



## ORIGINAL PAPER

**EROSION RATES USING IN-SITU COSMOGENIC NUCLIDES  $^{10}\text{Be}$  AND  $^{26}\text{Al}$ : A CASE STUDY OF THE JIZERA RIVER (BOHEMIAN MASSIF).****Roman GARBA <sup>1,2)\*</sup>, Václav SUCHÝ <sup>1)</sup>, Jan KAMENÍK <sup>1)</sup>, František VESELOVSKÝ <sup>3)</sup>,  
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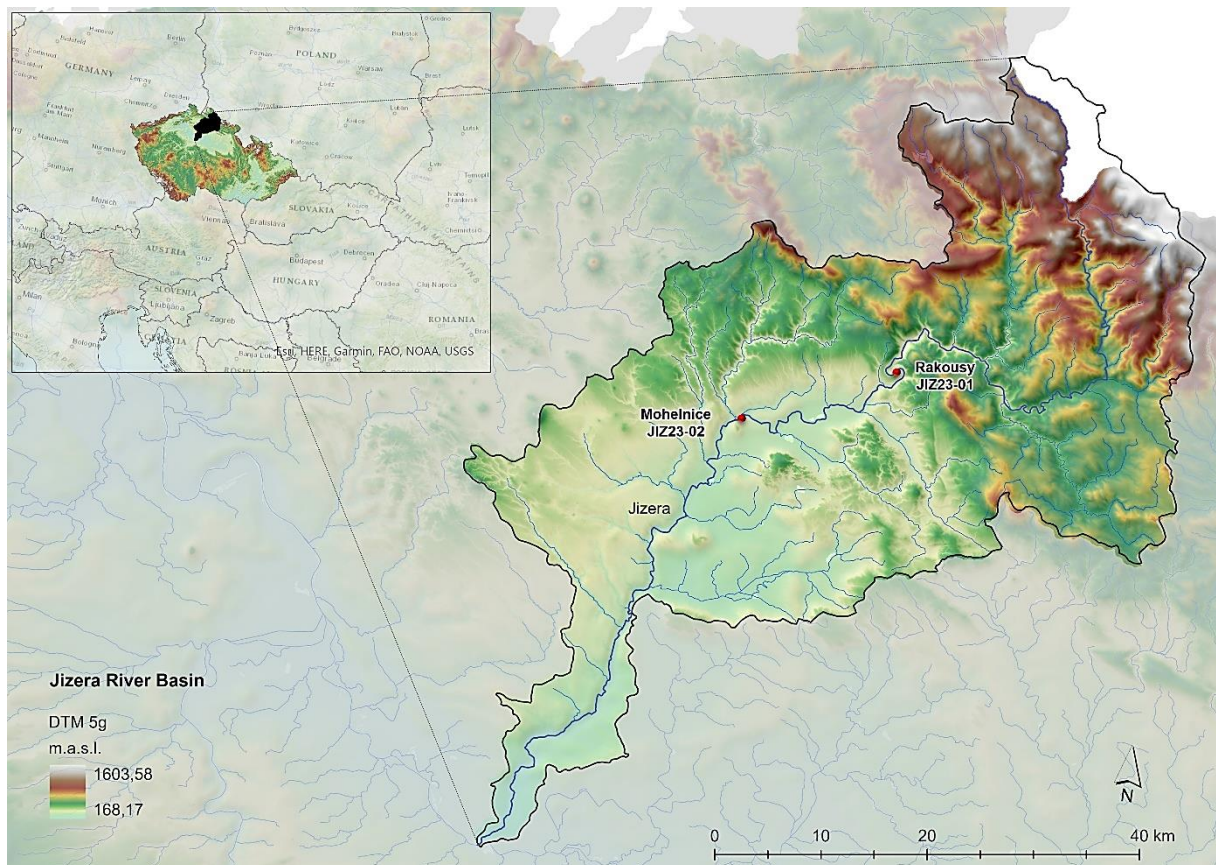
**ABSTRACT**

Erosion rates derived from in situ-produced cosmogenic nuclides (CN) have made a significant contribution to quantitative geomorphology. In Europe, extensive CN-based erosion rate datasets mainly cover the Alps and western Europe. However, there is hardly any data from Central and Eastern Europe. This pilot study employs the analysis of in-situ produced cosmogenic  $^{10}\text{Be}$  and  $^{26}\text{Al}$  to reveal the erosion rate of alluvial sediments of the Jizera River, in the northern part of the Bohemian Massif. Samples of recently deposited alluvial quartz-rich sands were collected from two sites located on the upper and middle river drainage and CN concentrations were analyzed using the multi-isotope accelerated mass spectrometry (AMS) facility newly operating at the Nuclear Physics Institute in Řež. Multi-grain size analysis was applied to identify complex sedimentary histories of the sediment. The calculated erosion rates 42 to 52 m  $\text{Myr}^{-1}$  are generally consistent between nuclides and align well with similar  $^{10}\text{Be}$ -derived erosion rates of 22 to 51 m  $\text{Myr}^{-1}$ , which have been recently established for the southern part of the Bohemian massif by Robl et al. (2025). At one locality studied, the multi-nuclide technique revealed the coexistence and mixing of non-buried and buried sediments within the alluvial deposits. As an independent check of the erosion rate measurements, the cosmogenic dataset of Jizera River sediments was supplemented with the estimates of the uplift rate of respective bedrocks (45 to 100 m  $\text{Myr}^{-1}$ ), based on available apatite fission-track analysis data. Taking together, these data reveal the general predominance of uplift over erosion over the region, which is a widespread pattern characteristic of the Neotectonic period of accelerated uplift in compressional tectonic zones. Our case study demonstrates the potential of a paired CN technique as a modern tool for quantitative geomorphologic analyses applicable to various other terrains in Central and Eastern Europe.

**INTRODUCTION**

In-situ-produced cosmogenic nuclides (CNs) such as  $^{10}\text{Be}$  and  $^{26}\text{Al}$  are produced in quartz by interactions of high-energy cosmic-ray particles with quartz mineral lattices in rock and sediments at or near the Earth's surface. The dominant production mechanism near the surface is spallation of oxygen and silicon by high-energy neutrons, with smaller contributions from muons. The neutron production rate ceases in the upper few meters of rock layers and fast muon production dominates at greater depths (Lal, 1991; Gosse and Phillips, 2001; Braucher et al., 2011; Schaefer et al., 2022). CN production varies on latitude, longitude, elevation and other parameters, and decreases exponentially with depth due to shielding by overlying material (Granger et al., 1996; Gosse and Phillips, 2001; Balco et al., 2008). The material erodes across the mountainous upstream catchment and each individual grain in quartz-bearing river sediments is carrying a cosmogenic inventory reflecting its local production–erosion balance. When mixed in river channels, these sand grains yield a concentration-weighted average representing the

catchment-average erosion rate (Granger et al., 1996; von Blanckenburg, 2006). The  $^{10}\text{Be}$  concentration in quartz provides robust single-nuclide erosion rates and is used in a vast majority of erosion rate studies. Using multi-nuclide approach with nuclide pair  $^{26}\text{Al}/^{10}\text{Be}$  offers useful complementary information because nuclides are produced at different rates but removed by the same erosion process. Their surface production rate ratio is typically  $\sim 6.75$  seen in most calculations but it ranges from 6.75 to 7.15 (Balco, 2017; Heyman, 2019). The  $^{26}\text{Al}/^{10}\text{Be}$  ratio lower than 6.75 could indicate burial or complex sediment transport histories (Granger and Muzikar, 2001). Nuclide production rate is mainly calculated using three scaling models such as those of Stone (Stone 2000; “St”), Lal/Stone modified (Lal, 1991; Stone, 2000; “Lm”), and Lifton–Sato–Dunai (Dunai, 2001; Lifton et al., 2014; “LSDn”) ensuring accurate conversion of measured nuclide concentrations to erosion rates across different geographic settings (Balco et al., 2008). Large amount of denudation or erosion rates using CN was gathered for the western Europe (Codilean et al., 2018), mainly on alluvial sediments of Alpine rivers (Schaller et al.,



**Fig. 1** Jizera River basin. Location of the study area within central Europe and Jizera river basin topography. Data source ERSI, HERE, Garmin, FAO, NOAA and USGS.

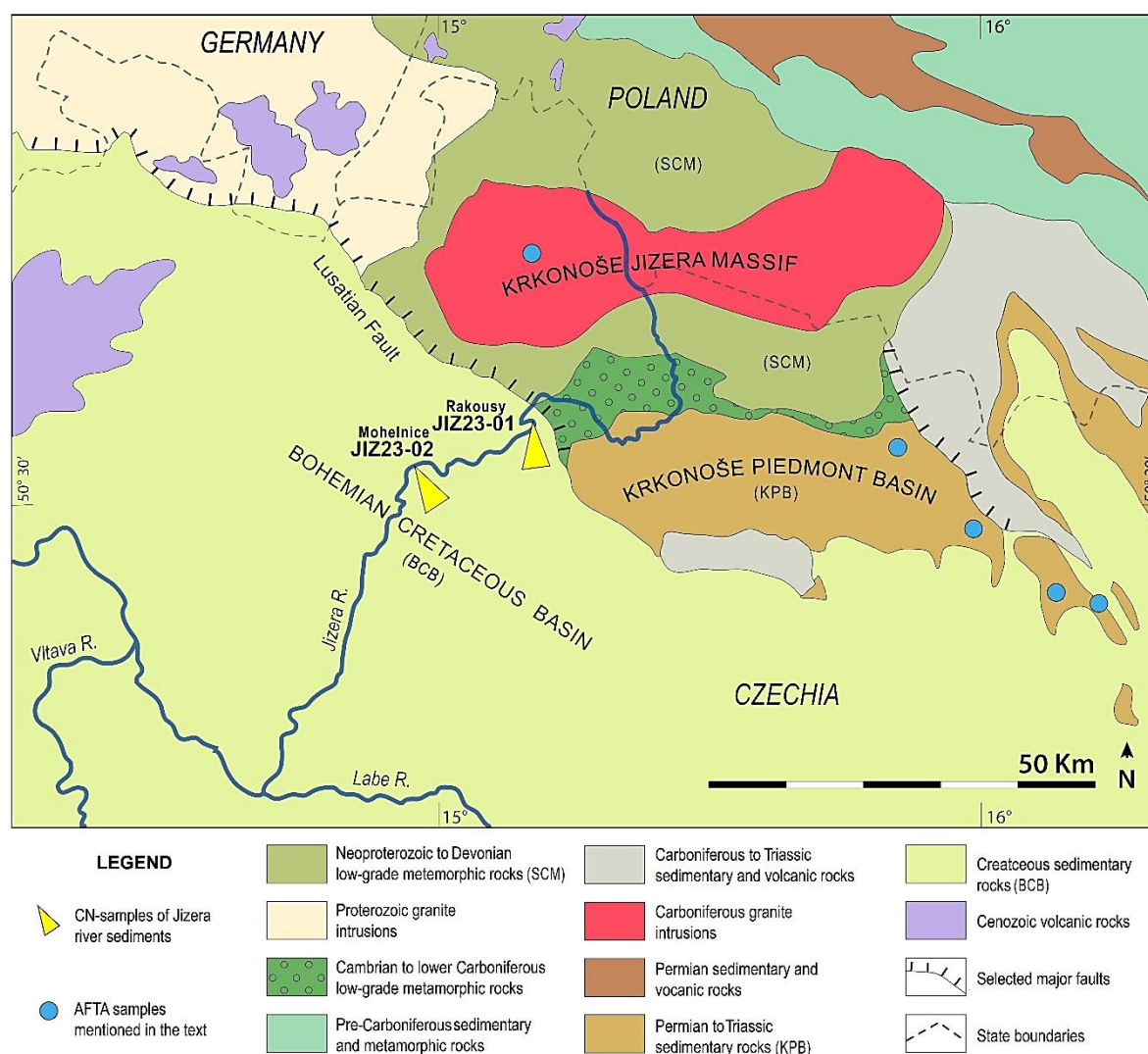
2001; Norton et al., 2011; Wittman et al., 2016; Delunel et al., 2020; Dieleman et al., 2025), while similar research on river catchments of the Bohemian Massif has been seldom conducted. Schaller et al. (2016) have used in-situ  $^{10}\text{Be}$  technique and showed that the erosion rates of the Vltava River draining the central part of the Bohemian Massif ranges from 23 to 31  $\text{m Myr}^{-1}$ . More recently, Robl et al. (2025) calculated the catchment-wide erosion rates using cosmogenic  $^{10}\text{Be}$  in river sands of the Austrian part of the southern Bohemian Massif, to 22–51  $\text{m Myr}^{-1}$ .

Several methodological studies addressed the sand-size variation (van Dongen et al., 2019), climate change and denudation (Schaller and Ehlers 2006), the use of  $^{10}\text{Be}$  combined with  $^{26}\text{Al}$  and  $^{21}\text{Ne}$  (e.g., Wittmann et al., 2016) or using  $^{36}\text{Cl}$  in karst landscapes (Krklec et al., 2022). Study of Jautzy et al. (2024) showed the importance of paired-nuclide approach ( $^{10}\text{Be}$  and  $^{26}\text{Al}$ ) to test steady-state assumption and sediment burial or transit time especially in slowly eroding landscapes. Some studies also used meteoric ( $^{10}\text{Be}$  is produced in atmosphere representing  $^{10}\text{Be}$  flux coming to the surface with the rainfall)  $^{10}\text{Be}/^9\text{Be}$  ratios (Maher and von Blanckenburg, 2016; Dannhaus et al., 2018; VanLandingham et al., 2022). Several works changed earlier assumptions by demonstrating that catchment-wide erosion rates are rather independent of glaciation or anthropogenic activities such as modern dams

(Willenbring and von Blanckenburg, 2010; Wittmann et al., 2016), or there is no correlation with precipitation (von Blanckenburg, 2006). CN was also used for different applications in Czechia such as  $^{10}\text{Be}$  exposure age dating rockslides (Lenart et al., 2023). Another CN application involved the in situ  $^{26}\text{Al}/^{10}\text{Be}$  isochron burial dating of the fluvial terraces of the Ploučnice River in the northern Bohemian Massif (Štor et al., 2019).

## STUDY AREA

The Bohemian Massif is a remnant of the Variscan orogen, which resulted from complex collisions and amalgamation of several microcontinents during the Devonian – Carboniferous time (Matte et al., 1990; Franke, 2006; Kroner et al., 2008; Schulmann et al., 2014). The northern borderland of Czechia, which geologically belongs to the northern rim of the Bohemian Massif, is mostly mountainous and built of crystalline rocks of metamorphic and igneous origin. The studied area of the Jizera watershed (Fig. 1) spreads out from the Jizerské hory Mountains in the river Jizera source region in West Sudetes of the north of Bohemia down to the central Středočeská tabule Table of the Czech Cretaceous Basin. In this area, four principal geological units are intersected by the Jizera River (Fig. 2; Cháb et al., 2007):



**Fig. 2** Simplified geological map of study area showing the locations of CN and AFTA samples discussed in the text. After Cháb et al., 2007; Migoń and Danišík, 2012, modified. Drawing by Maria Pia Maiorano.

Krkonoše-Jizera massif – is nearly exclusively composed of medium to coarse-grained Variscan granites and granodiorites, and minor pre-Variscan crystalline rocks (Kröner, 1994; Marheine et al., 2002; Klomínský et al., 2018), which are penetrated by rare Cenozoic volcanic bodies (Klomínský and Sláma, 2023). Locally developed Quaternary deluvial soils, peat bogs, glacial deposits, and Pleistocene fluvial sediments arranged into rare river terraces form a post-Variscan sedimentary cover of the Krkonoše-Jizera Massif in this region.

Submontane crystalline metamorphic units (SCM) surroundings the Krkonoše Jizera Massif. They are mainly composed of Neoproterozoic to Devonian low-grade metamorphic rocks dominated by phyllites, mica schists, quartzites, minor gneisses, and greenschists, with some intercalations of crystalline carbonate rocks (e.g., Hladil et al., 2003). Slightly metamorphosed Cambrian to Lower Carboniferous sedimentary and volcanic rocks form the southern part of the unit. Pleistocene river terraces are not known.

Krkonoše Piedmont Basin (KPB) is composed of Carboniferous to Triassic sedimentary and volcanosedimentary formations (Opluštil et al., 2016; Ulrych et al., 2002) locally penetrated with Cenozoic igneous rocks (Ulrych et al., 2013). Minor Pleistocene alluvial terraces are also found in this area, as well as aerially limited fluvial and aeolian sediments. Unstable deluvial soils prone to landslides are the most common representatives of Quaternary sediments in this part of the river.

Bohemian Cretaceous Basin (BCB) is the lowermost geological domain along the river flow of Jizera dominated by Cretaceous shallow marine siliciclastic sediments and Cenozoic volcanites (Uličný et al., 2003; Uličný et al., 2009; Ulrych et al., 2011). Scattered gravels of unspecified origin and age along with Pleistocene river terraces and aeolian deposits locally cover the Cretaceous basement.

Previous geomorphological investigation of the Jizera River have mainly focused on the development of the Jizera alluvial fan in the Middle and Upper



**Fig. 3** Field photos of Jizera River localities and microphotographs of respective riverbed sediments after their physical treatment. Red circles in field photographs show positions of individual sampling sites in the river channel. A – Rakousy site, B – Mohelnice site, C – JIZ23-01A (Rakousy) quartz grains, D – JIZ23-02A (Mohelnice) quartz grains.

**Table 1** Jizera CN sample overview.

| Sample ID | Grains [mm] | Locality  | Source material | Catchment area [km <sup>2</sup> ] | Lat (CM)* [°N] | Long (CM)* [°E] | Elev (CM)* [m] |
|-----------|-------------|-----------|-----------------|-----------------------------------|----------------|-----------------|----------------|
| JIZ23-01A | 0.125–0.5   | Rakousy   | riverbed sand   | 793                               | 50.6834        | 15.3827         | 634            |
| JIZ23-01B | 0.5–1.1     | Rakousy   | riverbed sand   | 793                               | 50.6834        | 15.3827         | 634            |
| JIZ23-02A | 0.125–0.5   | Mohelnice | riverbed sand   | 1305                              | 50.6491        | 15.3353         | 559            |
| JIZ23-02B | 0.5–1.1     | Mohelnice | riverbed sand   | 1305                              | 50.6491        | 15.3353         | 559            |

\*catchment mean

Pleistocene (Balatka, 1966), the accumulation of river terraces and fluvial sediments (Balatka and Kalvoda, 2008), and the evolution of the confluence area of the Labe and Jizera rivers (Stekla and Kalvoda, 2024). Several recent studies have also addressed the tectonic morphology of the wider region of the Sudetes where complex fault dynamics and the Cenozoic uplift have influenced evolution of the upper part of Jizera watershed (e.g., Danišík et al., 2010, 2012; Coubal et al., 2015; Różycka and Migoń, 2017). So far, however, the determination of catchment-wide erosion rates using cosmogenic nuclides has not been carried out in the northern Bohemian Massif.

## SAMPLES AND METHODS

To estimate erosion, samples were taken from the modern quartz-rich river sediments of the Jizera River

at two specific sites. The Rakousy location represents the upper, Jizera River drainage, while the Mohelnice location is situated in the central part of the meandering floodplain (Figs. 1 and 2). The river sand was sampled using wet sieving with stainless steel sieves (mesh sizes 125  $\mu$ m and 1.2 mm) in two steps: first to separate the finer, muddy fraction (<125  $\mu$ m), and then to separate the coarser fraction (>1.2 mm) (Fig. 3). Table 1 provides an overview of the samples with geographical metadata. The coordinates of the sampling locations were used to calculate the mean latitude, longitude and elevation of sample's catchment area using a digital elevation model.

Physical sample preparation was performed at the Czech Geological Survey. The presence of luminescence minerals (e.g., zircon, scheelite, andalusite) was investigated using ultra-violet light

(254 and 365 nm) on cut faces and crushed grains with negative result. Untreated samples contained common accessories such as mica (biotite, muscovite), feldspars (albite, orthoclase), and quartz grains intergrown with the mica. The material was crushed using a Retsch BB300 jaw crusher. The crushed material was washed in distilled water to remove fines, treated in hot HCl 1:1 for 5 min., washed with distilled water several times, and then dried in a porcelain dish at room temperature. The samples were then sieved into fractions using stainless steel sieves with 0.125 mm, 0.5 mm, 0.75 mm and 1.1 mm mesh. Two-step magnetic separation was conducted: firstly, manual separation using an FeNdB magnet, followed by separation using a Cook separator (Frantz isodynamic electromagnetic separator; current 2.3 A; forward tilt 30°, pitch 10°). After magnetic separation, the samples were sieved again to eliminate the smaller particles that had formed during the process. All usable fractions were divided separately in a heavy liquid with a density of 2.631 g/cm<sup>3</sup>. This heavy liquid was a mixture of 1,1,2,2-tetrabromethane and dioxane; its density was measured using a Mohr–Westphal balance. The quartz grains were in the heavy fractions and the intergrowths with the feldspars were in the lighter fractions. The fractions were then washed with ethanol. An optical microscope with 10x magnification was used to visually inspect the samples. While the mineralogical composition of both samples was similar, the JIZ23-01 sample contained more magnetite and the JIZ23-02 sample contained more mica.

The subsequent chemical sample processing (quartz purification, beryllium and aluminium separation) and accelerator mass spectrometry (AMS) measurements were performed at the Nuclear Physics Institute (NPI) of the Czech Academy of Sciences (Kučera et al., 2023). Quartz purification involved treatment with HCl and H<sub>2</sub>SiF<sub>6</sub> in several steps. Meteoric  $^{10}\text{Be}$  contamination from grain surface was removed by leaching with 2–10 % HF. Approximately 300 µg of stable Be was added to each sample as gravimetrically recorded aliquot of Low-Level Beryllium Carrier (2017.11.17-Be, Prime lab). After dissolution of quartz in HF and conversion to 6 M HCl, an aliquot of about 5 % of total volume was taken from each sample as dried aliquot for Al determination by Instrumental Neutron Activation Analysis (INAA). Be and Al were separated and purified by pH-dependent precipitation steps and ion exchange chromatography. Be and Al were isolated as hydroxides and calcinated at 900 °C in quartz crucibles. The prepared BeO was mixed with Nb in ratios of approximately 1:5. Similarly, Al<sub>2</sub>O<sub>3</sub> was mixed with Ag powder with mixing mass ratio of approximately 1:1. The mixtures were pressed into Cu cathodes (compatible with MICADAS ion source, Ionplus) using pneumatic sample press.

The AMS measurement was performed by MILEA 300 kV system (Maxeiner et al., 2019; Kučera et al., 2023) against the  $^{10}\text{Be}$  and  $^{26}\text{Al}$  standards KN

14-5-8-A ( $2.507 \times 10^{-12}$ ,  $^{10}\text{Be}/^9\text{Be}$ ) and KN 14-5-4 ( $2.501 \times 10^{-12}$ ,  $^{26}\text{Al}/^{27}\text{Al}$ ), respectively. For details on standards see Nishiizumi (2004) and Nishiizumi et al. (2007). The normalized isotope ratios ( $^{10}\text{Be}/^9\text{Be}$  and  $^{26}\text{Al}/^{27}\text{Al}$ ) were converted to CN concentrations (atoms g<sup>-1</sup> quartz). The processing-blank-corrected values are summarized in Table 2. The reference quartz material CoQTZ (Binnie et al., 2019) was processed together with the samples. The determined  $^{10}\text{Be}$  and  $^{26}\text{Al}$  concentrations included in Table 2 agree well with the consensus values within the uncertainty margins (Binnie et al., 2019). For complementary burial age calculations, we used half-life for  $^{10}\text{Be}$  1.387 Ma (Chmeleff et al., 2010; Korschinek et al., 2010) and  $^{26}\text{Al}$  0.708 Ma (Nishiizumi, 2004). The  $^{26}\text{Al}/^{10}\text{Be}$  production rate ratio 7.0 was used as suggested for lower-elevation locations (Balco, 2017; Heyman, 2019).

The computed erosion rates were based on the concentration of cosmogenic  $^{10}\text{Be}$  and  $^{26}\text{Al}$  in river sands by employing the web-facility of the online CRONUS-Earth calculator v3.0. (Balco et al., 2008) with sample density of 2.7 g cm<sup>-3</sup>. Erosion rates were calculated without taking topographic shielding into account.

Estimates of the uplift rates of the rocks forming the basement of the Jizera River drainage basin were made using published apatite fission-track analysis (AFTA)-based time-temperature plots (Fig. 4; Dobeš et al., 2018; Svojtka et al., 2005), which were converted into respective time-burial plots. This was done by assuming a geothermal gradient of 30–35 °C per kilometer (e.g. Šafanda et al., 1990), a surface temperature of 25 °C and a linear increase in temperature with depth. Because of the arbitrary nature of these basic assumptions, the resulting uplift rates should only be considered as first-order approximations (e.g., Brown and Summerfield, 1997; Kohn et al., 2005). Nevertheless, these estimates can be useful in providing an independent check of CN-derived erosion rates.

## RESULTS

The results of calculated erosion rates using three scaling models (St, Lm and LSDm) are shown in Table 3. For mid-latitude sites such as the Jizera Mountains, differences among St, Lm, and LSDn scaling are below 5 % and all schemes yield comparable erosion rates. The LSDn scaling-model-based erosion rates, which are discussed further in the text in more details, are more robust and represent physical, fully dynamic scaling model. The results show that the total erosion rate derived from the Jizera River catchment sediments ranges from 43 to 84 m Myr<sup>-1</sup> with a small multi-nuclide and multi-grain-size variations.

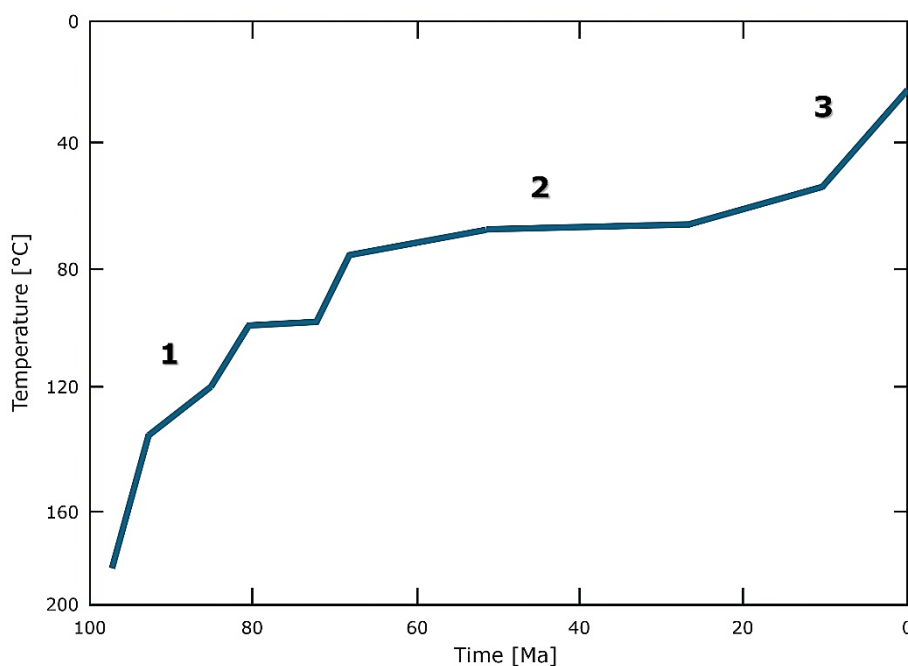
The uplift rates of bedrocks forming the basement of Jizera River drainage basin derived from AFTA data (Svojtka et al., 2005; Dobeš et al., 2018), ranged between 60–100 m Myr<sup>-1</sup> and 45–80 m Myr<sup>-1</sup> for the granite rocks of the Krkonoše-Jizera Massif

**Table 2** Measured AMS ratios, quantity of stable isotope and calculated  $^{10}\text{Be}$  and  $^{26}\text{Al}$  concentrations in quartz. The values after  $\pm$  are combined uncertainty ( $k=1$ ).

| Sample               | Be cathode | Al cathode | Total quartz [g] | $^9\text{Be}$ added [ $\mu\text{g}$ ] | $^{27}\text{Al}$ in sample [ $\mu\text{g/g}$ ] | $^{10}\text{Be}/^9\text{Be}$ [ $10^{-15}$ ] | $^{26}\text{Al}/^{27}\text{Al}$ [ $10^{-15}$ ] | Conc. $^{10}\text{Be}$ [ $10^3$ atoms $\text{g}^{-1}$ QTZ] | Conc. $^{26}\text{Al}$ [ $10^3$ atoms $\text{g}^{-1}$ QTZ] | $^{26}\text{Al}/^{10}\text{Be}$ |
|----------------------|------------|------------|------------------|---------------------------------------|------------------------------------------------|---------------------------------------------|------------------------------------------------|------------------------------------------------------------|------------------------------------------------------------|---------------------------------|
| Process blank        | B0057      | A0015      | –                | $321 \pm 2$                           | –                                              | $2.6 \pm 0.9$                               | $< 1.5$                                        | –                                                          | –                                                          | –                               |
| CoQTZ-N              | B0058      | A0016      | 4.9602           | $320 \pm 2$                           | $28 \pm 4$                                     | $613 \pm 10$                                | $3260 \pm 60$                                  | $2630 \pm 50$                                              | $14700 \pm 400$                                            | $5.59 \pm 0.19$                 |
| CoQTZ-N <sup>a</sup> | –          | –          | –                | –                                     | –                                              | –                                           | –                                              | $2530 \pm 90^a$                                            | $15600 \pm 1600^a$                                         |                                 |
| JIZ23-01A            | B0052      | A0010      | 25.82579         | $320 \pm 2$                           | $167 \pm 4$                                    | $130 \pm 2$                                 | $199 \pm 4$                                    | $106 \pm 2$                                                | $720 \pm 30$                                               | $6.79 \pm 0.31$                 |
| JIZ23-01B            | B0053      | A0011      | 21.26828         | $321 \pm 2$                           | $154 \pm 3$                                    | $118 \pm 3$                                 | $218 \pm 5$                                    | $116 \pm 3$                                                | $720 \pm 40$                                               | $6.21 \pm 0.38$                 |
| JIZ23-02A            | B0054      | A0012      | 23.98866         | $321 \pm 2$                           | $114 \pm 2$                                    | $85 \pm 2$                                  | $164 \pm 6$                                    | $73 \pm 2$                                                 | $400 \pm 30$                                               | $5.48 \pm 0.44$                 |
| JIZ23-02B            | B0055      | A0013      | 9.99624          | $320 \pm 2$                           | $127 \pm 3$                                    | $54 \pm 4$                                  | $234 \pm 6$                                    | $110 \pm 9$                                                | $640 \pm 40$                                               | $5.82 \pm 0.60$                 |

**Table 3** Calculated erosion rates. Using online CRONUS-Earth calculator v3.0. (Balco et al., 2008).

| Sample    | Nuclide | St                                   |                      |                         |                         | Lm                                   |                      |                         |                         | LSDn                                 |                      |                         |                         |
|-----------|---------|--------------------------------------|----------------------|-------------------------|-------------------------|--------------------------------------|----------------------|-------------------------|-------------------------|--------------------------------------|----------------------|-------------------------|-------------------------|
|           |         | Erosion rate [g/cm <sup>2</sup> /yr] | Erosion rate [m/Myr] | Internal uncert [m/Myr] | External uncert [m/Myr] | Erosion rate [g/cm <sup>2</sup> /yr] | Erosion rate [m/Myr] | Internal uncert [m/Myr] | External uncert [m/Myr] | Erosion rate [g/cm <sup>2</sup> /yr] | Erosion rate [m/Myr] | Internal uncert [m/Myr] | External uncert [m/Myr] |
| JIZ23-01A | Be-10   | 0.0125                               | 46.4                 | 0.88                    | 3.79                    | 0.0127                               | 47.1                 | 0.89                    | 3.67                    | 0.0126                               | 46.7                 | 0.89                    | 2.91                    |
| JIZ23-01B | Be-10   | 0.0114                               | 42.2                 | 1.10                    | 3.53                    | 0.0116                               | 42.9                 | 1.12                    | 3.43                    | 0.0115                               | 42.6                 | 1.11                    | 2.76                    |
| JIZ23-02A | Be-10   | 0.0173                               | 64.0                 | 1.76                    | 5.38                    | 0.0175                               | 64.9                 | 1.79                    | 5.21                    | 0.0173                               | 64.3                 | 1.77                    | 4.20                    |
| JIZ23-02B | Be-10   | 0.0113                               | 42.0                 | 3.46                    | 4.81                    | 0.0115                               | 42.7                 | 3.52                    | 4.77                    | 0.0114                               | 42.3                 | 3.48                    | 4.30                    |
| JIZ23-01A | Al-26   | 0.0129                               | 47.8                 | 2.02                    | 5.42                    | 0.0131                               | 48.6                 | 2.05                    | 5.06                    | 0.0131                               | 48.6                 | 2.05                    | 4.70                    |
| JIZ23-01B | Al-26   | 0.0129                               | 47.8                 | 2.69                    | 5.70                    | 0.0131                               | 48.6                 | 2.73                    | 5.37                    | 0.0131                               | 48.6                 | 2.73                    | 5.04                    |
| JIZ23-02A | Al-26   | 0.0224                               | 83.0                 | 6.27                    | 10.70                   | 0.0227                               | 84.1                 | 6.35                    | 10.20                   | 0.0227                               | 84.0                 | 6.34                    | 9.65                    |
| JIZ23-02B | Al-26   | 0.0137                               | 50.8                 | 3.21                    | 6.24                    | 0.0139                               | 51.6                 | 3.26                    | 5.90                    | 0.0139                               | 51.7                 | 3.26                    | 5.55                    |



**Fig. 4** Typical time-temperature plot, based on AFTA thermochronology of the Krkonoše-Jizera Massif forming the bedrock of the Jizera River. The uplift rate estimates mentioned in the text relate to the final post-Paleogene stage of accelerated cooling since  $\sim 20$  Ma.

1–Late Cretaceous uplift and cooling; 2–Paleogene period of thermal stagnation; 3– Post-Paleogene stage of accelerated cooling and uplift to surface temperature. Modified after Dobeš et al., 2018.

and Permian clastic sedimentary rocks filling the Krkonoše piedmont basin, respectively. These uplift rates were effective during the final, Neotectonic uplift of the region which affected the whole Bohemian Massif during the post-Paleogene time (e.g., Kopecký, 1972, 1989; Vyskočil, 1988; Suchý et al., 2007, 2015, 2019; Heberer et al., 2024).

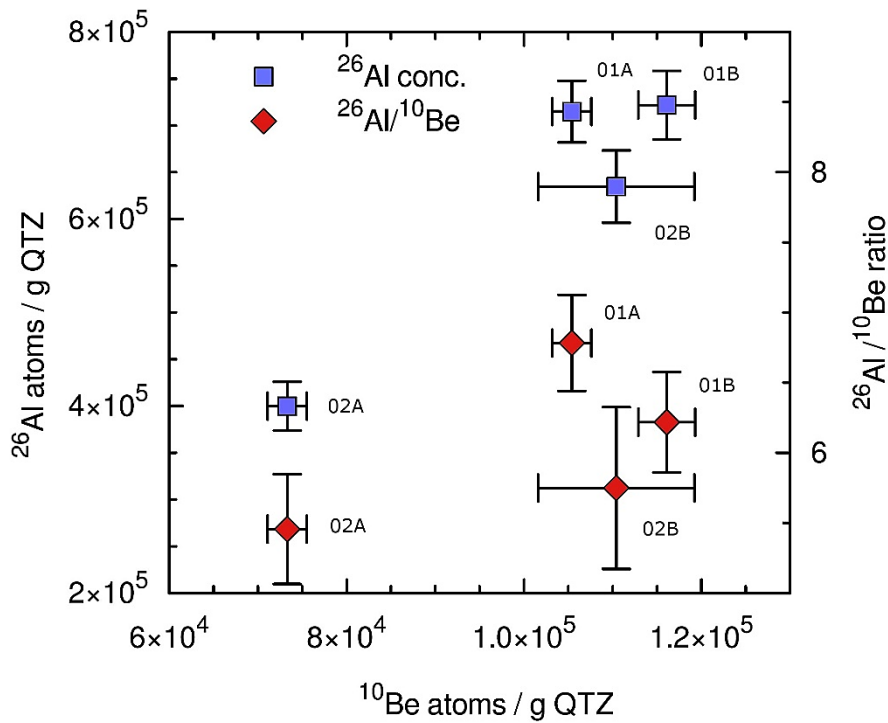
## DISCUSSION

Understanding the rates and distribution of geological erosion is crucial for comprehending landscape evolution, the impact of human activity on sedimentation, and soil health. Here, we report erosion rates using cosmogenic nuclides in the northern part of the Bohemian Massif. Initial results determined using  $^{10}\text{Be}$  alone showed erosion rates of 42–64  $\text{m Myr}^{-1}$ . Using  $^{26}\text{Al}$ , we obtained erosion rates of 49–84  $\text{m Myr}^{-1}$ . These rates are slightly higher than the 22–51  $\text{m Myr}^{-1}$  recently reported for Moldanubian rocks in the southern part of the Bohemian Massif using  $^{10}\text{Be}$  in river sands (Robl et al., 2025). It is also worth noting that in an early geochemical study by Pačes and Modan (1979), similar erosion rates were proposed for the Moldanubian gneisses forming the interior of the Bohemian Massif, based on geochemical cycling of Si and Na. The erosion rates of these crystalline rocks were largely controlled by the type of vegetation cover and/or human agricultural activities. While gneisses sheltered by heavy forests experienced only low intensity erosion (8.5–12.3  $\text{m Myr}^{-1}$ ), the naked, natural outcrops of these rocks, which were fully

exposed to weathering and decomposition in an open lowland agricultural landscape, revealed considerably higher erosion rates of 38–130  $\text{m Myr}^{-1}$ .

To enable a wider geomorphological comparison, we also estimated uplift rates for a similar region at 60–100  $\text{m Myr}^{-1}$  based on published AFTA data for the Krkonoše-Jizera granite (Dobeš et al., 2018), and at 45–80  $\text{m Myr}^{-1}$  for the Krkonoše basin (Svojtko et al., 2005). These uplift rate estimates are generally higher than newly calculated CN-based erosion rates. This points to the phenomenon of uplift rates predominating over erosion rates, which is recently observed in most mountainous collision zones throughout the world (Kukal, 1970; Ollier, 1981; see also England and Molnar, 1990; Hay et al., 2002 for the reviews).

The  $^{10}\text{Be}$  data alone suggest that the landscape is rather in dynamic equilibrium, a steady state. However, the multi-nuclide approach can test the key assumptions for erosion rate calculations: a) Cosmogenic steady-state/equilibrium (grains transported on or near the surface without burial); b) Short sediment transport time. The  $^{26}\text{Al}/^{10}\text{Be}$  surface production ratio would be expected to range from 6.75 to 7.15 (Balco, 2017). If the ratio is lower, then a burial event has occurred. Burial age dating (Granger and Muzikar, 2001) uses this principle to date geomorphic processes (Štor et al., 2019) and archaeological sites (Garba et al., 2024). Here, the Rakousy sample (JIZ23-01) shows a  $^{26}\text{Al}/^{10}\text{Be}$  ratio of  $\sim 6.21$ – $6.79$ , indicating nearly no burial and a short



**Fig. 5**  $^{26}\text{Al}$  and  $^{10}\text{Be}$  concentrations and  $^{26}\text{Al}/^{10}\text{Be}$  ratios. The  $^{26}\text{Al}$  and  $^{10}\text{Be}$  concentrations in quartz of the Jizera samples studied based on the AMS counting statistics provided in Table 2. Error bars represent the full analytical uncertainties ( $\pm 1\sigma$ ) for each value.

sediment transit time. However, the Mohelnice sample (JIZ-02), situated further downstream, yielded a  $^{26}\text{Al}/^{10}\text{Be}$  ratio of  $\sim 5.5$ – $5.8$ , indicating cosmogenic disequilibrium and a cumulative burial age of  $\sim 400$ – $500$  ka. This suggests that non-buried and buried floodplain sediments were mixed during transport between the Rakousy and Molenice locations. Long-term deposition is also evident from the significant loss of CN concentration due to nuclide decay, as can be seen in Table 2 and Figure 5. This indicates that the meandering Jizera River incised into Middle Pleistocene sediments and mixed with non-buried sediments during the relatively short drainage distance of  $\sim 23$  km between the Rakousy and Mohelnice sites. A similar case of cosmogenic disequilibrium was observed in the modern Amazon River, where the  $^{26}\text{Al}/^{10}\text{Be}$  concentration ratio was found to be  $\sim 3.8$ – $5.5$  (Wittmann et al., 2011). On the other hand, a study of the Po River catchment did not reveal sediment trapping or residence in the river floodplain (Wittmann et al., 2016). This suggests that local geomorphology plays a key role and that the multi-nuclide approach can detect such unconformities. A comprehensive investigation of the area, involving the collection of additional samples, is needed to improve our understanding of the Jizera transport process from source to sink. To offset the effect of mixing deeply buried sediments, we excluded the JIZ23-02A sample (labeled in Fig. 5), which produced exceedingly high erosion rates. Our calculated Jizera River erosion rates then range from 42 to 52 m  $\text{Myr}^{-1}$ .

The present analysis of  $^{10}\text{Be}$  concentrations in the alluvial deposits of the Jizera River also revealed that different sand fractions are being eroded with different rates. Medium to fine-grained sand grains (0.125–0.5 mm) generally exhibited higher erosion rates than the coarser 0.5–1.1 mm sand fraction. At the Rakousy location (JIZ23-01), variations in grain size related to respective erosion rates remain negligible, being within the uncertainty ranges. However, at the Mohelnice location (JIZ23-02), the finer fraction (JIZ23-02A) exhibits a notably higher erosion rate than the coarser fraction (JIZ23-02B). The finer fraction had an apparently longer burial history, suggesting different sediment transportation from source to sink. A precise mechanism behind this phenomenon is at present difficult to elucidate, as sediment grain size in alluvial systems is a complex function of many variables (e.g., Kukal, 1970; Schumm, 1977; van Dongen et al., 2019), the exact identification of which is beyond the potential of the single-nuclide ( $^{10}\text{Be}$ ) technique alone (e.g., van Dongen et al., 2019). It is apparent that a larger dataset and a more extensive geomorphological study is needed to detect statistically robust dependency patterns.

## CONCLUSIONS

In this pilot study, we presented the cosmogenic nuclide (CN)-based erosion rates in the northern Bohemian Massif, as well as the routine analyses of  $^{10}\text{Be}$  and  $^{26}\text{Al}$  concentrations, which were carried out

using a newly established CN sample preparation laboratory and accelerator mass spectrometry (AMS) facility at the Nuclear Physics Institute of the Czech Academy of Sciences. Using a multi-nuclide approach, we have detected a significant mixing of buried and non-buried sediments over a relatively short distance between individual sample localities. The multi-grain-size approach enabled to recognize the effect of an inflated erosion rate affecting only the fine-grain size fraction. Excluding sample JIZ23-02A, the results show erosion rates based on in-situ cosmogenic nuclides  $^{10}\text{Be}$  and  $^{26}\text{Al}$  of 42–52 m  $\text{Myr}^{-1}$  for the upper Jizera River catchment (Northern Bohemian Massif). Comparison of the calculated erosion rates of Jizera River sediments with uplift rate estimates of respective bedrocks provides a broader geomorphological context and supports the observation of uplift predominance over erosion in compressional tectonic zones. Future studies can build on these methodological foundations to conduct larger-scale, quantitative geomorphological assessments of erosion rates and compare them with rates calculated from respective bedrocks. Such approach can be instrumental in revealing the evolution of erosion processes over time. Moreover, combining these techniques with the analysis of in-situ  $^{14}\text{C}$  nuclide in quartz could reveal these thousand-year-long geomorphologic disturbances in more details, especially in relation to human activities.

#### AUTHOR CONTRIBUTIONS

Conceptualization: RG, VSu, BM | Methodology: RG, JK, VSu | Investigation: RG, JK, VSu, BM, VH | Funding acquisition: BM | Project administration: RG, BM | Writing original draft: RG, VSu, VSt, JK, BM | Writing review & editing: RG, VSu, JK, FV, VSt, VH, BM

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