June 8–10, 2016

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Third Nordic Workshop on cosmogenic nuclide techniques

Celebrating 30 years of counting cosmogenic atoms

Editors
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Preface

This proceedings volume contains the extended abstracts presented at the *Third Nordic Workshop on Cosmogenic Nuclide Techniques: Celebrating 30 years of counting cosmogenic atoms*, arranged by Stockholm University, June 8–10, 2016, and co-sponsored by SKB. It also contains the field guide for the post-workshop excursion to Forsmark, held on June 11, 2016. The excursion is closely linked to the ongoing SKB-funded project *Long-term safety assessment of a planned deep repository for spent nuclear fuel in Forsmark, Sweden: Impact of glacial erosion over the next 0.1–1.0 Myr,* performed by Stockholm University and University of Gothenburg.

Stockholm, May 2016

Jens-Ove Näslund
Research coordinator Climate programme SKB

Third Nordic Workshop on Cosmogenic Nuclide Techniques: Celebrating 30 years of counting cosmogenic atoms

Stockholm University, June 8-10, 2016

Cosmogenic nuclide exposure dating is recognized as one of the most significant advances in Geosciences during the late 20th Century. Since the first demonstrated applications of the method in the mid- to late-1980's, its impact in the study of the Earth, geologic and biologic, past and present, has resulted in paradigm shifts in concepts and models. The measure of cosmogenic nuclides produced in the atmosphere or within the shallow lithosphere in a myriad of natural archives has given scientists a means to quantify the spatial and temporal scales of processes and interactions that shape our planet. The theoretical principles of the cosmogenic nuclide method were laid out in a seminal paper by Lal & Peters (1967; *Handbook of Physics* **46**, 551-612). However, a means to measure the predicted miniscule concentrations of cosmogenic nuclides was not available. The catalyst for realizing the ideas of Lal and Peters came with the invention in 1978 of Accelerator Mass Spectrometry (AMS) – an analytical technique with unprecedented sensitivity. Initial effort in AMS was directed to a study of meteorites and lunar rocks. With commensurate advances in both AMS techniques and sample preparation, a series of papers in Nature and Science in 1986 heralded the application of cosmogenic nuclides in the study of Earth surface processes providing 'dates and rates'. A range of isotopes (^{3}He, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, and ^{21}Ne) has been applied to geochronology by dating distinct 'events' such as glacial moraine formation and landslides. Alternatively, where surfaces erode incrementally, cosmogenic nuclides can be used to determine erosion rates over geological timescales. Today, the cosmogenic nuclide dating technique represents one of the most reliable tools for quantifying how the Earth's surface responds to climate and tectonic processes.

However, as with all new techniques, there have been major efforts in the demonstration of its reliability and reproducibility, for example, through the comparison of the cosmogenic nuclide technique as a dating tool with independently-dated locations and via international laboratory inter-comparison of standards. This has also yielded independent checks on (theoretical) models of the distribution of nuclide production rates across Earth's surface, which changes with latitude and elevation, and through time. Recent efforts in conjunction with the North American CRONUS-Earth and European CRONUS-EU projects have made major strides towards this goal of reliable production rates. Given this success, the technique is now routinely used across a range of Earth surface applications, including glacial paleoclimate change, sediment burial dating (including archaeology), point measurements of bedrock erosion and soil production rates, catchment-wide mean denudation rates, and many others.

The Nordic community has developed a legacy of being on the forefront of cosmogenic nuclide applications in glacial settings – both regarding the history and dynamics of glaciers and former ice sheets (such as, and primarily, the Fennoscandian ice sheet), and landscape development in formerly glaciated regions (worldwide). A new development is that the Nordic cosmogenic nuclide community is becoming less reliant on AMS analytical support from UK-France-Swiss-USA laboratories because both Trondheim and Aarhus are developing the in-house capability to run the isotope measurements; a capability also available at Uppsala University.

In recognition of the emerging strength of the Nordic cosmogenic isotope community, and the potential for close and innovative international collaboration, Norwegian colleagues in Trondheim organized a first Nordic workshop in 2012. This was repeated 2014 with a meeting organized by Aarhus University, Denmark, and contained in this issue you will find the proceedings of the third Nordic workshop hosted by Stockholm University.

This open meeting in cosmogenic nuclide techniques attracted more than 70 participants from all over the world although, given its focus, predominantly from Nordic (41%) and European (40%) countries. Additional countries represented included USA (9%), Australia, China, and South Africa (3%), and Chile (1%). The meeting commemorated the 30-year anniversary of the first studies to apply CNs to understanding Earth-surface processes. To highlight the achievements, six keynote lectures were presented by British, Swiss, American and Australian-based colleagues who have been instrumental in shaping the CN and AMS methods over the past 30 years.

Thirty lectures presented at the three-day workshop were structured around four themes; scaling (4), paired nuclides (8), landscape evolution in formerly glaciated regions (12), and mass wasting/others (6). Eighteen poster presentations were similarly structured into three themes; methodological/technique development (5), landscape processes (2), and glacial chronology (11). In total, fifty out of seventy participants engaged in active presentations!

On behalf of the organizing committee[†] I would like to acknowledge the financial support of Stockholm University and SKB – the Swedish Nuclear Fuel and Waste Management Company – which allowed this workshop to be organized free of registration charges, and the publication of this book of extended abstracts. We are also indebted to the Program committee[‡], who helped shape the meeting and the promotion of junior (PhD, Post-doc) presentations (50%).

Stockholm, 2016-05-12

Arjen P. Stroeven

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Tick-tock there is a clock in my rock – 30 years of counting atoms with Accelerator Mass Spectrometry

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Abstract

Accelerator Mass Spectrometry is recognized as one of the most significant advances in analytical isotope research of the 20th century. Since the 1980's its impact in science and technology has been immeasurable. In all subjects related to the study of planet Earth, geologic and biologic, past and present, outcomes facilitated by the unprecedented sensitivity afforded by AMS have resulted in paradigm shifts of prevailing concepts and models. The art of in-situ produced terrestrial cosmogenic radionuclides (specifically ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl) was borne out of AMS methodologies developed in the study of precious lunar and meteoritic samples to unravel their formation, distribution and exposure histories. As a result, measurement of miniscule concentrations of cosmogenic radioisotopes produced in the atmosphere, or within the shallow lithosphere in a myriad of natural archives has enabled scientists to quantify the spatial and temporal evolution of climatic and environmental processes which has shaped our planet.

Enabling these advances were commensurate revolutions in AMS technology with the continual drive to reduce complexity, accelerator size and costs. Equivalent AMS performance for ^{14}C, ^{10}Be and ^{26}Al is now possible on dedicated accelerator systems operating at 0.5MV - a considerable step down in size from the shared 10MV nuclear research laboratories of the past. Increased performance in ion detection, background suppression, efficiency, and innovative ion-source developments, together with fully computerised and remote operations afforded by new generation AMS systems has led to ever-increasing sample throughput and improved sensitivity. Together with continual improvements in global production rate calibration, scaling and modelling, a spectrum of diverse applications to "date events, changes in climatic conditions and trace processes across the landscape" has now become part of the researcher's toolbox which augers well for future years of exciting discoveries. This talk will present a brief 35-year overview of key advances since the time of the first terrestrial in-situ ^{10}Be, ^{26}Al and ^{36}Cl measurements were published in 1986.

The SPICE Project: Preliminary cosmogenic nuclide production rates in quartz calibrated at the ~70 ka SP lava flow, AZ, USA

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Abstract

The formally named SP Flow is a quartz-, olivine- and pyroxene-bearing basalt with an $^{40}Ar/^{39}Ar$ age of 72±4 ka (±5.6%; 2σ). The flow is preserved in the arid desert climate of northern Arizona, USA and its unweathered appearance and the lack of soil development indicate it has undergone negligible erosion. Earlier cosmogenic nuclide data from the CRONUS-EU project corroborate this assessment. Cosmogenic ^{3}He and ^{21}Ne production rates in pyroxene from the SP Flow are consistent with a 72 ka eruption age (Fenton et al., 2013, 2014), and they are in excellent agreement with other rates reported in recent literature. Furthermore, the uncertainties (7%; 2σ) associated with the SP Flow production rates are low due to the high-precision $^{40}Ar/^{39}Ar$ age.

The SPICE Project (**S**P Flow **P**roduction-Rate **I**nter-calibration Site for **C**osmogenic-Nuclide **E**valuations Project) grew out of our CRONUS-EU study at the SP flow. During this project, we will measure, for the first time and at one calibration site, cross-calibrated production rates of each of the most commonly used cosmogenic nuclides – ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl – integrated over the past 72 ka. Never before have all these commonly used terrestrial cosmogenic nuclides been inter-calibrated in co-existing quartz, pyroxene, and olivine at one calibration site, much less integrated over the past ~70 ka ($^{40}Ar/^{39}Ar$ age). A large number of existing cosmogenic nuclide studies have been performed in the southwestern USA. SPICE data will provide another much needed local production-rate calibration site, especially for surfaces and landforms older than 20 ka. Currently, all existing ^{10}Be primary production rates are calibrated on surfaces that have been exposed to cosmic rays for less than ~20 ka. Here we present preliminary results of cosmogenic nuclide production rates in quartz from the SP lava flow.

Nearly all Quaternary paleoclimate synthesis studies make use of glacial geology and glacial chronology studies; most of these rely in large part on cosmogenic nuclide data. Though impressive progress has been made over the past 20 years in determining cosmogenic nuclide production rates, there still exist significant systematic uncertainties that stem from production rates and scaling schemes. Research is still needed to minimize these uncertainties to <5%. Cosmogenic nuclide exposure ages can only be as accurate as the production rates themselves. The SPICE Project thus aims to help increase the accuracy of studies involving these six in-situ cosmogenic nuclides (^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl).

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The CREp program and the ICE-D production rate calibration database: a fully parameterizable and updated online tool to compute exposure ages from cosmogenic ^{3}He and ^{10}Be

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Abstract

Cosmogenic exposure dating brought major advances in earth surface sciences and particularly in palaeoclimatology over the last decades. Yet, exposure age calculation is a dense procedure. It requires numerous choices of parameterization and the use of an appropriate production rate. Nowadays, earth surface scientists may either calculate exposure ages on their own or use the available programs. However, these programs do not offer the possibility to include all the most recent advances in Cosmic Ray Exposure (CRE) dating. Notably, they do not propose the most recent production rate datasets and they let few possibilities to test the impact of the geomagnetic model on the computed ages.

We present the CREp program, an online Octave code that computes CRE ages for ^{3}He and ^{10}Be over the last 2 million years (http://crep.crpg.cnrs-nancy.fr). The CREp program includes the scaling models of Lal-Stone in the "Lal modified" version (Balco et al., 2008; Lal, 1991; Stone, 2000) and the LSD model (Lifton et al., 2014). For any of these models, CREp allows choosing between the ERA-40 atmosphere model (Uppala et al., 2005) and the standard atmosphere (National Oceanic and Atmospheric Administration, 1976). Regarding the geomagnetic database, users can opt for one of the three proposed datasets: Muscheler et al. 2005 and the composite reconstructions of Lifton et al. (2014) and Lifton (2016). They may also import their own geomagnetic database.

Importantly, the reference production rate can be chosen among a large variety of possibilities. We made an effort to propose a wide and homogenous calibration database in order to promote the use of local calibration rates: CREp includes all the calibration data published until July 2015. These data are stored on the updated online ICE-D database, making it possible to include all the newly published production rates. As the use of local production rates contributes to reduce the dependency of the ages on the scaling models, this new possibility provides an efficient way to improve the ages accuracy. Users may also choose the global production rate or use their own data to either calibrate a production rate or directly input a Sea Level High Latitude value.

The program is fast to calculate a large number of ages and to export the non-trivial final density probability function associated with each age into an Excel spreadsheet format.

Implications from secondary cosmic ray neutron spectra measurements to cosmogenic isotope scaling models

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Abstract

A necessary requirement in studies using in-situ cosmogenic isotopes is to convert the measured isotope concentrations to exposure ages or geomorphic process rates. This involves using an accepted reference production rate, derived experimentally at a calibration site that has independent age control, and applying factors for latitude and altitude in order to calculate a site-specific production rate. Throughout the development of the in-situ cosmogenic dating method, although reference production rates are necessarily nuclide specific, the scaling factors were not.

The first atmospheric scaling model by Lal and Peters [1967] and others that followed, were based on the principle that as the cosmic ray particle flux attenuates with depth, the energy spectrum of nucleons of energy below 400 MeV becomes invariant at atmospheric depths greater than 200 g/cm^2 (altitude < 12 km). Hence scaling factors would thus be isotope independent resulting in production rate ratios of different isotopes to be invariant as a function of altitude. However, recent models by Argento et al. [2012, 2015] and Lifton et al. [2014] suggest that the energy spectrum is not invariant and scaling factors should in fact be isotope specific.

The essential feature of the new models is that the focus is on generating the energy spectrum of cosmic-ray nucleons that is then converted into scaling factors with known cross sections. To benchmark the new scaling models I have collated secondary cosmic-ray neutron spectra measurements from the last 20 years and utilised these to calculate site-specific production rates. When using both ground-based and airborne neutron spectra measurements, the result follows the general trend predicted by the new models requiring isotope specific scaling. In contrast, using only the ground-based measurements, which range from sea-level to ~4000 m in altitude, no evidence for isotope specific scaling is apparent. To study this apparent discrepancy development of a model to estimate the effect of the measurement uncertainties in the neutron spectra to the calculated cosmogenic nuclei production rates is on-going.

Proposed community-based measures for improving the accuracy and reliability of cosmogenic nuclide measurements, based on findings of the CRONUS-Earth and CRONUS-EU projects

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Abstract

The CRONUS-Earth and CRONUS-EU Projects were established to assess the utility of cosmogenic-nuclide analytical methods and interpretations. Results have been published in volumes 26 and 31 of *Quaternary Geochronology* (2015-2016). Based on the findings of the projects, the following community-based measures have been proposed to improve analytical results and the confidence that can be reposed in them, and to improve the tools used to interpret the data: (1) Establish a systematic analytical intercomparison effort, including continuing production of intercomparison materials (ICM) at low, intermediate, and high concentrations. (2) Set up an ICM reporting site on a dedicated website, with statistical analysis tools. (3) Establish an interactive 'wiki-type' best practices website for preparation of samples for analysis of all commonly used nuclides. (4) Establish an international oversight committee for advising modifications and improvements to the CRONUScalc web calculator. (5) Employ the same, or a similar, committee to evaluate new nuclide production-rate calibrations with respect to inclusion in default global production-rate sets. (6) Set up regular meetings of the cosmogenic-nuclide committee patterned after the triennial Radiocarbon Conferences. The purpose of this presentation is to encourage further discussion of these proposals.

Cosmic-ray-produced nuclides in solar systems materials: a short overview of production mechanisms, applications, and the evolution of planetary materials

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Abstract

Since the condensation of the first solids in our solar system 4.56 Gyr ago galactic cosmic ray (GCR) and solar energetic particle (SEP) interactions have been responsible nuclear transmutations. These cosmic-ray-produced (cosmogenic) nuclides serve as a clock that can be used to determine chronologies. Cosmogenic ^{3}He was first discovered in iron meteorites. Subsequently, many pioneering searches for cosmogenic nuclides in both terrestrial and extra-terrestrial materials were conducted; these studies established techniques for cosmogenic nuclide extraction and established linkages between the extra-terrestrial and terrestrial applications.

Earth is constantly bombarded by materials either scattered out of the asteroid belt or ejected off planetary surfaces. These materials represent a near unique opportunity to study solar system processes; the study of extra-terrestrial materials has accordingly received considerable attention from geochemists and geochronologists. Key questions for any material that impacts Earth are long has it been in an Earth-crossing orbit, what size was it before it collided with Earth, and what processes were responsible for putting it on a collision course with Earth. Cosmogenic nuclides address these questions. All meteorites record an exposure to GCRs. Ordinary chondrites (H, L, and LL), for example, typically have long exposure ages (up to tens of Myr) and show peaks in their exposure age distributions. These peaks are interpreted as a fragmentation of the parent body, an event that excavated material from a parent body. This excavation starts a 4π exposure to cosmic rays, which continues until its collision with Earth. Some meteorites record a complex exposure history: the most recent exposure, its cosmic-ray exposure age, and an earlier exposure which occurred within a shielded position (2π) while resident in a larger body. While complex exposures are observed, they are not common. Dynamicists studying the evolution of the asteroid belt believe that these complex exposures should be more prevalent. One possibility is that our understanding of the processes that liberate and transport these smaller bodies is incomplete. Alternatively, these complex exposures may occur in the expected frequency, but our techniques are not sensitive enough to detect them; this hypothesis can be tested by undertaking multiple nuclide studies. Key among understanding the evolutionary history of a sample is its most recent production rate, which is a function of the pre-atmospheric size of the meteorite and its specific location with the pre-atmospheric body. To determine these exposure parameters, we measure a suite of cosmogenic radionuclides (^{10}Be, ^{26}Al, and ^{36}Cl) and compare these to production rates determined by modeling. Having obtained accurate production rates and exposure durations for the most recent exposure a more thorough investigation of exposures occurring during an earlier epoch can be undertaken.

Although the geologic settings are strikingly different, the parallels are apparent. Both terrestrial and extra-terrestrial studies require accurate assessments of production rates, post-excavation knowledge of the exposure geometries. Complex exposures undoubtedly occur. These factors may complicate the determination of a single stage exposure age but the development of tools to identify and quantify them will lead to a more complete reconstruction of their chronology, both for terrestrial and extra-terrestrial samples.

Headwall erosion rates from cosmogenic ^{10}Be in supraglacial debris, Chhota Shigri Glacier, Indian Himalaya

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Abstract

Debris-covered glaciers are widespread within the Himalaya and other steep mountain ranges. They testify to active erosion of ice-free bedrock hillslopes that tower above valley glaciers, sometimes more than 1 km high. It is long known that debris cover significantly reduces surface ablation rates and thereby influences glacial mass balances; but its dynamic evolution along with climatic and topographic changes is poorly studied. Better understanding the coupling of ice-free bedrock hillslopes and glaciers in steep mountains requires means to assess headwall erosion rates. Here, we present headwall erosion rates derived from ^{10}Be concentrations in the ablation-dominated medial moraine of the Chhota Shigri Glacier, Indian Himalaya. We combine our empirical, field-based approach with a numerical model of headwall erosion and glacial debris transport to assess permissible patterns of headwall erosion on the ice-free bedrock hillslopes surrounding the Chhota Shigri Glacier.

Our five samples, each separated by approximately 500 m along the glacier, consist of an amalgamation of >1000 surface clasts with grain sizes between ~1 and ~30 mm that were taken from the medial moraine. Our results show that ^{10}Be concentrations increase downglacier from $\sim 3\times10^4$ to $\sim 6\times10^4$ atoms g^{-1}, yielding headwall erosion rates of ~1.3-0.6 mm yr^{-1}. The accumulation of ^{10}Be during debris residence on the ice surface can only account for a small fraction (<20%) of the downglacier increase. Other potential explanations include (1) heterogeneous source areas with different average productions rates, and (2) homogeneous source areas but temporally variable headwall erosion rates.

We use the ^{10}Be-derived headwall erosion rates to define debris supply rates from ice-free bedrock hillslopes in the numerical ice model iSOSIA. Headwall debris that is deposited in the ablation zone of the ice surface becomes englacial, is passively advected with the ice and emerges in the ablation zone where it forms supraglacial debris cover that influences surface melting. Preliminary results show that the model reproduces the actual medial moraine of the Chhota Shogri Glacier quite well.

We conclude that the observed ^{10}Be concentrations in the medial moraine of the Chhota Shigri Glacier yield reasonable headwall erosion rates, and that the systematic downglacier change in the concentration may reflect a changing erosion rate through time. Combining the ^{10}Be results with the numerical model we are presently exploring new avenues to test simple models of debris production by frost cracking, e.g., spatially uniform versus temperature dependent.

Evaluation of rock slope failures and rockslides in steep permafrost slopes using ^{10}Be- and ^{36}Cl-dating

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Abstract

Due to its steep sided valleys and fjords Norway is characterized by many recent slope instabilities and deposits of historic rock slope failures and rockslides. As part of the CryoWALL project this study addresses the time evolution of instabilities located around and above the (assumed) lower permafrost boundary.

During the last twenty years surface exposure dating using terrestrial cosmogenic nuclides has been used in several studies to identify the approximate ages of large postglacial rock slope failures (e.g. Hermanns et al., 2001, 2004; Ivy-Ochs et al., 2009; Penna et al., 2011). This has recently been supplemented by assessing sliding velocities of large instabilities through dating their characteristic back scarps (Hermanns et al., 2012, 2013). One of the key study sites of the CryoWALL project is the Mannen instability in Møre og Romsdal, south-west Norway. The instability reaches an altitude of almost 1300 m asl and the depositional area in the valley stretches down below the marine limit following the retreat of the Scandinavian ice sheet. The area was subjected to intense glaciation during the last ice age which created the characteristic U-shaped valleys. The Proterozoic gneissic country rock is fractured due to tectonic deformation with steep foliation surfaces typically concordant with the slope angle. Although recent permafrost studies suggest a regional boundary of altitudinal permafrost of ~1500 m asl (Steiger, 2015), data collection is under way to determine whether the north facing rock walls of 1295 m asl Mannen are influenced by permafrost.

The Mannen site is one of four high-risk rock instabilities in Norway and continues monitoring and early warning practises are in place. Preliminary dating results of the 20 meter high sliding surface using the cosmogenic nuclide ^{36}Cl are available. According to the preliminary movement pattern, sliding started ca. 8 kyr ago with slow rates (a few mm/yr). Indistinguishable ages measured 8 m apart suggest fast sliding at ca. 3 kyr ago. The height of the back scarp indicates that slip rates have slowed since then until the recent acceleration to today's velocity. Currently the upper part of the 15-20 Mm^3 rock mass moves at a rate of 5-6 cm/yr (Kristensen & Blikra, 2013).

A complex system of various quaternary deposits exists at the foot of the slope indicating a long and complex history of rock-avalanche activity. The lowermost unit is comprised of terraces built up of rock avalanche material, which in turn are overlain by glacio-fluvial deposits. Those are covered by at least two end moraines predominantly made up of material from rock slope failures. The youngest deposits represent at least three generations of rock-avalanche lobes. Besides complementing the ages from the sliding surface with four new sample points (Figure 1), different parts of the deposits have been sampled. To evaluate the time evolution of the rock avalanche activity with respect to climate variability, at least five different depositional events are covered with 14 sample points.

Figure 1. *20 m high back scarp of the Mannen rock slope instability with marked points of sample location for cosmogenic nuclide dating.*

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Reconstruction of the rock fall/avalanche frequency in the Mont Blanc massif since the Last Glacial Maximum by means of TCND and reflectance spectroscopy

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Abstract

In the Mont Blanc massif (Western Alps), current climate warming leads to significant increase of high elevation rockfalls and rock avalanches (RFs/RAs). To apprehend present and future morphodynamics of high mountain slopes, a database of the past events as exhaustive as possible is imperative. It can be built by studying both valley floor deposits and scars of rockfalls located at high elevation of the valley sides.

We started to evaluate the frequency of RFs/RAs during the last glacial-interglacial cycle by studying their high-elevated scars to establish the relationship between their colour and their age, in order to unravel their control factors. Fresh rock colour of the variscan Mont Blanc granite is light grey, as observed in recent rockfall scars, but colour of rock surfaces exposed to weathering evolves from grey to orange/red, leading the following hypothesis: the redder a rock surface, the higher its age.

In order to understand the relationship between surface colour and surface exposure age, two techniques are correlated: reflectance spectroscopy and TCND, carried out on samples of representative surfaces of different exposure ages. A laboratory reflectance spectroscopy is used to obtain measured and continuum-removed spectra of samples, and ^{10}Be dating on granite (mean quartz content: 20-35%) is used to establish a rock surface exposure age.

Pilot studies have been carried out at the Aiguille du Midi (2007) and three other sites in the Mont Blanc massif (2011). We are currently studying the relation between colour and age at a larger scale, with a 3rd campaign of sampling carried out in autumn 2015, and a 4th one planed for spring 2016. Microscope, X-ray spectrometry and microbiological analysis will be carried out on these samples, in order to understand the formation of the orange rock coating.

Figure 1. Rockfall scars in the Pointe Adolphe Rey (Mont-Blanc massif), showing the 5 sampling sites of the 2015 campaign. Note the difference of colour between the surface of the younger scars (in yellow and orange, T2 and T1) and the other surfaces, exposed to weathering since long before.

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Evaluating geochemical evidence of earthquake periodicity, Sparta Fault, southern Greece

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Abstract

Determining prehistoric earthquake periodicity and magnitudes is important for hazard risk assessments in seismically active areas. Using the Sparta Fault, Greece, as a case study, we re-evaluate the application of ^{36}Cl exposure dating and measurements of Yttrium and rare-Earth elements (REY) to determining paleoseismicity on limestone normal fault scarps. We find that REY and ^{36}Cl concentrations correlate well with abundance of quartz in the fault scarp (Figure 1A and B). We interpret the quartz as being sourced from underlying psammitic sedimentary rocks that has been crushed through tectonic movements, transported by fluids flowing along the fault, and cemented by microcrystalline calcite precipitates to form a protocataclasite that now lines the fault scarp surface. The abundances of quartz may be influenced by asperities along the fault surfaces (at depth, at the time of cementing) but do not directly record paleoseismicity. Through their positive correlation with quartz abundances, REY concentrations are therefore unreliable indicators of paleoseismicity in fault scarps where quartz is present. Furthermore, it appears that ^{36}Cl concentrations may have been impacted by meteoric contamination during the formation of the protocataclasite (Figure 1C and D). This meteoric component is difficult to remove using standard laboratory preparation procedures for accelerator mass spectrometry, and may therefore provide a misleading view of paleoseismicity. Work is presently ongoing to clarify ^{36}Cl-based interpretations of paleoseismicity on the Sparta Fault, with implications for limestone normal faults elsewhere.

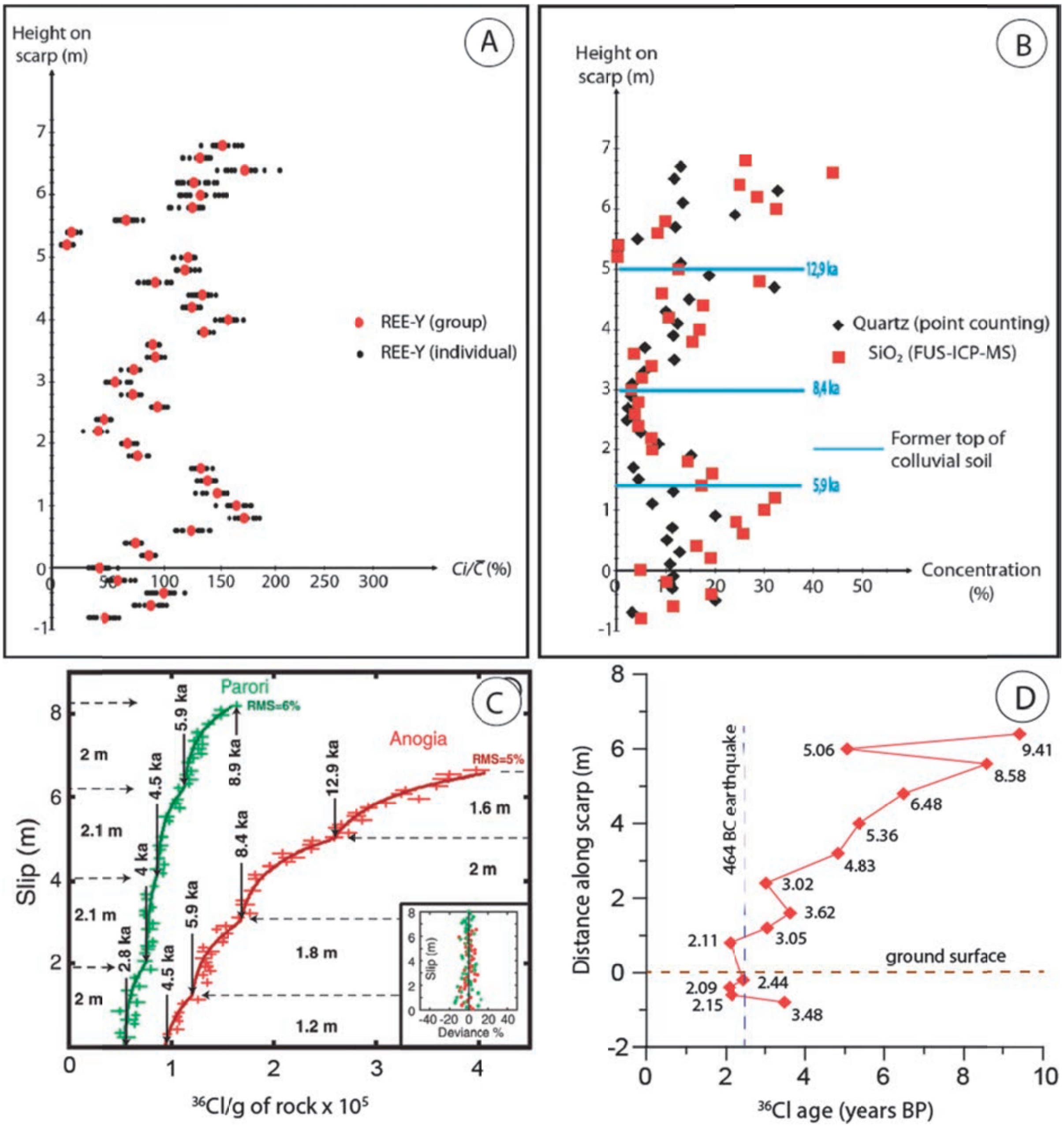

Figure 1: *Geochemical data for the Sparta Fault scarp, Greece. A. REY concentrations measured at Anogia using portable XRF. Note the wave-like variations in concentrations along a vertical transect. B. Quartz and SiO_2 concentrations along the same vertical transect as in panel A. Blue lines indicate earthquake events interpreted from Benedetti et al., (2002). Note the spatial correlation between REY and quartz concentrations. C. ^{36}Cl data from Benedetti et al. (2002) showing 4 steps interpreted as representing 4 earthquakes at Anogia and a second site, Parori. The Anogia sampling transect is about 50 m North of the sampling transects shown in panels A and B. D. ^{36}Cl data from our study for samples taken on a vertical transect at Anogia located 30 cm from the Benedetti et al. (2002) Anogia transect shown in panel C. Ages for each data point are notated. Note a similar general trend but with significant local deviations. We interpret these data as indicating contamination by meteoric ^{36}Cl.*

Antarctic erosion rates dependent on lithology and sample type

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Abstract

Cosmogenically derived erosion rates in Antarctica have been used to adjust cosmogenic nuclide ages, confirm long-term stability and preservation of old features, and determine the evolution of the landscape. However, carbonate bedrock has not been considered in previous studies. New ^{36}Cl carbonate bedrock samples from the Ellsworth Mountains are within the range of other reported Antarctic erosion rates, although with a slightly higher mean than for other lithologies. In other areas of the world, it difficult to accurately compare erosion rates across different lithologies due to complicated relationships between erosion rates and other factors, such as precipitation, temperature, and other weathering processes, such as dissolution of carbonates. Antarctica's consistently cold, desert environment reduces or eliminates the dependence on many of these factors, leading to more consistent comparisons between samples. A data set of Antarctic erosion rate samples was compiled from 28 cosmogenic nuclide studies involving close to 200 unique samples analysed for ^{10}Be, ^{26}Al, ^{3}He, and ^{21}Ne. All the samples were run through the CRONUScalc code to produce consistent erosion rate results between nuclides, and this final data set was used to examine the erosion rates reported across the continent. For lithologies with a significant number of samples, the mean maximum erosion rates are different between lithologic groups (see Figure 1). Another significant relationship is that boulders appear to show lower erosion rates than bedrock of the same lithology. Most other variables investigated in this study, such as precipitation or temperature, do not show any significant relationship to erosion rates.

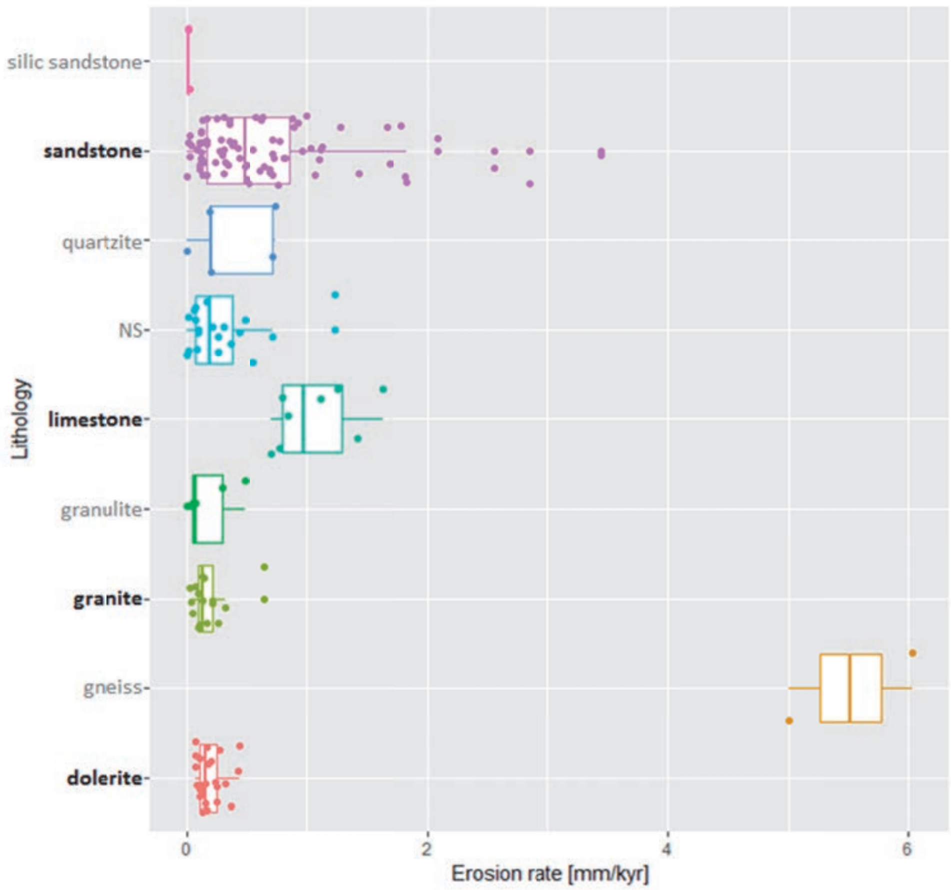

Figure 1. *Comparison of erosion rates grouped according to lithology. Limestone erosion rates are newly reported in this study. Bold lithologies are statistically significant. Lithologies for 'NS' samples were not specified in the original paper.*

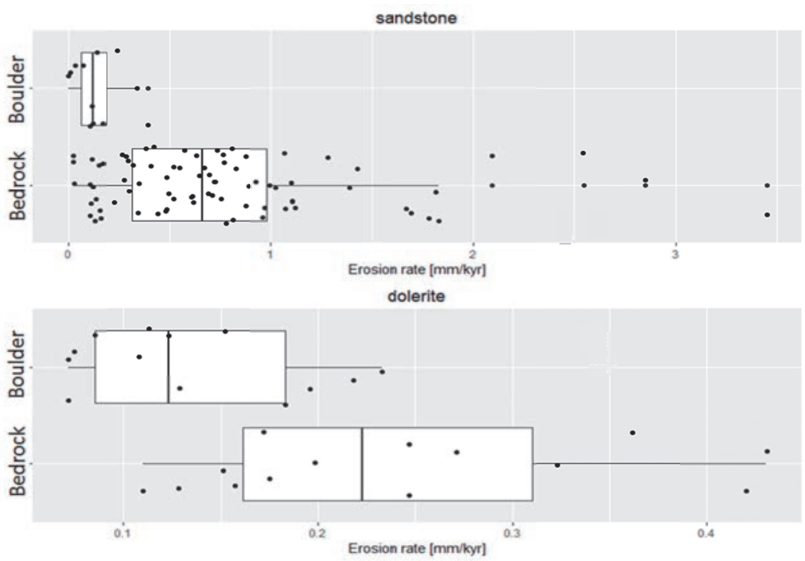

Figure 2. *Bedrock and boulder populations for two different lithologies. Note the difference in erosion rate scale.*

Expanding monitoring of rock slope deformation into the geological past by cosmogenic nuclide dating

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Abstract

Rock avalanches have been in the past centuries those geological disasters in Norway that caused largest live loss per event (Hermanns et al., 2012a). This is in general not due to the impact of the run-out of the rock avalanche itself but by the displacement wave caused by rock avalanching into a fjord or fjord lake causing complete destruction along the coast lines. Due to the high life loss during these events in earlier centuries, systematic mapping of unstable rock slopes was started in the 21st century and more than 250 unstable rock slopes are known today. Many of them are positioned in remote mountain settings and rock slope failure will neither reach the fjord nor any settlement. However at 80 localities consequences might be severe and monitoring procedures of rock slopes have been taken into action in the past decade giving a maximum of 12 years of observations. Velocities detected so far range from a few millimetres to up to 10 cm, however some of the unstable slopes have slid for more than 150 m while others show only few meters of deformation. The short observation window of monitoring data is often not satisfactory to interpret actual deformation rates in relation to the total deformation on the slopes. Therefore, we applied terrestrial cosmogenic nuclide (TCN) dating on sliding surfaces exposed by deep seated gravitational slope deformation (DSGSD) and rockslides as well as on deposits of related failures in northern and western Norway in order to determine long-term displacement rates to compare them to present-day slide velocities. This will help determine if rock slopes are in an accelerated state of movement today or if today's deformation rates are indistinguishable from long term deformation rates.

In western Norway at two localities—Oppstadhornet (1) and Skjeringahaugane (2)—sliding started at 16.6-14.2 kyr and 10 kyr ago, respectively (Hermanns et al., 2012b; Hermanns et al., 2013) and thus right after deglaciation when compared to the latest reconstruction of the Scandinavian ice sheet (Hughes et al. 2015). The long-term displacement rates match short-term displacement rates measured with differential Global Navigation Satellite Systems (dGNSS), thus indicating constant conditions. The results obtained on the sliding plane of the Middagstinden (3) rockslide are different from those sites as they indicate that Middagstinden became an active rockslide at 4.5 kyr and early paleo-slip rates were in the order of 7 mm/yr. Since then, they have accelerated to up to 3 cm/yr until ca. 700 years ago when they started to decelerate to about 1 cm/yr, velocities measured also today by dGNSS. At the Skurgeurda (4) site a large rock avalanche occurred at 14.1 kyr. At the same time the main sliding surface was exposed. This event was followed by a minor collapse at ca. 10 kyr as a secondary sliding plane gives consistent ages along its entire length. A third sliding surface delimiting a decomposing block became also active ~10 ka but ages downslope along the plane are younging suggesting that the block is actively sliding. This is different from the Ivasnasen (5) site. The main sliding surface has an age of ~3.5 kyr consistent with a rock avalanche deposit at the foot. At the same site a further block of 2.2 Mm^3has slit 12 m down slope along the same structure as the failure surface of the rock avalanche. This sliding plane also gives consistent ages of ~3.5 kyr along its length, indicating that initially the block slid rapidly but has been inactive since. At the Storhornet (6) site in western Norway sliding planes date between 13.8 and 11 kyr while a related rock-avalanche deposit below to 3 kyr.

In northern Norway at the Gamanjunni 3 site (7) TCN dating indicates that sliding has started 6 kyr ago with displacement rates ranging from 1.3 to 2.5 cm/yr until ca. 2 kyr ago (youngest sample). These velocities are significantly slower than present-day displacement rates of 4 to 5 cm/yr measured today, thus indicating acceleration of displacements after ca. 2 kyr. We also sampled sliding planes of two DSGSDs and rock avalanche deposits at their foot in northern Norway. At the Litledalen site (8) sliding started ca. 70 kyr ago, and hence prior to LGM, while on Nomandalstinden site sliding prior to 20 kyr and thus earler than deglaciation of the Scandinavian ice sheet. Rock-avalanche deposits at both sites date to the late Pleistocene at ca. 11.5 kyr.

In summary, most of the rockslides in western Norway started shortly after deglaciation while this trend does not hold for northern Norway. Instead DSGSDs here have been active already prior to the last glacial maximum. A combination of TCN-determine rates on slip faces and landslide deposits, in combination with monitoring of selected sites has demonstrably provided very useful information upon which to base our risk analyses and guide our future targets of study.

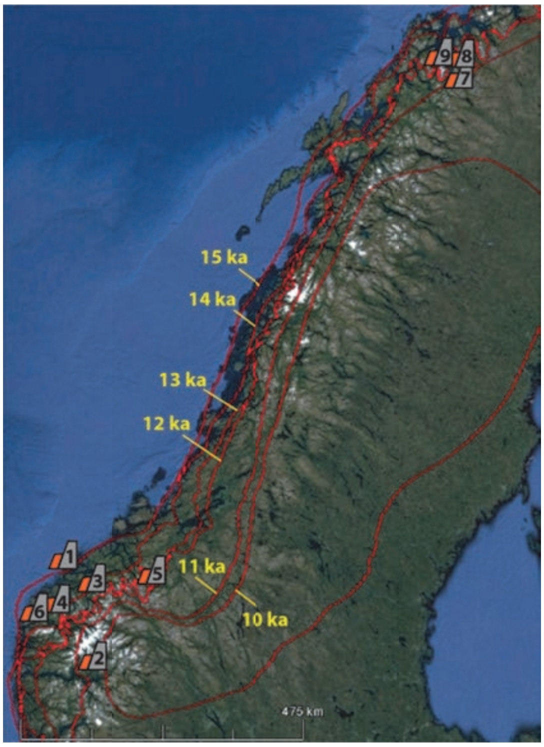

Figure 1. *Localities of dated sliding surfaces compared to the maximum possible extension of the Scandinavian ice sheet after Hughes et al. (2015).*

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Cosmogenic nuclides in Quaternary sciences and geomorphology

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Abstract

Here in the Erice maze

Cosmic rays are all the craze

Just because a guy named Hess

When ballooning up found more not less.

This inscription commemorates Victor Hess's 1912 demonstration of the existence of penetrating radiation entering Earth's atmosphere from space. In 1925 Robert Andrews Millikan coined the term 'cosmic rays', and in 1936 Hess received the Nobel Prize in Physics for their discovery. As early as 1934 it was hypothesized that cosmic rays could produce nuclides by interaction with Earth surface materials (Grosse 1934). Davis and Schaeffer (1955) developed the main methodological principles for exposure dating after being the first to detect *in situ* produced cosmogenic nuclides (^{36}Cl) in rock. The work was discontinued because of the difficulty in determining the extremely small concentrations of *in situ* produced cosmogenic nuclides in rocks. The timing of the discovery of *in situ* ^{10}Be and ^{26}Al and the revival of ^{36}Cl in coincided with a major analytical improvement – the development of accelerator mass spectrometry (AMS) – which made the measurements possible. Eight seminal papers in 1986/87 reported cosmogenic ^{3}He, ^{21}Ne, ^{22}Ne, ^{10}Be, ^{26}Al, and ^{36}Cl in terrestrial rocks (Craig and Poreda 1986; Klein *et al*. 1986; Kurz 1986a,b; Marti and Craig 1987; Nishiizumi *et al*. 1986, 1987; Phillips *et al*. 1986). In 1991 Devendra Lal synthesized a range of atmospheric data related to cosmic-ray fluxes into polynomial equations that could be used to scale cosmogenic nuclide production anywhere on Earth to a common reference of high latitude and sea level (Lal, 1991). Combined these two advances, measurement capability and a globally applicable methodology, provided the foundation of terrestrial cosmogenic nuclide research.

Since the quantitative revolution in the 1950s there had been a growing need for chronological tools able to elucidate landscape age and process rates. Those of us involved in long-term landscape evolution relied on thermochronological techniques to provide stratigraphic markers against which to assess geomorphic processes. But like radiocarbon dating these techniques do not date landscapes or quantify erosion rates directly. The advent of surface exposure dating using terrestrial cosmogenic nuclides provided such a chronological tool for the first time, and it remains unique in the chronology toolbox because in many cases we can derive the age of landform formation directly from the landform (e.g. glacial moraines, fault planes, landslides). The capabilities provided by terrestrial nuclide techniques to quantify the geomorphic stability of surfaces exposed to cosmic rays and to determine long-term erosion rates have been adopted to address, and resolve for the first time, a wide range of first-order problems in the fields of geomorphology, glaciology, palaeoclimatology, palaeoseismology, soil science, volcanology and geohazard research.

Over the last 25 years the cosmogenic nuclide technique has continued to evolve in terms of different applications and methodological improvements. The temporal extent and volume of palaeo and current ice masses have been constrained. Preservation of landscapes under ice sheets and the limits of the nunatak hypothesis have been demonstrated. Erosion rates have been quantified at outcrop, slope, catchment, and continental scales. Depth profiles have been successfully used to resolve age and erosion rate ambiguities, especially when applied using paired nuclides. Burial dating with ^{26}Al/^{10}Be has allowed dating of cave deposits with implications for hominid and landscape evolution. The development of the isochron method for burial dating has removed most of the uncertainties involved with postburial production. *In situ* produced ^{14}C in quartz is resolving shorter duration complex exposure histories. Production rates and analytical precision are being continuously improved.

Overall, the novel ability to use cosmogenic nuclides to date geomorphic surfaces, and determine process rates from rock, regolith and soils, revolutionized and rejuvenated many fields of geomorphology. Cosmogenic nuclide techniques have left the realm of specialist interest to become a widely used tool in Quaternary sciences and will continue to be developed as the user community expands and new questions are being asked.

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Direct dating of the oldest known glacial landforms in Patagonia

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Abstract

The earliest records of glaciation in Patagonia are bracketed in age by K-Ar and $^{40}Ar/^{39}Ar$ ages from lava flows interbedded with till, which remain preserved on elevated mesetas to the east of the cordillera. The ages indicate major glaciations in the mid-latitudes of the Southern Hemisphere occurred several million years ago in the Pliocene, before major Northern Hemisphere ice sheets developed. These early glaciations produced piedmont-style lobes discharging onto plains to the east of the cordillera. In central Patagonia, there exists evidence for such glaciations in the form of the Chipanque Moraines. These moraines are preserved on a plateau northeast of Lago Buenos Aires, 46° S, Argentina. The moraines are undated, but are thought to be several million years old based on correlation to dated lava flows that bracket till on the Meseta del Lago Buenos Aires 100 km to the SW. If correct, this makes the Chipanque Moraines perhaps the oldest preserved moraine sequence in the southern mid-latitudes. Here we attempt to directly date this early advance and subsequent surface erosion with cosmogenic nuclides. We measure the concentrations of cosmogenic ^{10}Be, ^{26}Al and ^{21}Ne in depth-profiles within outwash sediment associated with the Chipanque Moraines. I will present these data and our efforts at modelling the age and erosion rate of the surface.

^{36}Cl dating of Holocene moraines in the semi-arid Andes of central Chile: the case of the Maipo and Juncal river basins (33ºS)

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Abstract

The central Andes of Chile, a glaciated semi-arid mountainous area with elevations over 6000 m asl., are a climatically very sensitive zone, embracing a key location for uncovering the ENSO-like climate conditions during the (Late) Holocene. However, the evolution of local ice bodies since the last deglaciation (i.e., last ~12,000 years), and their feedback with climate is fairly unknown. Understanding ice variability in the semi-arid Andes of Chile during the pre-instrumental time can provide the urgent climate background before the 20th/21st century global warming, and is needed to assess local atmosphere-cryosphere linkages. Glacial landform preservation is excellent and provides an opportunity to reconstruct Holocene ice/climate fluctuations. This multifarious, patrimonial natural heritage and geological archive in the Chilean Andes is nowadays not only threatened by climatic change but also economic activities (e.g., mining).

By applying an integrative geomorphologic and chronologic approach, we study cryospheric changes and the long-term evolution of glaciers. Distinct moraine ridges at three study sites in watersheds around Santiago (the Chilean capital) are the focus of our research: Juncal Norte, Loma Larga and Nieves Negras glaciers (33ºS). At all three sites, we distinguished at least three moraine systems of a Holocene putative age. These prominent moraine belts show that glaciers were at least 5 km longer than at present. We use ^{36}Cl cosmogenic nuclides to date Andesite boulders resting on top of moraine ridges and thereby reconstruct the regional glacial history. We complement our ^{36}Cl data with ^{14}C ages that suggest that glaciers advanced before ~2500 and before ~1000 years before present.

This is the first time moraines are directly dated using ^{36}Cl in central Chile and therefore we assess the potential of this terrestrial cosmogenic nuclide for future glacial geomorphologic applications in the area. We present first results, including a detailed geomorphological mapping and analysis of the landform dynamics. Deglaciation from these ice marginal positions was gradual and complex in response to the detrital cover on the glaciers. Differences in ice thickness of the main glaciers in the respective valleys amount to about 100 m. Due to the partial, extensive debris coverage, the glaciers diminished in thickness without significant retreat of the glacier front. Another geomorphological feature identified is the separation of ice facies, from ice dynamically flowing with an active ice front, to dead ice covered by debris. In parallel, paraglacial processes affect the morphology of the moraines.

Late Pleistocene deglaciation and Scandinavian Ice Sheet dynamics in NE-Germany: new results from surface exposure dating in Mecklenburg-Vorpommern

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Abstract

Recent age compilations documenting the late Quaternary spatial evolution of the Scandinavian Ice Sheet (SIS) have highlighted that last glaciation advance and retreat timings varied significantly across different sectors of the SIS (e.g. Hughes et al. 2015). Although the overall pattern is by now well established, there are still numerous areas with contradictory evidence and/or gaps in the record due to a lack of absolute age information on glacial landforms and stratigraphies. Among the regions where significant chronological uncertainties persist is the North-German Plain, in spite of representing one of the classical landscapes for glacial research since the mid-19th century. As a consequence, there is an ongoing lively debate around a series of SIS research questions including: (a) if and how far a potential mid-Weichselian ice advance extended into northern Germany; (b) whether or not the local maximum of the Odra ice stream pre-dates or coincides with the overall SIS maximum at c. 21 ka; and (c) at what time did the LGM retreat commence and when was the deglaciation of the German mainland completed? Here we present new information on the regional deglaciation history of the SIS based on a total of 38 CRN surface-exposure-ages (^{10}Be) from moraines between the Pomeranian ice margin and the Baltic coast. Based on the global ^{10}Be-production-rate by Heyman (2014), we find that ice retreat from the Pomeranian moraine (W2) commenced at around 16.5 ± 0.9 ka (n = 11). Further to the northeast, ice positions such as the Rosenthal ice marginal zone ($W3_R$) yielded a mean age of 16.0 ± 0.9 ka (n = 12), while glacial boulders from the Islands of Rügen and Usedom, deposited just before the SIS retreated into the Basltic Sea Basin, returned a mean age of 14.9 ± 1.2 ka (n = 15). Our record shows that the post-LGM deglaciation of northern Germany, referring to ice retreat from the Pomeranian moraine to the present day coast, covering a distance of c. 130 km, occurred between 16.5 – 15 ka. This indicates a relatively rapid final SIS retreat from the North German Plain, probably accelerated by widespread glacier calving into large proglacial lakes, and was completed before the onset of the Bølling-Allerød interstadial. Contrary to previous models, which infer the $W3_R$ ice position to represent a last SIS re-advance out of the Baltic Sea Basin (the so-called Mecklenburg Phase), we suggest that the minor age difference between the W2 (16.5 ka) and $W3_R$ ice positions (16.0 ka) indicates that the W3 complex formed as a recessional stillstand within the context of the SIS retreat.

The Scandinavian Ice Sheet Last Glacial Maximum extent in the Valdai Heights, western Russia: the ^{10}Be evidence.

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Abstract

Constraining the extent and dynamics of former ice sheets are *sine qua non* conditions for our understanding of ice sheets contribution/reaction to past climate change and sea level variations. The importance of these reconstructions is comforted to some extent by the wide range of disciplines involved in the task: e.g. glacial geology, geochronology, modelling. From the accuracy of these reconstructions depends the degree of refinement with which we are able to reconstruct the mechanisms involved in past global changes and our capabilities to predict future changes. Recent synoptic studies have summarized the former spatial extent and chronology of the last Scandinavian Ice Sheet (SIS) and provide exceptional state of the art empirical datasets (Hughes et al., 2016; Stroeven et al., in press). The latter represent the primary source of information for the modelling community to test and develop glaciological models which are then further embedded into climatic and other general circulation models. The LGM extent and chronology of the SIS across continental Europe were highlighted as being the least well-known thus generating the biggest uncertainties in the reconstruction of the ice sheet. While early geomorphological studies of the ice sheet marginal belt are numerous and fruitful in western Russia, geochronological data are virtually inexistent over more than ~1000 km of the former ice sheet margin (Figure 1). In an attempt to fill this gap, we conducted a series of sampling campaigns for surface exposure dating using Be-10 in the western and northwestern regions of Russia. We present here the first results from the Valdai Heights where significant glacial deposits constitute well-preserved margins of the SIS. 33 samples were processed at the University of St Andrews and the Laboratoire National des Nucléides Cosmogéniques, and were analyzed at the French national AMS facility ASTER. These samples firmly establish the timing of the LGM in the Valdai Heights at 20.0 ± 0.4 ka and allow to refine the position of the former SIS margin in this region. The Valdai Heights acted as a natural wall for the last maximum advance of the SIS during MIS2, constraining the eastern flank of the Ladoga-Ilmen-Lovat ice stream to the west of the hills, except for the short (~175 km long) Msta ice stream. The Valdai Heights were only overran by previously more extensive glacial advances as suggested by older exposure ages obtain on erratic boulders (30.8 ± 1.3 to 46.6 ± 1.5 ka) located on the eastern side of the hills.

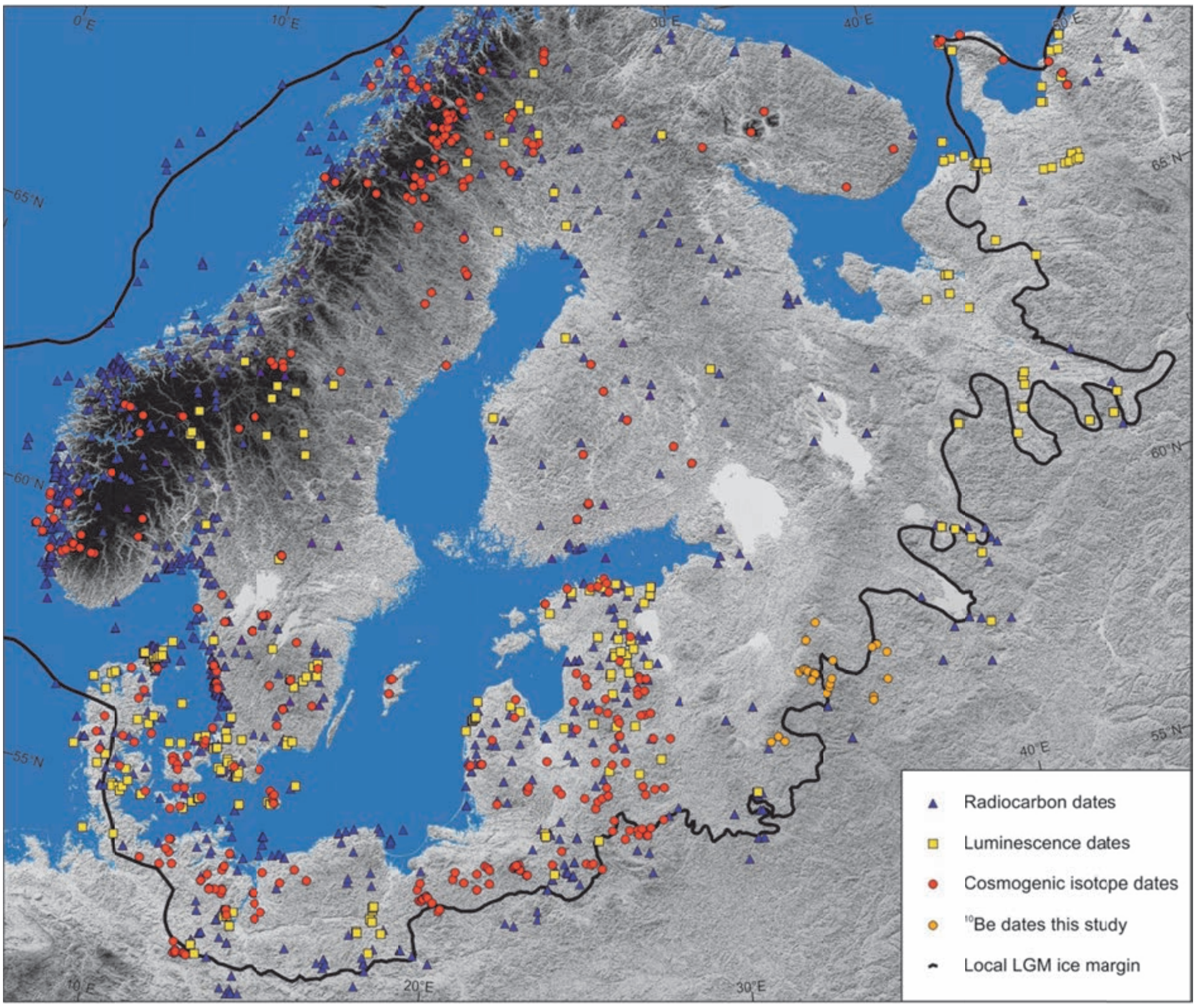

Figure 1. *Locations of previously dated sites (yellow, blue and red symbols) compiled from Hughes et al. (2016) and Stroeven et al. (in press). Orange discs are new Be-10 exposure ages.*

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30 years of cosmogenic nuclides in geochronology

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Abstract

Although first efforts at cosmogenic nuclide exposure dating (in that example ^{36}Cl) were reported already in 1955, difficulty measuring the extremely low nuclide concentrations in terrestrial rock samples delayed true application until the development of accelerator mass spectrometry in the mid-1980s. One of the first applications, and to this day the dominant one, is in constructing glacial chronologies. Moraines are the single most important record of the extent of past continental ice sheet and mountain glaciations. Relative chronologies could be established through field relationships, but moraines have always proven notoriously difficult to date. The possibility of directly dating a boulder on a moraine came as a boon for glacial geologists. With exposure dating, the evidence contained in ice-marginal landforms could be placed into the chronostratgraphic framework of past climate change on Earth. In subsequent years, the list of landforms that could be dated with surface exposure dating expanded to include all of those with large boulders at the surface; rock avalanche deposits, debris-flow fans, among others. The possibility to date the time of origin of a bedrock surface became reality, something hardly even imaginable before cosmogenic nuclides. Glacially modified bedrock surfaces are dated and the information is combined with data from ice-marginal landforms. The release area scarp surface of a rock avalanche can be dated and compared with ages from boulders in the deposits. A bedrock fault surface can be directly dated to determine slip rates.

Even in light of the great success of dating large boulders on various landforms, the dating of deposits lacking boulders posed a challenge. In the late 1990s, the idea of dating amalgamated clast samples emerged. The idea was to average out the various pre- and post-depositional effects in individual clasts on the top surface of a deposit. This was quickly followed by introduction of the depth-profile dating technique. This method is based on the analysis of several sand samples along a depth profile going down 2-3 m for ^{10}Be. The unique shape of the of ^{10}Be concentration vs. depth curve is strictly controlled by exposure time and erosion (or in some cases aggradation) rate of the landform top surface. Since its introduction, this method has proven to be an extremely robust and adaptable tool. The availability of MATLAB calculation programs has greatly increased accessibility of the depth-profile dating method. By dating river terraces and alluvial fans numerous scientific questions could be addressed. These include assessment of the impact of climate forcings vs. internal catchment-fan dynamics on fan aggradation phases, as well as determination of fault slip and uplift rates based on dating of offset landforms. Recent work has shown that deposits ranging in age even to millions of years can be dated using ^{10}Be depth-profile dating.

But what about sedimentary units with unexposed or greatly modified top surfaces? How can we date those? Although anticipated by the precocious 'banana' papers of the late 1980s, the dating of buried sediments using cosmogenic nuclides did not reach fruition until the late 1990s when the burial dating technique was introduced. With burial dating one can determine the time elapsed since deposition and rapid, deep burial of sediment. This is therefore a stratigraphic dating tool rather than a landform dating tool as are the methods described above. The time since burial is based on the difference in half-lives of ^{26}Al and ^{10}Be; ^{26}Al decays about twice as fast as ^{10}Be. If we can assume the ratio of ^{26}Al to ^{10}Be at the moment of burial then we can determine how much time has passed since burial by measuring the $^{26}Al/^{10}Be$ today. With this method, we can study sediments that were deposited hundreds of thousands of years up to millions of years ago. This fills a critical gap in accessible time range left open by shortcomings of other numerical geochronological tools. The combination of ^{14}C with ^{10}Be is opening up new directions of study that are only now being explored, for example constraining periods of ice coverage of bedrock surfaces during the late Holocene.

Over the past 30 years, the endeavor of constructing chronologies, 'what happened when' with cosmogenic nuclides has been a dynamic and exciting field. Reflecting the variety of novel ways to date and combine nuclides, the spectrum of landforms and deposits that can be dated has exploded in that time. Nevertheless, construction of a site chronology is only possible when the field relationships are completely understood. Indeed, well-established mapped and interpreted relative chronologies are often completely overthrown when absolute dating with cosmogenic nuclides is applied.

Investigating the dynamics of deglaciation in coastal areas of southeast Greenland

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Abstract

Southeast (SE) Greenland has experienced large glaciological changes over the last two decades. Glacial retreat, acceleration, and thinning have resulted in substantial mass loss. However, despite its significance, relatively little is known about the glacial history of SE Greenland. Reconstructions of glacier behaviour provide valuable context for assessing the magnitude of present-day changes. They can also be used to better-understand the mechanisms that control glacier behaviour.

We present 11 new cosmogenic exposure ages from previously uninvestigated coastal areas of SE Greenland. Paired erratic and bedrock samples from low-elevation locations were analysed for ^{10}Be content. Samples were collected from central areas of Køge Bugt and Ikertivaq; consequently, these samples track the retreat of the major, marine terminating outlet glaciers here. Samples from Gerners Ø and Tugtilik were collected from locations away from major outlet glaciers; these samples track the deglaciation of `passive' margins of the Greenland Ice Sheet (GrIS). Comparing the timing of deglaciation in these areas with different dynamic regimes permits investigation of the relative influence of ice dynamics on deglaciation.

Results from ^{10}Be analysis are complicated; understanding their significance requires careful interpretation and consideration of the individual sample settings. The timing of glacier retreat appears to have been largely dependent on the local physiographic setting and glaciological regime. The deglaciation of Køge Bugt occurred broadly contemporaneously with retreat in Sermilik Fjord, 100 km to the northeast. Fjord retreat in Køge Bugt probably occurred in response to climatic amelioration at the start of the Holocene (Hughes et al., 2012). The deglaciation of Ikertivaq occurred marginally later, but likely also in response to early-Holocene climatic warming. The minor difference in timing may be attributable to the specific geometry of Ikertivaq. The deglaciation of passive areas appears to have occurred later than in the major fjord systems; this suggests that ice dynamic processes were a key driver of deglaciation in SE Greenland.

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Constraints on the deglaciation chronology of the southeastern margin of the Greenland Ice Sheet

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Abstract

The Greenland Ice Sheet (GrIS) is responding rapidly to climate change. Marine terminating outlet glaciers that drain the GrIS have responded especially sensitively to present-day climate change by accelerating, thinning and retreating. In southeastern Greenland several outlet glaciers are undergoing rapid changes in mass balance and ice dynamics. To improve our understanding of the future, long-term response of these marine-terminating outlet glaciers to climate change, we focus on the response of three outlet glaciers to climate change since the Last Glacial Maximum.

The timing and rates of late-glacial and early Holocene deglaciation of the southeastern sector of the GrIS are relatively unconstrained due to the inaccessibility of the region. Using a helicopter and a sailboat, we collected samples for ^{10}Be surface exposure dating from three fjords in southeastern Greenland: Skjoldungen (63.4N), Uvtorsiutit (62.7N), and Lindenow (60.6N). These fjords drain marine terminating glaciers of the GrIS. Here we present 18 new ^{10}Be ages from ~50 km long transects along these fjords that mark the timing of deglaciation from the outer coast inland to the present-day GrIS margin.

Together with previously constrained deglaciation chronologies from Bernstorffs, Sermilik, and Kangerdlussuaq fjords in southeastern Greenland, these new chronologies offer insight into the late-glacial and early Holocene dynamics of the southeastern GrIS outlet glaciers. We compare the timing and rate of deglaciation in southeastern Greenland to climate records from the region to examine the mechanisms that drove deglaciation during late-glacial and early Holocene time. These new ^{10}Be ages provide a longer-term perspective of marine terminating outlet glacier fluctuations in southeastern Greenland and can be used to model the ice sheet's response to late-glacial and early Holocene climate changes.

New chronological constraints on the deglaciations of northernmost and southernmost Norway based on in-situ cosmogenic nuclides.

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Abstract

The northernmost coastal areas of Scandinavia hold a unique record of end moraines that are more or less coast-parallel and can be followed over long distances. Several of the most prominent end moraines were mapped and described by exploring geologists already over a hundred years ago. Since the very earliest descriptions, raised shorelines were used for correlating sets of end moraines between different fjords, and also for relative dating of the halts in deglaciation (sub-stages) that produced the end moraines. The retreat chronology of Northern Norway has attained renewed interest during the last few years, as the fjords of Finnmark constitute a valuable analogue to the currently deglaciating coastline of Greenland. Also, a great body of work from the Barents Sea offshore Finnmark is now present, and chronological uncertainties in ice sheet reconstructions are particularly present near the coast. Still, up until today little effort has been put into improving the deglaciation history of Finnmark by direct dating. With the aim to improve this, we conducted a field campaign from the outer coast to the inland of eastern Finnmark to collect samples from end moraines for terrestrial cosmogenic dating. We measured the concentration of ^{10}Be (N=22) and ^{36}Cl (N=18) from boulders located at the crest of major moraine ridges at the localities Porsangen, Kongsfjorden, Vardø and Kirkenes. Also, a ^{36}Cl depth-profile based on 7 bag samples was obtained from a glaciofluvial deposit at Tana bru. Our results generally confirm the ages that have been suggested from previous reconstructions based on shoreline correlation, with a steady retreat from the the coast at around 15.5 ka to a distinct Younger Dryas stage at Kirkenes.

The status is similar for southernmost Norway with very little absolute chronological control of the deglaciation, despite direct proximity to the contentiously discussed Norwegian channel ice stream. Southern Norway was mapped by the famous glacial geologist Bjørn Andersen already in the early 1950s, using basic aerial photographs and topographic maps. Andersen reconstructed two distinct glacial sub-stages (the Lista stage and Spangereid stage) that were older than the Younger Dryas (YD), and one main glacial stage of assumed YD age (the Ra stage). This interpretation has remained untested and is still used in reconstructions of the Fennoscandian ice sheet. In this study we test the reconstruction of Andersen by remapping the whole area using newly aquired LiDAR data (high resolution laser scanning of terrain), together with in-situ cosmogenic nuclide exposure ages of boulders on marginal moraines. The study comprises mapping of more than 6000 km^2 of forested and dissected landscape, measurement of ^{10}Be concentrations (N=53) from boulders/bedrock, one cosmogenic ^{10}Be depth profile in a coarse-grained glaciofluvial deposit, and finally one lake record.

Our study shows that the oldest of Andersen's glacial stages, the Lista stage on the outermost south coast, likely should be rejected since it consists of consolidated subglacial till and therefore is not an end moraine system. However, our ^{10}Be depth profile shows that this area probably was ice free already by around 19 ka BP, almost 4 ka earlier than previously thought. At the same time the ice sheet surface slowly lowered, and the first inland hills of about 450 m. asl. became ice free at around 17 ka BP. Ice retreat continued slowly 10-15 km inland and halted as a calving fjord stage at the Spangereid stage with an approximate age of 15 ka BP. The subsequent deglaciation appears to have been very rapid where the ice front retreated 30-50 km inland to a position inside of the Ra stage, until a readvance in Older Dryas around 14.5 ka BP. The ice front might have retreated inland again in the Bølling-Allerød interstadial, but readvanced to almost exactly the same position in the early YD and with possible oscillations until late YD. The complexity of the cosmogenic exposure ages from the Ra moraine system is supported by LiDAR mapping that often shows multiple moraine ridges that sometimes onlap each other and sometimes are separated by as much as 5 km.

Blockfields in Reinheimen Nationalpark, Norway – Neogene weathering remnants or Quaternary periglacial origin?

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Abstract

It is an ongoing debate whether the degree of chemical weathering in mountain regolith can be used to infer a pre-Quaternary formation history (e.g. Strømsøe and Paasche, 2011; Goodfellow 2012). Here we present a new dataset of in-situ produced cosmogenic ^{10}Be and ^{26}Al along with sediment analyses from five pit profiles dug through regolith mantle on the easternmost summits of Reinheimen Nationalpark in Norway. The study area shows only sporadic signs of glacial erosion, and could be classified as a relict non-glacial surface. We aim to use the residence time of regolith in this area to infer rates of landscape evolution of the mountain summit.

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Cosmogenic ages constraints of Late Glacial and Early Holocene alpine glaciers advances in upper Peio Valley (Rhaetian Alps, Italy). Preliminary results.

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Abstract

A pronounced climate reorganisation characterized the Late Glacial – Holocene transition in Northern Hemisphere. Glaciers reacted to climate variations leaving landscape features suitable for investigating ice masses evolution and dynamics. In this context well preserved undated moraines of La Mare Glacier and Careser Glacier (upper Peio Valley, Ortles-Cevedale Group, Italy) were studied and sampled. Surface Exposure Dating was selected as a tool for chronologically constrain the reconstructed glacial phases in the study area. ^{10}Be exposure ages define the timing of Egesen (Younger Dryas) position of La Mare Glacier and Early Holocene position for both glaciers. Morphometric parameters of reconstructed phases will allow estimation of areal and volumetric variations of the studied glaciers as well as Equilibrium Line Altitude (ELA) variations for comparison with data of the Little Ice Age maximum expansion and with present day minimal extension. The high resolution of geomorphological mapping and the new cosmogenic dates will therefore highlight the sensitivity of alpine glaciers as a tool for reconstructing climate variations since the Late Glacial/Early Holocene transition.

Surface exposure dating of moraines in the Chagan Uzun Valley, Altai Mountains

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Abstract

The mountains in southern Siberia (Altai, Sayan, Transbaikalia) were glaciated repeatedly during the Quaternary, and the glacial sediments and landforms there are valuable archives for paleoenvironmental and –climate reconstructions. However, studies focusing on glacial chronologies in these mountain ranges are still very scarce, and the extent and timing of glacier advances remains poorly constrained (e.g., Lehmkuhl et al. 2011; Agatova et al. 2014).

We have used cosmogenic ^{10}Be surface exposure dating to establish a glacial chronology for the Chagan Uzun Valley in the southern Chuja Range in the Russian Altai. We targeted six moraine complexes and sampled gneiss boulders and quartz cobbles. Exposure ages vary widely on the individual moraines, making interpretations in terms of depositions ages and timing of glacial advances difficult. Assuming negligible nuclide inheritance and interpreting the oldest sample from a moraine as best available estimate, massive glaciation occurred as early as ~84 ka. Subsequent, successively less extensive glacial advances probably occurred at >40 ka (MIS4?), and 21-24 ka.

Our data highlight the difficulty to apply surface exposure dating of glacial landforms in cold, continental regions, most likely due to long-lasting landform surface instability. Our results nevertheless add additional evidence for an early local LGM in Siberia, significantly predating the global LGM.

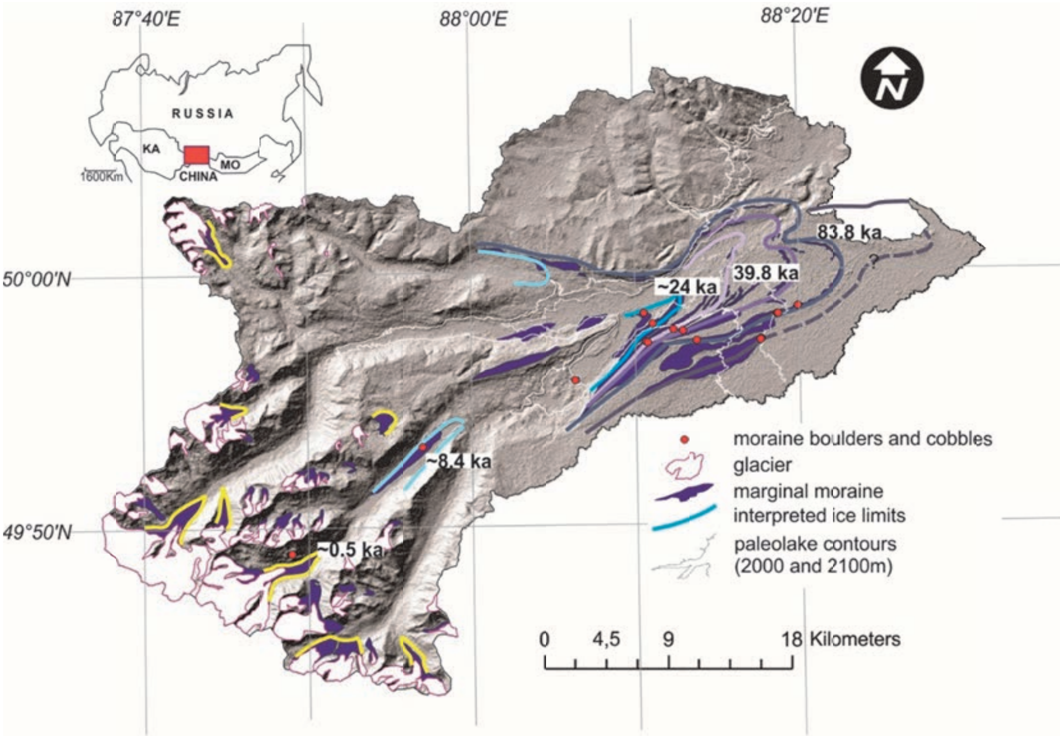

Figure 1. *Dem (SRTM 30m, artificially illuminated) of the Chagan Uzun catchment showing principal ice limits, moraines, paleolake levels and sample sites.*

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Southern Patagonian Ice Field palaeo-elevation constraints and thinning rates during the Late-Holocene

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Abstract

The work presented here relies on exposure ages obtained from two nunataks, Witte and Garcia, located in the present day accumulation areas of glacier Viedma and Chico, respectively. Both glaciers currently drain the Southern Patagonian Ice Field toward east and north-easterly direction at 48-49°S, Argentina/Chile. Bedrock exposure ages (n=5) from nunatak Witte fall into the late-Holocene and span an altitudinal range of ca. 400 meters above the current Viedma ice surface. Ice thinning rates at glacier Viedma show continuous acceleration toward present. Bedrock-erratic pairs from nunatak Garcia (n=6) are obtained from three distinct bedrock ledges and span ca. 300 meters above the current glacier Chico surface. The constrained palaeo-ice surface elevations of glacier Chico fall between LIA peak III and I, with accelerated thinning toward present. During LIA peak III, glacier Chico and Viedma were ca. 100 and 140 meters above the present day ice surface, respectively. Previous mapping and calculation of Southern Patagonian Ice Field's LIA cover and ice loss has excluded the configuration and contribution of the accumulation area, based on a lack of data. The work presented here forms the first empirical constraint of palaeo-ice surface elevations in the accumulation area of the Southern Patagonian Ice Field during LIA peaks I-III. The results highlight that previous glacier cover and sea level equivalent contributions from/during the LIA have been underestimated for the Southern Patagonian Ice Field.

Use of cosmogenic nuclides to date relict rock glaciers

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Abstract

Exposure dating of relict rock glacier only have been applied in few cases, but with promising results. Rock glaciers are tongue- shaped mixtures of rock and ice, that creep downhill. Their existence is restricted to areas with very specific climatologic and petrologic conditions. They need mean annual air temperature of less than -2 °C and annual precipitation of less than 2500 mm/yr, and they only occur where the lithology of the mountain leads to abundant talus. Relict rock glacier lost their ice due to warming and are therefore not moving anymore. This make them an interesting study site to reconstruct the paleoclimatic situation. The exposure ages of a relict rock glacier give a temporal assignment and shows how long since a rock glacier stabilized (end of a cold period). In the province of Carinthia (Austria), at the western valley side of the Maltatal, along the north facing flank of the Reisseck mountain range, the Tandl rock glacier is situated. It is a relict rock glacier with a series of very low- reaching lobes. The deposit covers approximately 0.9 km^2 and has its lowest limit around 1220 m above sea level (a.s.l.) and hence lies nearly 1300 m below modern permafrost limits. According to Reitner (2007) the Tandel rock glacier is therefore the lowest relict rock glacier of the Eastern Alps. This makes it a source of highest interest in regional paleoclimate reconstruction. Recently completed ^{10}Be exposure dating of two gneissic boulders gave ages around 14-15 kyr, the lowest lobe may be even older. Therefore, in fall 2015 eleven more samples on different lobes were collected and will be prepared for ^{10}Be exposure dating in 2016. No further than 10 km south-west of the Tandl rock glacier deposit, in a side valley (Im Goassel) north of Mühldorf, nine more samples of two relict rock glacier deposits were taken. The intention is to assess the influence of the exposition, as those two relict rock glaciers are the lowest south facing rock glacier deposits. They have their lowest limit around 1680 m. and 1530 m a.s.l.. The detailed study, including field mapping as well as ^{10}Be exposure dating on two sites with different geographical exposition, is an exceptional opportunity to elucidate regional paleoclimatic variations during the Lateglacial.

First evidence of a Younger Dryas re-advance in Greenland

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Abstract

The Younger Dryas (YD) is a well-constrained cold event from 12,900 to 11,700 years ago but it remains unclear how the cooling and subsequent abrupt warming recorded in ice cores was translated into ice margin fluctuations in Greenland. In a recent study we presented ^{10}Be surface exposure ages from three moraines in front of local glaciers on a 50 km stretch along the north coast of Greenland, facing the Arctic Ocean (Larsen et al., 2016). Ten ages range from 11.6 ± 0.5 to 27.2 ± 0.9 ka with a mean age of 12.5 ± 0.7 ka after exclusion of two outliers. We consider this to be a minimum age for the abandonment of the moraines. The ages of the moraines are furthermore constrained using Optically Stimulated Luminescence (OSL) dating of epishelf sediments, which were deposited prior to the ice advance that formed the moraines, yielding a maximum age of 12.4 ± 0.6 ka, and bracketing the formation and subsequent abandonment of the moraines to within the interval 11.8-13.0 ka ago. This is the first time a synchronous YD glacier advance and subsequent retreat has been recorded for several independent glaciers in Greenland. In most other areas, there is no evidence for re-advance and glaciers were retreating during YD. We explain the different behaviour of the glaciers in northernmost Greenland as a function of their remoteness from the Atlantic Meridional Overturning Circulation (AMOC), which in other areas has been held responsible for modifying the YD drop in temperatures.

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Larsen NK, **Funder S, Linge H, Möller P, Schomacker A, Fabel D, Xu S, Kjær KH, 2016**. First evidence of Younger Dryas re-advance in North Greenland. Quaternary Science Reviews.

Glacial and periglacial landform formation during MIS 3-1 on Andøya, northern Norway

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Abstract

The age and relationship between glacial and periglacial landforms on Andøya (Figure 1) have been investigated. A compilation of more than 80 published and unpublished cosmogenic ^{10}Be surface exposure ages provides new information on the timing and extent of regional and local glaciation for the last glacial period. Insight into the dynamics of past terrestrial environments is moreover added by dating of relict talus-derived rock glaciers.

Activity of local glaciers is recorded between 65 and 12 ka from boulders on marginal moraines. Talus-derived rock glaciers were active at least in the 30-15 ka interval. Changes in the lateral and horizontal extent of the Scandinavian Ice Sheet between 40 and 25 ka are suggested from cosmogenic ^{10}Be surface exposure ages from glacially transported boulder (on bedrock), as well as from boulders on marginal moraines. In addition, marine modified marginal moraines give boulder ages around 15.5 ka, suggesting a minimum age for a marine high stand at 31 m a.s.l. These findings show fluctuating local glaciers, as well as asynchronous timing of the maximum extent of regional and local glaciation.

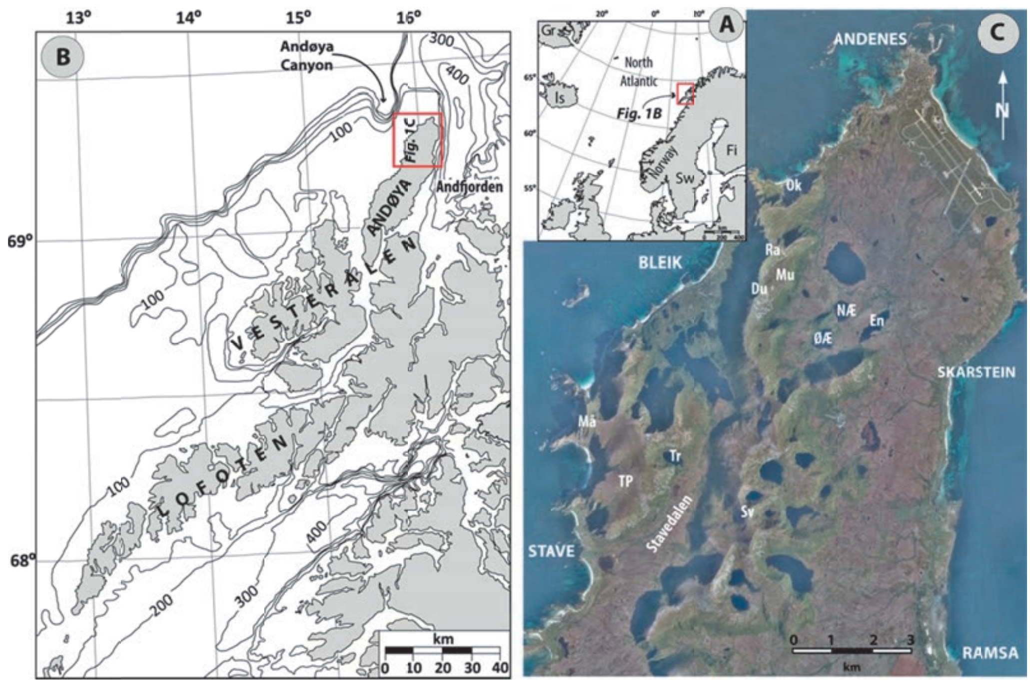

Figure 1. *A) Map of the North Atlantic and Scandinavia showing the location of the Lofoten-Vesterålen (L-V) archipelago (rectangle). B) Map of the L-V archipelago showing the location of northern Andøya (rectangle), and the shallow and narrow shelf area (bathymetry below 500 m is not shown). C) Aerial photo of northern Andøya.*

Glacial chronology and palaeoclimate in the Bystra catchment, Western Tatra Mountains (Poland) during the Late Pleistocene

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Abstract

Deglaciation chronology of the Bystra catchment (Western Tatra Mountains) has been reconstructed based on ^{10}Be exposure age dating (Figure 1). Fourteen rock samples were collected from boulders located on three moraines that limit the horizontal extent of the LGM maximum advance and the Lateglacial recessional stage. The oldest preserved, maximum moraine was dated at 15.5 ± 0.8 ka, an age that could be explained more likely by post-depositional erosion of the moraine. Such scenario is supported by geomorphologic and palaeoclimatological evidence. The younger cold stage is represented by well-preserved terminolateral moraine systems in the Kondratowa and Sucha Kasprowa valleys. The distribution of the moraine ridges in both valleys suggest a complex history of deglaciation of the area. The first Late-glacial readvance (LG1) was followed by a cold oscillation (LG2), that occurred at around 14.0 ± 0.7 - 13.7 ± 1.2 ka. Glaciers during both stages had nearly the same horizontal extent, however, their thickness and geometry changed significantly, mainly due to local climatic conditions triggered by topography, controlling the exposition to solar radiation. The LG1 stage occurred probably during the pre-Bølling cold stage (Greenland Stadial 2.1a), however, the LG2 stage can be correlated with the cooling at around 14 ka during the Greenland Interstadial 1 (GI-1d - Older Dryas)(Rasmussen et al., 2014). This is the first chronological evidence of the Older Dryas in the Tatra Mountains. The ELA of the maximum Bystra glacier was located at 1480 m a.s.l. in accordance with the ELA in the High Tatra Mountains during the LGM (Makos et al., 2014). During the LG1 and LG2 stages, the ELA in the catchment rose up to 1520 - 1530 m a.s.l. and was located approximately 100 - 150 m lower than in the eastern part of the massif. Climate modelling results show that the Bystra glacier (maximum advance) could have advanced in the catchment when mean annual temperature was lower than today by 11 - 12 °C and precipitation was reduced by 40 - 60%. This is in accordance with LGM conditions previously reported for the High Tatras. During the LG1 and LG2 stages the temperature decrease in the study area reached 10 °C and precipitation was lower by ~30% compare to modern conditions. This resulted in slightly higher accumulation (20 - 30%) in the Western Tatra Mountains compare to the High Tatra Mountains (Makos et al., 2013).

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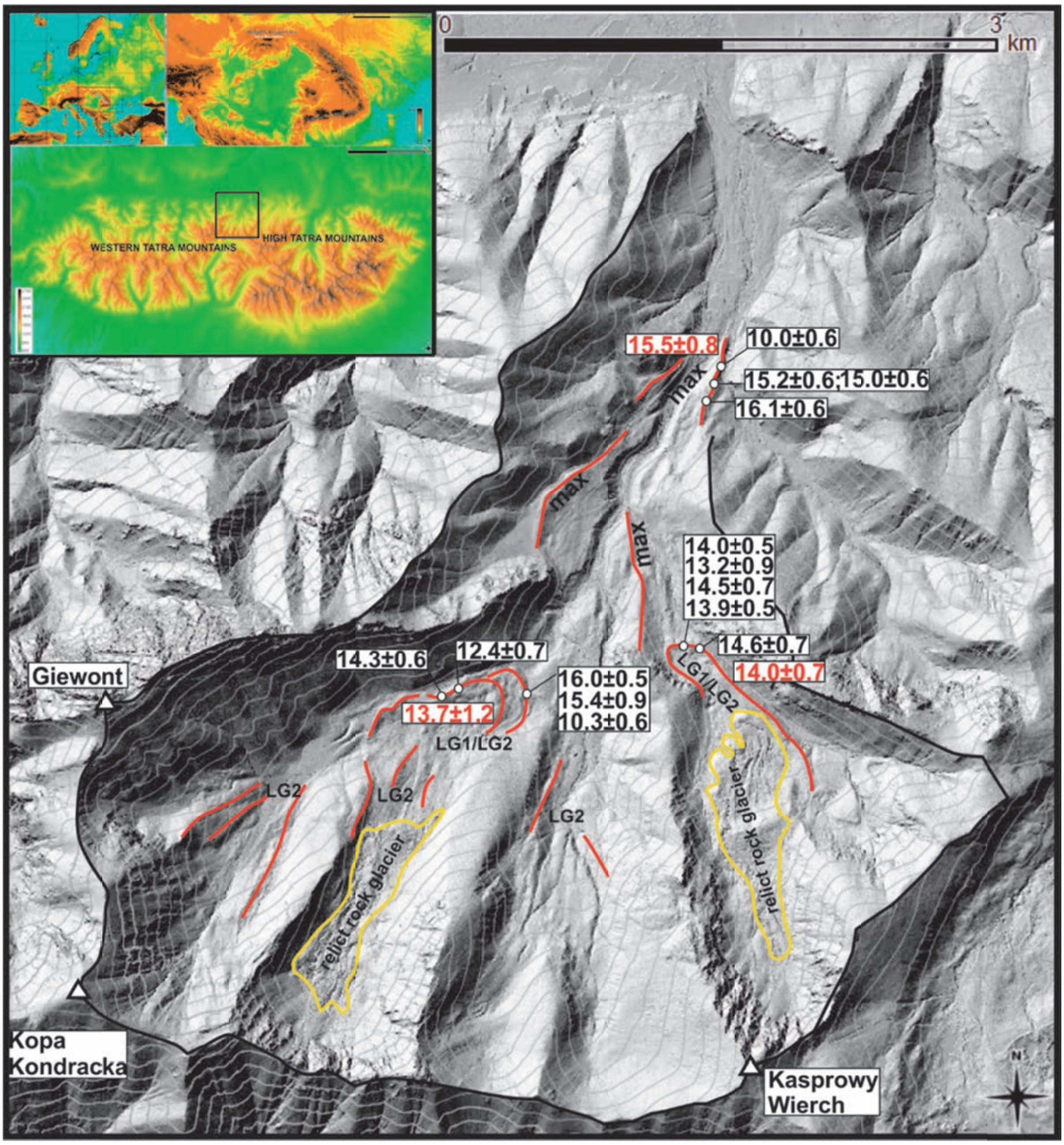

Figure 1. *Major terminal and lateral moraines (red lines) with exposure ages, fossil rock glaciers (yellow outline) and sample locations on the LiDAR digital elevation model of thestudy area. Individual exposure ages are in black, mean moraine ages are in red. The contour interval line (thin grey lines) is 50 m.*

Constraining ice sheet basal thermal regime across an ice stream-dominated region: Insights from North West Scotland.

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The British-Irish Ice Sheet (BIIS) is predicted to have deglaciated rapidly from ~ 18 ka, in response to rising sea level and temperature, similar forcings experienced by modern polar ice sheets. As the main conduits of ice mass loss, the reaction of ice streams to these forcings is thought to have been central in determining the mode and timing of this deglaciation. However, lack of understanding of ice stream influence on the glaciology and deglaciation of ice sheets limits confidence in ice sheet model predictions. NW Scotland is an area of the last BIIS predicted to have been dominated by ice stream onset conditions (Bradwell et al., 2007) and offers an rare opportunity to study long term landscape evolution features in a region dominated by hard crystalline lithologies which, in some locations, preserve evidence of multi-stage environmental change (Krabbendam & Bradwell, 2014).

We presents results from a geomorphological and terrestrial cosmogenic nuclide (TCN) analysis study which resulted in the production of a composite ice-sheet thermal regime map and retreat chronology for the last BIIS in this region. Mapping and surface exposure dating suggest that the regional glaciology and landscape evolution was dominated by the presence of ice-stream onset zones during Greenland Stadial-2 (GS-2). Mountain top erratics were uplifted and transported to high elevation during GS-2, before 16.5 ka BP. By inference, mountain summits were covered by ice during maximal ice sheet conditions.

The existence of sharp thermo-mechanical contrasts, developed in response to ice streaming (Bradwell, 2013), are proposed as the main controls on bedrock erosion and terrestrial sediment deposition. Significant nuclide inheritance in glacially overridden bedrock surfaces at high and low elevation indicates the previous existence of persistent frozen bed patches.The interpretation of 'trimlines' in NW Scotland as englacial thermo-mechanical boundaries (Fabel et al., 2012), is verified in this field area by the identification of 'rip-offs', similar to the transverse lee side scraps of Clarhäll and Kleman (1999), a newly recognised geomorphic feature in the UK, and by quantitative demonstration of the increase in glacial erosion in the vicinity of these boundaries. Geomorphic and TCN data supports a conceptual model of thermal inversion following ice-stream cessation. The first description of 'till tails' in the UK provides insight into the glaciological organisation and thermal evolution of the BIIS.

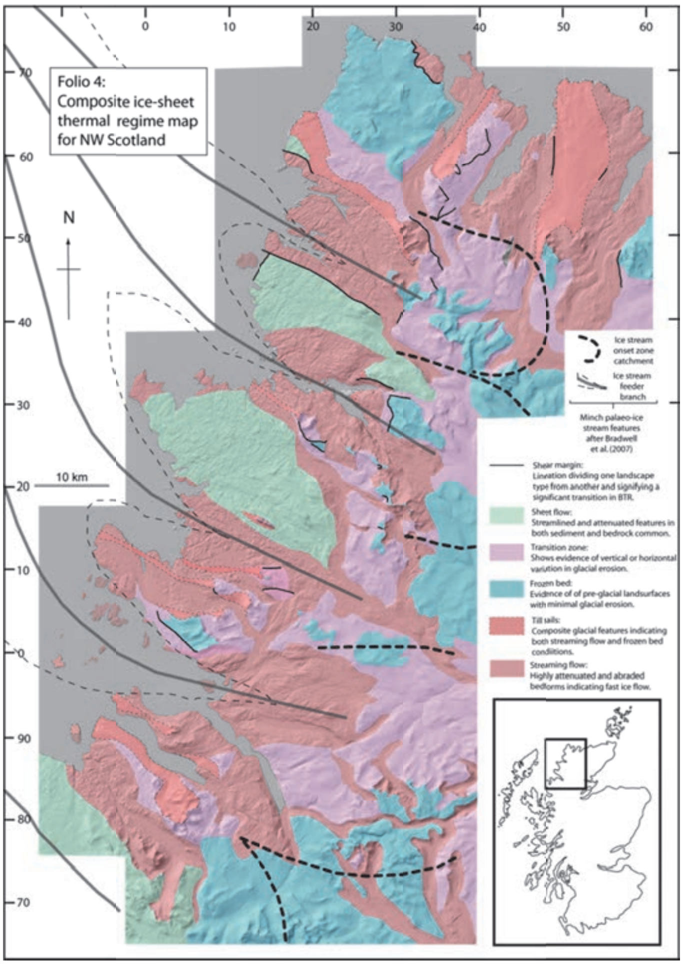

Figure 1. *Composite ice sheet thermal regime map for NW Scotland.*

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Interlaboratory comparison of sample preparation in Vienna and Budapest by isochron burial dating of Danube terraces

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Abstract

Quaternary sediment transport via the Paleo-Danube River into the Vienna Basin resulted in deposition of fluvial terrace bodies largely influenced by glacial-interglacial cycles in a generally uplifting area. Today, these sediments form terrace staircases east and west of the Vienna Basin. The area within the Vienna Basin is in addition shaped by the tectonic regime of a large subsiding structure between the Eastern Alps and the Western Carpathians. Thus, fault activity dissects the terrace staircases after primary fluvial deposition. To constrain the age of climatically and/or tectonically driven terrace formation during the last 5 Million years tectonic features have to be separated from climatically driven depositional events to create a chronology for selected tectonic units. To do so it is essential to compile geochronologic, geomorphologic, geologic, and tectonic datasets of the study area, to provide a robust relative chronology and, in a second step, complement this relative chronology by an independent numerical chronology.

Terraces south of the Danube form a staircase with altitudes ranging between 25 and 130 m above todays water level, which have been strongly dissected by faults related to the sinistral movement of the Vienna Basin Transform Fault System (Decker, et al. 2005, Salcher et al., 2012).

To better understand the Quaternary terrace sequence and its displacement in a fault segment south of the Danube, we use the cosmogenic nuclide pair of ^{26}Al and ^{10}Be for isochron burial dating of a Danube terrace at Haslau an der Donau (~40 m above river level). This terrace is locally the lowest of a staircase of a total of 6 different levels. Based on published geomorphological works, the expected age is Middle Pleistocene (Fuchs and Grill, 1984). The isochron burial dating method is therefore well-suited to date this sedimentary setting due to the presence of large individual cobbles that share the same post-depositional history, but have different pre-exposure and transport histories (Balco and Rovey, 2008).

The sandy gravel of the Haslau terrace was sampled in an active gravel pit. At this location, two major sedimentary units are separated by an erosional hiatus of unknown duration. The upper sequence was sampled at 5.5 m depth and the lower one was sampled at 11.8 m depth. From both depths six quartzite or quartz-bearing cobbles were taken together with a bulk sample from the matrix for isochron burial duration determination. Five samples from the level at 5.5 m depth were split after crushing and sieving and were processed at both the Cosmogenic Nuclide Sample Preparation Laboratory at Vienna and at Budapest (http://www.geochem.hu/kozmogen/Lab_en.html), in order to assess and compare the sample processing procedures of these recently operating sample preparation laboratories. AMS measurements were performed at the French national facility ASTER (CEREGE (Aix-en-Provence, France) and at the Vienna Environmental Research Accelerator (VERA).

Preliminary results show that ^{10}Be concentrations of the first three samples processed independently at both laboratories overlap within error. First results of ^{26}Al concentrations and the inferred ages will be presented for discussion at the workshop.

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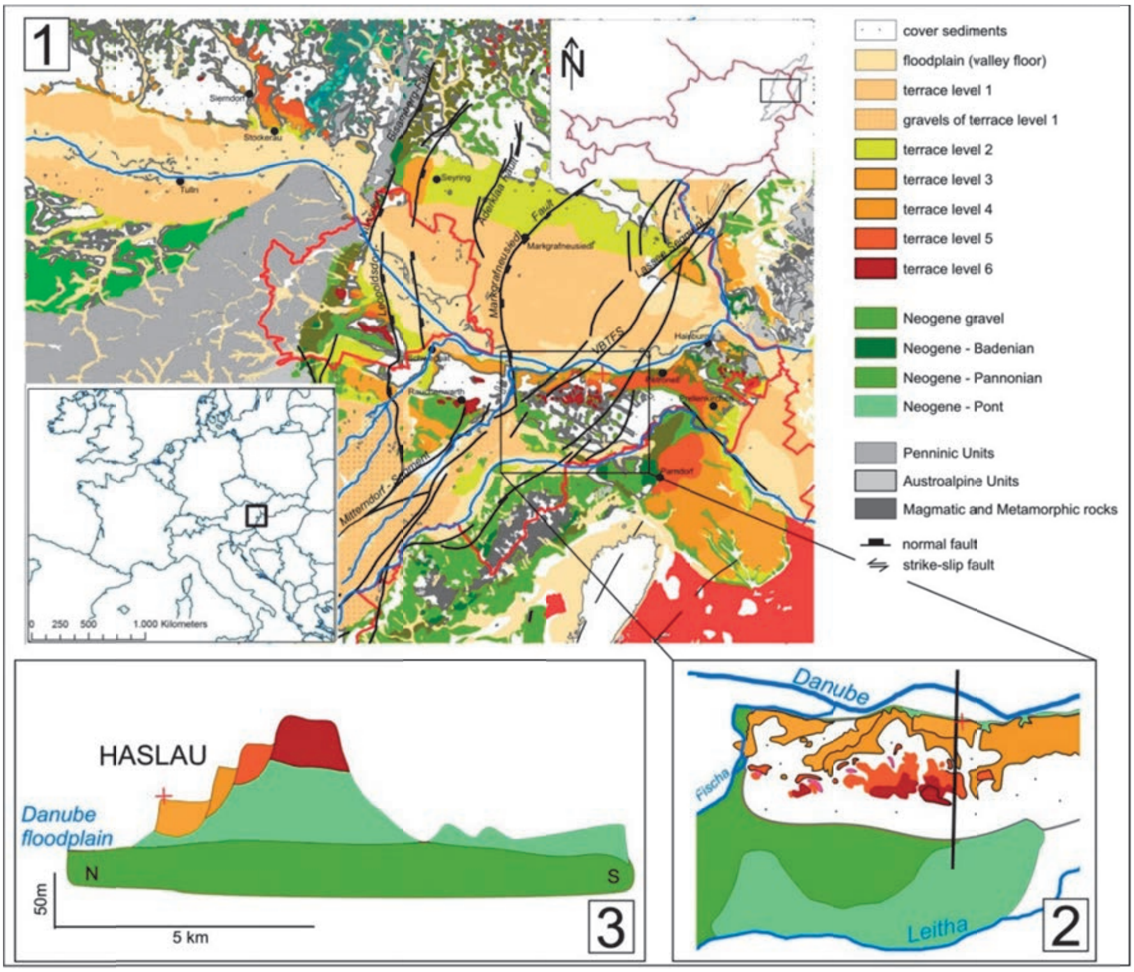

Figure 1. *1: Overview: bedrock and terraces in the Vienna Basin (Schnabel, 2002) and its borders, position of faults 2: Detail of study area (Fuchs and Grill, 1984); 3: N-S cross section of terrace staircase using Fuchs and Grill, 1984; Position of outcrop marked with red cross in 1 and 2.*

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Reconstructing the glacial history of the East Antarctic Ice sheet in Dronning Maud Land: Changes in spatial patterns of vertical ice extent

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Abstract

Given current concern about the stability of ice sheets, and potential sea level rise, it is imperative that we are able to reconstruct and predict the response of ice sheets to climate change. The Intergovernmental Panel on Climate Change (IPCC), amongst others, have highlighted that our current ability to do so is limited. Numerical ice sheet models are a central component of the work to address this challenge. An unresolved key issue in this work concerns the volume and rate of ice mass loss needed to explain the large difference between late glacial and interglacial global sea levels. Some 20% of observed sea level rise since the Last Glacial Maximum (LGM) cannot be attributed to any known former ice mass, indicating that this inconsistency arises from the deficiencies in modelled reconstructions of ice sheet volumes and postglacial rebound. Ice sheet models are tested and refined by comparing model predictions of past ice geometries with field-based reconstructions from geological, geomorphological and ice core data. However, on the East Antarctic Ice sheet, Dronning Maud Land (DML) presents a critical gap in the empirical data required to reconstruct changes in ice sheet geometry. In addition, there is poor control on regional climate histories of ice sheet margins, because ice core locations, where detailed reconstructions of climate history exist, are located on high inland domes. This leaves numerical models of regional glaciation history largely unconstrained.

MAGIC-DML is a Swedish-US-Norwegian-German-UK collaboration with a focus on filling the critical data gaps that exist in our knowledge of the timing and pattern of ice surface changes on the western Dronning Maud Land margin. A combination of geomorphological mapping using remote sensing data, field investigations, cosmogenic nuclide surface exposure dating, and numerical ice-sheet modelling are being used in an iterative manner to produce a comprehensive reconstruction of the glacial history of western Dronning Maud Land. Here we present results from the first phase of this project - preparing for the field work commencing during the 2016/17 austral summer. We present the initial mapping and modelling experiments that have highlighted high potential sampling sites.

Latest Pleistocene glacial advances in the Veľká Studená Valley (Tatra Mountains, Slovakia)

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Abstract

The Tatra Mountains (2654 m) are the highest mountain massif in the Carpathian arc. The massif presents also the most spectacular alpine-type relief inherited from Pleistocene glaciations to the north and east of the Alps, however present-day glaciers are absent there. Recent investigations in these mountains have substantially improved our knowledge about late Pleistocene glacier fluctuations, nevertheless there are still unresolved questions about the extent and chronology of the latest glacier advances and the timing of final deglaciation of high elevated glacial cirques. The vast and high elevated (1850-2150 m) glacial cirque in the head of the Veľká Studená Valley on the southern slope of the High Tatra Mountains, presents a unique archive of well-developed landforms attributed to the latest stages of glacier activity within the massif. The results of detailed geomorphological mapping and surface exposure dating using ^{10}Be and Schmidt hammer (SH) methods indicate that in the study area two distinct systems occur associated with two glacial stages.

The older system is represented by multilobate pattern recorded as bouldery moraine cover with hummocky topography delimited with a distinct latero-frontal moraine. The moraine was formed by the south-facing glacier which almost entirely covered bottom of the cirque. Several rock failures which must have supplied the glacier resulted in an extensive debris cover and implied an extended glacier readvance. Preliminary results of surface exposure dating reveal similar age of this advance and the rock avalanche event which took place in the southern part of the valley. Ice-moulded bedrock locally covered with till and dispersed glacial boulders, which occur outside the older system and the extent of rock avalanche, does not reveal significantly older exposure ages. In contrary, noticeable difference in rock surface weathering between the older and younger glacial systems has been investigated. The younger system is apparently spatially limited and distributed in close proximity to the cirque backwalls. It constitutes an assemblage of fresh in shape, bouldery moraines and relict rock glaciers developed on north-facing slopes. During this stage several small glaciers and rock glaciers advanced from the inner cirques towards the center of outer cirque bottom. This system has been marginalized and cross-cutting relations with the older moraine system can be observed in the field.

Our results shows that in the youngest marginal glacier advance occurred during the Younger Dryas (YD). The extent of this moraine system is well-discernible as a contrast in landform development and freshness. This corresponds to the well-known morphostratigraphic definition of YD glacier advances in the Alps and Scottish Highlands. The obtained results implies that glaciers in this valley had finally vanished with the termination of the YD cold phase.

This research was funded by the Polish National Science Centre (NCN) grant No. 2015/17/B/ST10/03127. We thank the Ion Beam Physics AMS group for laboratory support and AMS measurements.

Exposure ages of terminal and lateral moraines disclose complex history of climate change upon retreat of valley glaciers in Yusufeli Turkey

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Abstract

Retreats of glaciers have conventionally been explored through the exposure dating of erratic boulders on terminal and lateral moraines. This information has allowed determining changes in lengths and thicknesses of valley glaciers upon their retreats. Here, we focus on the Çoruh valley glacier situated in Yusufeli, Turkey. This valley was covered by a > 200 m-thick and > 10000 m-long paleoglacier during the LGM. Glacial deposits were mapped in the field and on satellite images. Moraines occur at the valley bottom and the lateral valley flanks, where they are preserved as distinct levels. We have collected a total of 31 boulders and one bedrock sample for exposure dating purposes with in-situ 36Cl encountered in volcanic lithologies. Oldest ages of ca. 35 ka have been measured for blocks that occur in the terminal moraines. Farther up-valley, lateral moraines occur ca. 200 m above the valley floor, and exposure ages cluster around 22-17 ka. Youngest ages of 12-10 ka have been measured on boulders in the highest cirque areas of the valley system. Interestingly, no pre 25 ka ages have been encountered in moraines along the valley flanks. This implies that the ice thickness was greater at 22 ka than during the time of the glacier's maximum extent ca. 35 ka. Accordingly, the age patterns on the flank suggest that ca. 35 ka, the paleoglacier was longest but not thickest, and that the ice thickened upon oscillations and retreat (22-17 ka). We do acknowledge that possible drawbacks of the proposed mechanisms are related to the lack of archives for the maximum glacial extent on the lateral sides. Nevertheless, if our inferences from the morphochronological data are correct the spatial-temporal differences in the ice thicknesses can be used to reconstruct the mechanical state of a glacier. Theory about mechanics of solid material (Davis et al. 1983) such as glaciers predicts that the taper or surface angle, and thus the thickness of an ice body, depends on the shear resistance at the base of a glacier and the cohesion within the ice. Accordingly, a glacier that is e.g. frozen at the base and dry can sustain greater topographic tapers than a wet glacier; therefore such a glacier tends to be thick. If correct, our suggestion that the palaeoglacier at ca. 35 ka was relatively wet during its maximum extension and then became drier upon retreat. We thus propose that this is consistent with a palaeoclimate in the Çoruh valley where conditions were cold and wet during its maximum extent, and then turned colder towards the global LGM 22.1 ± 4.3 ka (Shakun & Carlson 2010). A subsequent period of warming and possibly drying finally leads to the full decay of the glacier to the current block glaciers in the cirques.

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Late Pleistocene glacier chronology of the Retezat Mts, Romania, Southern Carpathians

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Abstract

Extensive Quaternary glaciations of the Southern Carpathians have long been recognised and comprehensively described (Urdea, 2004). Even if their chronology and pattern are of special interest due to the transitional position of the mountain range between continental and Mediterranean climate zones, they remain poorly constrained. During the Quaternary, the Retezat Mts were one of the most glaciated ranges in the Southern Carpathians with peak elevations reaching 2500 m asl. The largest reconstructed glaciers descended to ~1030 m in the northern and to ~1120 m in the southern valleys, with some variations owing to different local conditions.

We present new and recalculated Surface Exposure Dating (SED) results using in-situ produced cosmogenic ^{10}Be from the northern side of the Retezat Mts (Ruszkiczay-Rüdiger et al., 2016) together with additional ^{10}Be SED ages from the southern valleys. According to our data, glacier retreat started no later than ~20-21 ka, which suggests that the maximum ice extent in the Retezat Mts coincided with the maximum extentof the Eurasian ice sheet complex (Hughes et al., 2016). The glacier retreat took place in at least five phases until the smallest dated cirque glaciers at ~2100 m asl. at ~13.5-14.1 ka ago. Younger glaciations may have occurred, but no proof of their existence could be delivered so far, due to extensive rock glacier activity, which destroyed their morphological evidences in several valleys of the study area (Figure 1)

The paleo-glaciers were reconstructed from the mapped glacial landforms. The paleo-equilibrium line altitudes (ELA) were estimated for the different deglaciation phases (Pellitero et al., 2015) and are compared to ELA reconstructions available for other Carpathian ranges as well as for the Alps and Dinarides. First estimates of regional LGM paleoELA using the ssAAR method (Kern and László, 2010) ranged from ~1826 m during the LGM to ~2200 m for the smallest cirque glaciers at 13.5 ka, respectively. These values are ~100 m higher than those previously suggested for the study area (Reuther et al., 2007).

New samples were processed at the Sample preparation laboratory for in-situ produced cosmogenic nuclides of Budapest (http://www.geochem.hu/kozmogen/Lab_en.html), and AMS measurements were performed at the French national facility ASTER (CEREGE-LN2C, Aix-en-Provence, France).

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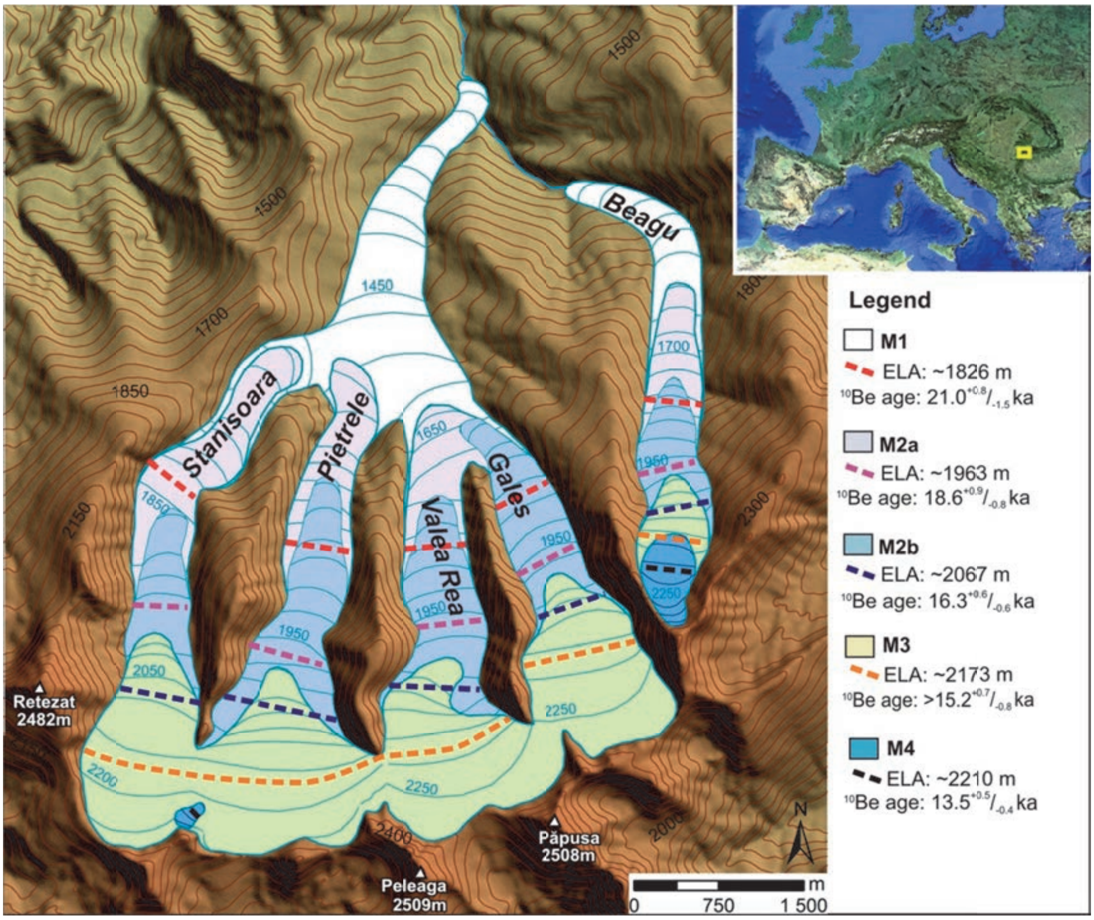

Figure 1. *Deglaciation phases of the Northern Retezat Mts with the reconstructed glaciers and ELAs. Age constraints are provided by ^{10}Be SED of moraine boulders (Ruszkiczay-Rüdiger et al., 2016).*

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^{10}Be measurement at Trondheim 1 MV AMS

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Abstract

The 1 MV AMS system in Trondheim is regularly used for radiocarbon dating and provides stable measurement conditions for reliable results. Although the system has also been designed for ^{10}Be and ^{26}Al, these elements have never been measured after the initial acceptance tests. In order to extend the capabilities of the National Laboratory of Age Determination at NTNU, we are planning to add ^{10}Be measurements for surface exposure dating to our repertoire.

The system requires BeO samples which are mixed into a metal matrix such as Nb. Negatively charged BeO ions are extracted from the ion source and a bouncing magnet is used for quasi-simultaneously injection of different ion masses. In the center of the 1 MV tandem accelerator, the molecules are dissociated in collision with the Ar stripper gas. After mass separation in a magnet, the abundant ^{9}Be ions can be measured in a Faraday cup. The rare ^{10}Be ions are overlain by much more abundant ^{10}B ions, which requires an additional separation step in a degrader foil. This silicon nitride foil has a thickness of 150 nm. Passing the foil, different ion species undergo a specific energy loss, which allows separating the ion species in the following electrostatic analyzer. The final particle identification happens in a gas ionization chamber, which is used for counting single ^{10}Be ions.

In this contribution, we present results which determine the limits for the analysis performed in our laboratory. This includes the transmission for different charge states through the stripper, which is an important part of the measurement efficiency. Even more important is the interaction in the degrader foil because it is not only contributing to the measurement efficiency, but also for the background level which can be achieved in the measurement. Based on these measurements the overall efficiencies and background levels are evaluated for possible charge state combinations. While we could reproduce the values from the acceptance test, we figured that we can increase the measurement efficiency by changing the measured charge state to 2+. This change leads to a gain in overall efficiency of almost 100 % and the background level could be reduced by almost a factor of 2. The final background level corresponds to a ^{10}Be/^{9}Be ratio of $5 \cdot 10^{-15}$. This corresponds to an exposure age of about 500 years in the Scandinavian region and allows dating of a large range of geological process after the last glacial maximum (LGM).

As an example study we are working on an exposure dating project in Finnmark and northern Finland. The aim of the project is to improve the timing constraints for the retreat of the Scandinavian ice sheet after the LGM. The first set of measurements represents a coarse measurement of the region and will allow identifying regions where a more detailed analysis should be performed.

^{10}Be and ^{26}Al measurements at Aarhus AMS center

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Abstract

A new multi-element AMS system by High Voltage Engineering Europa B.V. was installed at Aarhus AMS center in the beginning of 2014. The system is designed around a 1 MV Tandetron accelerator with two optional stripping gases (He or Ar). The injector of the system features a 120 degree bouncer magnet and two independently operating ion sources. Isotope separation and suppression of isobar are carried out with a 90 degree high-energy magnet, a degrader foil, a 120 degree electrostatic analyzer and an additional 30 degree magnet for background reduction. A variety of diagnostics tools including Hall probes allows accurate tuning and stable operation for several days. The AMS system provides performant measurements of a great selection of isotopes: ^{3}H, ^{10}Be, ^{14}C, ^{26}Al, ^{41}Ca, ^{129}I and actinides (Pu, U). The results of acceptance test (Heinemeier et al., 2015) and full description (Klein et al., 2014) of the AMS system were already published.

Regarding ^{10}Be and ^{26}Al, a complete infrastructure from quartz sample preparation to AMS data reduction was set up at Aarhus University through 2015. A number of tests were performed to ensure internationally recognized performance of ^{10}Be and ^{26}Al laboratory preparation and AMS measurements. Among test results, the most remarkable are suppression of ^{10}Be isobar (^{10}B) of 11 orders of magnitude, ^{10}Be/^{9}Be background level of $6.9 \pm 2.7 \cdot 10^{-16}$ and ^{26}Al/^{27}Al background level of $6.0 \pm 1.9 \cdot 10^{-16}$.

Routine sample preparation and AMS measurements of ^{10}Be and ^{26}Al are established at Aarhus University since 2016.

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Announcement of in-situ ^{14}C extraction system of Aarhus University

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Abstract

Surface exposure dating with long-lived and stable cosmogenic isotopes has developed enormously the last three decades. A recent and one of the most remarkable achievement of this field is addition of in-situ ^{14}C isotope to the well-known ^{10}Be, ^{26}Al, ^{36}Cl, ^{3}He and ^{21}Ne. Carbon-14 has a short half-life ($T_{1/2}$ = 5730 yr) compared to ^{10}Be and ^{26}Al ($T_{1/2}$ = 1.36 Myr and $T_{1/2}$ = 0.72 Myr) which are routinely applied to determine the age of quartz lithologies and sediments. Thus the short half-live makes in-situ ^{14}C dating a unique tool for studies on short-term changes in denudation rates and on late glacial oscillations. More important, a multi isotope approach of in-situ ^{14}C together with ^{10}Be and ^{26}Al allows recovering of complex deglaciations histories, transport of river sediments and erosion rates of soils.

The extraction of in-situ ^{14}C from quartz was the major hampering point of the isotope implementation. Still, there are only few successful projects on an extraction system of in-situ ^{14}C from quartz, e.g. ETH-Zürich Switzerland, Purdue University USA. The fusion of quartz sample at high-temperatures (1100-1700º C) is the only well-known way to extract in-situ accumulated ^{14}C. Any contamination of the sample surface or extraction system with atmospheric radiocarbon ruins the result. These and other technical problems turn a realization of the in-situ ^{14}C extraction systems into a challenging task.

Through the last year, a design of in-situ ^{14}C extraction system was developed at Aarhus AMS Centre. The design includes established solutions, like high-temperature extraction and graphitization, as well as novel ideas, like gaseous carrier injector. Modular design of our system will allow upscaling of the number of extracted samples in the future. Assembly work on the system is in progress, and the first tests are planned for the beginning of the summer of 2016.

Suitability of erratic boulders in NW Poland for cosmogenic dating of the last Scandinavian Ice Sheet recession

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Abstract

North-western (NW) Poland is a key region to complete cosmogenic chronology of the last Scandinavian Ice Sheet (SIS) retreat available south of the Baltic Sea. A new cosmogenic dating project (http://www.daterr.ug.edu.pl/home.html) in this region will bridge the existing gap between the records available in the "west" (Denmark, Germany) and "east" (north-eastern Poland, Lithuania and Belarus). However, the reliable dating of a paleo-ice sheet retreat with cosmogenic nuclides requires sampling of glacially eroded bedrock surfaces or well-preserved erratic boulders resting on moraines. In the area south of the Baltic Sea, where usually soft sediments cover occurs, well-preserved erratics from the Fennoscandian Shield are the best candidates for cosmogenic sampling. We present the results of our desk-based selection and ground truthing of massive erratics in NW Poland for cosmogenic dating with ^{10}Be.

Our analysis was achieved in three phases. At first, a broad GIS database of large boulders in NW Poland was created based on all available information about massive erratics: lists of natural monuments, database of geosites, geologic and geotourism maps, books, forest ranger interviews, local commune reports, landscape park reports, etc... The GIS database includes basic information about boulders, such as: location (coordinates), dimensions (perimeter and height), petrography and other remarks (e.g. if given - boulder's name). The second phase included the analysis of boulders dimensions, petrography as well as distribution against the digital elevation model and geologic maps. All boulders with perimeter <5 m and height <0.5 m as well as located in valleys and extensive outwash plains were rejected. Boulders already dated with ^{10}Be were also ignored. The largest boulders located on ice-marginal belts or on moraine plateaux were pre-selected and compiled in a list of over 100 objects potentially suitable for further investigation. In the final phase, these boulders have been ground truthed in the field with special focus on: geomorphological position, height above the ground, shape, petrography, evidence of glacial erosion, and potential marks of anthropogenic impact. Finally, over 60 massive, located in-situ, quartz-rich erratic boulders were identified as suitable for sampling and ^{10}Be dating (Figure 1). Because almost all of pre-selected boulders are natural monuments protected by law, special permissions for their examination are required as well as special sampling techniques to minimize the visual impact on the selected objects.

Some of the boulders rest on the ice-marginal belts along the limits of the last SIS glacial phases, whereas others are located between the limits of particular glacial phases - on moraine plateaux. This allows us to document the deglaciation chronology in detail, i.e. to date ice-sheet limits and to estimate timing of the ice-sheet retreat along broad north-south transects.

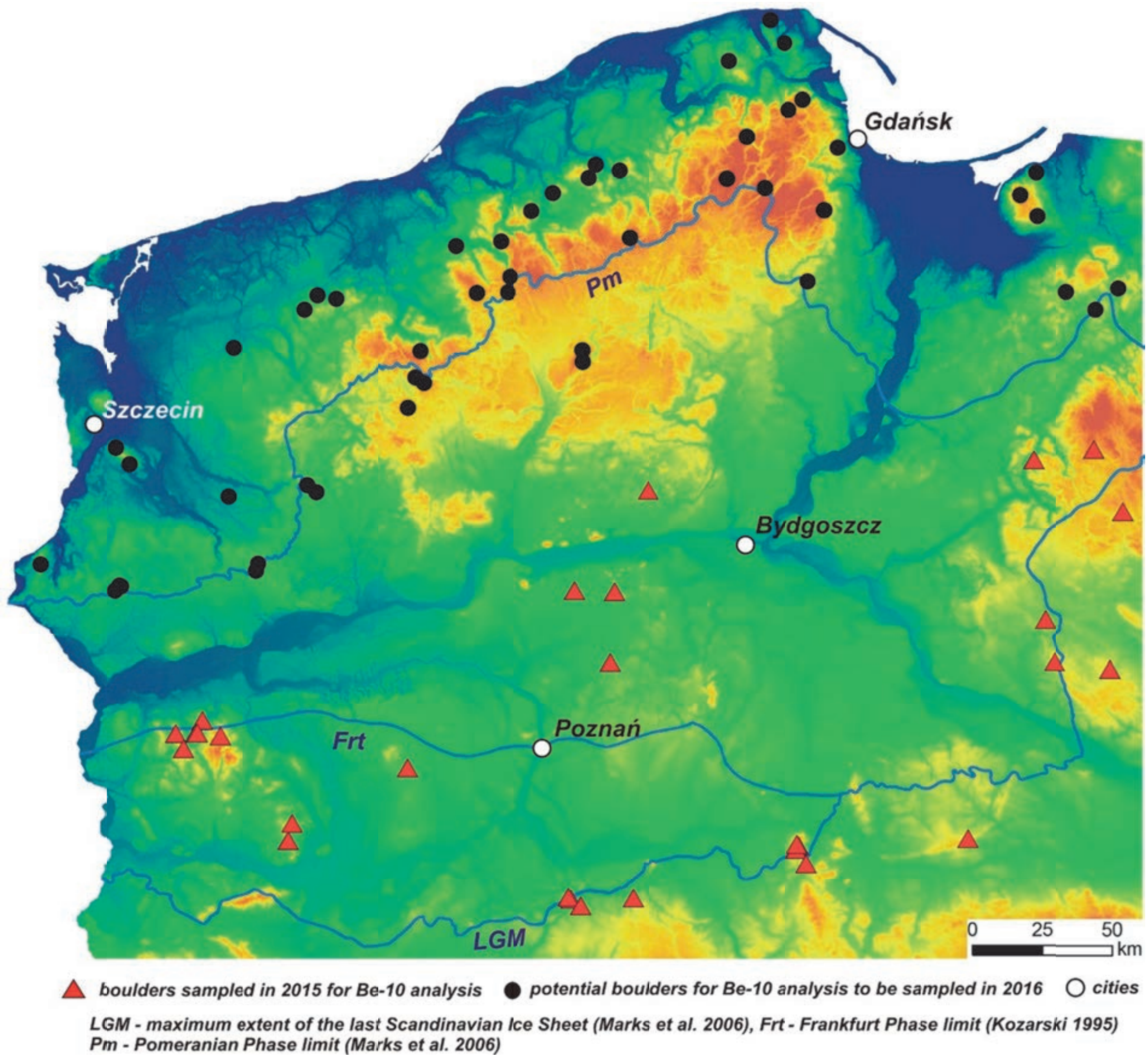

Figure 1. *Distribution of erratic boulders sampled in 2015 and potentially suitable for sampling in 2016.*

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Quantifying Soil Production and Transport Processes Using Cosmogenic Nuclides

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Abstract

Soil-covered upland landscapes comprise a critical part of the habitable world. Our understanding of how they evolve as a function of different climatic, tectonic, and geologic regimes is important across a wide range of disciplines and depends, in part, on understanding the links between chemical and physical weathering processes. Our extensive previous work showed that soil production rates decrease with increasing soil column thickness. Soil production rates also vary extensively with field location (Figure 1). Here I review how in situ produced cosmogenic nuclides (10-Be and 26-Al) can determine soil production rates, and, if appropriate for this meeting, show how we couple these measurements with several new methodologies to quantify the underlying material strength, weathered state, and chemical weathering rate. Specifically, we use measurements of the immobile element Zr in soils and saprolite with our rates of total denudation to determine chemical weathering rates. Major and trace element analyses, as well as measurements of pH, quantify the extent of weathering in the saprolite, while measurements of shear strength constrains the competence of the weathered bedrock underlying the soil mantle. In addition, we use the short-lived isotopes (210-Pb and 137-Cs) to quantify soil mixing and transport processes and rates. Also, if appropriate, I will present a summary of recent work using fallout derived 10-Be to quantify sediment transport rates and processes across two different field areas studied by other research groups. Results from this multi-pronged approach are extensive, but this presentation will be focused to show how a diverse set of field measurements can significantly improve our understanding of how soil mantled landscapes are evolving. Measuring concentrations of cosmogenic nuclides and interpreting those concentrations correctly underpin all of these field measurements. If time allows, I will also present some modeling work to quantify just how far off our interpretations can be if our underlying assumptions are incorrect. For example, quantifying soil production using in situ cosmogenic nuclides measured in the parent material beneath an upland soil mantle depends on assuming a locally steady state soil thickness (i.e. neither thinning or thickening with time). Similarly, utilizing hillslope-scale sediment traps or landscape-scale basin analyses depends on assumptions of steady state processes and constraining the timescales represented by the captured sediment. As our analyses of landscapes have expanded into the details of how spatial and temporal gradients of all driving variables (lithology, climate, tectonics, distribution of biota, etc.) influence hillslope evolution, our adherence to the assumptions and simplifications necessitated by our methods becomes questionable. I may synthesize recent work quantifying soil production and transport processes using a range of different methodologies to assess how well the governing assumptions have held up.

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Heimsath, A.M., DiBiase, R.A.*, and Whipple, K.X., 2012. Soil production limits and the transition to bedrock dominated landscapes. *Nature Geosciences*, **5**: 210-214.

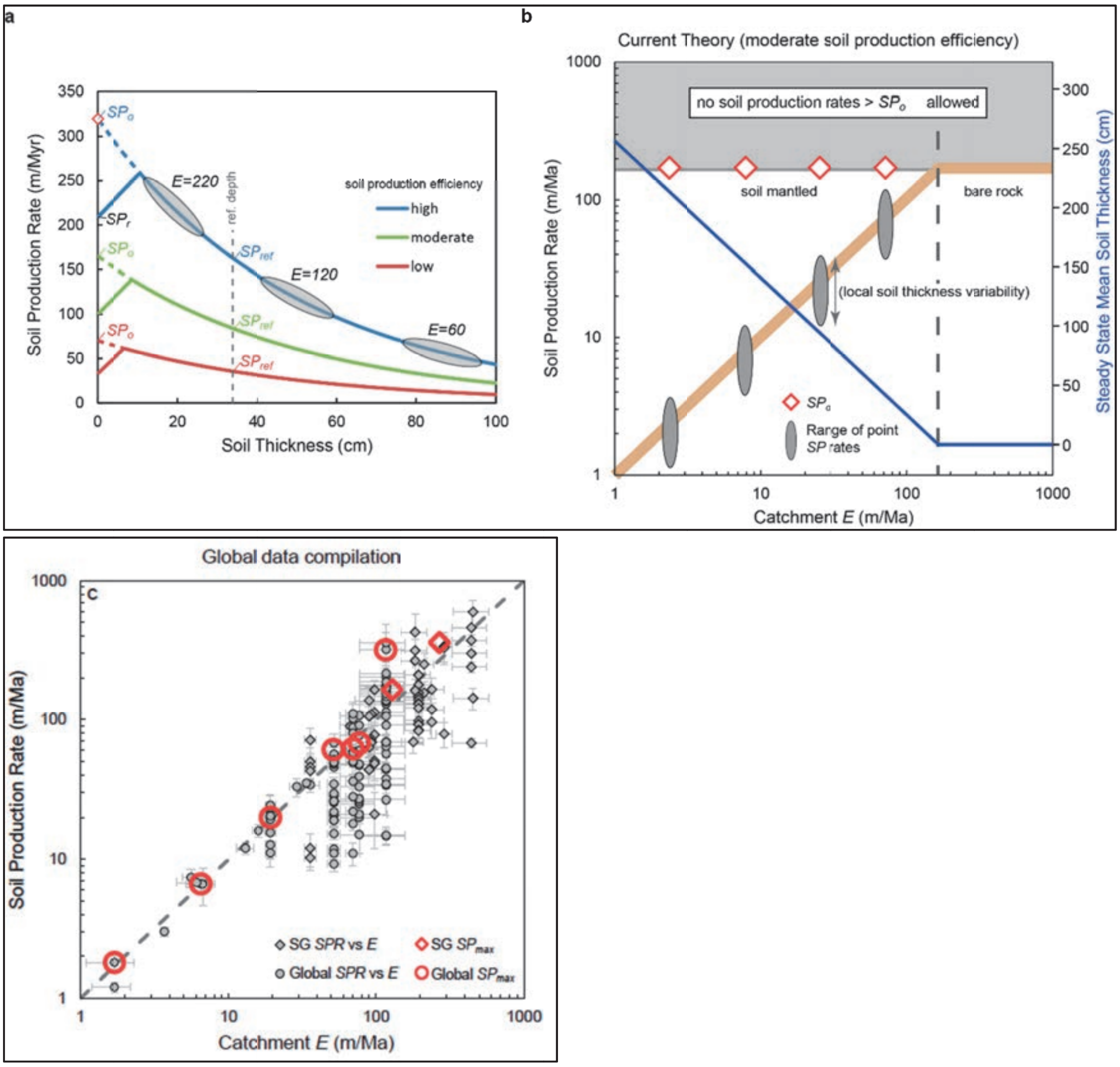

Figure 1. *Established theory, top, with global data, bottom.* ***A****. Illustration of humped and exponential soil production functions with range of soil production efficiencies, holding h* = 0.5m. SP_o, SP_r, and SP_{ref} are illustrated (SP_r , soil production of bare rock, only indicated for one case). Grey ovals show expected range of soil production rate and thickness for different erosion rates for constant SP_o for the high case.* ***B****. Illustration of previously well-established theory for the relations among soil production rate constant, SP_o, soil thickness, local soil production rates, and erosion rate. Soil Production rate (SP) is shown on the left axis (gray ovals are local measurements (analogous to ovals in* ***A****, data in* ***C****), red diamonds are SP_o values (moderate case from A), orange line is mean soil production rate. Steady-state mean soil thickness, h, is shown on the right axis (blue line). Vertical dashed line marks the predicted transition from soil-mantled to rocky landscapes at E = SP_o. Note that while local soil production rates must match the catchment-mean erosion rate at steady state (orange line), previous theory suggests no variation of SP_o with erosion rate if climate and rock properties are invariant (red diamonds).* ***C.*** *Global compilation of ^{10}Be-based soil production rates from studies also quantifying ^{10}Be catchment-averaged erosion rates. Black outlined grey symbols are individual point measurements, while red open symbols indicate SP_{max} where soil production function was quantified. Modified from Heimsath et al., 2012. Soil Production limits and the transition to bedrock dominated landscapes. Nature Geoscience.*

Evaluating the timing of former glacier expansions in the Tian Shan, Central Asia

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Abstract

Reconstructing the dynamics of past glaciation across Central Asia has over the past 10 years received an increased research interest because glacier change provides a proxy for past climate change. However, observed large scatter in ^{10}Be surface exposure data hampers the reconstruction of accurate glacial chronologies. The aim of this study is to evaluate new and existing ^{10}Be data from glacial moraines across the Tian Shan and to assess whether these can be used to provide robust glacial chronologies for regional correlation. In order to quantify the robustness of the dating control, we compile, recalculate, and perform statistical analyses on sets of ^{10}Be surface exposure ages from moraines. Our methodology includes; assessment of boulder age scatter, dividing boulder groups into quality classes and rejecting boulder groups of poor quality. This has allowed us to distinguish and correlate robustly dated glacier limits resulting in a more conservative chronology than advanced in previous publications. Our analysis shows that only one regional glacial stages can be reliably correlated across the Tian Shan marine oxygen isotope stage (MIS) 2 (15 - 28 ka) (Figure 1).

There exists, however, reliable glacial stages during MIS 3 (36 – 47 ka) in eastern Chinese Tian Shan and during MIS 5 (71 – 85 ka) in the central Kyrgyz Tian Shan (Figure 1). These are apparent exposure ages because we do not account for erosion. Paleoglacier extent during MIS 2 was mainly restricted to valley glaciation. Local deviations occur, for example in the central Kyrgyz Tian Shan where paleoglaciers were more extensive and formed a composite ice tongue filling the nearest depression, and we propose that the topographic context explains this pattern. Correlation between glacial stages prior to late MIS 2 is unreliable, because of the low number of samples and/or the poor resolution of the dating control. With the current resolution and spatial coverage of robustly-dated glacier limits we advise that paleoclimatic implications for the Tian Shan glacial chronology beyond MIS 2 should remain speculative and that continued work towards robust glacial chronologies is needed to resolve questions regarding drivers of past glaciation in the Tian Shan and Central Asia.

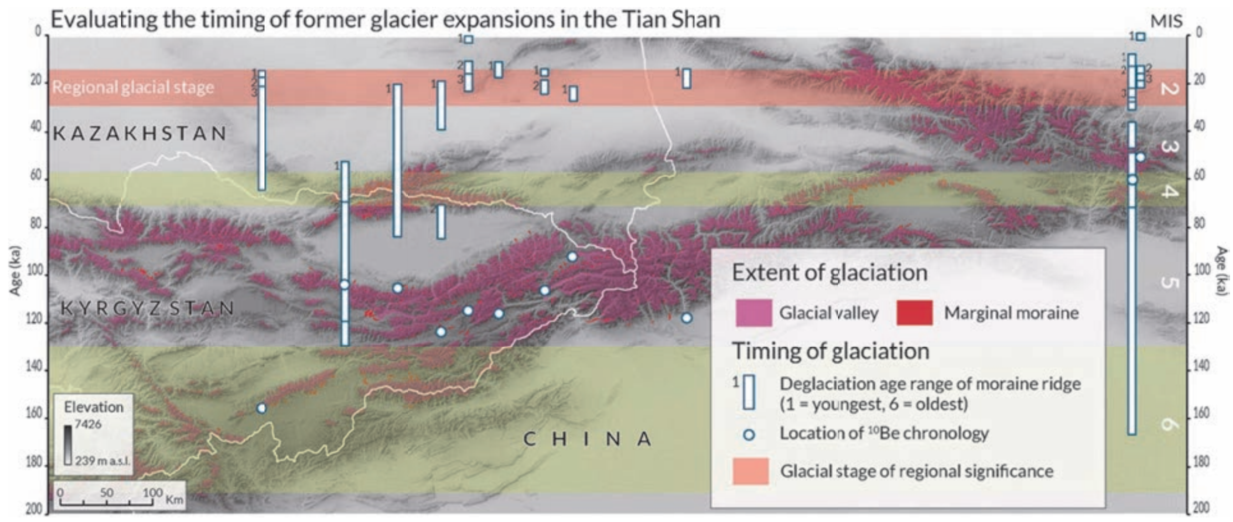

Figure 1. *Timing of former glacier expansions across the Tian Shan.*

Be-10 dating of boulders on moraines from the last glacial period in the Nyainqentanglha mountains, Tibet

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Abstract

Chronologies of glacial advances during the last glacial period in the Nyainqentanglha mountain range may provide constraints on the past climate in a transition zone of the Asian monsoon. We present 15 new ^{10}Be exposure ages from two moraines in the Payuwang valley, on the north slope of the range. The inner moraine has exposure ages ranging from 18.0±1.7 to 30.6±2.8 ka (n=10), with a mean age of 23.8±4.0 ka, corresponding to the global Last Glacial Maximum (LGM). The outer moraine yields exposure ages ranging from 18.0±1.6 to 39.9±3.7 ka (n=5). Evidence for weathering leads us to view the oldest age as a minimum age, placing moraine formation during MIS3. Chronologies from the last glacial period from south slope of the Nyainqentanglha support this interpretation. Thus, there appears to have been a local LGM (LLGM) during MIS3 and a more limited glacial advance during the global LGM. Glacial advances during MIS3 in the Nyainqentanglha may correlate with millennial- scale climate change (Heinrich events).

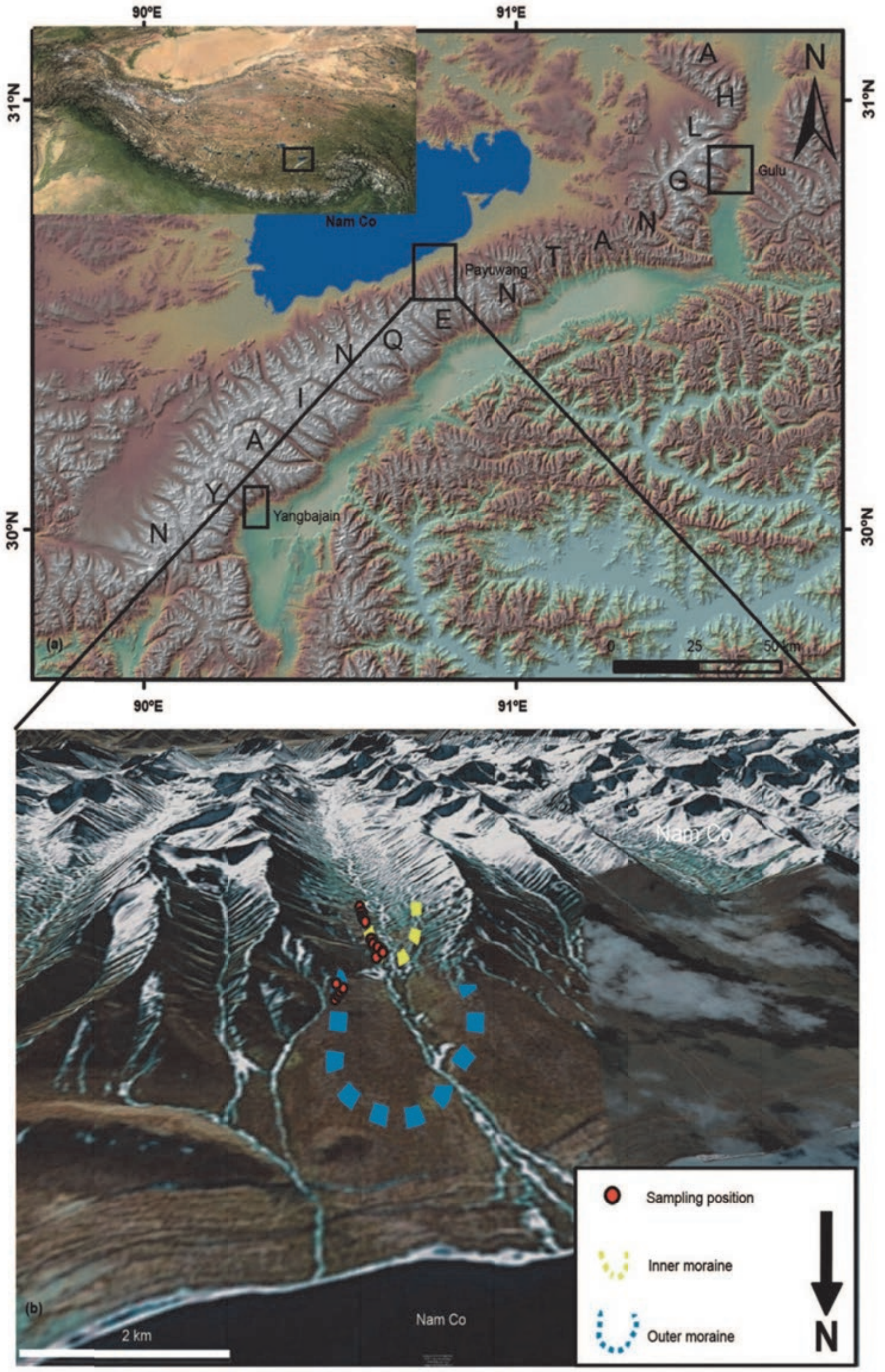

Figure 1. *Map showing study area. (a) ASTER DEM of the Nyainqentanghla mountains; (b) oblique Google Earth image.*

Cosmogenic dating and complex patterns of glacier advances during the Lateglacial in the Chagan-Uzun Valley, Russian Altai

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Abstract

Over the last decades, numerous paleoglacial reconstructions have been carried out in Central Asian mountain ranges because glaciers in this region are sensitive to climate change, and thus their associated glacial deposits can be used as proxies for paleoclimate inference. However, non-climatic factors can complicate the relationship between glacier fluctuation and climate change. Careful investigations of the geomorphological and sedimentological context are therefore required to understand the mechanisms behind glacier retreat and expansion.

In this study we present the first detailed paleoglacial reconstruction of the Chagan Uzun Valley, located in the Russian Altai. This reconstruction is based on detailed geomorphological mapping, sedimentological logging, and *in situ* cosmogenic ^{10}Be and ^{26}Al surface exposure dating of glacially transported boulders.

The Chagan Uzun Valley includes extensive lobate moraine belts (>100 km^2) deposited in the intramontane Chuja basin, reflecting a series of pronounced former glacial advances. Observation of "hillside-scale" folding and extensive faulting of pre-existing soft sediments within the outer moraine belts, together with the geomorphology, indicate that these moraine belts were formed during glacier-surge like events. In contrast, the inner (up-valley) glacial landforms of the Chagan Uzun valley indicate that they were deposited by temperate alpine glaciers at balance velocity during recessional phases. Cosmogenic ages associated with the outermost, innermost and intermediary stages, all indicate deposition times clustered around 19.2 ka, although the ^{10}Be ages of the outermost margin are likely slightly underestimated due to brief episode of glacial lake water coverage. Such close deposition timings are consistent with periods of fast or surge advances, followed by active glacier retreat.

This is the first study reporting surge-like behaviour of former glaciers in the Altai mountain range, supported by detailed geomorphological and sedimentological evidences. Such findings are crucial for paleoclimate inference, as the surge-related features cannot be attributed to a glacier system in equilibrium with the contemporary climate, and cannot be interpreted with traditional ELA reconstructions. This study also highlights the complexity of establishing robust paleoglacial chronologies in highly dynamic environments, with interactions between glacial events and the formation and drainage of lakes.

Rapid deglaciation of the last ice sheet in the Grampian Mountains, Scotland.

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Abstract

During the Pleistocene, ice sourced from the western Highlands of Scotland flowed down Strath Spey towards the Moray Firth. Towards the end of the last, Late Devensian glaciation, Strath Spey ice advanced on to the northern flanks of the Cairngorm Mountains and its maximum extent and subsequent withdrawal is marked by well-defined sequences of ice-marginal deposits and landforms (Figure 1). Further up-valley, Strath Spey ice was confluent with ice moving out of the main valleys and corries of the northern Cairngorms. Early unzipping of the two ice masses is recorded by ice-marginal meltwater channels, kame terraces and moraines found at 740-540 m O. D. between Glen More and Strath Nethy.

New cosmogenic ^{10}Be exposure ages are presented for boulders on large moraines. Discounting outliers, the ages indicate deglaciation of the flanks of the northern Cairngorms at 15.0 ± 0.6 ka. This timing matches closely existing age data for deglaciation at other sites along Strath Spey. The implication is that active ice retreat along a 50 km-long stretch of Strath Spey occurred rapidly and within the ~1 kyr uncertainty of the cosmogenic exposure ages. A major ice advance occurred at the end of Greenland Stadial 2a (GS-2a) (16.9-14.7 ka). Deglaciation probably began under cold conditions and continued after 14.7 ka during the rapid warming of the Windermere Interstadial.

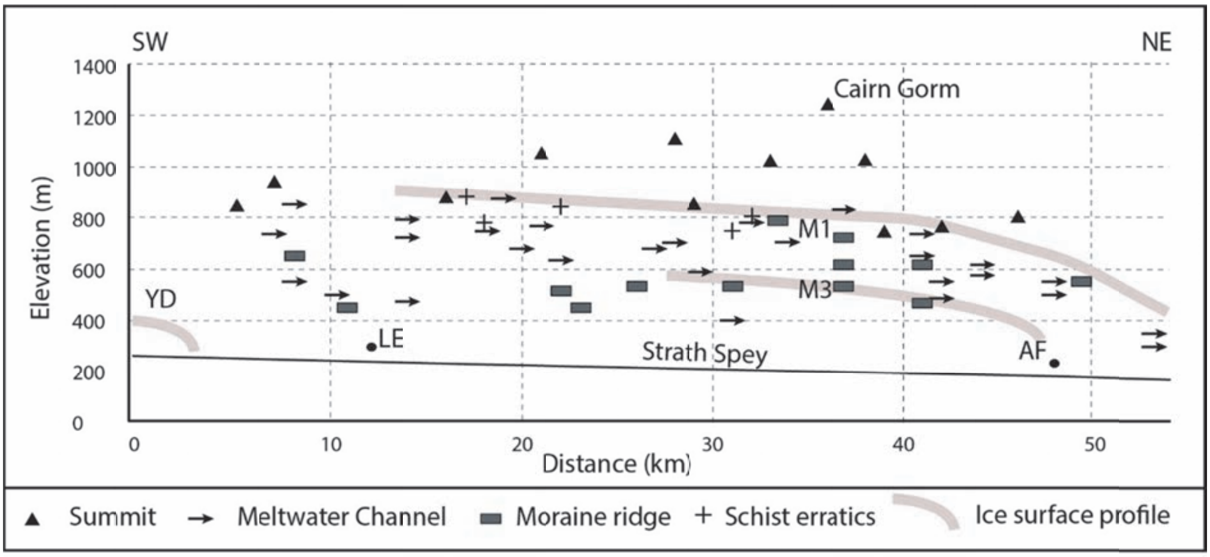

Figure 1. *Ice margins in Strath Spey, Scotland. M1 and M3 are ice limits marked by major moraines. LE Loch Etteridge. YD Younger Dryas.*

A global compilation of glacial ^{10}Be and ^{26}Al exposure age data

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Abstract

Cosmogenic dating of glacial landforms and deposits has become a key tool in paleoglaciology and it represents perhaps the most common usage of cosmogenic nuclide analysis within geosciences. Cosmogenic analysis has been used for defining the timing of past glaciations, constraining the amount of glacial erosion, and estimating durations of burial under non-erosive ice. The number of published glacial ^{10}Be and ^{26}Al measurements grew slowly during the 1990s, but has after year 2000 increased rapidly. Over the same time, there have been major development of methods for cosmogenic nuclide measurement and exposure age calculation, and an exposure age published some years back in time will often be different from the exposure age calculated today based on just the same data but using updated exposure age models. To enable smooth recalculation of glacial exposure ages and reuse of published data, I have compiled a global database of published glacial ^{10}Be and ^{26}Al exposure age data (Figure 1). The database contains necessary data for exposure age calculation for more than 10800 ^{10}Be measurements and more than 1600 ^{26}Al measurements (April 2016). The source of the data is recorded (e.g. corrected data mistakes) and all samples have been organized in groups representing distinct units (e.g. one moraine ridge). An analysis of the sample group exposure age clustering shows that a disturbingly large amount of the sample groups include scattered exposure ages that must be explained by prior and/or incomplete exposure. The time-span with the most well-clustered exposure age groups coincide with the last deglaciation post-dating the global LGM, and beyond 25-30 ka the fraction of well-clustered exposure age groups rapidly drops to very low numbers. Comparing boulder and bedrock exposure ages from the same locations, there is some overweight for younger boulders resting on older bedrock, indicating that bedrock samples are more prone to be affected by prior exposure and/or boulder samples more prone to be affected by incomplete exposure. Of the samples that have both ^{10}Be and ^{26}Al data, 53% have concentrations that coincide within uncertainties with a simple exposure history, 7% fall clearly in the forbidden zone (too high $^{26}Al/^{10}Be$ ratio), and 40% have a clear burial signal (reduced $^{26}Al/^{10}Be$ ratio). The data from Antarctica stick out with a large number of long exposure and long burial duration samples.

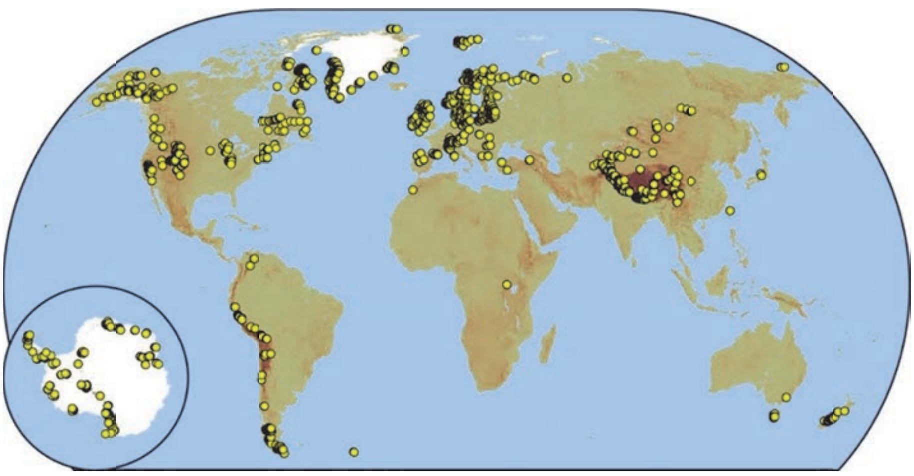

Figure 1. *Spatial distribution of glacial ^{10}Be and ^{26}Al samples in the global compilation.*

Quantifying the amount of glacial modification of inherited landscapes

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Abstract

The potential for inheritance of old landscapes despite repeated ice coverage has been recognized for over a century in both Scandinavia and the Canadian Arctic. The preservation of weathering features (e.g., tors) on dissected plateaus and the occurrence of disjunct species in formerly glaciated regions were often interpreted to indicate ice-free biological refugia and therefore minimal extents of ice sheets. However, TCN dating of erratics scattered on the plateaus reveal ice coverage as recent as the last glacial cycle (e.g., Corbett et al., 2016). Furthermore, the measurement of two radiogenic isotopes (e.g., ^{10}Be and ^{26}Al) in weathered bedrock surfaces indicate repeated ice coverage by predominately cold-based, weakly-erosive ice (e.g., Bierman et al., 1999), supporting a model of maximal ice coverage. The notion of cold-based ice, in which the glacier is frozen to its substrate—protecting, not eroding the regolith—enables preservation of old landscapes throughout multiple glaciations, although the amount of modification by subaerial weathering and limited subglacial erosion remains largely unknown.

By applying a two-isotope approach to adjacent but differentially weathered bedrock surfaces at the same tor, we are able to reconstruct the complex exposure and erosion history of upland plateaus on Cumberland Peninsula, Baffin Island, in the Eastern Canadian Arctic (Margreth et al., 2016). We sampled twelve tor sites at different elevations and from different topographic positions. High nuclide concentrations and high ^{26}Al/^{10}Be measured in two tors located on narrow, high-elevation ridges suggest ice-free conditions throughout the Quaternary and constrain the long-term steady subaerial erosion rate to 0.8-1.9 mm ka^{-1} (1σ range, Figure1a). Lower nuclide concentrations and ^{26}Al/^{10}Be of all other samples indicate repeated coverage by cold-based ice. A Monte Carlo approach, based on a proxy record of global ice volume, is used to constrain the complex exposure history and infer long-term rates of subglacial erosion. The results show that i) summits on broad interior plateaus were covered longer by cold-based ice causing the least modification (subglacial erosion rate of 0.5-6.4 mm ka^{-1}) owing to predominately divergent ice flow (Figure 1b), ii) ice cover duration decreases but subglacial erosion rates increase towards the edge of these plateaus (1.0-7.8 mm ka^{-1}) because of changes in ice dynamics at the slope break (Figure 1b), and iii) low-elevation, coastal plateaus experienced the greatest amount of glacial modification (2.0-10.8 mm ka^{-1}) yet the shortest ice duration, probably related to thickening of warm-based outlet glaciers in adjacent troughs (Figure 1c). The total average lowering rate of 2-18 mm ka^{-1} (combined subaerial and subglacial erosion) determined from the 20 TCN measurements is comparable with thermochronologically-derived long-term exhumation rates (7-20 m Ma^{-1}, McGregor et al., 2013) and denudation rates estimated from late Quaternary marine sedimentation rates (1.7 cm ka^{-1}, Aksu and Piper, 1987). Despite the lower erosion of plateaus relative to enhanced glacial erosion by warm-based ice in adjacent valleys and fjords, lowering of upland surfaces may have contributed up to 10% of the total Quaternary sediment flux. Our results indicate that plateaus were lowered by 5-50 m throughout the Quaternary, suggesting that the first order geomorphology of the plateaus may have been inherited from pre-Quaternary times and that glacial- and periglacial processes have had limited influence on highland surface development. Our results are relevant for the ongoing debate about the origin of the Scandinavian landscape (e.g., paleic surfaces and strandflat) and will assist in devising a strategy to establish the spatial and temporal variability of erosion processes and rates.

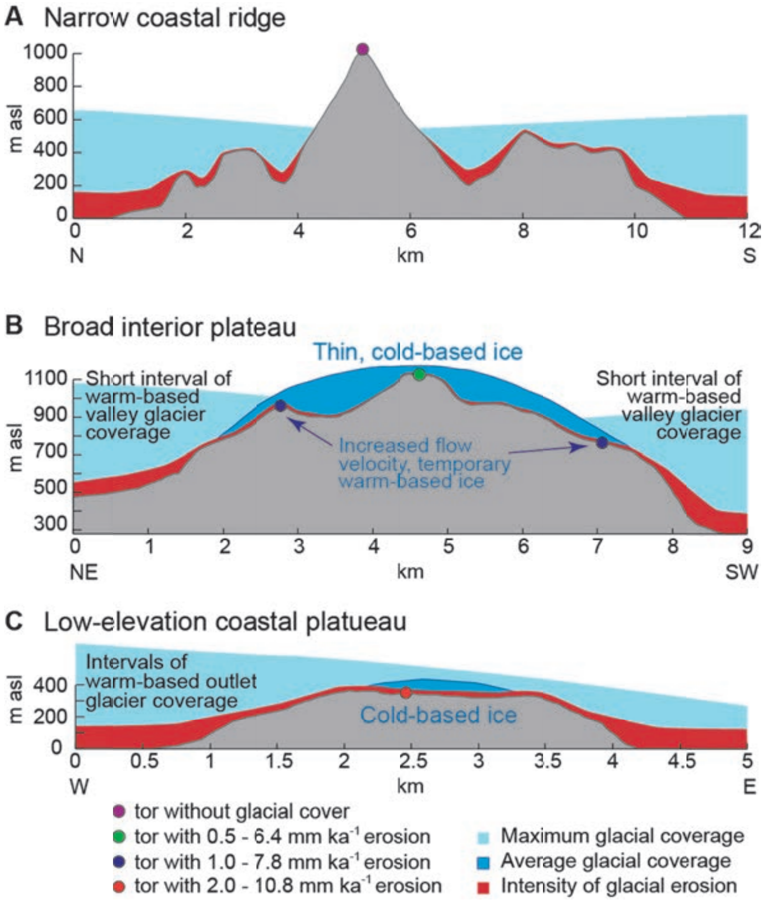

Figure 1. *Conceptual illustration of the intensity of glacial erosion (dark red) related to topographic location of tors. Elevation (vertical axis) is shown at the same scale, but horizontal axis is shown at different scales. A. tors at narrow coastal ridge remained likely above the vertical limit of maximum ice coverage. B. Broad interior plateau, where tors at the edge experienced more intense glacial erosion than tors at summits. C. Low-elevation coastal plateau, where tors are most intensely modified by glacial erosion.*

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Landscape preservation under ice? In-situ ^{10}Be and ^{26}Al from summit surfaces along Sognefjord, Norway

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Abstract

In-situ cosmogenic nuclides demonstrate existence of landforms preserved under glacial ice in regions such as Northern Sweden (Fabel, 2002), Svalbard (Gjermundsen, 2015) and New England (Bierman, 2015). Elsewhere, the existence of relict landforms is inferred from landscape morphology. Low-relief mountain summits along Sognefjorden in Norway have in the past been used as a base for re-constructing a regional pre-Quaternary surface (Nesje, 1994). The underlying assumption of this approach is that Quaternary surface processes eroded the summits very little, and the reconstructed surface can then be used to determine the total Quaternary bedrock erosion between the summits. However, the amount of Quaternary erosion of these summit flats remains debated (e.g. Steer, 2012)

Here, we present an extensive new dataset of in-situ produced cosmogenic ^{10}Be and ^{26}Al in bedrock and boulders from high and flat summits along a 200 km long transect from the coast to the inner parts of Sognefjorden. Our results indicate substantial glacial modification of the summits within the last 50 ka. Close to the coast, at an elevation of around 700 meters, the cosmogenic nuclide signal was reset around the Younger Dryas. Further inland, our results indicate very little cosmogenic nuclide inheritance prior to the last deglaciation. We do not find any signs of exceptional longevity of the low-relief landscape around Sognefjord. In contrast, our results indicate that the low-relief areas were continuously eroded by glacial and periglacial processes in the Quaternary, and that excluding recent erosion of the summits is likely to underestimate total Quaternary erosion.

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Constraining the detailed glacial history by inverse modelling of paired multiple cosmogenic nuclides

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Abstract

Constraining the landscape history and past erosion rates in previously glaciated terrains is notoriously difficult because it involves a large number of unknowns. It is therefore considered almost impossible to determine the timing and duration of ice-free intervals, prior to the last deglaciation. As very few deposits remain to bear witness of earlier interglacials, very little is known about the extent of the Greenland Ice Sheet (GIS) prior to LGM. Such knowledge about the extent of the GIS during earlier interglacial periods is essential in order to understand the complex relationship between climatic changes, growth/decay of the ice sheet, and changes in global sea level.

We recently published a novel multi-nuclide approach to study the landscape evolution and past erosion rates in terrains with a complex exposure history (Knudsen et al., 2015). This model approach, based on the Markov Chain Monte Carlo (MCMC) technique, focuses on mapping the range of landscape histories that are consistent with a given set of measured cosmogenic nuclide concentrations in areas repeatedly covered by glaciers or ice sheets during the Quaternary. A fundamental assumption of the model approach is that the exposure history at the site/location can be divided into two distinct regimes: i) interglacial periods characterized by zero shielding due to overlying ice and a uniform interglacial erosion rate, and ii) glacial periods characterized by 100 % shielding and a uniform glacial erosion rate. The exposure history in the model framework is incorporated by applying a threshold value to the global marine benthic $\delta^{18}O$ record, and this threshold value is included in the model as a free parameter, hereby simulating global changes in ice volume.

In this study, we use the new MCMC model approach to show that it may in fact be possible to extract valuable information about the timing and duration of earlier interglacial periods. For instance, it is not possible to determine the detailed exposure/burial history during Marine Isotope Stage (MIS) 5 by using paired $^{26}Al/^{10}Be$ data from the surface only. However, simulations with the MCMC model show that the inclusion of a few additional cosmogenic nuclides, such as ^{14}C and ^{21}Ne, and/or inclusion of a sample from a depth of 1 m below the surface make it possible to study the detailed exposure/burial history during MIS 5, and assess if the sample location was ice free or covered by ice during MIS 5a and 5c. Depending on the sampling strategy, it may also be possible to determine the timing of the last deglaciation event in those cases where this information cannot be obtained through other sources. The MCMC model approach may thus be used to tailor the sampling strategy to address specific scientific questions.

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Windows on erosion rates under polythermal ice in Fennoscandia via computational experiments with paired CNs

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Abstract

Cosmogenic nuclide (CN) abundances at Earth's surface reflect the balance of accumulation during intervals of cosmic-ray exposure and loss via erosion or radioactive decay. Yet for landscapes periodically covered by Quaternary ice masses this equation readily becomes complicated. Exploitation of CN inventories produced during exposure intervals prior to the last glaciation (viz, inheritance) has led to progress in understanding polythermal ice masses at high-latitudes. CN abundances on bedrock surfaces are a valuable clue to the spatial patterns and rates of subglacial erosion, and hence the history of subglacial thermal regimes. Bedrock surfaces with an exposure age that matches the timing of deglaciation are interpreted as having experienced >2-3 m of subglacial erosion. This implies the existence of warm-based ice with the capacity to remove all prior CN inheritance. Conversely, significant CN inheritance indicates minimal subglacial erosion and implies the development of frozen-bed patches beneath the ice sheet. Comparison of 310 'apparent ^{10}Be exposure ages' to a recently published deglaciation chronology of Fennoscandia reveals that 58 % of sampled bedrock surfaces contain appreciable (>2σ) CN inheritance.

With the aim of extracting deeper landscape history information from inherited CN inventories, we devised a Markov Chain Monte Carlo (MCMC) inverse approach that matches present-day CN (^{10}Be and ^{26}Al) abundances with the most probable permutation of exposure history and erosion rates over multiple glacial and interglacial periods. Shifts in ice cover over successive glacial cycles are simulated via a free parameter threshold applied to a benthic δ^{18}O record. The MCMC model yields two key outputs integrated over the last one million years: mean denudation rate and total exposure time. In addition, we propose a new quantitative measure of surface exposure and erosion termed the '^{10}Be-memory', defined as the time after which 95% of the present-day ^{10}Be atoms were produced. The ^{10}Be-memory is effectively year zero for landscape histories recorded by ^{10}Be. We apply the MCMC model to a subset (n=26) of Fennoscandian data for which ^{10}Be-^{26}Al paired measurements are available for five bedrock landform types: tors, mountain blockfields, ice-carved valleys, ice-carved lowlands, and fluvial channels.

Mean denudation rates (±1σ) on lowland tors (4.3±1.3 m/Myr, n=6) and mountain blockfields (5.8±2.8 m/Myr, n=5) are tightly clustered and overlap at 1-sigma. Erosion of ice-carved valleys, on the other hand, varies widely: one subgroup (5.9±3.4 m/Myr, n=4) is eroding equally slowly as tors and blockfields, and another includes more recently eroded troughs (20±7 m/Myr, n=5) plus one outlier (~105 m/Myr). Erosion rates on ice-carved lowlands fall roughly midway between the two subgroups of valley troughs (11.4±4.0, n=4), plus an outlier (~62 m/Myr) that matches the fluvial channel site (~68 m/Myr). The 10Be-memory predates the last deglaciation at all sites and reaches back nearly 3 million years for some tors, blockfields, and ice-carved landforms. Total exposure times are the least well constrained of the model outputs (262–424 kyr, Q1–3, n=26) and suggest that about one-third of the last one million years was ice-free in Fennoscandia.

Despite their clearly disparate origins, lowland tors, mountain blockfields, and several ice-carved valleys in our dataset have remarkably similar histories of exposure and erosion over the last one million years. This leads us to speculate that the erosion dynamics at these sites differed markedly prior to the Mid-Pleistocene transition. The MCMC inverse approach is a useful tool for extracting landscape histories from the inherited CNs that are ubiquitous in Fennoscandia. We reflect on the opportunities offered by this new tool and discuss implications of our findings for the interpretation of bedrock landscapes at high-latitudes.

Arctic investigations of boulders and bedrock surfaces preserved beneath non-erosive glacial ice using paired ^{10}Be and ^{26}Al analyses

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Abstract

Landscapes preserved beneath cold-based, non-erosive glacial ice violate assumptions associated with simple cosmogenic exposure dating. Because bedrock surfaces and boulders plucked from those surfaces are not deeply eroded during glaciation, they contain nuclides from previous periods of exposure. Analyses of cosmogenic nuclides in samples with complex exposure/burial histories yield simple exposure ages that are older than expected and complex age distributions; hence, alternate approaches are required to constrain the multi-stage histories of samples from such landscapes. To study the exposure and burial history of long-preserved landscapes in the Arctic, we employed paired analysis of ^{10}Be and ^{26}Al in three locations: Upernavik, central-western Greenland; Thule, northwestern Greenland; and Cumberland Sound, southern Baffin Island, Canada. We assess our data using two-phase exposure/burial models, multi-phase forward models, and Monte Carlo simulations to constrain uncertainties.

Bedrock surfaces, sampled at two sites, exhibit evidence of long-lived subaerial weathering and have simple 10Be exposure ages up to 104 ka in Upernavik and 160 ka on Baffin Island. Simple exposure ages tend to increase with elevation, suggesting more effective erosion in the fjords and longer-term preservation of the uplands. Minimum-limiting total histories calculated with ^{26}Al/^{10}Be range up to 1 My in Upernavik and several My on Baffin Island, with periods of exposure representing ~20% of the total history. High-elevation bedrock surfaces at both sites indicate long-lived preservation by cold-based ice over numerous glacial/interglacial cycles.

Boulders, sampled at all three sites, also contain nuclides from previous periods of exposure, presumably because they were plucked from subglacially-preserved bedrock surfaces and/or recycled through different generations of till. Simple 10Be exposure ages of boulder samples are up to 46 ka in Upernavik, 78 ka in Thule, and 79 ka on Baffin Island, and yield multi-modal age distributions. Simple exposure ages of boulders tend to under-estimate bedrock ages in the cases of paired bedrock/boulder samples. Minimum-limiting total histories calculated with 26Al/10Be range up to 600 ky in Upernavik, 700 ky in Thule, and several My on Baffin Island, with periods of exposure representing only a small portion of the total history. Forward numerical models suggest that boulders have been repeatedly reworked, likely experiencing partial or complete shielding during interglacial periods because of rotation and/or burial by till.

The landscapes we assess here preserve histories of hundreds of thousands to millions of years, and represent a complex interplay of interglacial exposure, subglacial preservation beneath cold-based ice, periglacial processes, and subaerial weathering. Although such landscapes represent methodological challenges, they contain valuable information about long-term variations in glacial extent and climate.

Isochron-burial dating in glacial landscapes

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# Abstract

The isochron-burial dating technique has been introduced within the last decade to interpret the chronostratigraphy of ca. 0.1 to 5.0 Ma old terrestrial deposits (Balco and Rovey, 2008; Erlanger et al., 2012; Balco et al., 2013; Çiner et al., 2015; Bender et al., 2016). Isochron-burial dating is a variation on traditional burial dating methods which uses the difference in the ^{10}Be and ^{26}Al half-lives to determine an age. Isochron-burial dating uses the ^{26}Al/^{10}Be surface production ratio at the time of burial and the ^{26}Al/^{10}Be ratio measured in buried sediment in order to determine sediment burial time (e.g., Granger, 2006). While the more conventional burial dating technology is based on the following preconditions: (i) the exposure history prior to burial is simple and long enough to attain steady state nuclide concentrations, and (ii) that post-burial nuclide production did not occur (i.e., the sediment is buried too deep), isochron-burial dating removes the need for these assumptions. It uses ^{10}Be and ^{26}Al concentrations in quartz bearing cobbles or sediment (sand or >50 pebbles) from the same stratigraphic horizon. Ideally, such samples would have the same post-burial history but different pre-burial histories (e.g., catchment/source areas, distance, transport, reworking). Different pre-burial histories yield different inherited nuclide concentrations and thus enable modeling of the post-burial component. The value of the initial isochron line (i.e., ^{26}Al/^{10}Be ratio at the time of burial) must be assumed. The isochron-burial age can then be calculated using initial and measured ratios. As isochron-burial dating is independent of burial depth, post-burial exposure, and erosional modification of the top surface of the deposit, it can be applied to naturally outcropping, relatively thin (ca. 2m) quartz-bearing terrestrial deposits (Balco and Rovey, 2008; Erlanger et al., 2012; Balco et al., 2013; Çiner et al., 2015; Bender et al., 2016).

Inherited nuclide concentrations of the clasts are key components when using the isochron-burial dating approach. Sediments derived from repeatedly glaciated landscapes, such as the Alps, may contain low amounts of ^{10}Be and ^{26}Al due to continuous and deep glacial erosion (e.g., Delunel et al., 2014). In this context, the Deckenschotter, which are the oldest Quaternary units in the northern Swiss Alpine Foreland, thought to have been formed both by rivers proximal to the glaciers and the glaciers themselves, are a good candidate for testing the isochron-burial dating method in glacial landscapes. Therefore, we focus, in this study, on the isochron-burial dating of one 0.5 m thick gravel bed at Siglistorf (Canton Aargau) (Akçar et al., submitted). Analysis of 22 clasts of different lithology, shape, and size indicates low nuclide concentrations: <20000 10Be atoms/g and <150000 26Al atoms/g. Using the 26Al/10Be ratio we calculate an isochron-burial age of around 2 Ma. Our results indicate that isochron-burial dating can be successfully applied to glaciofluvial sediments despite very low cosmogenic nuclide concentrations.

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Advances in Quaternary Geochronology: Examples from combined *in situ* cosmogenic ^{14}C-^{10}Be analysis

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Abstract

Combining two cosmogenic nuclides of different half-lives provides a valuable approach to resolve and quantify complex exposure histories in Quaternary Geochronology and Earth surface process dating. While the ^{26}Al-^{10}Be nuclide ratio is frequently applied for burial dating, the long half-lives of both nuclides set the datable age range to a few 105 to few 106 years. To study younger chronologies, the in situ cosmogenic ^{14}C isotope is particularly useful as its short half-life makes it sensitive to signals in the 102 to 104 years' time range. Although the number of applications of in situ ^{14}C is slowly increasing, its analysis has so far been limited due to the challenging and elaborate procedure of extracting in situ ^{14}C from quartz.

With its fast adaptation to geomorphological changes provoked, e.g., by changes in climate, tectonics or human activity, in situ ^{14}C is especially suited to reconstruct post-LGM chronologies of glacier decay and readvance. Unravelling complex glacial chronologies has therefore been the main focus of most studies using in situ ^{14}C in combination with the ^{10}Be (and ^{26}Al). Examples for the application of combined in situ ^{14}C-^{10}Be analysis in the context of late Pleistocene deglaciation and the identification of Holocene surface shielding will be presented at the meeting (Fogwill et al., 2014; Hippe et al., 2014).

Further, not yet much explored applications of in situ ^{14}C arise in the field of quantitative geomorphology. In sedimentary fluvial systems, combined in situ ^{14}C-^{10}Be analysis allows to investigate both sediment input rates and sediment transfer times concurrently. With the long-lived 10Be providing reliable long-term estimates of sediment production by hillslope erosion, in situ ^{14}C can be used to detect episodes of intermittent sediment storage and to determine the pathways and transit times of sediment through a basin (Figure 1). Preliminary results from ongoing research will be presented together with a critical evaluation of potential difficulties/limitations in the general applicability of in situ ^{14}C in sedimentary geology.

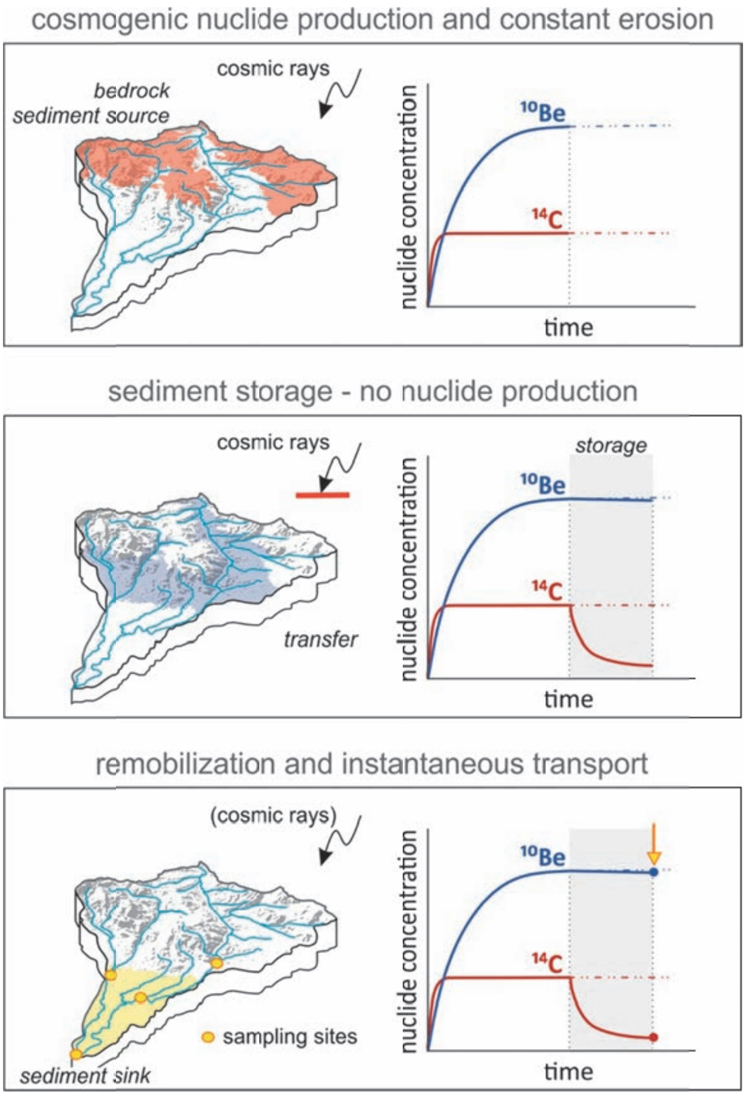

Figure 1. *Concept of using combined in situ ^{14}C-^{10}Be analysis in fluvial sediments to constrain sediment storage times from the offset in the in situ ^{14}C concentration.*

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A multi-nuclide approach to quantify long-term erosion rates and exposure history through multiple glacial-interglacial cycles

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Abstract

Cosmogenic nuclides are traditionally used to either determine the glaciation history or the denudation history of the most recent exposure period. A few studies use the cosmogenic nuclides to determine the cumulative exposure and burial durations of a sample. However, until now it has not been possible to resolve the complex pattern of exposure history under a fluctuating ice sheet. In this study, we quantify long-term erosion rates along with durations of multiple exposure periods in West Greenland by applying a novel Markov Chain Monte Carlo (MCMC) inversion approach to existing ^{10}Be and ^{26}Al.

The new MCMC approach allows us to constrain the most likely landscape history based on comparisons between simulated and measured cosmogenic nuclide concentrations. It is a fundamental assumption of the model that the exposure history at the site/location can be divided into two distinct regimes: i) interglacial periods characterized by zero shielding due to overlying ice and a uniform interglacial erosion rate, and ii) glacial periods characterized by 100 % shielding and a uniform glacial erosion rate. We incorporate the exposure/burial history in the model framework by applying a threshold value to the global marine benthic d^{18}O record and include the threshold value as a free model parameter, hereby taking into account global changes in climate. The other free parameters include the glacial and interglacial erosion rates as well as the timing of the Holocene deglaciation. The model essentially simulates numerous different landscape scenarios based on these four parameters and zooms in on the most plausible combination of model parameters.

We apply the MCMC-model to the concentrations of ^{10}Be and ^{26}Al measured in previously published studies from Upernavik, Uummannaq and Sisimiut and quantify the most likely exposure/burial history integrated with erosion rates. Our results show a clear trend of decreasing erosion rate with increasing altitude, with a lowest total denudation rate of 1.7±0.2 m/Ma at 841 m a.s.l. and the highest rate of 25.6 ± 10.4 m/Ma at 150 m a.s.l. We find that the three areas have been exposed during 17 previous interglacials and quantify the most likely temporal extent of each of these, which enables us to reconstruct the ice margin fluctuation across the West Greenland fjord area throughout the last 1 million years. Our results contribute to understanding the landscape evolution under multiple glacial-interglacial cycles and provide a temporal framework for the sparse pre-LGM data that has been found, but have proven difficult to constrain in time.

Field guide to the site of the planned deep repository for spent nuclear fuel at Forsmark

Nordic workshop on cosmogenic isotopes, June 11, 2016

An overview of power generation at Forsmark, planned long-term storage of spent nuclear fuel, geological background, and selected field sites for erosion rate measurements using cosmogenic nuclides

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Fieldtrip schedule

- Bus transport will be provided and we will depart at 9:30 am from Frescatihallen (Figure 1).
- The trip from Stockholm University to the Forsmark site is about 140 km and will take about 2 hours (Figure 1).
- A packed lunch and cold drinks will be provided and we will make a refreshment stop along the way, where coffee can be purchased.
- To access the site we will pass through a security gate. Please bring your photo ID (passport, Swedish driver's license).
- We will be given an introduction to the Forsmark site by two guides from SKB.
- We will only be walking short distances off-road. The terrain is low relief (some meters) but it may be wet underfoot. Please take appropriate footwear and remember your rain jackets.
- We will tour a selection of field sites where long term erosion rates are being measured using cosmogenic nuclides as part of the SKB-funded project: *Long-Term Safety Assessment Of A Planned Deep Repository For Spent Nuclear Fuel In Forsmark, Sweden: Impact Of Glacial Erosion Over The Next 0.1-1.0 Myr.* We will also visit some other localities at Forsmark to look and hear about SKB:s activities at the site.
- We will return to Stockholm late-afternoon. Those of you who have indicated that they need an early return to Arlanda will depart separately and be taken directly to the airport.

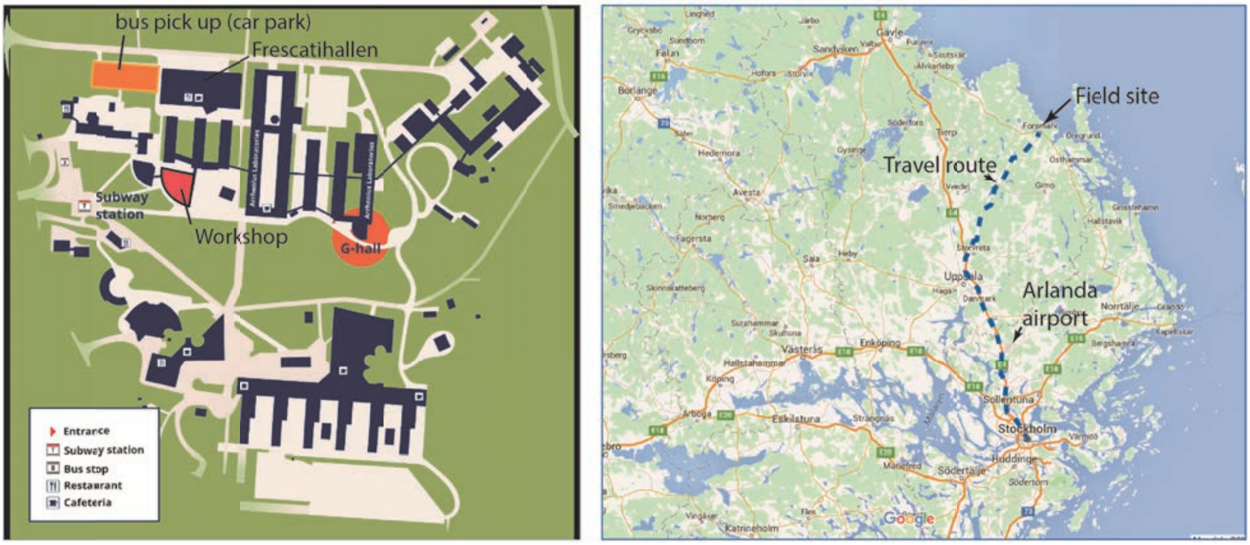

Figure 1: *General maps showing the excursion pick up location in the Frescatihallen carpark (left panel) and the excursion site relative to Stockholm and Arlanda Airport (right panel). The travel route is also shown.*

Introduction

Nuclear power generation at Forsmark

The Forsmark nuclear power plant site is operated by a subsidiary of Vattenfall and contains three boiling water reactors, which generate 20-35 billion kilowatt-hours of electricity a year. This is sufficient to meet one-sixth of Sweden's annual electricity demand. The three reactors have been operational since 1980, 1981, and 1985, and Forsmark is one of three remaining nuclear reactors sites in Sweden. The other two are located at Oskarshamn, south of Stockholm (three reactors) and at Ringhals, south of Gothenburg (four reactors). A fourth site, located at Barseback in southern-most Sweden, was closed for decommissioning between 1999 and 2005. Nuclear power generation in Sweden is almost equal in output to hydropower, the most abundant source. On April 27 1986, Forsmark was the first place outside of the former Soviet Union to detect the Chernobyl accident, forcing the Soviet government to publicly acknowledge it after almost a day after the accident.

Storage of radioactive waste

The Swedish Nuclear Fuel and Waste Management Company (SKB) is tasked with handling all the radioactive waste from nuclear power plants, research facilities, hospitals etc in Sweden in a safe way. At present, SKB operates a Final Repository for Short-Lived Radioactive Waste (SFR) at Forsmark and a Central Interim Storage Facility for Spent Nuclear Fuel (Clab) in Oskarshamn. Transport of radioactive waste from the nuclear power plants to Oskarshamn is done by ship, the M/S Sigrid.

In addition, since the 1970s, SKB has undertaken extensive research to develop a method, the KBS-3 method, to securely store spent nuclear fuel safely over a 10^5–10^6 year timescale. From this research, it has been decided that the spent fuel will be encased in copper canisters embedded in bentonite clay in tunnels excavated in granitic/gneissic bedrock about 450 meters beneath the ground surface at Forsmark (Figure 2). The overall safety concept of the KBS-3 method is total containment of the radionuclides within the repository over a time period of 100 ka up to 1 Ma.

(i) Copper canisters

The copper canisters will have cast iron inserts for strength. They are five meters long and each capsule will weigh about 25 tons when it is filled with spent nuclear fuel. The outer casing consists of five-centimeter-thick copper. The canisters have in this way been constructed to withstand corrosion and mechanical forces from the surrounding geological and hydrological environment, including the effect of future glaciations.

(ii) Buffer

The copper canisters will be embedded in bentonite (a clay mineral, specifically a type of smectite that expands upon hydration) in the drilled deposition holes. Also the deposition tunnels of the repository will be filled with bentonite clay. The bentonite will protect the canister from ground water flow and associated corrosion, and act as a buffer protecting the canister from minor bedrock displacements. After deposition, the clay buffer will gradually absorb water and swell to fill the space around it and adjacent bedrock fractures.

(iii) Bedrock

The outermost barrier consists of the sparsely-fractured granitic/gneissic bedrock, which provides a stable chemical environment and protects the canisters from subaerial processes, such as chemical weathering. The proposed 450 m depth of the repository would also help minimize the risk from any potential leakage of radionuclides from a malfunctioning repository.

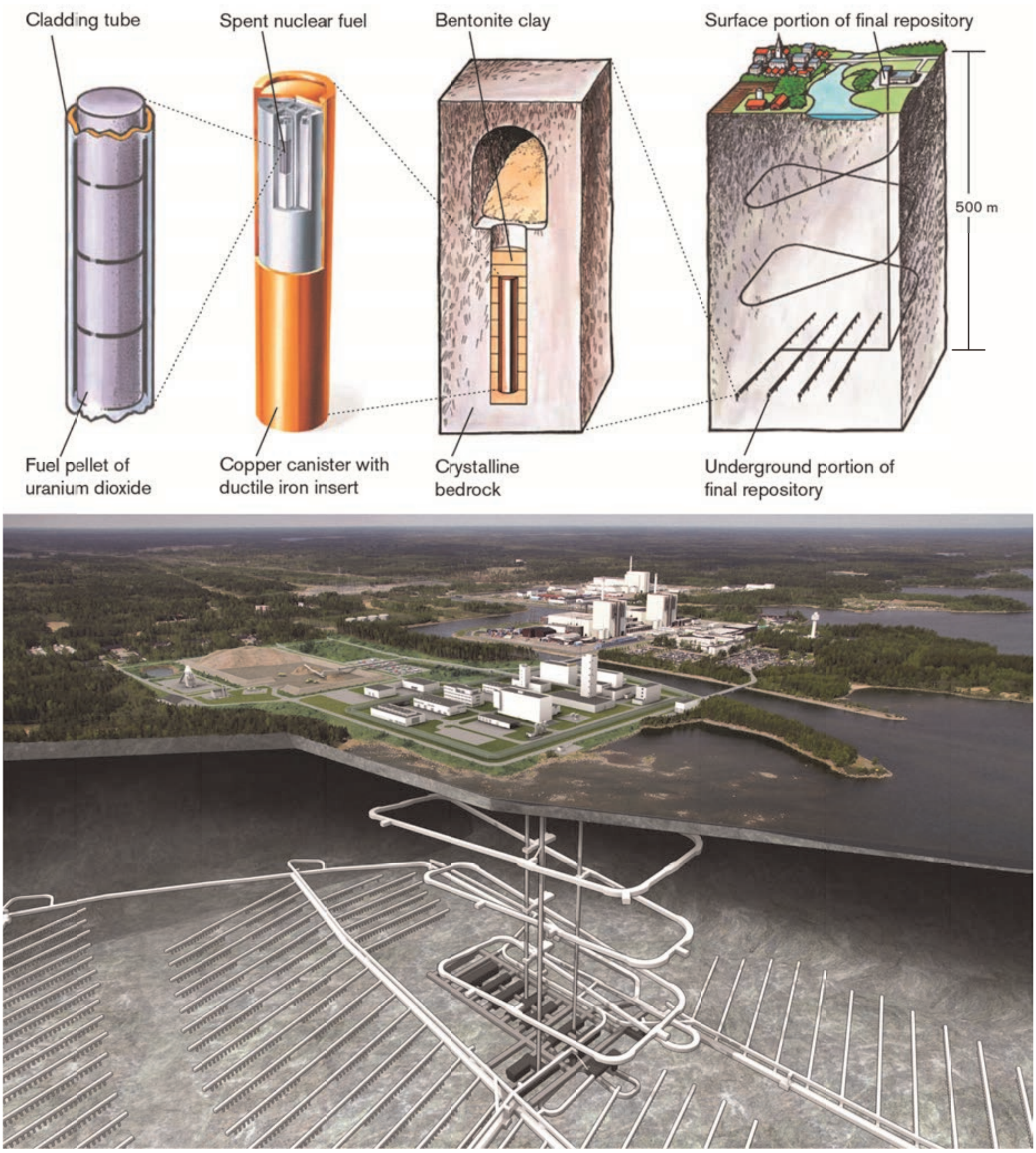

Figure 2: *Proposed long- term storage system for radioactive waste. Top panel: The KBS-3 concept for storage of spent nuclear fuel. Bottom panel: Schematic map for the proposed nuclear waste repository at Forsmark.*

(iv) Long-term safety

The radiation authority requirement is that the annual risk for humans, in terms of getting cancer or other similar health issues, from the repository for spent nuclear fuel must not exceed one per one million for a representative individual of the group exposed to the largest risk. This corresponds to around one per cent of the corresponding risk from the natural background radiation. To meet this necessarily stringent risk criteria, the safety assessments completed by SKB and its consultants comprise modelling of expected geological and environmental conditions over the next 10^5–10^6 years at the location for the planned repository in Forsmark. In this assessment, one aspect is to look at the most extreme impact that the repository barriers (bedrock, bentonite, and copper canisters) may be exposed to in the future. These analyses include the potential effects of short and long-term climate change, i.e. the growth and melting of permafrost, ice sheet growth and decay (including glacially induced faulting), climate warming due to anthropogenic activity, sea-level change, and surface denudation. The effect of these processes on, for example, ground water flow and chemistry, bedrock stability and faulting, repository barrier integrity, surface biosphere development and land use etc., all need to be part of the integrated safety assessment. In 2011, SKB submitted a license application for building the repository for spent nuclear fuel at Forsmark, with the so-called SR-Site safety assessment demonstrating long-term repository safety. Ongoing research at SKB, such as the present study on bedrock stability and glacial erosion at Forsmark, are conducted partly to update that safety assessment for the next steps in the process towards a final repository for spent nuclear fuel in Sweden. Construction of the repository for spent nuclear fuel at Forsmark is planned to begin, following a referendum and government approval, in the early 2020s.

Geological background

Forsmark is located ~120 km north of Stockholm within a landscape of low elevation and relief (local relief is up to a few tens of meters). Unconsolidated Quaternary glacial and post-glacial deposits overlie granitic-gneissic bedrock of the Fennoscandian Shield. The Forsmark landscape comprises part of an unconformity labeled the sub-Cambrian peneplain (e.g. Lidmar-Bergström, 1994) and is situated within the region of ~1.8 – 1.9 Ga Svecokarelian orogen (Figure 3a; Koistinen *et al.*, 2001). The continental crust thickness in the Forsmark area is ~50 km (Stephens, 2010). Neoproterozoic and Phanerozoic sedimentary cover rocks of the East European Platform are located nearby, beneath the Baltic Sea, and the Caledonian nappes are located to the north-west. The tectonic domain of Svecokarelian orogen in which Forsmark is located contains broad belts of rocks that have been affected by strong ductile deformation under amphibolite-facies metamorphic conditions (Figure 3b–c; Koistinen *et al.*, 2001; Stephens *et al.*, 2007; Stephens, 2010). These ductile high-strain belts have a subvertical dip and strike approximately WNW−ESE to NW−SE. They anastomose around tectonic lenses in which the bedrock is commonly folded and are generally affected by lower ductile strain (Figure 3c; Stephens *et al.*, 2007; Stephens, 2010). The high strain belts also contain retrograde deformation zones formed in both the ductile and brittle regimes (Figure 3c; Stephens *et al.*, 2007; Stephens, 2010). The overall structural character of the bedrock is strongly anisotropic. The site at Forsmark targeted for the disposal of highly radioactive spent nuclear fuel is situated in one of the tectonic lenses (Figure 3c; Stephens *et al.*, 2007; Stephens, 2010).

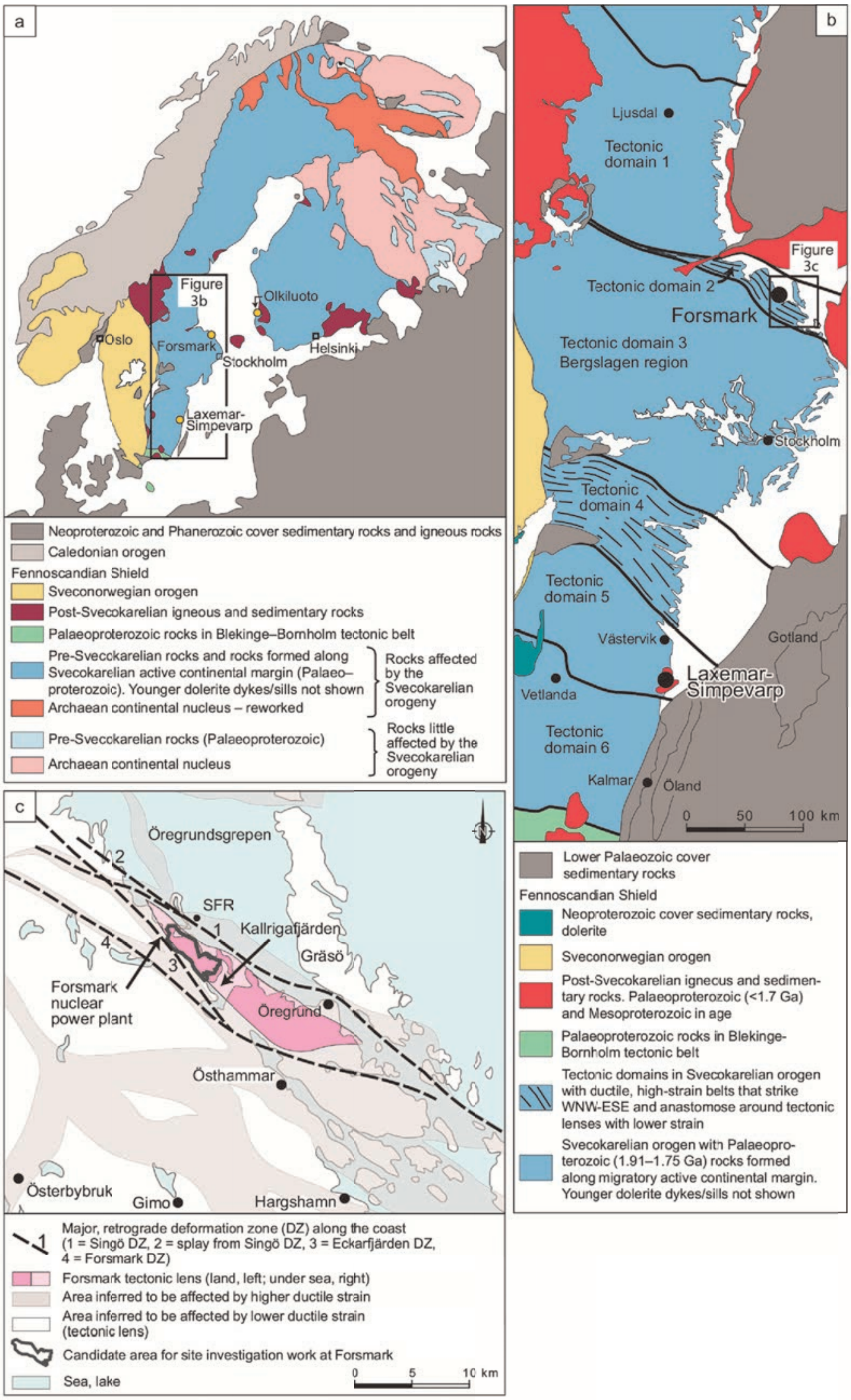

Figure 3: *Regional geological setting of Forsmark. (a) Major tectonic units in Scandinavia (modified from Koistinen et al., 2001 and Stephens, 2010). The locations of Forsmark as well as the corresponding proposed Finnish repository site at Olkiluoto are shown on the map. (b) Svecokarelian tectonic domains and post-Svecokarelian rock units in the south-western part of the Fennoscandian Shield, south-eastern Sweden (modified from Koistinen et al., 2001 and Stephens, 2010). (c) Inferred high-strain belts and tectonic lenses, including the Forsmark tectonic lens, in the area close to Forsmark, all situated along a coastal deformation belt in the northern part of Uppland, Sweden (modified from Stephens et al., 2007 and Stephens, 2010).*

Evaluating past glacial erosion using cosmogenic analysis

With cosmogenic nuclide production in the upper few meters of Earth's surface, the concentration of cosmogenic nuclides can potentially help constraining past glacial erosion rates. If the total depth of erosion during a period of glacial coverage is less than 2-3 m, the amount of cosmogenic nuclides produced (at depth) before the last glaciation may be large enough to be detected in samples collected from present-day bedrock surfaces. A prerequisite for this analysis is that we know the amount of post-glacial cosmogenic production so that we can subtract the concentration expected from a simple one period post-glacial exposure from the concentration measured in a sample. With the recent reconstructions (Hughes *et al.*, 2016; Stroeven *et al.*, in press) for the deglaciation of the Fennoscandian Ice Sheet (FIS) we have a good idea of the timing of deglaciation that can be used to quantify the amount of cosmogenic nuclides inherited from exposure prior to the last period of glaciation.

Comparing existing zero erosion ^{10}Be exposure ages from Fennoscandian bedrock surfaces with the FIS deglaciation ages (Stroeven *et al.*, in press), more than half of the samples have recognizable inheritance from prior exposure (Jansen *et al.*, 2016) indicating that glacial erosion during the last glaciation was limited to meter-scale. However, a large part of these bedrock surfaces are from elevated surfaces sampled to test the idea of preservation under non-erosive ice and there are few samples from low elevation low relief surfaces. In the present project we will measure ^{10}Be and ^{26}Al concentrations in multiple bedrock samples from the low elevation low relief region around Forsmark. The landscape is characterized by low relief terrain with hills (100s to 1000s meter scale) protruding maximum a few tens of meters above surrounding plains. Parts of the landscape displays weak glacial lineations, indicating glacial erosion, whereas other parts of the landscape show no clear indication of glacial action (Figure 4).

To evaluate and potentially quantify past glacial erosion rates we will measure ^{10}Be and ^{26}Al in a range of bedrock samples from the Forsmark region. In a first round of the project, we will collect samples from a range of bedrock surfaces including both glacially modified areas and regions lacking large-scale geomorphological evidence of glacial erosion. Presuming that we do get samples with inherited cosmogenic nuclides, compared to the expected concentrations given the time of deglaciation (Stroeven *et al.*, in press) and post-glacial uplift and emergence through water (Berglund, 2005), we will in a second round of the project collect shallow bedrock cores for cosmogenic depth profile analysis. Cosmogenic analysis of shallow depth profiles from sites with inherited analysis will potentially help quantify past glacial erosion rates as the past erosion rates will influence the cosmogenic nuclide concentration depth profiles (Figure 5).

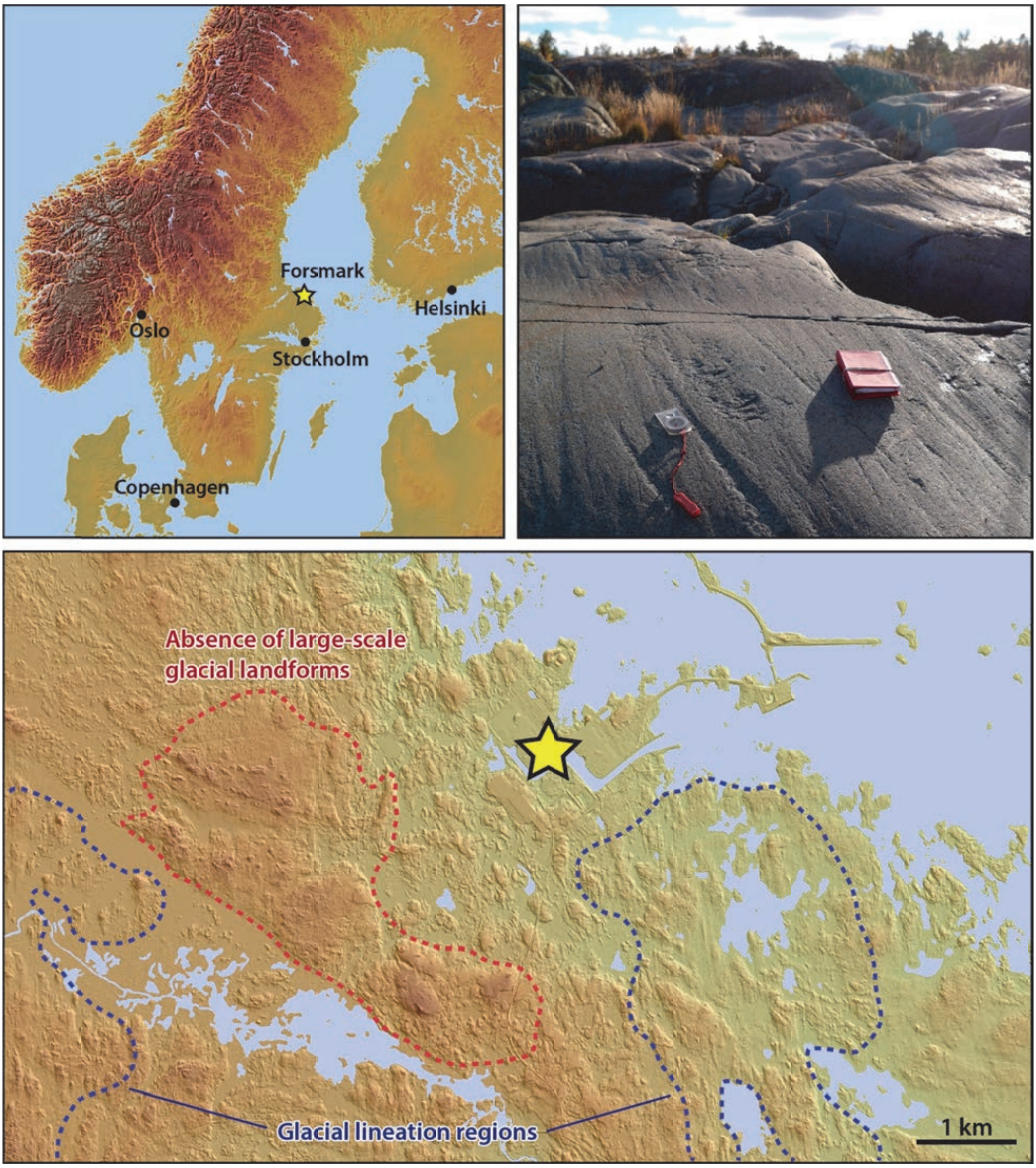

Figure 4: *Location map (upper left), elevation model of the Forsmark region (lower panel), and a photograph of striated bedrock at the coast of Forsmark (upper right). Areas with poorly-developed glacial lineations are marked in the Forsmark elevation model.*

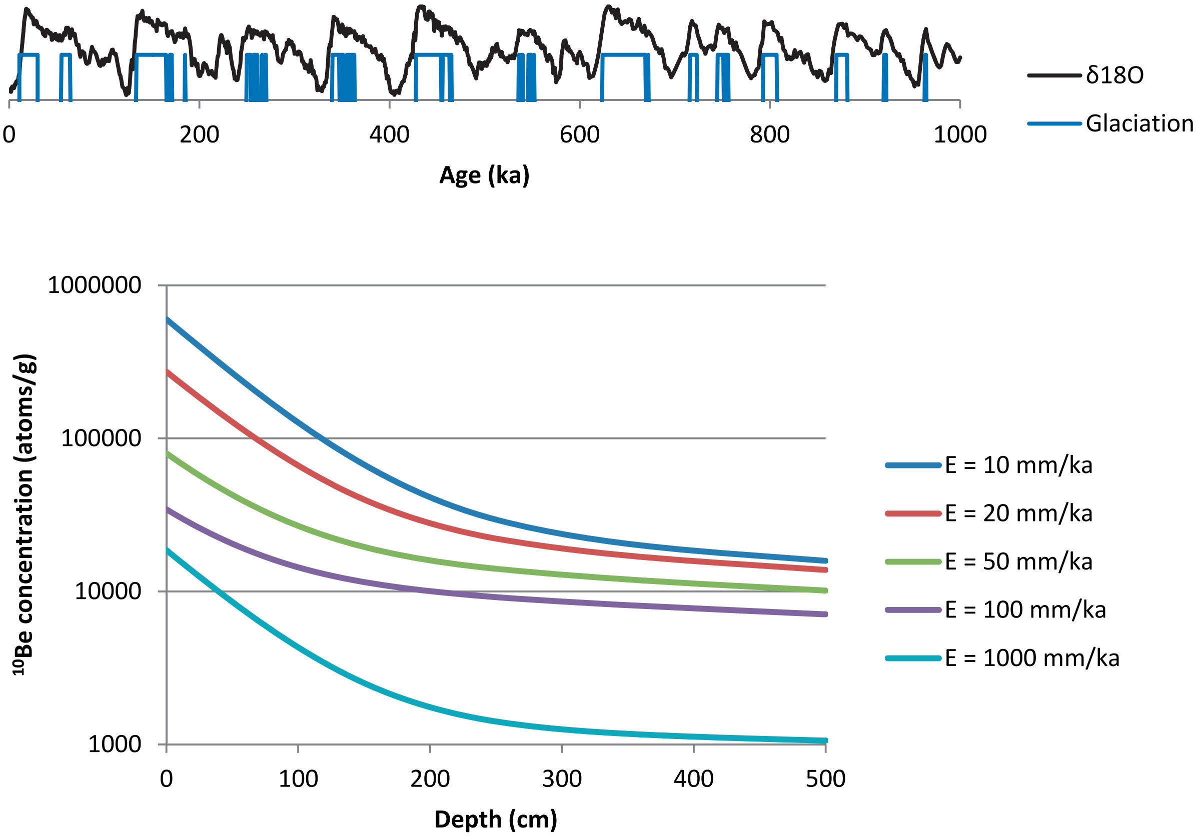

Figure 5: *Depth profile ^{10}Be concentration simulation for various glacial erosion rates. The upper panel shows the stacked δ^{18}O curve (Lisiecki and Raymo, 2005) and the assumed periods of glaciation at Forsmark used in the simulation. The lower panel shows the present-day ^{10}Be concentrations in 5 m depth profiles at Forsmark assuming glacial erosion rates ranging from 10 mm/ka to 1000 mm/ka. For the non-glacial periods an erosion rate of 1 mm/ka is assumed. The simulation is carried out using the nuclide specific LSD scaling for spallation with production rate based on the Scandinavian calibration dataset (Stroeven et al., 2015), muon production parameterization of Marrero et al. (2016) and Phillips et al. (2016), and with emergence through water following Berglund (2005).*

Site Visits

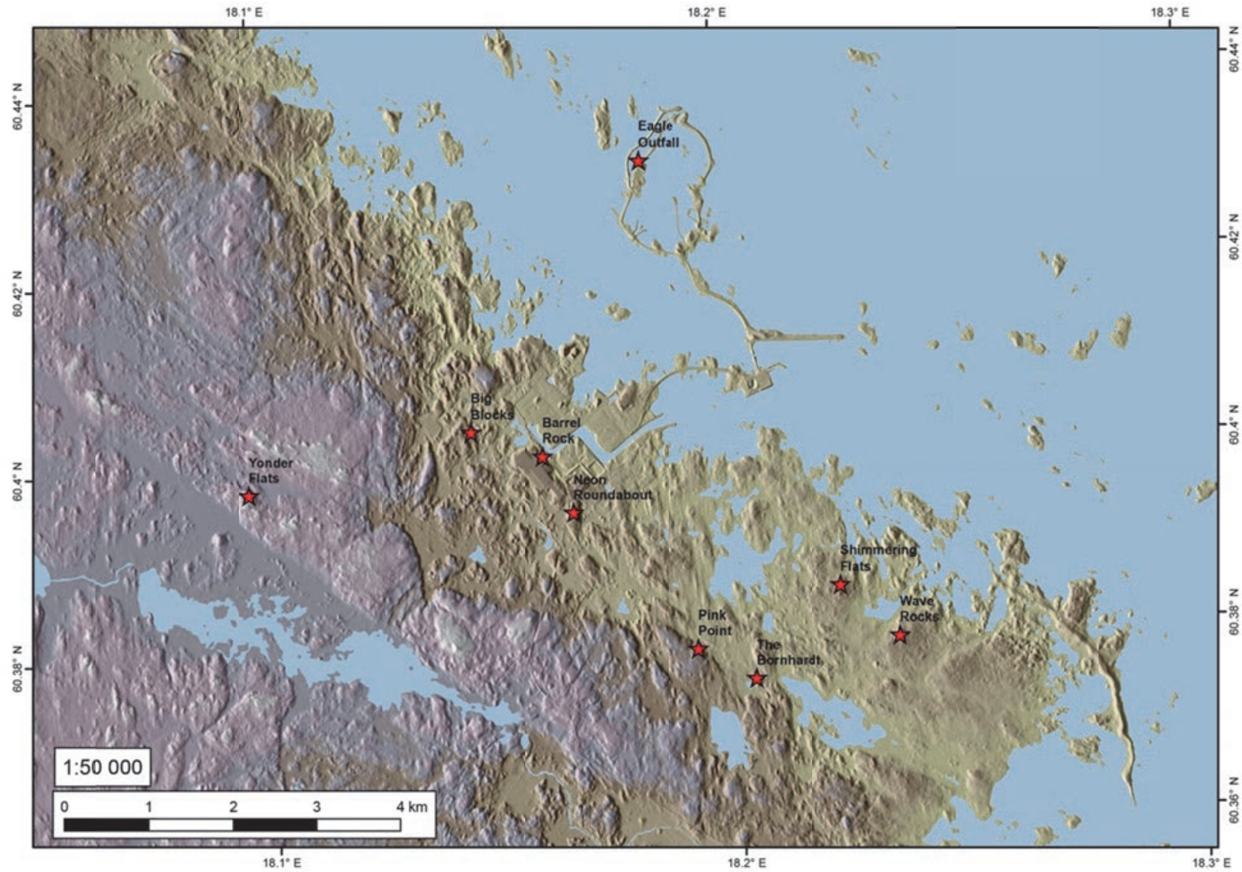

Figure 6: *Map of field sites. Eagle Outfall, Barrel Rock, and Neon Roundabout will be visited on this excursion.*

Site 1: Eagle Outfall

Latitude: 60.43053 Longitude: 18.18305 Elevation (m a.s.l.): 1

The road to the cooling water outfall is on a causeway that links low islands in the Öregrund Sound (Figure 6). The road provides access to an area of bedrock that has emerged recently from the Baltic. Emergence rates are ~5 mm/yr, indicating that the highest parts of this former island at ~5 m a.s.l. first emerged around 1 ka ago. On the foreshore, we have the opportunity to examine freshly exposed and pristine glacial microforms. These microforms include:

1. Crossing striae, with a young set oriented to 350^0 and an older set to 310^0. Kleman (1990) interprets both sets of striae as formed towards the close of last glaciation as the ice margin retreated towards the north.
2. Crescentic chocks with similar orientations.
3. Triangular sockets, 20-50 cm wide, from which blocks have been plucked. Some appear fresh; other are striated and smoothed, indicating multiple phases of quarrying.
4. A few sinuous P-forms cut by glacial meltwater.

We propose to sample a surface with crossing striae and a surface on the highest point of a set of whalebacks to test for nuclide inheritance. Given the recent emergence, an apparent exposure age of >1 ka (plus the time equivalent to subaquatic exposure, as cosmic rays penetrate c 5 m of water) would indicate that erosion by the last ice sheet did not remove the >2.5 m of rock needed to reduce nuclide inventories to zero.

Site 2. Neon Roundabout

Latitude: 60.39412 Longitude: 18.16689 Elevation (m a.s.l.): 12

This site gives ready access to a set of rock outcrops that typify the higher terrain found south of the power stations (Figure 6). The mafic gneiss here has veins of banded granite gneiss with N-S, NW-SE and NE-SW oriented fracture sets. Glacial abrasion has smoothed the upstanding rock masses but weathering since emergence from the sea has already removed fine striae. The most resistant rock masses, where fractures can be >5 m apart, have been shaped by glacial erosion to give roches moutonnées of different sizes, mostly oriented with an abraded stoss face to the N and a plucked cliff face to the S. The roadside roche moutonnée has a low till tail. Fracture-aligned clefts separate the rock humps.

DEM images and the general accordance of summit heights for the roches moutonnées on this bedrock high indicate that the surrounding bedrock surfaces have been lowered by glacial erosion. To test for nuclide inheritance, we intend to sample the highest point at this site on an abraded surface of a roche moutonnée. An apparent ^{10}Be exposure age older than the marine emergence age, corrected for nuclide penetration through shallow water, would indicate limited glacial erosion. Further sampling then may be undertaken to establish depth profiles. The quartz vein in the road cut has been sampled at different depths to check its inventories of ^{21}Ne.

Site 3. Barrel Rock

Latitude: 60.40023 Longitude: 18.16038 Elevation (m a.s.l.): 13

This roadside site exposed a 5 m high face in a massive mafic gneiss (Figure 6). The fracture surface that bounds the massive gneiss carries remnants of late calcite and goethite fissure fills. The exposure is dominated by a striking, glacially-abraded stoss surface with two sets of striae. The upper surface has low, abraded rock steps, with friction cracks, on stoss faces and small lee side cliffs. Rock fracture density drops to ~1 m in the lee of the massive unit. Here the bedrock has been disrupted by traction under glacier ice. Pull-apart structures are developed on rock surfaces along fractures transverse to ice flow. Cuboidal blocks have been transported a few meters in a down-ice direction to produce blankets of angular boulders. The distribution of blocks could be interpreted in terms of a late and brief phase of glacial entrainment operating beneath thin ice. Whatever the mechanism, the mobilization of blocks on this scale clearly represents an important component of glacial erosion in closely fractured rocks.

We propose to sample for cosmogenic nuclides on the top surface of Barrel Rock. The Rock has protected the more fractured rock in its lee from glacial excavation and represents a more stable element in a landscape that has been lowered by glacial erosion to a depth of >5 m. Again, an apparent ^{10}Be exposure age that is older than the marine emergence age, after correction for nuclide penetration through shallow water, would indicate limited glacial erosion.

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SKB is tasked with managing Swedish nuclear and radioactive waste in a safe way.

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