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Editorial

A Special Issue of *Geosciences*: Cutting Edge Earth Sciences—Three Decades of Cosmogenic Nuclides

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"What we know is a drop, what we don't know is an ocean."

Isaac Newton

A key breakthrough in Earth Sciences was triggered in 1955 when Davis and Schaeffer [1] measured cosmogenic ^{36}Cl *for the first time in history* in two igneous rock surface samples: one specimen of phonolite from a high-altitude (ca. 3300 m a.s.l.) unglaciated cliff in Colorado, and one specimen of syenite from a quarry located close to sea level (ca. 300 m a.s.l.) and within the extent of the Wisconsin glaciation in New Hampshire. This spark gave rise to the unique "cosmogenic nuclide tool" that enables Earth scientists to disentangle the unsolved pieces of Earth's history. The application of cosmogenic nuclides to geomorphological problems emerged gradually right after the publication by Davis and Schaeffer in 1955 [1]; expanded almost exponentially in the early 1990s; and has reached a prominent position during the last decade, with about more than 100 publications coming out per year. The success of the unique "cosmogenic nuclide tool" is reflected in the literature, with more than 2000 publications since conception (available online: scopus.com, accessed on 20 September 2022, searched for "cosmogenic nuclide"). *Why during the past three decades?* During this period, the physical processes responsible for the production of cosmogenic nuclides became better understood. In addition, sampling strategies, analytical sample preparation, and the accelerator and noble gas mass spectrometric analyses were astoundingly improved. As a consequence, the wide applicability of cosmogenic nuclides in solving geological problems in Earth Sciences rapidly increased. Today, cosmogenic nuclides are an amazingly versatile tool for dating landforms and deposits and for deciphering landscape evolution processes during the Quaternary. Cosmogenic nuclides have been widely applied in dating Quaternary ice volume fluctuations, and volcanic and palaeoseismic events; in quantifying surface and/or rock uplift and denudation rates; and in locating sediment sources in highly dynamic landscapes. Moreover, due to the sensitivity of cosmogenic nuclide accumulation to surface erosion and depths below the surface, the application of the technique has led to significant breakthroughs in establishing terrace chronologies, the rates and styles of local and large-scale erosion, and soil development.

Over the past three decades, the "cosmogenic nuclide tool" did not only become a universal and standard method, but it also has kept its momentum gained during this time and is at the forefront of cutting-edge research in Earth Sciences. Scientists from all over the world are exploring new challenges that require improvement and additional knowledge and are still ambitiously diving into the unknown ocean of methodologies to tackle these challenges. It was under these circumstances that this Special Issue of *Geosciences* arose. We launched this Special Issue with a call for contributions illustrating the novel applications of cosmogenic nuclides (^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, and ^{36}Cl, including new and less frequently used nuclides such as ^{38}Ar and ^{53}Mn) in diverse disciplines in the field of Geosciences, as well as contributions from purely methodological and measurement arenas (AMS and noble gas mass spectrometry). This Special Issue contains 12 papers that well portray the

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realm of cosmogenic nuclide applications in Geosciences. What follow are the contributions grouped into the following topics: dating Quaternary ice volume fluctuations, gauging erosion rates (glacial, catchment-wide, and soil erosion), dating the landforms created by natural hazards (landslides and earthquakes), and specific themes of the cosmogenic nuclide methodology and measurement infrastructure.

We introduce this Special Issue with three papers about the application of cosmogenic nuclides in establishing the timing of events in Quaternary glacial settings. Dieleman et al. [2] focused on one of the longest standing questions in Swiss Quaternary geology: When did glaciers from the Alps reach their farthest extent? To solve this mystery, the authors explored the Bünten Till layer exposed in a gravel pit in Möhlin (Canton of Aargau, Switzerland). Prior studies there had suggested the presence of moraine ridges, which have recently been shown to be loess swales [3]. In this Special Issue, Dielmann et al. [2] combined field sedimentology and cosmogenic $^{26}Al/^{10}Be$ isochron-burial dating on clasts in the till. The authors concluded that an alpine glacier reached its farthest position at 500 $\pm$ 100 ka during the Middle Pleistocene, which is contemporaneous with the maximum expansion of glaciers in the northern hemisphere. The study by Reber et al. [4] illustrated the use of cosmogenic nuclides in reconstructing the chronology of the Quaternary glacier fluctuations in northeastern Anatolia. In particular, they map the extent of paleoglaciers in the Barhal Valley in the southern ranges of the Kaçkar Mountains by using field and photogrammetric data. They established the glacial chronology by exposure dating 32 glacially transported boulders of volcanic origin with cosmogenic ^{36}Cl. The data point to three independent periods when the glaciers were stable, which occurred at 34.0 $\pm$ 2.3 ka, 22.2 $\pm$ 2.6 ka, and 18.3 $\pm$ 1.7 ka during the global Last Glacial Maximum (LGM; after [5]). In addition, they noted the occurrence of an early advance phase of the LGM glacier. They also showed the rapid downwasting of the glaciers at the end of the LGM. Evidence for Lateglacial advances is absent, and the Holocene is dominated by rock glacier activity that developed in the cirques. An equilibrium line altitude (ELA) of 2900 m a.s.l. for the LGM, which is a 600 m drop with respect to modern ELA, is documented in this study. Reber et al. [4] closed their work by proposing that, during the LGM, lakes in central–western Siberia, and the Aral and Caspian Seas served as moisture sources for the build-up of ice and that a southward migration of the Polar Jet Front and the Siberian High Pressure System controlled moisture transport during this time. In their paper, Anjar et al. [6] called into question ^{36}Cl exposure age calculations of volcanic rocks with high native Cl. They instead presented a noteworthy example of how much young exposure ages can be impacted when modeling the amount of cosmogenic ^{36}Cl produced through non-cosmogenic neutron capture reactions. Anjar et al. [6] determined 89 cosmogenic ^{36}Cl exposure ages from rock surfaces primarily exposed to glacial and volcanic events on Jan Mayen Island, located 550 km north of Iceland. For accurate age calculations, they first updated the CRONUScalc code; then, they recalculated the ages with an assumption of non-equilibrated background ^{36}Cl production [7] using the independently determined eruption ages for the volcanic rocks. They showed that almost 30% of the exposure ages underestimate the real age by up to four times. The only briefly exposed rock surfaces suffered most from the equilibrated background assumption (correction for background non-cosmogenic production was too high). Anjar et al. [6] closed their contribution by recommending the exclusion of assumed equilibrium conditions for background production when calculating exposure ages for young volcanic rock surfaces containing high native Cl, or high U and/or Th.

In the second group of contributions, Steinemann et al. [8], da Silva Guimarães et al. [9], and Musso et al. [10] delved into the realm of estimating erosion rates using cosmogenic nuclides. Upon quantifying erosion, Steinemann et al. [8] showed that a significant role of glaciers in sculpting mountain landscapes is not only their potential to deeply carve the landscape but also, surprisingly, their ability to not erode the bedrock. In their striking study, they investigated the abrasion of limestone bedrock in the forefield of the Vorab glacier in the eastern Swiss Alps. Based on measured cosmogenic ^{36}Cl concentrations, a numerical model was used to quantify subglacial erosion rates over the last 15 ka. The modeled abrasion rates were at the submillimeter scale, varying from 0.01 to 0.16 mm per year, which were astonishingly low in comparison to the rates measured on crystalline bedrock (typically more than 1 mm per year) [11]. They explained the low erosion rates with the immediate drainage of subglacial meltwater into the karst passages at the base of the glacier. They concluded that the sudden escape of water hinders basal sliding, allowing only limited subglacial erosion. As a consequence, broad and flat limestone plateaus arose. da Silva Guimarães et al. [9] exemplified the unique application of cosmogenic ^{10}Be to riverbed sediments to gauge basin-wide denudation rates and sediment fluxes, a methodology that has been successfully applied for more than two decades. They explored one of the tributary streams to the Alpine Rhine, namely the Plessur basin in the eastern Swiss Alps. The combination of the cosmogenic ^{10}Be-derived denudation rates with the geomorphological and sedimentological analysis of the drainage basin enabled them to reveal the adjustment of the Plessur basin to the landscape perturbation created by the thick Alpine Ice Sheet during the Last Glacial Maximum. The results from the highly erodible North Penninic flysch and Bündnerschist in the downstream portion of the basin indicate the most efficient adjustment there, where glacial landforms from the Last Glacial Maximum are completely absent. In contrast, hardly erodible South Penninic and Austroalpine bedrock in the upstream part promote good preservation of the glacial landforms. They concluded that the bedrock geology, geodynamics, and glacial molding are substantial factors in the processes of local uplift and denudation. Musso et al. [10] tracked the fingerprint of chemical weathering recorded by the evolution of calcareous and siliceous soils in two proglacial areas in the Swiss Alps by analyzing the meteoric ^{10}Be. They showed that the chemical weathering rate in siliceous soils is high in the early stage of formation and that it rapidly decelerates after a few thousand years. Erosion rates in calcareous soils are compensated by the soil production rates, resulting in a delay in the development of soil and vegetation cover. They concluded that vegetation is an important factor in the evolution of soil because it augments the rate of chemical weathering and surface stabilization, and it modifies the hydrogeological properties.

Mozafari et al. [12], Aksay et al. [13], and Ruggia et al. [14] validated the novel use of cosmogenic nuclides in disentangling the timing of events in natural hazard research and highlighted the importance of such an analysis for risk assessment and hazard mitigation. Mozafari et al. [12] showed the potential of cosmogenic ^{36}Cl analysis to gather crucial information required for a precise evaluation of seismic risk by exploring normal faults for unknown major prehistorical earthquakes in Western Anatolia, one of the seismically most active extensional regimes of our planet. On scarps of the Manastır and Mugırtepe faults in the Manisa Fault Zone, they modeled the occurrence of three major earthquakes at 6.5 ± 1.6 ka, 3.5 ± 0.9 ka, and 2.0 ± 0.5 ka with vertical displacements of 2.7 ± 0.4 m, 3.3 ± 0.5 m, and 3.6 ± 0.5 m, respectively. Combining their results with the existing geological and paleoseismological data [15], they demonstrated that the reconstructed seismic activity resulted in a syn-depositional rotation in the Manastır fault during the Late Pleistocene–Early Holocene, which was followed by the formation of secondary faults during the Early–Late Holocene. Aksay et al. [13] investigated the Sennwald landslide, located in the Rhine Valley. They combined detailed field mapping of the rock avalanche deposits with dynamic run-out modelling and cosmogenic ^{36}Cl dating of limestone boulders. The data point to a single catastrophic failure at 4.3 ± 0.5 ka. This coincides with a past earthquake identified in lake sediments within the region by [16], implicating a seismic origin for the Sennwald event. This provides further support for a major earthquake at the Mid–Late Holocene transition. Ruggia et al. [14] combined field mapping, runout modeling, and surface exposure dating with cosmogenic ^{36}Cl to reconstruct the evolution of the giant Gorte rock avalanche at the northeastern end of Lake Garda in northern Italy. They successfully simulated the rock avalanche and reproduced the size and the thickness of the landslide deposits. They documented a single collapse in a rock mass of about 70–75 Mm^3 at 6.1 ± 0.8 ka, which resulted in a deposit volume of about 85–95 Mm^3. The initial collapse of bedrock was followed by rapid disintegration and spreading. They argued that heavy precipitation might have triggered the rock avalanche because the timing of the rock avalanche falls into a relatively warm and wet period of the Middle Holocene when a period of frequent flooding 6900–6200 years ago was already identified for the region. However, they did not exclude a seismic trigger because of the occurrence of three contemporaneous landslides in the nearby region (within 15 km distance).

Finally, we close this Special Issue with three contributions on the brass tacks of cosmogenic nuclide methodologies. Halsted et al. [17] investigated one of the recent critical topics of the cosmogenic nuclide community: the cosmogenic $^{26}Al/^{10}Be$ surface production ratio, which is vital for two-isotope applications. To test the overlap of the theoretical production ratio with that from analyzed data, they scrutinized the Informal Cosmogenic-nuclide Exposure-age Database (ICE-D) and selected 313 samples from ice-molded bedrock and glacial boulders located between 53° S and 70° N and at altitudes up to 5000 m above sea level, which are assumed to have experienced the same exposure history. They determined insignificant interlaboratory systematic differences and a negative correlation between the $^{26}Al/^{10}Be$ production ratio and elevation, which agrees well with the assumptions based on the measured energy dependence of nuclear reaction cross sections and the spatial variability of the cosmic ray cascade. They also identified a positive correlation between the production ratio and latitude, but they noted the occurrence of a bias in the dataset, which they related to the altitude of the samples. They concluded that a global value of 6.75 for the $^{26}Al/^{10}Be$ production ratio is not appropriate for high-altitude samples and maybe even for high latitude ones. They suggested employing a nuclide-specific production rate spatial scaling scheme, such as the LSDn [18], to avoid potential biases. Ángel Rodés [19] addressed the challenge of applying the cosmogenic nuclide methodology in glacial landscapes, which particularly emerges when the exposure ages of the landforms deviate from the timing of deglaciation. This occurs as a consequence of post-depositional and post-exposure geological processes. Researchers applying cosmogenic nuclides to nunataks to reconstruct the history of ice thinning face such challenges especially in continental polar regions, where extreme aridity and cold conditions prevail. Ángel [19] provided a new user-friendly tool to model cosmogenic nuclide accumulation along the elevation profiles: The NUNAtak Ice Thinning model (NUNAIT). In brief, NUNAIT calculates cosmogenic nuclide concentrations by tailoring the exposure time, pre-exposure, subaerial weathering, subglacial erosion, uplift, and subglacial muon production to an array of apparent exposure ages gathered from nunataks along an elevation profile. Györe et al. [20] introduced a new infrastructure for high-precision analysis of cosmogenic Ne in terrestrial and extra-terrestrial rocks. They connected a Thermo Fisher ARGUS VI mass spectrometer with an automated laser gas extraction and purification system and adapted this line for high-throughput and high-precision analysis. The stunning outcome of this new system is its ability to measure Ne isotopic ratios in very small samples (~20 mg) with very low uncertainties. For example, while measuring the extra-terrestrial material, they were able to reduce the overall uncertainty of the Ne isotope ratio down to 0.5% (four times less with respect to earlier systems) by analyzing two to six times less material. In addition, they can successfully analyze samples that are two to five times smaller than what is commonly used for noble gas spectrometry, and they are able to measure Ne isotopes at high precision even if the samples have low noble gas concentrations, which is generally the case for the terrestrial material. They discussed how their system can further be improved particularly for the analysis of terrestrial samples. This new system expands our capabilities and paves the way for novel research, as it enables us to analyze sample material that is extremely valuable and limited, such as the rock samples from space missions (perhaps even rock samples from Mars).

In brief, the studies compiled in this Special Issue show how cosmogenic nuclides are, at present, in full bloom as an amazingly versatile tool after the past three decades and nearly 70 years after the first spark by Davis and Schaeffer [1]. As quoted by Sir Isaac Newton: "What we know is a drop, what we don't know is an ocean"; there are certainly more drops in the ocean of cosmogenic nuclides to be discovered in the future that will keep cosmogenic nuclides at the cutting edge of Earth Sciences research.

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