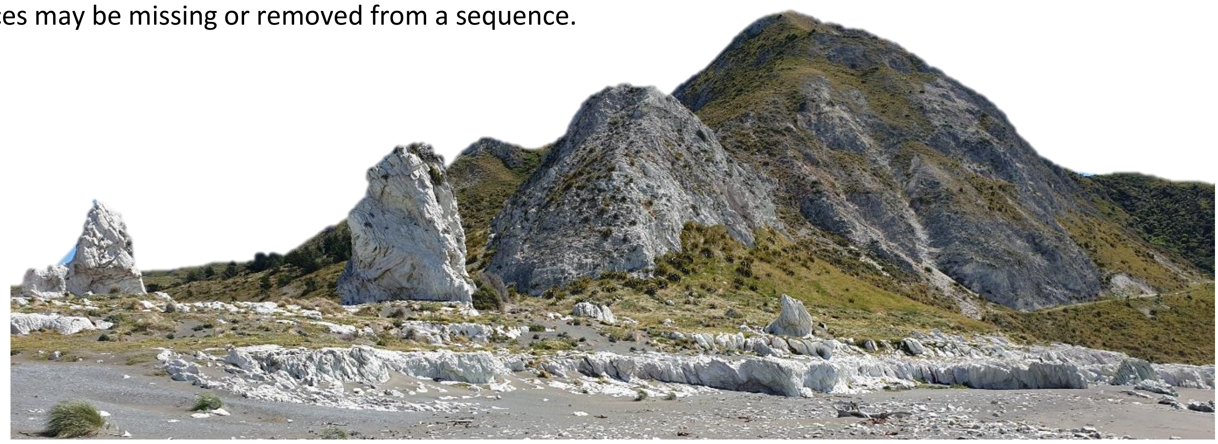

Figure 1: Marine terraces at Needles Point, Marlborough, NZ. Prominent limestone terrace risers are visible, along with the Needles (Stacks), after which this point is named for. Photo: A. McLean, 2019.

Unique altitude scaling of cosmogenic ^{36}Cl production on Fe

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Cosmogenic nuclide production rates at any location on Earth's surface depend on the excitation functions of the underlying nuclear reactions and the intensity and energy spectrum of the cosmic radiation at that location. Nucleon energy spectra shift towards lower average energies with decreasing elevation, which suggests that the production ratio between two reactions with widely separated energy sensitivities may change measurably with altitude. The excitation function for ^{36}Cl production by spallation on Fe peaks at approximately 1 GeV, which is higher than most other production reactions. Thus, production of ^{36}Cl on Fe may attenuate more rapidly in the atmosphere. Here, I explore the possibility for unique altitude scaling of ^{36}Cl production on Fe by modelling the change in the ^{36}Cl on Fe to ^{36}Cl on K and ^{10}Be in quartz production ratios with altitude using energy spectra from the analytical PARMA model of the cosmic ray cascade. I then compare the modelling predictions to measured production ratios across an elevation transect between 1700 and 4300 m asl in the western United States using mineral separates that isolate individual production pathways. The results confirm that the production of ^{36}Cl on Fe increases more rapidly with increasing altitude than production of ^{36}Cl on K or ^{10}Be in quartz. This raises the intriguing possibility of using these reaction pairs as a novel cosmogenic nuclide altimeter.

Tracing transient landscapes with the $^{14}C/^{10}Be$ pair

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Geomorphologists have spent many years writing papers about steady state landscapes, where erosion equals uplift. You might get the impression that we really like steady state landscapes and we think they are present everywhere. In fact, geomorphologists don't believe in steady state landscapes and think they are boring. This assumption is only used because landscapes where the erosion rate is changing are very difficult to quantify. We have, in recent years, been approaching this by looking for topographic signatures of transience. But even if the landscape really, really looks transient, we haven't had a good way to show it is transient with millennial-scale dating methods. The few exceptions usually rely on some unique feature, like a conveniently located tephra layer. But there is an enormous amount of promise in catching a transient landscape in the act using the in-situ 10Be/14C isotope pair, which could be applied everywhere. Or everywhere with quartz, at least. I will show what sort of things geomorphologists are looking for, how any combination of long-lived CRNs are unable to find them, and how in-situ 14C unlocks numerous new possibilities. If you are lucky I will show some brand new results. But even if I do not have time for that you will get to see some pictures of waterfalls and I promise not to show that tedious image of production pathways since everyone at the conference can probably draw it in their sleep.

P-PINI: A cosmogenic nuclide burial dating method for landscapes undergoing non-steady erosion

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Existing methods of cosmogenic-nuclide burial dating perform well provided the sediment sources undergo steady rates of erosion and the samples experience continuous exposure to cosmic rays. These premises exert limitations on the applicability of the methods. And yet, high mountain sediment sources are rife with transient processes, such as non-steady erosion by glacial quarrying and landsliding, along with temporary cosmic-ray shielding beneath glaciers or sediment. As well as breaching the premises of existing burial dating methods, such processes yield samples with low nuclide abundances and variable initial $^{26}Al/^{10}Be$ ratios that may foil both isochron and simple burial-age solutions. P-PINI (Particle-Pathway Inversion of Nuclide Inventories) is a new dating tool designed for dating the burial of sediments sourced from landscapes characterized by abrupt, non-steady erosion and discontinuous exposure. P-PINI merges a Monte Carlo simulator with established cosmogenic nuclide production equations to simulate millions of samples (^{10}Be-^{26}Al inventories). The simulated samples are compared statistically with ^{10}Be-^{26}Al measured in field samples to define the most probable burial age.

We've used three published ^{10}Be-^{26}Al datasets to test the versatility of the P-PINI model for dating fluvial and glacial sediments in different geological settings. (1) First dataset [a] comes from the Pulu fluvial gravels (China), we obtain a burial age of 1.34 ± 0.09 Ma (1σ), which accords with the isochron burial age (1.38 ± 0.07 Ma) and two independent chronometers at the site. This serves as a robust validation of P-PINI. The second and third cases, however, reveal marked divergence between P-PINI and isochron-derived ages. (2) The second dataset[b] comes from the fluvial Nenana Gravel (USA), where obtain a burial age of 4.77 ± 0.63 Ma (1σ), which differs significantly from the isochron age (2.34 ± 0.27 Ma), but is compatible with unroofing of the Alaska Range starting ~ 6 Ma. (3) The third dataset[c] comes from the Bünten Till (Switzerland), where we obtain a limiting burial age of < 206 ka (2σ), which conforms with the classical notion of the most extensive glaciation in the northern Alpine Foreland assigned to Marine Isotope Stage 6 contrary to the older isochron burial age (500 ± 100 Ma). Discrepancies between P-PINI and isochron ages are rooted in the challenges of assessing the diverse pre-burial $^{26}Al/^{10}Be$ ratios produced under conditions characteristic of high mountain landscapes; i.e., transient conditions incompatible with the isochron method, but accommodated by the stochastic design of P-PINI.

[a]Zhao et al. (2016), *Quaternary Geochronology* 34, 75-80
[b]Sortor et al. (2021), *Geology* 49, 1473-1477
[c]Dieleman et al. (2022), *Geosciences*, 12, 39

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Rapid retreat of the southwestern Laurentide Ice-Sheet during the Bølling-Allerød interval

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Oral presentation preference

The timing of Laurentide Ice Sheet deglaciation, along its southwestern margin, controls the evolution and drainage of large glacial lakes and has implications for the migration of early humans into the Americas. Accurate reconstruction of the ice sheet's retreat also constrains glacial isostatic adjustment models and is imperative for our understanding of ice sheet sensitivity to climate forcings. Despite its importance, much of the retreat history of the southwestern Laurentide Ice Sheet is still poorly constrained by minimum limiting ^{14}C data. Here, we present a database of 26 ^{10}Be surface exposure ages from glacial erratics spanning southwestern Alberta to northwestern Saskatchewan, Canada. Using a Bayesian framework, we combine these data with geomorphic mapping, 10Be, and high-quality minimum-limiting 14C ages to provide an updated chronology. This dataset presents an internally consistent retreat record and indicates that the initial detachment of the SWLIS from its convergence with the Cordilleran Ice Sheet began by ca. 15.0 ka, concurrent with or slightly prior to the onset of the Bølling-Allerød interval (14.7–12.9 ka) and retreated >1200 km to its Younger Dryas (YD) position in ∼2500 yr. Ice-sheet stabilization at the Cree Lake Moraine facilitated a meltwater drainage route to the Arctic from glacial Lake Agassiz within the YD, but not necessarily at the beginning. Our record of deglaciation and new YD constraints demonstrate deglaciation of the Interior Plains was ∼60% faster than suggested by minimum 14C constraints alone. Numerical modelling of this rapid retreat estimates a loss of ∼3.7 m of sea-level equivalent from the SWLIS during the Bølling-Allerød interval.

USING METEORIC 10BE TO ASSESS SOIL EROSION RATES IN VOLCANIC ECOSYSTEMS (GALAPAGOS, ECUADOR)

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Understanding spatial variation of soil processes across heterogeneous landscapes is important to constrain ecosystem processes. The meteoric ^{10}Be isotope ($^{10}Be_m$) is commonly used as a geochemical tracer of soil processes over long timescales (> 10^3 years), and allows one to quantify physical erosion based on $^{10}Be_m$ inventories. Despite its large potential for soil studies, the use of $^{10}Be_m$ in soils is not yet well constrained. The $^{10}Be_m$ can be lost by leaching and deep percolation in well-developed, acidic soil profiles. It is therefore important to account for incomplete retention of $^{10}Be_m$ while using meteoric ^{10}Be to constrain soil redistribution processes.
Along a climatic gradient in Santa Cruz island (Galapagos archipelago), 10 soil profiles have been sampled to explore the mobility of $^{10}Be_m$ in the soil system. Our monitoring sites cover a ~10 km long NW-SE stretch with a 10-fold increase in precipitation rates. In five distinct altitudes, we monitor two sites along the climatic gradient: one that is developed on a basaltic lava flows and a second one on basaltic scoriae. By controlling for the age, composition of the basaltic parent material and topography, we focused on the unique natural soil erosion rates along the sharp hydroclimatic gradient. A large range of soil weathering intensities and soil acidity is observed along the climatic gradient: soil pH varies between 7.75 in arid sites (198 mm/yr) and 4.34 in humid sites (1588 mm/yr). The geochemical data from the 10 monitoring sites are used to further develop the methodology based on ^{9}Be chemical mass balances to correct $^{10}Be_m$ inventories for incomplete retention. We also take advantage of the large range of soil properties along the climatic gradient and analyse the Be retention in distinct soil phases. Our first results indicate an enrichment of Be in the amorphous and crystalline phases and a loss in the residual phase. There exists variation in the redistribution of Be in the soil profiles between arid and humid sites. Preliminary results indicate that leaching of meteoric Be increases with precipitation and increasing soil pH, with losses that exceed 25% in scoria sites with 198 and 1588 mm/yr.

Determining relief evolution in the Alps with muon paleotopometry

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Understanding topographic relief evolution and its changes over hundreds of thousands to million-year timescales remains challenging. Recent approaches usually combine numerical modelling of terrestrial cosmogenic nuclide exposure ages on strath terraces, exhumation histories based on thermochronology, drainage basin evolution, and basin stratigraphy. However, even when combined, these methods are unable to measure the rate changes with precisions needed to differentiate climate from tectonic drivers over multiple glacial cycles and longer timescales.

Muon-paleotopometry (MPT) is a new method that may address the methodological gap of determining relief generation. MPT utilizes the dependence of cosmic ray muon flux on crustal shielding depth. The spatial pattern of concentrations of multiple stable and terrestrial cosmogenic nuclides measured along a near-horizontal under valleys and peaks relates to the evolution of that surficial relief. It provides paleotopographical variation above the sample datum over an isotope-specific monitoring duration as a function of erosion rate and decay rate. Early proof-of-concept investigations at Dalhousie (M. Soukup, Hon. Thesis, 2017) provided encouraging results to allow for a large-scale relief investigation of the European Alps.

For centuries, the Alpine relief evolution has been studied to evaluate if the Alpine exhumation patterns are the result of Pleistocene incision, or mantle driven rock uplift. Here we present our project strategy and progress of applying the new MPT method along near horizontal transect in the Gotthard Base Tunnel (Switzerland; Fig. 1) to quantify the Alps relief evolution and potentially resolve the scientific dispute. Samples have already been obtained and are being processed. Will the DREAM-P project provide an answer to this decade long debate?

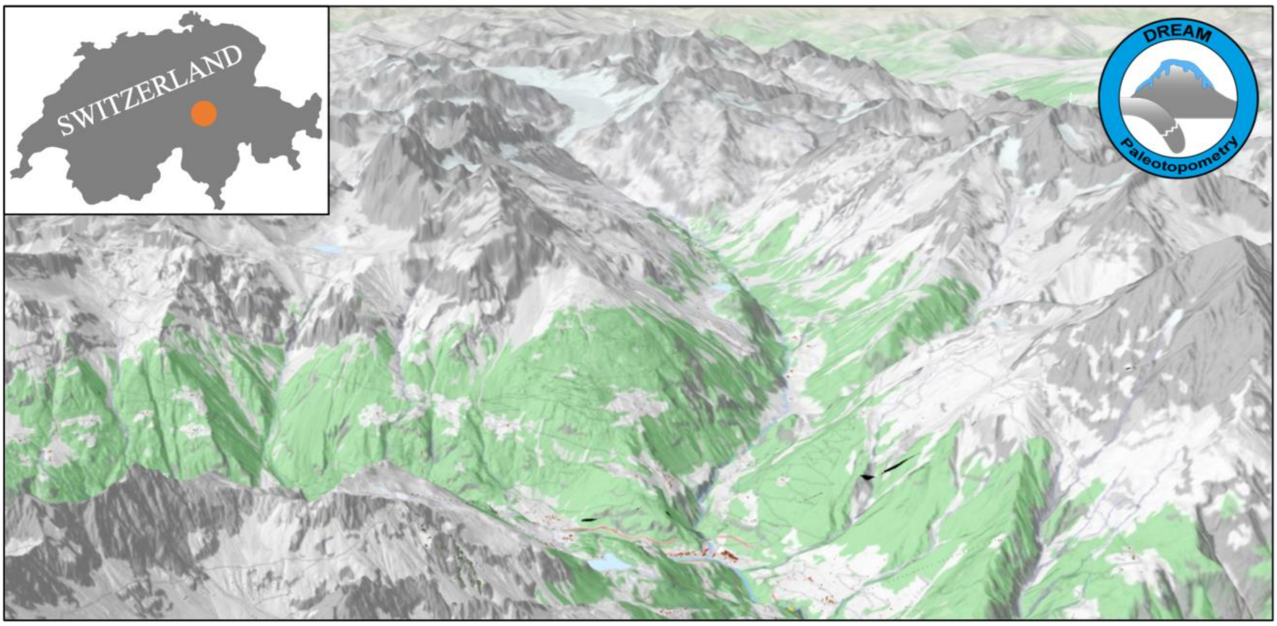

Fig. 1: View of the study area (orange dot) in central Switzerland (© swisstopo; www.geraldraab.com).

TRACK & TRACE: TRACKING LANDSLIDE RECURRENCE INTERVALS AND TRACING LANDSLIDE-SOURCED SEDIMENT WITH IN-SITU ^{10}Be AND ^{14}C

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Landslides are a dominant erosional mechanism in many orogens, a major geohazard, and sensitive to both tectonic and climatic perturbations. Because landslide scars and landslide deposits are often obliterated in <10^2 yrs, it remains difficult to quantify long-term rates of landslide activity and landslide-derived sediment fluxes. Here, we use the concentrations of in-situ ^{10}Be and ^{14}C from recent landslide deposits from the Fiordland and the Southern Alps of New Zealand to (a) estimate landslide recurrence intervals over 10^3-10^4 yr timescales, and (b) to test whether paired ^{14}C-^{10}Be measurements can be used to trace bedrock depth-provenance, and hence, landslide-sourced sediment.

Our analysis demonstrates that ^{10}Be concentrations in landslide deposits can be used to estimate landslide recurrence intervals and frequency, when combined with detailed DEMs of the landslide scars built from photogrammetry. Resulting ^{10}Be-based, long-term landslide frequency estimates, from samples collected at lower elevations, are an order of magnitude lower than the frequencies inferred from a decadal landslide inventory based on aerial imagery up to the tree line. This discrepancy suggests spatial and/or temporal differences in landslide activity. Our data empirically confirm that ^{14}C/^{10}Be ratios on landslide-derived sediment are greater than those expected for continuous surface erosion, and increase with landslide depth, hence potentially fingerprinting landslide-sourced sediment. Finally, we show that ^{14}C/^{10}Be ratios on fluvial sediment are greater in the Southern Alps, where landslides are more frequent and deeper, than in Fiordland, that is characterized by less frequent and shallower landsliding. Therefore, landslide-related ^{14}C/^{10}Be signals can be effectively propagated at the catchment scale and potentially used to infer catchment-wide landslide activity. These new approaches open up possibilities to quantify sediment generation from landslides on >10^2 yr timescales.

IMPORTANCE OF PERIGLACIAL AND PARAGLACIAL EROSION IN THE WESTERN SOUTHERN ALPS OF NEW ZEALAND

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Examining the links and potential feedbacks between tectonics and climate requires understanding the processes and variables controlling erosion. At the scale of mountain ranges, glacial erosion, and coupled river incision and landsliding, are the only processes that have been observed to be capable of balancing rapid rock-uplift rates. These processes are thought to link tectonics and climate through the influence of mountain elevations on orographic precipitation or glaciation.

The western Southern Alps of New Zealand (WSA) are one of the fastest-eroding ranges on Earth, where erosion has long been thought to be dominated by landsliding and glacial scouring. However, previous erosion studies in the WSA have been restricted to very few catchments, to decadal timescales, or to elevations below the tree line, which has prevented evaluating the variables and processes controlling erosion at the orogen-scale over longer timescales. Here, 20 new in-situ ^{10}Be catchment-averaged denudation rates, which mostly range between ~0.6-9 mm/yr, allow us to examine the controls and spatial distribution of denudation. We find that the proportion of catchment area within the 1500-2000 m elevation window explains >70% of the variability in denudation rates, more than any other variable. This elevation range corresponds to the previously identified frost-cracking window in the WSA, and includes the zone of recent glacial retreat and permafrost degradation. Our data hence suggests that temperature-controlled peri- and paraglacial erosional processes dominate erosion in the range and can balance some of the fastest rock-uplift rates on Earth, of several mm/yr. Therefore, these processes, which are also elevation-dependent, can play an important role in linking tectonics and climate and limiting mountain elevations.

INHERITED COSMOGENIC NUCLIDE INVENTORY IN THE CIRQUE AREA OF FORMERLY GLACIATED MOUNTAIN RANGES OF SOUTHEASTERN EUROPE

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When studying glacial landforms, the presence of cosmogenic nuclide concentrations inherited from previous exposure(s) may hinder the determination of their age. Inheritance is indicative of limited glacial erosion and/or of a complex exposure history, and this might, in turn, be revealed by a bias towards older ages in apparent exposure durations. Several studies have suggested that the existence of cosmogenic nuclides accumulated in bedrock before the last glaciation is indicative of limited glacial erosion.

Here a published case study of the Retezat Mts [1], Southern Carpathians will be presented together with new data from the Jakupica Mts, Central Balkan Peninsula. At both areas a plateau glacier was reconstructed for the Last Glacial Maximum, followed by glacier recession during the Late glacial. The samples from the landforms related to the cirque glaciers in both areas provided cosmic ray exposure ages with large scatter and biased towards old ages, which was attributed to the presence of inherited cosmogenic nuclide concentrations within the rock.

The case study from the Southern Carpathians permitted the quantification of the amount of inherited ^{10}Be in glacial boulders and bedrock samples in the cirque area. In lack of independent geochronological data, the amount of inherited cosmogenic nuclides was tentatively estimated by accepting the youngest cosmic ray exposure age(s) as the time of moraine deposition. The calculated amount of inherited ^{10}Be enabled the estimation of a glacial erosion depth of 1.1–1.4 m for the bedrock samples and 1.4–1.7 m for the glacial boulders. The duration of the ice-covered and ice-free periods was adjusted in relation to independent paleoenvironmental and paleoclimatological data.

The limited glacial erosion in the cirques is attributed to frozen-bed conditions with no considerable glacial deepening during the more extended glacial phases. Only when warming led to retreat of the glaciers to their cirques, they become steeper and shift to being warm-based, and thus more erosive. However, the limited time spent under these conditions appears to be too short to remove material from the cirque floors in sufficient depth (>3 m) to reset the cosmogenic clock.

Funding: NKFIH FK124807; RADIATE 19001688-ST. We are grateful to Silke Merchel to her contributions to the cosmogenic radionuclide measurements.

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COMPARISON OF THREE COSMOGENIC RADIONUCLIDE METHODS OF SEDIMENT BURIAL DATING

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This study applies three published cosmogenic ^{10}Be and ^{26}Al burial age calculation methods suitable for buried sediments that undergo post-depositional nuclide production. We compare the variability of calculated ages depending on the method, assess similarities, and explore limitations. ^{26}Al and ^{10}Be concentrations for age determination originate from a terrace of the Danube river located in the Central Vienna Basin (Austria) [1]. In the aggradational sandy gravel two horizons at 5.5 m and at 11.8 m subsurface depth were sampled. Each sample set contained 6 quartz or quartzite cobbles.

The first objective was to compare burial age dating by inverse modelling (INV, [2]) to isochron burial age dating (ISO; [3], [4]) and Particle Pathway Inversion of Nuclide Inventories (P-PINI, Knudsen et al., 2020). The advantage of ISO is that it is not sensitive of changes in sample depth over time. However, it cannot model pre- and post-burial denudation rates. INV and P-PINI are capable of modelling pre- and post-burial denudation rates but are sensitive to sample depth. All methods should provide the same burial ages and denudation rates within uncertainties if applied correctly and in accordance with the inherent assumptions of the respective models. The second objective was to investigate the effect of randomly including or excluding data points (bootstrapping) for INV and ISO. This enables us to estimate to what extent numerical ages depend on sample selection. In addition, we assess whether bootstrapping applied on the entire dataset supports outlier identification. The last aim was to explore systematic shifts between the methods.

The same outliers were identified by ISO and INV bootstrapping. After outlier exclusion, both methods provided similar and geologically consistent ages for the two sampled horizons, that overlap with burial ages and denudation rates calculated by P-PINI. For INV and ISO outlier exclusion is essential, as a single sample potentially biases the calculated burial age considerably whereas P-PINI utilizes the complete dataset.
If the two sample sets from different depths are merged, INV and P-PINI provided different burial ages and different denudation rates at the sampling site. The reasons for the discrepancies need further investigations. First results will be presented at the workshop.

Funding: NKFIH FK124807; OMAA 90ou17; OMAA 98ou17.

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Holocene glacier advance and retreat chronologies: novel contributions involving ^{36}Cl and ^{14}C

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Most existing Holocene glacial chronologies are based on ^{10}Be dating of moraines, which provide valuable information on large glacier extents that occurred during cold episodes. Robust, precise ^{10}Be moraine records are becoming increasingly abundant for the Holocene, thus allowing for meaningful paleoclimatic interpretation. The more difficult question to tackle is how glaciers behaved during the warm periods of the Holocene, from which moraines are not preserved. Another challenge resides in reconstructing accurate glacier chronologies in environments with quartz-lacking lithologies, where the well-established 10Be-dating method cannot be applied. Here, I present results from recent studies that involve the less-routinely used nuclides in situ ^{14}C and ^{36}Cl to deal with these challenges.
In the forefield of Steingletscher (European Alps, Northern mid-latitudes), we applied the emerging approach of paired ^{10}Be-^{14}C dating of recently deglaciated bedrock (Fig. 1) to constrain the duration of Holocene glacier recession. Combining the results with the ^{10}Be moraine chronology from the same site allowed reconstructing the glacier's Holocene retreat and advance history (Schimmelpfennig et al., Clim. Past 18, 23-44, 2022). Large glacier extents prevailed in the Earliest and the Late Holocene, while in between significant retreat occurred during several millennia. This pattern agrees well with existing glacier chronologies not only in the Alps and other parts of the North-Atlantic region, but also in the Tropics, as shown in Jomelli et al. (Nat. Comm. 13, 1419, 2022).
In the Southern mid-latitudes, we reconstructed a Holocene glacier pattern on the basaltic Kerguelen archipelago, using ^{36}Cl dating of moraines and paired bedrock and erratic boulder surfaces (Charton et al., QSR 283, 107461, 2022). The results imply that glaciers had significantly retracted extents throughout the Holocene, while Holocene maximum extents occurred only in the last millennium. This pattern is quasi-unique and highlights the non-uniformity of Holocene glacier behavior throughout southern mid-latitudes.
Finally, I will present ongoing work on new ^{36}Cl production rate calibrations and the implementation of an online ^{36}Cl exposure age calculator into the existing CREp interface.

Fig. 1: Glacially polished bedrock in the forefield of Steingletscher (Central Swiss Alps), deglaciated in the 2000s.
Photo: I. Schimmelpfennig in 2010.

Developing the first North Greenland in-situ ^{14}C chronology

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Determining the sensitivity of the Greenland Ice Sheet during the Holocene is a key prerequisite for understanding the future response of the ice sheet to global warming. It has proven difficult to constrain the glacial history of particularly North Greenland, an area predicted to be a key component in future mass loss from the ice sheet [1]. To fill this gap, this project will be the first to use cosmogenic in-situ ^{14}C exposure dating to constrain Holocene ice sheet fluctuations in North Greenland (Fig. 1).

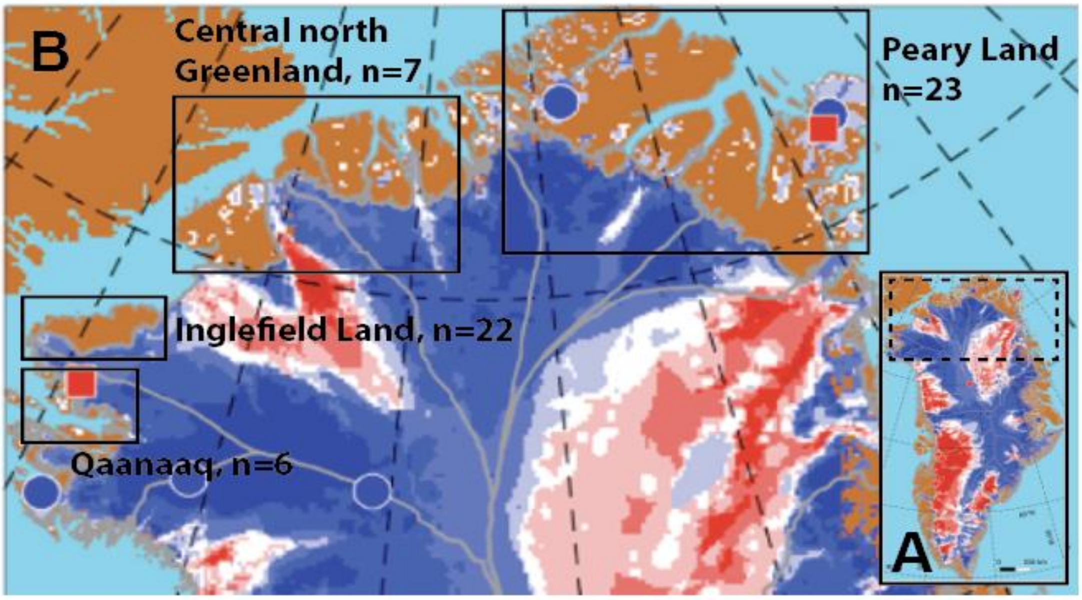

Fig. 1: *A) Modelled present-day subglacial thermal state of the Greenland Ice Sheet. B) North Greenland and the four main study areas. Modified from [2].*

Cosmogenic nuclides are produced in rocks when cosmic rays hit the surface of the Earth. The cosmogenic nuclide inventory of a rock surfaces is therefore a key tool for chronicling the waxing and waning of ice [3]. The most commonly analysed nuclide is ^{10}Be, which has a half-life of 1.4 Myr. However, a particular challenge arises in regions where the ice sheet base is cold and slow-moving. In these regions, erosion rates are low and ^{10}Be inventories produced during earlier exposure periods accumulate instead of being removed, which result in exposure ages older than the last period of exposure [4].
To circumvent this problem, we use in-situ produced cosmogenic ^{14}C. Due to the shorter half-life (5730 yr), in-situ ^{14}C inventories will, contrary ^{10}Be, decrease not only because of rock surface erosion but also due to shielding from ice cover (Fig. 2). Measurements of in-situ ^{14}C, carried out at the in-situ ^{14}C line at Laboratory of Ion Beam Physics, ETH Zürich [5], can therefore help to obtain more reliable ice reconstructions for North Greenland.

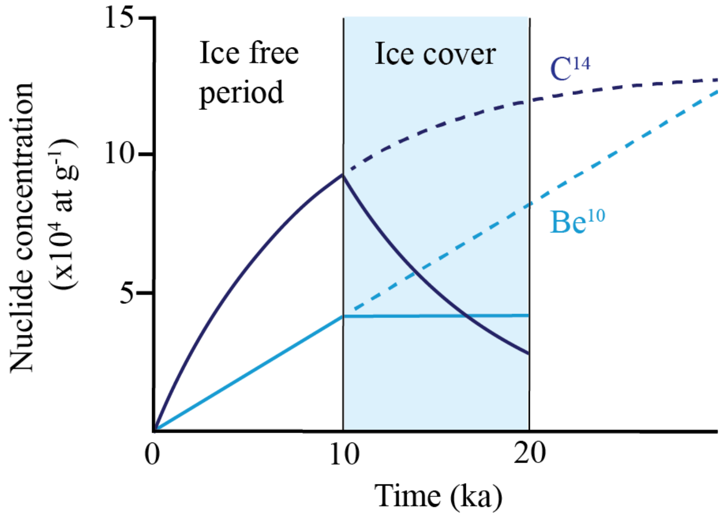

Fig. 2: *During exposure the concentration of in-situ ^{14}C and ^{10}Be builds up differently. During ice cover, the nuclide production stops. ^{10}Be has a half-life of 1.4 Myr, so no significant decay will be evident at 20 kyr, whereas the short half-life of ^{14}C (5730 yr) makes the concentration decrease significantly. Modified from [6]*
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Cosmogenic Ne provides first constraints on the complex burial history of lunar regolith from Apollo 12 basaltic soil grains

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The lunar surface has been exposed to solar particle events and high-energy galactic cosmic rays for billions of years. The absence of an atmosphere, and, for much of its history, and lack of a magnetic field means that cosmogenic nuclides in lunar surface material record the long-term history of regolith production and the evolution of the surface in response to large impacts. Previous studies have tended to use cosmogenic nuclide concentrations to determine cosmic ray exposure (CRE) ages that assume single stage exposure at lunar surface. Consequently there is little understanding of the rate at which lunar regolith is produced and how efficiently it is gardened by impacts and lower energy processes.

We have devised a method for using the cosmogenic Ne released by incremental heating 1-2 mg fragments of lunar regolith material to partition the cosmic ray exposure (CRE) history into deep (shielding of 5-500 g/cm^2) and near-surface (shielding of 0 g/cm^2) burial. We have applied the technique to ten basalt fragments derived from the upper 5 cm of the lunar regolith (sample 12003) collected from the flank of Surveyor crater at the Apollo 12 landing site. We use cosmic ray exposure and shielding condition histories to consider their geological context. Three samples show evidence of measurable exposure at the lunar surface of 6-7 ± 2 Ma, even samples have near-surface residence of less than a few hundred thousand years. One sample records a single stage cosmic ray exposure age range of between 516 ± 36 and 1139 ± 120 Ma, within 0-5 g/cm^2 of the lunar surface. This is consistent with derivation from ballistic sedimentation (i.e., local regolith reworking) during the Copernicus crater formation impact at ~800 Ma. The remaining samples show cosmic ray exposure age that cluster around 124 ± 11 Ma and 188 ± 15 Ma. We infer that local impacts, including Surveyor crater (180-240 Ma) and Head crater (144 Ma), may have brought these samples to depths where the cosmic ray flux was intense enough to produce measurable cosmogenic Ne. More recent small impacts that formed un-named craters may have exhumed these samples from depth. This model can be applied to previously acquired Ne isotope data from other Apollo mission lunar regolith samples to gains a more complete understanding to how the lunar surface has evolved. The sense that the Apollo 12 regolith fragments studied here have been brought to the surface in the last few million years suggests that combining cosmogenic Ne with ^{26}Al and ^{10}Be may provide more precision on the recent impact history of the lunar surface.

VARIABILITY OF THE AUTHIGENIC ^{10}BE/^{9}BE IN OFFSHORE TO DELTAIC SEDIMENTS IN EPICONTINENTAL BASIN SEQUENCES AND ITS RELEVANCE FOR GEOCHRONOLOGY

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The ratio of radionuclide ^{10}Be and stable nuclide ^{9}Be in a water column is affected by proximity of terrestrial sources, since ^{9}Be is derived from weathering of rock masses, while cosmogenic ^{10}Be has a meteoric origin. Prograding of river deltas forming deltaic parasequences (high frequency cycles) as well as prograding of shelf slopes (4th and higher order cycles) cause changes in proximity, which affect sediment delivery and potentially input of ^{9}Be. Hence, more proximal (e.g., deltaic) environments exhibit higher sedimentation rates which in turn is expected to decrease the potential post-depositional input of beryllium in a buried sediment. The authigenic rim formed around a sediment particle in a water column will therefore have higher ^{10}Be/^{9}Be ratio in distal settings. This effect was observed in the scale of river delta to continental slope (Wittmann et al., 2017: Geophys. Res. Lett.) However, studies focused on smaller scale proximity changes in epicontinental basins are missing despite their necessity to reveal the applicability of the authigenic ^{10}Be/^{9}Be dating.

We provide a review of the ongoing research on the authigenic ^{10}Be/^{9}Be in depositional record of some European Miocene basins. First results from the study of Slanicul de Buzau section (Dacian Basin, Romania) come from an interval dated to ~6.1–5.3 Ma by magnetostratigraphy (Matoshko et al*., in prep.*). The succession starts with offshore shelfal deposits, followed by regression and facies of delta front and delta plain, capped by a transgression and another offshore shelfal succession. The measured authigenic ^{10}Be/^{9}Be ratios and the magnetostratigraphic ages were used to back-calculate the initial ^{10}Be/^{9}Be ratios to reveal its variability. The lower shelfal unit exhibits the initial ^{10}Be/^{9}Be ratio of ~7.1×10^{-9}, while it decreased to ~1.7×10^{-9} in the regressive deltaic succession and increased to ~3.1×10^{-9} in the upper shelfal unit. Two parasequences sampled in detail imply a low variability in initial ^{10}Be/^{9}Be ratios, while few outliers exhibit high content of iron, carbonates, smectite and likely were affected by post-depositional growth of authigenic rims due to condensed sedimentation. Another study comprises Paks borehole cores from the central Pannonian Basin (Hungary), again dated by magnetostratigraphy (Kelder et al., 2018: Geochem. Geophys.). The distal lacustrine facies exhibit initial ^{10}Be/^{9}Be ratios ca. two to four times higher compared to the overlying proximal deltaic deposits. It is suggested that the mosaic of deep basins separated by basement highs hindered effective delivery of ^{9}Be from remote deltaic systems before their progradation. Finally, the study of the deltaic parasequences deposited on the boundary of Middle and Late Miocene (~11.6 Ma) in the Vienna Basin (Slovakia) yielded stable isotopic ratios, despite the samples were taken from environments of different proximity from delta top to shelf. Generally, the results of ongoing research indicate a low variability of authigenic ^{10}Be/^{9}Be within high frequency cycles (e.g., parasequences), while changes in sediment proximity in the scale of shelf slope migration affect the authigenic ^{10}Be/^{9}Be ratio significantly. Nevertheless, the changes of initial ^{10}Be/^{9}Be ratio could be predicted at this stratigraphic scale of 4th and higher order cycles.
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REDEPOSITION OF MUD DURING RIVER INCISION AFFECTS THE AUTHIGENIC ^{10}BE/^{9}BE DATING: MAMMAL FOSSIL-BEARING SITE NOVÁ VIESKA, WESTERN SLOVAKIA

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The authigenic ^{10}Be/^{9}Be ratio provides an important geochronological tool to date a depositional age of clay bearing sediment, nevertheless, recent studies showed that the initial ^{10}Be/^{9}Be ratio might be affected by changes in paleoenvironmental conditions and post-depositional processes. The method is based on the ratio of atmospheric cosmogenic radionuclide ^{10}Be transported to a sedimentary environment by meteoric precipitation and of stable ^{9}Be derived by weathering of rock massifs. This study examines suitability of the method to date river terrace sediments, accumulated during incision of a river. The Nová Vieska river terrace selected for the case study was deposited during the inversion of the Danube Basin (western Slovakia).

The facies analysis implies accumulation by a wandering river, comprising both lateral- and downstream-accreted sandy-gravelly bars, apart from thalweg basal coarse lag strata and minor oxbow lake and proximal floodplain facies, sampled for the authigenic ^{10}Be/^{9}Be dating. A high variability of flow speed, turbulence and sediment concentration is implied by the range of lithofacies. An extensive presence of mud intraclasts mirrors significant input of eroded material from below-lying older successions.

The ages of 13 authigenic ^{10}Be/^{9}Be dating samples form three groups: (1) samples below the base of the river terrace yielded ~4.13–3.70 Ma, (2) muddy intraclasts present in the river terrace with ages ranging in ~2.79–1.96 Ma and (3) *in situ* muddy layers from the river terrace representing oxbow lake or proximal floodplain facies, which provide ages in the range of ~1.91–1.39 Ma. The large mammal fossil assemblage from channel thalweg deposits yields biostratigraphic age of ~2.56–1.85 Ma, what fits to the age of intraclasts, emphasizing redeposited origin of fossils.

The relatively wide range of authigenic ^{10}Be/^{9}Be dating ages is interpreted as a result of redeposition of mud derived from below lying Upper Miocene, Pliocene and Lower Pleistocene alluvial strata. It is expected to appear at three scales: (1) decimeter-scale intraclasts, (2) millimeter-scale rip-up clasts mixed to the newly formed beds, and (3) mixing of individual clay particles, which have preserved internal older authigenic rim and newly formed outer rim, differing by ^{10}Be/^{9}Be record. Considering the mentioned settings, the age range of *in situ* layers reaching 1.91–1.39 Ma is proposed as the depositional age of the river terrace. The effect of redeposition limits application of the authigenic ^{10}Be/^{9}Be dating to incising rivers, in contrast with settings of aggrading rivers, where redeposition of older sediment is limited and the ^{10}Be/^{9}Be variability is low.

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High $^{26}Al/^{10}Be$ ratios in granitic regolith and their implications

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The cosmogenic $^{26}Al/^{10}Be$ ratio in quartz is an essential parameter to quantify the sediment burial and its complex transport process. The $^{26}Al/^{10}Be$ spallation production ratio of 6.75 is commonly assumed as the initial ratio for burial dating. However, recent studies suggest that the $^{26}Al/^{10}Be$ production ratio may be greater in sediments, boulders, and bedrocks due to different locations[1] or muon contributions[2].

We established a steady-state forward model to estimate the variation of $^{26}Al/^{10}Be$ with depth (Fig. 1). The model results illustrate that (1) lower denudation rates present relatively lower $^{26}Al/^{10}Be$ ratios due to the shorter half-life of ^{26}Al; (2) the $^{26}Al/^{10}Be$ ratio can reach a high value greater than 6.81 (total of surface spallation and muon production) due to the non-ignorable contribution of muon production; and (3) the $^{26}Al/^{10}Be$ ratio shows an increase with depth at high (e.g., 500 mm/kyr) and low (e.g., 0.1 mm/kyr) denudation rates, but a decrease with depth at medium denudation rates (e.g., 5 mm/kyr). We found that the $^{26}Al/^{10}Be$ ratios of Beacon Height show a plausible increase along with the best-fit surface denudation rate of 0.1 mm/kyr [3], and those of Leymon present a rough decrease along with the best-fit surface denudation rate of 20 mm/kyr[4]. Our data revealed a slight increase along with the best-fit surface denudation rates of 28-45 mm/kyr. The consistent result between the forward modelling and experimental data at Beacon Heights[3], Leymon[4], and this study suggests that the initial $^{26}Al/^{10}Be$ ratio derived from a steady-state surface systematically increases or decreases with depth, varying from 3.45 to 8.25.

Our forward model demonstrates that muon contributions can produce higher $^{26}Al/^{10}Be$ ratios in both steady-state and non-steady-state scenarios. This might potentially result in underestimated burial ages and exaggerated denudation rates for the application of dual-nuclides in the Earth's surface system.

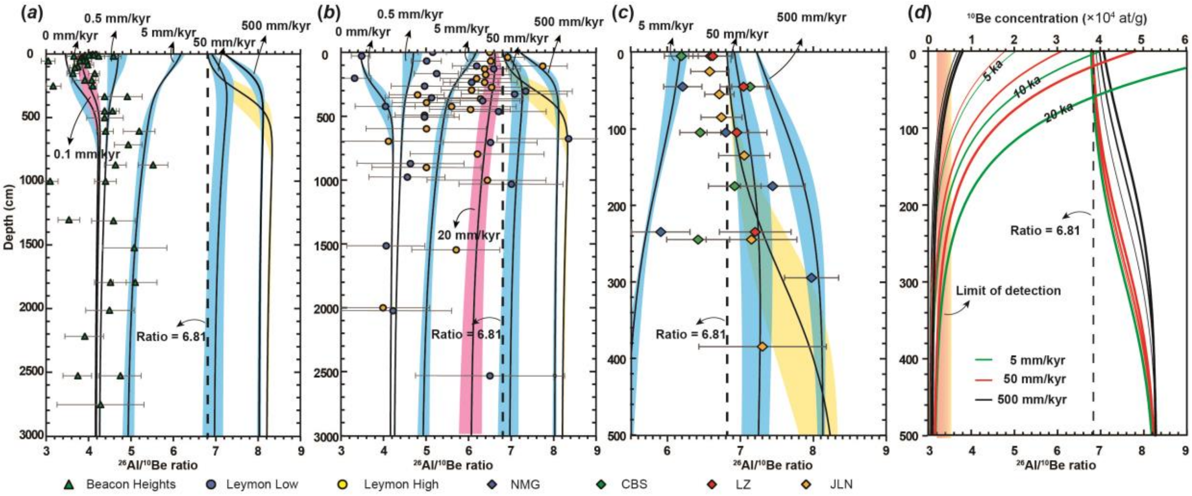

Figure 1. (*a-c*) Depth profiles of $^{26}Al/^{10}Be$ ratio at Beacon Heights[3], Leymon[4], and granitic regolith in eastern China. Yellow and blue areas show the variation of $^{26}Al/^{10}Be$ production rate ratios and modelled concentration ratio, respectively, based on the density of 2.0 ± 0.6 g/cm^3 and considered spallation and muon production[3]. Pink areas indicate the variation based on surface denudation rates of 0.1 mm/kyr at Beacon Heights[3] and 20 mm/kyr at Leymon[4]. (*d*) Modelling results of short surface exposure duration with different denudation rates present that the ^{10}Be production is higher than the detection limit (orange area).

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