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Abstract

This study examines the suitability of the authigenic 10Be/9Be dating method to the dating of the deposits of an incising river, taking as an example the Nová Vieska river terrace, which accumulated during the neotectonic inversion of the Danube Basin (western Slovakia). The succession was formed by a wandering river with minor preservation of proximal floodplain muds. The frequent occurrence of mud intraclasts reflects significant input of eroded material from underlying, older successions. The ages of 13 authigenic 10Be/9Be dating samples formed three groups: (1) samples from below the base of the river terrace yielded dates of ~4.13–3.70 Ma (including uncertainties); (2) muddy intraclasts from the river terrace gave an age range of ~2.79–1.96 Ma; and (3) in situ muddy layers had ages in the range of ~1.91–1.39 Ma. The large mammal fossil assemblage from channel thalweg deposits yielded a biostratigraphic age of ~3.6–2.2 Ma, matching the age of intraclasts, and thus emphasising the redeposited origin of those fossils. The relatively wide range of authigenic 10Be/9Be dating ages is interpreted as a result of the redeposition of mud from older strata on three scales: decimetre!scale intraclasts, millimetre!scale rip!up clasts mixed into the newly formed beds, and formation of two authigenic rims with different age and 10Be/9Be records around individual particles. Considering these observations, an age range of in situ layers of ~1.91–1.39 Ma is proposed as the depositional age of the river terrace, with the most probable age falling within the most recent part of this interval. The effect of redeposition is thus shown to be potentially limiting to

the application of authigenic 10Be/9Be dating to incising rivers, and stands in marked contrast to aggrading river settings, where redeposition of older sediments is limited and the degree of 10Be/9Be variability is low.

Key words: cosmogenic nuclides, authigenic beryllium, facies analysis, wandering river, redeposition, intraclasts, cryogenic deformations

1. Introduction

The authigenic $^{10}Be/^{9}Be$ dating method allows dating deposition of a clay-bearing sediment, provided that certain conditions are fulfilled (Bourlès et al., 1989; Lebatard et al., 2008; Šujan et al., 2016; Simon et al., 2020). Despite this great potential to maintain a depositional age for the most common type of sediment on the Earth (Schieber, 1998), limits of this method in continental environments are still not fully revealed. Complexity of factors possibly affecting the method rises from the different source of both isotopes employed in the system, as the radionuclide ^{10}Be being produced in the atmosphere by cosmic rays, while the stable ^{9}Be is derived by weathering of rocks. Both isotopes are mixed in a water column and incorporated into authigenic phase on the surface of sediment particles (Bourlès et al., 1989; Willenbring and von Blanckenburg, 2010; Wittmann et al., 2017; Bernhardt et al., 2020).

It has been shown that sedimentary successions accumulated in endorheic lacustrine basins, located in a craton setting with low tectonic activity and stable provenance, such as the Chad Basin in Africa, are beneficial for utilization of the method (Lebatard et al., 2008; Lebatard et al., 2010; Novello et al., 2015). The Danube Basin in more challenging conditions of an Alpine orogenic belt was proven to be suitable for dating using authigenic $^{10}Be/^{9}Be$, especially its alluvial sequence, thanks to the high accommodation to sediment supply rate (Šujan et al., 2016; Šujan et al., 2020). On the other hand, the alluvial succession in Upper Thrace Depression, Bulgaria, showed high authigenic $^{10}Be/^{9}Be$ variability preventing effective application of the method (Schaller et al., 2015), likely due to the significant tectonic activity of the pull-apart basins in this extensional province (Burchfiel et al., 2000).

This study aims to widen the knowledge about the applicability of the authigenic $^{10}Be/^{9}Be$ dating to alluvial sediments. A hypothesis to test is the assumption that one of the major factors affecting the beryllium isotopic ratio appears to be redeposition of older sediments, when river recycles its own floodplain during incision and older mud particles are incorporated into newly formed strata. The continuous growth of authigenic rims records changing $^{10}Be/^{9}Be$ ratio in a water column (Wittmann et al., 2017), whereas the shift in isotopic ratio might be caused by different age of the authigenic rim formation, associated to the process of redeposition of older mud particles.

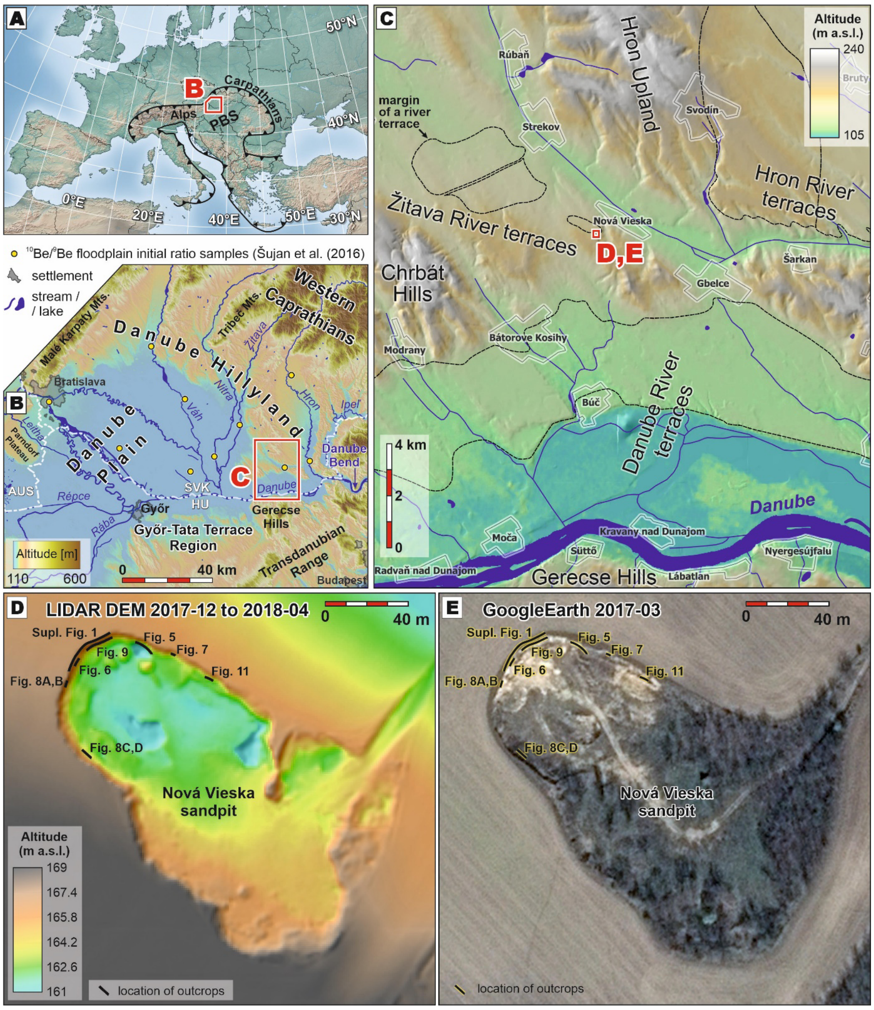

Fig. 1. Location of the study area. (A) Location of the Danube Basin within the Alpine-Carpathian orogenic belt. PBS – Pannonian Basin System (B) General topography of the Danube Basin and the present river network, with distribution of the samples used for calculation of the alluvial initial $^{10}Be/^{9}Be$ ratio in Šujan et al. (2016). (C) Topographic map of the vicinity of the Nová Vieska locality with marked margins of the river terraces of the Danube, Hron and Žitava rivers. (D) Lidar digital elevation model of the Nová Vieska sandpit showing the position of sampled outcrops. (E) GoogleEarth image of the Nová Vieska sandpit showing the position of sampled outcrops.

The Nová Vieska river terrace in the eastern Danube Basin (Slovakia) was selected for this study (Vlačiky et al., 2008; Vlačiky et al., 2017) (Fig. 1). The Early Pleistocene age of the locality was assumed based on the wealth of large mammal fossils, which were accumulated in coarse clastic channel-fill deposits. The succession was formed during inversion of the basin, when river gradually incised into its older alluvial sediments along with formation of river terrace staircases (Šujan and Rybár, 2014; Ruszkiczay-Rüdiger et al., 2018; Ruszkiczay-Rüdiger et al., 2020; Šujan et al., 2021). A detailed sedimentological analysis was performed with the goal to associate the observed authigenic $^{10}Be/^{9}Be$ variability to processes of alluvial mud redeposition in the river channel during the incision.

2. Geological setting

The Danube Basin is the northwesternmost depocenter of the Pannonian Basin System (Fig. 1A), and is surrounded by the Eastern Alps, Western Carpathians and the Transdanubian Range (Fig. 1A,B). It experienced four rifting phases during the period of ~16.0–9.5 Ma, with the last one giving rise to Lake Pannon in the region during the Late Miocene (Magyar et al., 1999; Kováč et al., 2011; Magyar et al., 2013; Sztanó et al., 2016; Šujan et al., 2021)(Fig. 2). The regression of Lake Pannon, caused by the progradation of deltaic to shelf slope depositional systems from the northwest to southeast (Magyar et al., 2013), led gradually to the dominance of alluvial deposition of the Volkovce Formation. High accommodation rate to sediment supply ratio conditions during sedimentation led to a high content of muddy floodplain facies reaching 50–80% (Šujan et al., 2020).

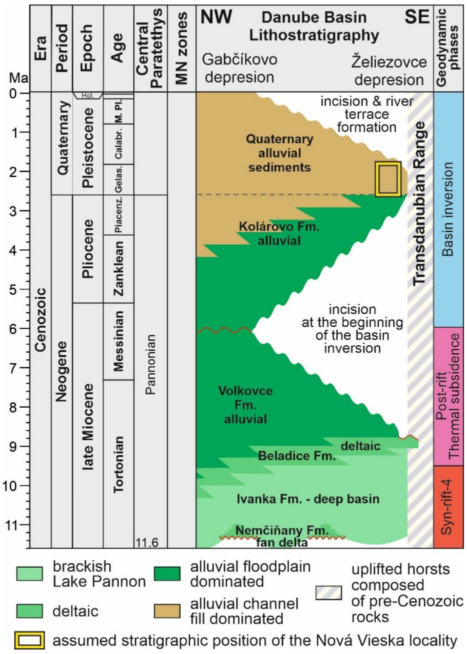

Fig. 2. Stratigraphy of the eastern Danube Basin with indication of the position of studied locality (Šujan et al., 2021). The studied succession was deposited during incision into thick underlying alluvial deposits, formed by the same rivers.

The floodplain-dominated sedimentation of the Volkovce Fm. ceased at ~6 Ma, when the basin inversion started (Tari, 1994; Vakarcs et al., 1994; Horváth, 1995; Horváth et al., 2006; Tari et al., 2020; Šujan et al., 2021). The basin inversion caused significant decrease in accommodation rates, uplift and partial denudation of the basin margins and subsidence of the central depression of the basin (Šujan et al., 2018) (Fig. 2). The syn-inversion alluvial deposition of the Kolárovo Formation gradually expanded from the central depression later on, and reached the margins of the basin at ~4–3 Ma (Ruszkiczay-Rüdiger et al., 2020; Šujan et al., 2021). The uplift of the margins overwhelmed the base-level rise after ~3 Ma, and river terraces started to be formed coevally with incision into the underlying alluvial Kolárovo Fm. and Volkovce Fm. (Šujan et al., 2021) (Fig. 2). One of the oldest sedimentary bodies deposited during this phase of the basin evolution is the Nová Vieska river terrace, investigated in this study. Base-level fall and low accommodation conditions led to the prevailing deposition of coarse-grained channel-fill facies in the regime of a wandering river in the Nová Vieska succession (Vlačiky et al., 2008). The uplift of the area continues up to the present day, what constraints active alluvial deposition mainly to the central depression of the basin (Fig. 2C). The Nová Vieska terrace is therefore in the middle of three terrace river systems, with Hron River stepping back to the east, Žitava River to the northwest and the Danube River to the south (Fig. 1C).

The Nová Vieska sandpit is located in an altitude range of 161 to 168 m a.s.l. (Fig. 1D), ca. 60 m above the water level on the present Danube River. The river terrace succession attains relatively low thickness not exceeding ~6 m. The walls facing northeast, southeast and southwest are excavated actively mostly due to the regular paleontological campaigns (Fig. 1D,E). The river terrace deposits are accumulated above the muds and sands of the floodplain that dominated Volkovce Fm. of the Late Miocene age (Vlačiky et al., 2008; Šujan and Rybár, 2014; Šujan et al., 2020).

3. Large mammal biostratigraphy

[A REVIEW OF PUBLISHED DATA TO BE ADDED]

Fig. 3. Overview of the large mammal fossil findings from the Nová Vieska sandpit and their chronostratigraphic range.

4. Methods

4.1 Sedimentology

The detailed facies analysis of the locality was performed by Vlačiky et al. (2008), nevertheless, continuous excavations led to exposure of new sedimentary bodies, allowing to verify the previous sedimentological assumptions. Hence, the sedimentological logs and schemes of the facies distribution on vertical outcrop walls was performed with two aims: (1) to interpret the depositional processes and asses the character of sedimentary environment, and (2) to precisely record the facies character of the strata sampled for dating, in order to understand possible variability in depositional processes that may affect the dating result. The field campaign and sampling took place during the years 2015, 2016 and 2017. The standard facies analysis of clastic sediments included description of grain size, structure, texture, geometry and size of the strata, and visualization of the gained information in logs and schemes (Stow, 2005; Miall, 2006). Paleocurrent directions of cross-strata were measured to evaluate the character of accretion of alluvial bars (Almeida et al., 2016), however, specific data are not presented due to the mainly geochronological focus of the study.

3.2 Authigenic $^{10}Be/^{9}Be$ dating

3.2.1 Principles of the method

The authigenic beryllium dating is based on the 10Be/9Be ratio measurement of stable nuclide ^{9}Be originating from chemical weathering of rocks, and of radioactive nuclide ^{10}Be produced by secondary cosmic rays in the atmosphere through spallation reaction on oxygen and nitrogen (Dunai, 2010). The ^{10}Be being very reactive gets adsorbed in aerosols and is transferred to the Earth surface in soluble form by precipitation (Raisbeck et al., 1981). ^{10}Be is removed from water column in aqueous settings and is incorporated in the authigenic phase, composed mostly of amorphous oxy-hydroxides, which cover the surface of sedimentary particles (Bourlès et al., 1989). The half-life of ^{10}Be of 1.387 ± 0.012 Ma (Chmeleff et al., 2010; Korschinek et al., 2010) offers the possibility to date the formation of the authigenic phase and hence deposition of sediments in the age range of 0.2 to 14 Ma (Ku et al., 1982; Bourlès et al., 1989; Lebatard et al., 2008), providing that the dated systems was chemically closed.

The age calculation is based on the radioactive decay of an initial concentration that follows the following equation : $N_{(t)}=N_0e^{-\lambda t}$, where $N_{(t)}$ is the authigenic $^{10}Be/^{9}Be$ ratio measured in the sample to be dated, N_0 is the initial authigenic $^{10}Be/^{9}Be$ ratio, λ is the ^{10}Be radioactive decay constant, and t is the time elapsed since deposition. This equation implies the essential need to establish the initial isotopic ratio, which depends on several factors such as the drainage basin lithology, denudation intensity, the latitude of the study area, depositional environment conditions and the proximity of the source of sediment to the place of deposition (Brown et al., 1992; Graham et al., 2001; Graly et al., 2010; Wittmann et al., 2012; Wittmann et al., 2017). Thus, the initial isotopic ratio might be established by analysis of samples taken from the same basin and with similar depositional conditions as the dated samples, which are either of the age 0–200 ka and assumed as actual, or of an independently determined age and the time elapsed is included in the calculation of the initial ratio. The analysis of a set of Holocene floodplain samples distributed across the Danube Basin (Fig. 1B) yielded a relatively low variability of authigenic $^{10}Be/^{9}Be$ values, what allowed to calculate the initial ratio for alluvial deposits used in this study with the value of $4.14 \pm 0.17 \times 10^{-9}$ (Šujan et al., 2016). Of course, the main assumption is that this ratio has remained stable through time

3.2.2 Sampling strategy and sample processing

Application of the authigenic $^{10}Be/^{9}Be$ dating to the Nová Vieska river terrace was decided as reasonable, since (1) the low thickness of the accumulation <6 m is expected to cause saturation of the *in situ* cosmogenic nuclide production in the context of the expected age of ~1.8–2.6 Ma, which would provide only a minimum exposure age, and (2) a relatively frequent presence of muddy alluvial strata within the sandy-gravelly succession, suitable for the method.

The samples for the authigenic $^{10}Be/^{9}Be$ dating were collected subsequently during the years 2015, 2016 and 2017, as new sedimentary units were exposed by continuous excavation. The sampling was focused on the muddy alluvial strata deposited either as overbank fines, or as oxbow lake fills or muddy accretion on bars. All the mentioned types of sampled facies are denoted here as *in situ* strata and provided 8 samples. In addition to the *in situ* strata, three samples were taken from redeposited intraclasts of alluvial mud. The lithology of the sampled intraclasts was visually comparable to the *in situ* layers. The strata, from which *in situ* as well as intraclast samples originate, are considered to represent single succession of a river terrace. Two samples were taken from the thick, muddy horizon, which appeared below the base of the river terrace.

The six samples taken in 2015 (first group) were processed at CEREGE, Aix-en-Provence (France), while the seven samples taken in the following years 2016 and 2017 (second group) underwent processing in the laboratory of the Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava (Slovakia). The workflow applied at both laboratories followed the methodology described by Bourlès et al. (1989) and Carcaillet et al. (2004). The authigenic phase was extracted from powdered samples using a leaching solution of acetic acid, hydroxilamonium hydrochloride and demineralized water. Aliquots taken from the resulting solution were analyzed to determine the concentrations of ^{9}Be using atomic adsorption spectrometry (AAS – first group) and by inductively coupled plasma mass spectrometry (CP-MS – second group). Replicability and consistency of both approaches was tested with positive results. The following processing involved addition of 300 mg (first group) or 450 mg (second group) of the Scharlau beryllium ICP standard solution (1000 ppm) with ^{10}Be/^{9}Be ratios in the range of $6–8 \times 10^{-15}$ (Merchel et al., 2021). Samples were evaporated and resin chemistry was applied to separate beryllium from other elements present in the authigenic phase (Merchel and Herpers, 1999). The purified samples were oxidized at 700°C for one hour in an oven, mixed with Niobium powder then transferred to copper cathodes for accelerator mass spectrometer (AMS) measurements. AMS measurements of ^{10}Be/^{9}Be isotopic ratios were done at the French national facility ASTER (CEREGE, Aix-en-Provence, France).

The AMS $^{10}Be/^{9}Be$ ratios of all samples reached values at least two orders of magnitude higher comparing to the two processing blanks and were normalized to their isotopic ratios. The calculated ages with one σ uncertainties were statisctically processed by KDX application on the Fig. 4 (Spencer et al., 2017).

3.3 Burial $^{26}Al/^{10}Be$ dating

Application of the burial $^{26}Al/^{10}Be$ dating to river sediments follows an assumption that quartz-bearing material was exposed on the Earth's surface to cosmic rays, then underwent denudation and fluvial transport, and finally was deposited and buried by aggradation of an alluvial succession. Nuclear reactions caused by interaction of quartz material with high-energy neutrons and muons included in secondary cosmic rays result in production of terrestrial cosmogenic nuclides ^{10}Be and ^{26}Al (Braucher et al., 2013; Balco, 2017). Considering long-enough surface exposure of a quartz clast, the $^{26}Al/^{10}Be$ ratio obtained at surface (denudational steady state) and is decreasing after burial due to radioactive decay with different half-lives of both radionuclides (e.g., Gosse and Phillips, 2001; Granger and Muzikar, 2001). Nevertheless, a depth of ~40 m below a rock or sediment is required for total shielding of cosmic rays, and hence post-burial production of cosmogenic nuclides may be involved into burial age calculation in the case of lower thickness of the overlying strata. The absolute concentrations of both nuclides together with their ratio could be employed also in determination of the maximum denudation rate before the burial of a sample (von Blanckenburg, 2005).

Sediment of the sandy-gravelly lithofacies SGmp was sampled in the position with thickest overburden reaching 6.6 m, providing the best available shielding for the burial dating. Nevertheless, the relatively low burial depth allows for calculation of only a minimum burial age. The sample was sieved and separated into two sub-samples, first containing quartz and quartzite pebbles (sample 6.6A) and the second one consisting sieved sandy fraction 0.25–1.00

mm (sample 6.6B). The sample composed of pebbles was crushed and sieved to the fraction 0.25–1.00 mm.

Chemical processing of the samples was performed at CEREGE, Aix-en-Provence (France). The samples underwent magnetic separation and two rounds of leaching in a solution of hexafluorosilicic and hydrochloric acid to eliminate other silicates (Merchel et al., 2019). The following sequential leaching in HF was repeated three times to dissolve the surficial parts of the grains potentially contaminated by the atmospheric ^{10}Be. An amount of ~100 µl of a (3025 ± 9) ppm of ^{9}Be in-house standard solution (Merchel et al., 2008) was added to the pure quartz, which was then totally dissolved in HF. An aliquot for ICP-OES measurements of concentrations of stable aluminium was taken after evaporation of the solution. Standard procedures of ion exchange chromatography were applied to separate Be and Al (Merchel and Herpers, 1999). Beryllium and aluminum hydroxides were oxidized and cathoded for AMS measurements, which were performed at French national facility ASTER (CEREGE, Aix-en-Provence, France).

5. Results

5.1 Facies analysis

Description of eight distinguished facies, their internal fabric, geometry and interpreted depositional processes are included in Table 1. The depositional record exhibits a prevailing coarse-grained nature, with the alternation of sandy-gravelly and sandy units. *In situ* muddy strata represent <15% of the documented succession. Lithofacies SGpm, St and Stb comprise the major volume reaching ca 60–70% proportion (Figs. 5–8). Lithofacies Sl is common, forming up to 20% locally (Fig. 5), while lithofacies Sr is rare and appears in few centimeters thin horizons or lenses (Fig. 6). All lithofacies are frequently arranged in inclined units of variable lithology 0.5 to 2.5 m thick (Figs. 5, 6, 8).

Beside the primary structures summarized in the Table 1, the locality Nová Vieska shows a wide range of penecontemporaneous deformations. Fig. 9 shows large involution structure (Vandenberghe, 2013), reaching thickness of >3 m in the lower part of the outcrop. The deformation partly preserves original structures, since rotated trough cross-bedding is observable in a number of horizons in Fig. 9E. The involution of strata caused sub-vertical orientation of the remnants of the primary bedding locally (Fig. 9F). The large involution is associated with decimeter-scale graben-like brittle collapse features, bounded by small faults, but also showing bending on the margins (Fig. 9G). The involution structure is cut by an erosional surface, while the overlying facies of Stb and St are undeformed.

Relatively common deformations comprise sand wedges reaching height of 5–20 cm (Fig. 10A). The deformation is limited from the lower part, includes bending of the surrounding strata and filling of the wedge by the overlying strata. Symmetrical rounded few centimeters to 15 cm high bending of the strata downwards with decreasing intensity of deformation towards the base is observed rarely (Fig. 10B).

Table 1. Description and interpretation of the lithofacies documented in the outcrops.

Code	Lithofacies description	Lithofacies geometry	Depositional process	Sedimentary environment	References
SGpm	coarse-grained sand with granules and mud intraclasts, ocasionally pebbles, massive to poorly-visible cross stratification, redeposited large mammal fossils	tabular and lenticular bodies with sharp base of complicated morphology and sharp upper boundary, 10–60 cm thick	rapid deposition from a wanning flow with high concentration of coarse-grained sediment	decelerating flood in a river channel	Mulder and Alexander (2001); Carling and Leclair (2019); Ghinassi and Moody (2021)
St	trough cross-stratified medium to coarse sand, occasionally with fine gravel or mud intraclasts at the base	lenticular body with sharp concave upwards base and sharp upper boundary, 10–50 cm thick	sandy bedload channelized traction current	3D dunes migrating in shallow parts of a channel and across bars	Allen (1982); Leclair and Bridge (2001); Reesink and Bridge (2011); Naqshband et al. (2017)
Stb	trough and planar cross-stratified units, foresets composed of various lithology (mud, intraclasts, fine- to coarse-grained sand, granules), strata form commonly internal angular contacts, foresets are occasionally formed by small scale trough cross-stratified sands and ripple cross-stratified sands with paleocurrent direction perpendicular to the foreset dip direction	lenticular body with sharp base of complicated morphology and sharp upper boundary, 20–60 cm thick	traction current of variable speed from ≤10 $cm \cdot s^{-1}$ to ~100 $cm \cdot s^{-1}$, flowing over an inclined surface	unit bar in a river channel, foresets formed by collapse of superimposed bedforms at the brink point (downstream accretion), or by bedforms migrating parallel to the bar surface strike (lateral accretion)	Miall (1985); Almeida et al. (2016); Reesink (2018)
Sl	medium- to coarse-grained sand with low angle inclined stratification, commonly lamination parallel to the basal acretionary surface, internal low-angle angular contacts of strata common	tabular bodies few cm thick with sharp boundaries	channelized traction current of upper plane bed flow to supercritical flow	upper plane beds to antidunes formed above bars in river channel during floods with increased flow speed	Bennett and Best (1997); Fielding (2006); Naqshband et al. (2017)
Sr	unidirectional ripples formed from medium- to fine-grained sand to silt	tabular body few cm thick with fluent boundaries or few cm thick lenticular body	shallow or slow traction current	ripples formed on a bar surface, in shallow channel or proximal overbank settings	Allen (1982); Baas (1999); Yawar and Schieber (2017)
Sm, FSm	massive medium to fine sand, containing muddy intraclasts, massive sandy mud	lenticular bodies 5-20 cm thick, with concave sharp erosional base and sharp upper boundary	rapid deposition from a wanning flow	suddenly decelerating flood in abandoned shallow channel, in an oxbow lake or in a proximal floodplain	Mulder and Alexander (2001); Baas et al. (2016), Burns et al. (2017)
Fl	planar laminated mud, beige to light grey, lamination subhorizontal or pallalel to the basal surface	continuous horizons few centimeters to 20 cm thick, with sharp lower and upper boundary	deposition from a slow traction current or from suspension	slack water deposition above a bar, in an oxbow lake or in a proximal floodplain	Aslan and Autin, (1999); Yawar and Schieber (2017)
Fm	massive mud, beige to light grey, locally lateral transition to intraclasts	continuous horizons and lenticular bodies few centimeters to 30 cm thick, with sharp lower and upper boundary	deposition from suspension of a high mud-concentrated wanning flow	decelerating flood with high content of mud, oxbow lake or proximal floodplain	Toonen et al. (2011); Baas et al. (2016)

5.2 Authigenic $^{10}Be/^{9}Be$ dating

Measured concentrations of nuclides, natural authigenic $^{10}Be/^{9}Be$ ratios and calculated ages are included in Table 2 and depicted on Fig. 4. Natural $^{10}Be/^{9}Be$ range from 5.541×10^{-10} to 20.175×10^{-10}. Ages reach values from 1.438 ± 0.048 Ma to 4.024 ± 0.111 Ma. The highest ages of 4.024 ± 0.111 Ma and 3.802 ± 0.094 Ma were yielded by the samples NV-2-4 and NV-2-5 taken from the basal muddy horizon, present below the base of the river terrace. Another group of ages is represented by the intraclast samples NV-1-4, NV-1-5 and NV-1-6, which attain 2.701 ± 0.093 Ma, 2.484 ± 0.096 Ma and 2.031 ± 0.076 Ma. The remaining seven samples originating from *in situ* layers reach ages in the range from 1.852 ± 0.060 Ma to 1.438 ± 0.048 Ma, except for the age 2.303 ± 0.093 Ma of sample NV-1-1, which appears to be an outlier. The ages of *in situ* samples are not distributed systematically regarding their vertical or lateral position.

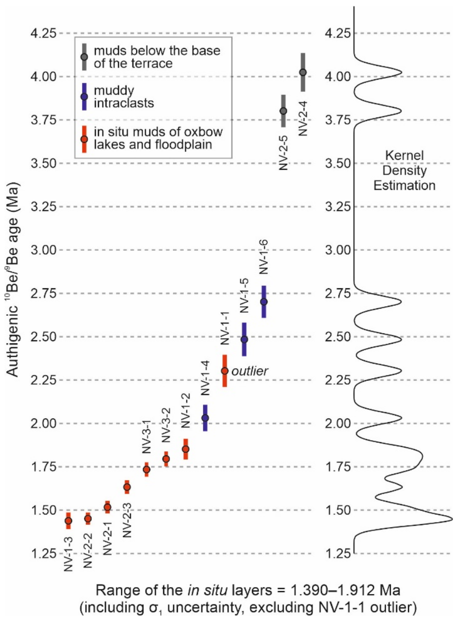

Fig. 4. Distribution of the authigenic $^{10}Be/^{9}Be$ ages depicted in ascending order of the values and Kernel Density Estimation, obtained by KDX application (Spencer et al., 2017). Depicted uncertainties are σ_1.

Table 2. Concentrations of ^{9}Be and ^{10}Be, ^{10}Be/^{9}Be ratios and calculated ages for the analyzed samples. Uncertainties are σ_1. Concentrations of ^{10}Be are corrected to the ^{10}Be/^{9}Be ratios of the two processing blanks reaching values of 7.75×10^{-15}, (sampling in 2016 and 2017) and 1.52×10^{-14} (sampling in 2015).

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Sample ID	Year of sampling	Sample type	AMS ^{10}Be/^{9}Be [$\times 10^{-12}$]	AMS uncertainty ^{10}Be/^{9}Be [%]	^{9}Be measurement	Natural ^{9}Be [atom g $\times 10^{16}$]	^{9}Be standard deviation [%]	Natural ^{10}Be [atom g $\times 10^{7}$]	Uncertainty ^{10}Be [atom · g $\times 10^{7}$]	Natural ^{10}Be/^{9}Be [$\times 10^{-10}$]	Uncertainty ^{10}Be/^{9}Be [$\times 10^{-10}$]	Authigenic ^{10}Be/^{9}Be depositional age [Ma]
NV-1-1	2015	in situ layer	1,545	3,503	AAS	2,391	2,941	3,132	0,110	13,098	0,528	2,303 ± 0,093
NV-1-2	2015	in situ layer	3,332	2,555	AAS	4,122	0,959	6,764	0,173	16,411	0,533	1,852 ± 0,060
NV-1-3	2015	in situ layer	3,041	2,674	AAS	3,046	1,398	6,145	0,164	20,175	0,674	1,438 ± 0,048
NV-1-4	2015	intraclast	2,936	3,171	AAS	3,961	1,429	5,942	0,188	15,002	0,562	2,031 ± 0,076
NV-1-5	2015	intraclast	2,736	3,323	AAS	4,622	1,441	5,529	0,184	11,963	0,464	2,484 ± 0,096
NV-1-6	2015	intraclast	2,503	2,800	AAS	4,712	2,931	5,057	0,142	10,733	0,369	2,701 ± 0,093
NV-2-1	2016	in situ layer	3,941	1,312	ICP-MS	6,252	5,438	12,128	0,159	19,397	0,464	1,517 ± 0,036
NV-2-2	2016	in situ layer	5,001	1,392	ICP-MS	7,667	4,980	15,371	0,214	20,049	0,489	1,451 ± 0,035
NV-2-3	2016	in situ layer	3,566	1,336	ICP-MS	5,944	5,074	10,882	0,145	18,306	0,440	1,633 ± 0,039
NV-2-4	2016	basal muds	1,739	1,912	ICP-MS	9,516	3,376	5,272	0,101	5,541	0,153	4,024 ± 0,111
NV-2-5	2016	basal muds	2,183	1,435	ICP-MS	10,785	1,968	6,679	0,096	6,193	0,152	3,802 ± 0,094
NV-3-1	2017	in situ layer	3,349	1,335	ICP-MS	5,896	2,692	10,261	0,137	17,403	0,419	1,734 ± 0,042
NV-3-2	2017	in situ layer	3,368	1,332	ICP-MS	6,084	4,145	10,270	0,137	16,881	0,406	1,795 ± 0,043

5.3 Burial $^{26}Al/^{10}Be$ dating

Commenté [RB2]: do you need this part and in general the 2 burial ages?

The two sub-samples analyzed from the same sampling point yielded comparable concentrations of ^{10}Be atoms. However, they show almost two-fold difference in concentration of ^{26}Al atoms with increased content in the sample consisting of the sieved sand. If both ages are considered as minimum burial ages due to the low burial depth, the data indicate burial age of the sampled horizon of at least 1.34 ± 0.32 Ma.

Table 3. ^{10}Be and ^{26}Al isotopic concentrations, $^{26}Al/^{10}Be$ ratios paleo-denudation rates and burial age of the analyzed samples.

Sample ID	Depth [m]	Sample type	^{10}Be [at·g^{-1}]	^{26}Al [at·g^{-1}]	$^{26}Al/^{10}Be$	Denudation before burial [m·Ma^{-1}]	Burial age [Ma]
6,6A	6,60	crushed gravels	80905 ± 4184	287955 ± 67130	3.56 ± 0.85	22,07	1.34 ± 0.32
6,6B	6,60	sieved sand 0.25–1.00 mm	88890 ± 6696	488964 ± 100507	5.5 ± 1.2	31,83	0.45 ± 0.1

6. Sedimentological interpretations

6.1 Depositional processes

Lithofacies SGpm was deposited during waning of a surge-type flow with high concentration of gravelly and sandy sediment, what led to low effectivity of turbulence causing low degree of sorting and only a weak development of stratification, which is even missing locally (Mulder and Alexander, 2001; Cartigny et al., 2013; Carling and Leclair, 2019; Ghinassi and Moody, 2021) (Figs. 5E, 6C). The base of SGpm units is usually complicated and erosional, and SGpm commonly contains intraclasts of the underlying cohesive strata (Fig. 6C). Trough cross-stratified sands were deposited as 3D dunes by traction currents (Allen, 1982; Leclair and Bridge, 2001; Reesink and Bridge, 2011; Naqshband et al., 2017) (Figs. 5D, 7, 10).

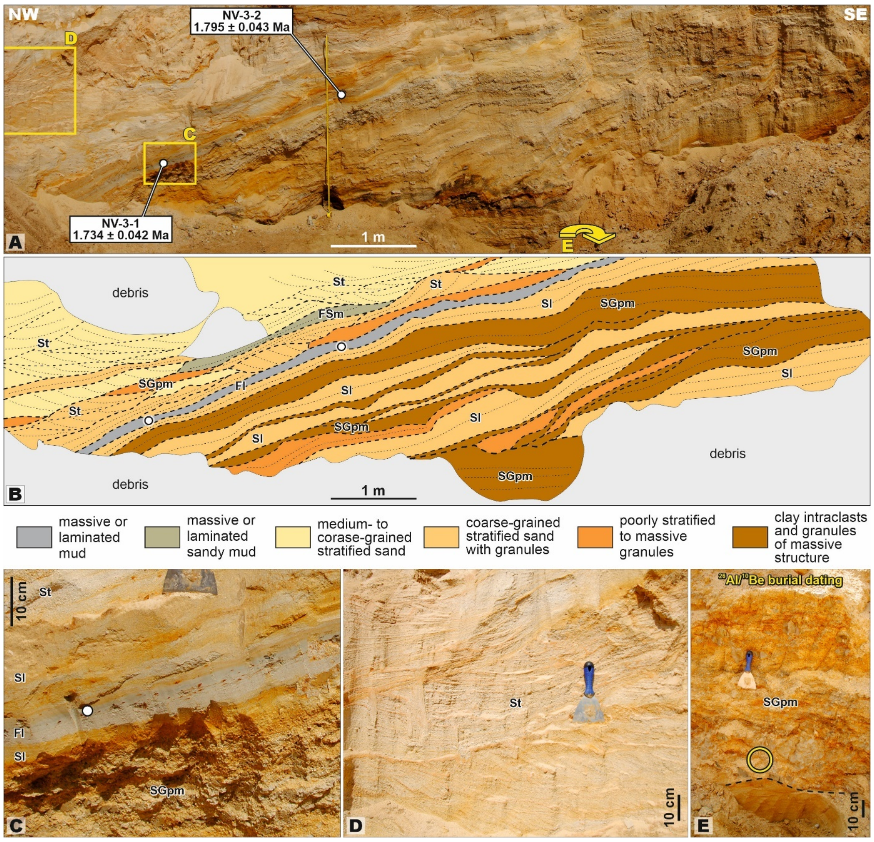

Fig. 5. Outcrop wall oriented in NW-SE direction and sampled for authigenic $^{10}Be/^{9}Be$ (white dots) and burial $^{26}Al/^{10}Be$ dating. (A,B) Inclined strata forming ca 2.5 m thick bar with variable lithology, implying changes in the current speed and sediment concentration. Orientation of trough-cross strata indicate lateral accretion origin of the bar. (C) Laminated mud strata sampled for the dating. (D) Trough cross-stratified strata. (E) Poorly sorted gravelly sand with intraclasts. For location of the outcrop, see Fig. 1D,E.

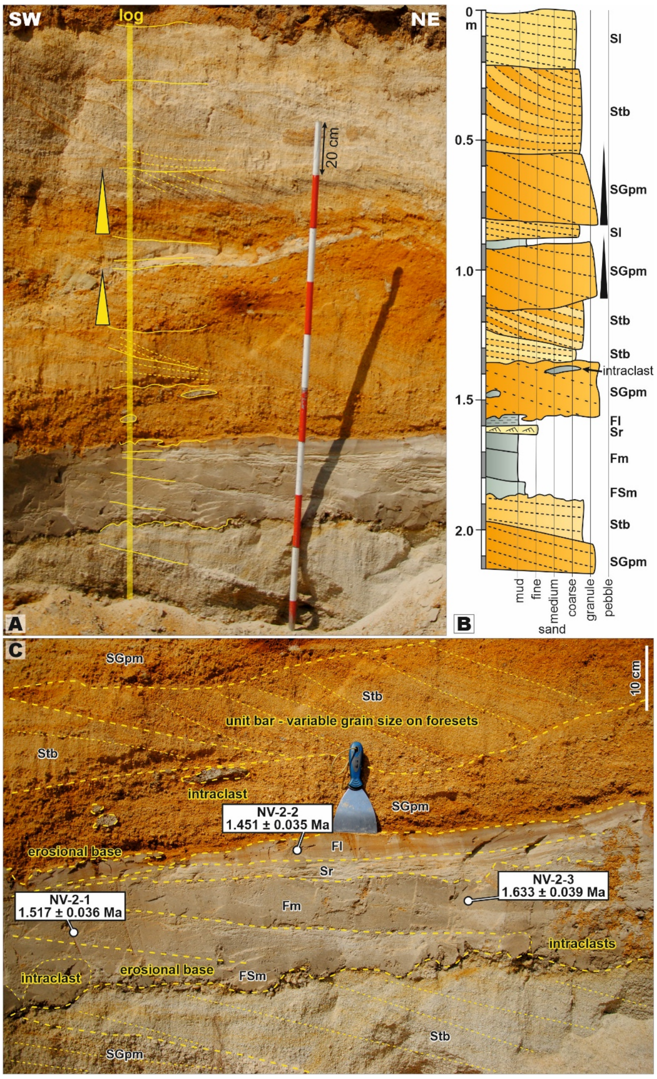

Fig. 6. Outcrop wall oriented in SW-NE direction and sampled for authigenic $^{10}Be/^{9}Be$ (white dots). Note the up to 30 cm thick, muddy horizon of a shallow oxbow lake fill and angular contacts within the unit bar of the Stb lithofacies on (C). For location of the outcrop, see Fig. 1D,E.

Facies Stb consisting of inclined strata of variable lithology from gravel to mud, and with presence of trough or ripple cross-strata within the inclined accretion units, represent fluvial bars formed in a channel (Miall, 2006; Almeida et al., 2016; Reesink, 2018; Herbert et al., 2020). The large variability of grain size indicates significant changes in the flow speed, while internal angular contacts of the accretion units resulted from erosion preceding reactivation of a bar. According to the geometry of the accretion, it is possible to distinguish downstream-accreted unit bars (Fig. 8A,B) (Reesink, 2018), and laterally accreted point bars (Fig. 8C,D), where paleocurrent depositing superimposed dunes was oriented perpendicular to the direction of accretion (Almeida et al., 2016).

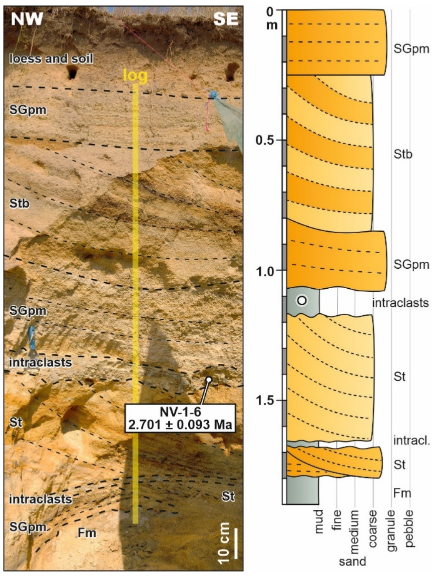

Fig. 7. Outcrop wall oriented in NW-SE direction and sampled for authigenic $^{10}Be/^{9}Be$ (white dot). The sample originate from a layer of accumulated intraclasts. For location of the outcrop, see Fig. 1D,E.

Medium- to coarse-grained sands showing subhorizontal or slightly inclined stratification or stratification parallel to an accretion surface of a bar is included in the lithofacies Sl (Figs. 5, 6, 9). It is interpreted to form upper stage plane beds or antidunes deposited by transitional or supercritical flow (Bennett and Best, 1997; Fielding, 2006; Naqshband et al., 2017). Silty, fine- to medium-grained sandy ripple cross-strata were deposited as ripple bedform by an unidirectional traction current with low speed and/or low depth (Allen, 1982; Baas, 1999; Yawar and Schieber, 2017) (Fig. 6C). On the other hand, bodies of massive fine- to medium-grained sand (Sm) or sandy mud with intraclasts (FSm) were accumulated from a wanning surge-type flow with high concentration of sediment, possibly in an abandoned channel, in an oxbow lake or in a proximal floodplain, depending on whether the unit forms a lens in a depression or a more continuous horizon (Mulder and Alexander, 2001; Baas et al., 2016) (Fig. 6C).

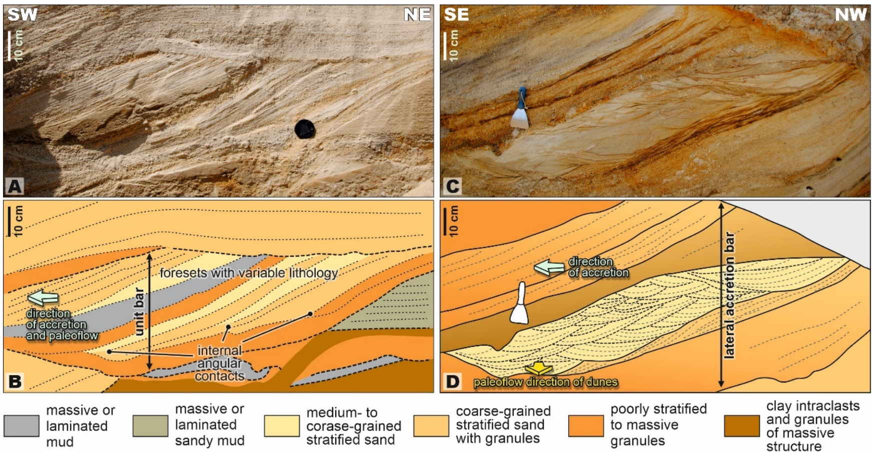

Fig. 8. Examples of a unit bar (A,B) and of lateral accretion bar (C,D). (A,B) Note the variable lithology and internal angular contacts in the unit bar, indicating variable transport capacity of a flow. (C,D) Note the perpendicular direction of bar accretion and of general paleoflow orientation indicated by trough cross-stratifications in the lateral accretion. For location of the outcrop, see Fig. 1D,E.

Planar laminated mud of the lithofacies Fl is interpreted as a deposit of slow traction current ($<0.25\ m \cdot s^{-1}$) or of a suspension fallout in slack water conditions (Aslan and Autin, 1999; Yawar and Schieber, 2017) (Figs. 5C, 6, 9C,D). It was formed above a bar, in an oxbow lake or in a proximal floodplain, depending on the relation to the geometry of underlying strata. The last observed lithofacies consisting of massive mud (Fm) is frequently associated with intraclasts and its appearance indicates rapid deposition from a wanning flow with high concentration of mud, likely represented by a flood decelerating in an oxbow lake or in a proximal floodplain (Toonen et al., 2012; Baas et al., 2016).

6.2 Deformations

The large-scale involution in Fig. 9 was formed during the deposition of the studied succession, since it is overlain by undeformed strata accumulated in a river channel (Stb, St and Sl facies). The deformed horizon also comprises river channel deposits, as indicated by the remnants of trough cross-stratification within the deformed beds. The preservation of primary bedding and the geometry of involution imply a plastic deformation by a relatively continuous process, what does not favor seismic shock as a trigger. The sediment was likely under the influence of a nearby stream, which deposited the overlying strata later, and hence the strata were saturated with water. Accordingly, changes in rheology during freeze-thaw cycles and related loss of frictional strength could be considered as the formation process of the involution (van Vliet-Lanoë et al., 2004; Vandenberghe, 2013). The decimeter-scale graben-like collapses (Fig. 9G) are likely associated with local extension due to frost contraction of the deformed unit. The evidence for deformation of the studied strata by cryoturbation is supported by the common presence of sand wedges (Fig. 10A). The wedges exhibit features of frost contraction, forming of an open crack, which is than filled by the overlying sediment (Murton et al., 2000). Flame structures and plastic deformation of the muds located below the base of river terrace (Fig. 11) could be also explained by plastic deformation due to differential loading by freeze-thaw cycles (Horváth et al., 2005; Vandenberghe, 2013). The cryogenic deformation of the basal muddy horizon indicates its surface exposure during glacial. All comparable structures of cryogenic deformation are commonly present in the region (Horváth et al., 2005; Ruszkiczay-Rüdiger and Kern, 2016).

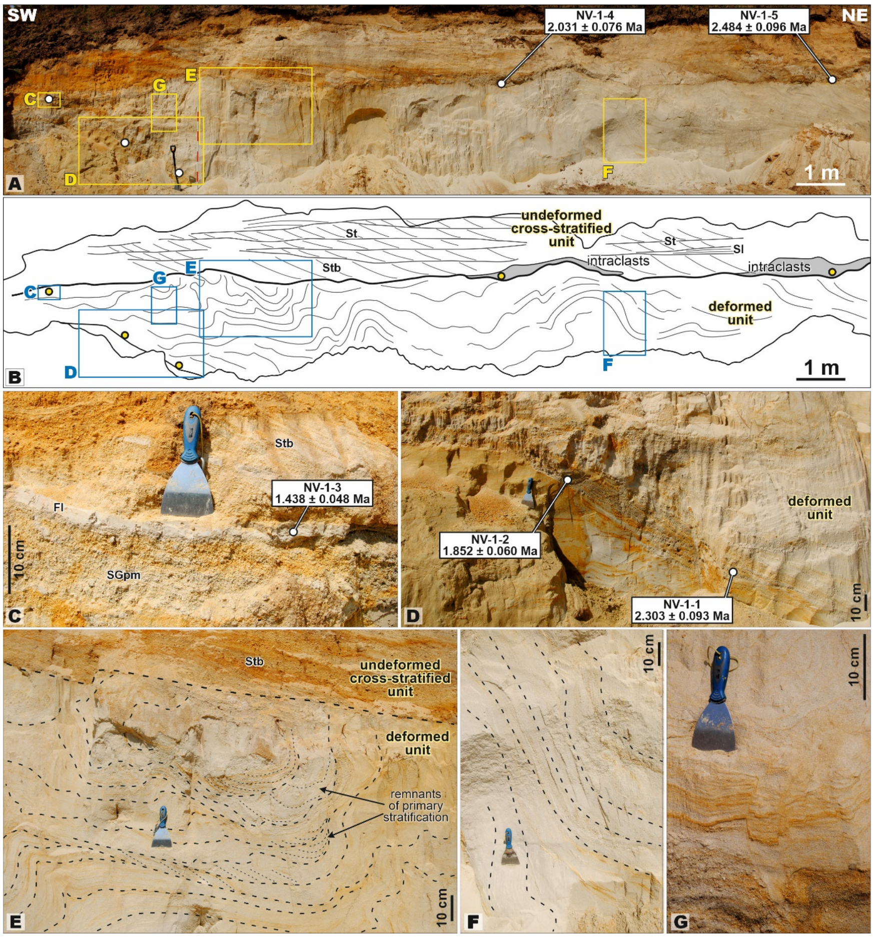

Fig. 9. Outcrop wall oriented in SW-NE direction and sampled for authigenic $^{10}Be/^{9}Be$ (white dots). (A,B) the lower unit exhibits intense deformation of the whole ca. 2.5 m thickness, while the original structures of the upper unit are preserved. Orientation of trough-cross strata indicate lateral accretion origin of the bar. (C,D) Laminated mud strata sampled for the dating. (E) Detail of the deformation with preserved remnants of the original trough cross-stratification. (F) Detail fo the deformation with almost vertically oriented strata. (G) Small-scale brittle collapse structure within the lower deformed unit. For location of the outcrop, see Fig. 1D,E.

The most rarely present deformation is symmetrical downwards bending of strata with decreasing intensity downwards (Fig. 10B). These marks are geometrically similar as foot tracks of large mammals (Nadon et al., 2001; Fornós et al., 2002; Milán et al., 2015). However, their isolated presence in the outcrops, a relatively deep reach of the deformation and the absence of some mixing of the uppermost strata due to the impact of a foot makes this interpretation problematic. Another explanation might be deformation of the sediment by a growing tree root (do Nascimento et al., 2019). Remnants of limonitized wood are common in the SGpm facies (Vlačiky et al., 2017).

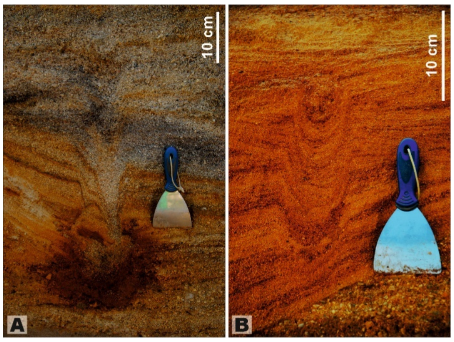

Fig. 10. Examples of deformations observable in the Nová Vieska locality. (A) Sand wedge formed by cryoturbation. (B) A mark possibly formed as a foot trace of a large mammal, or due to growth of a tree root.

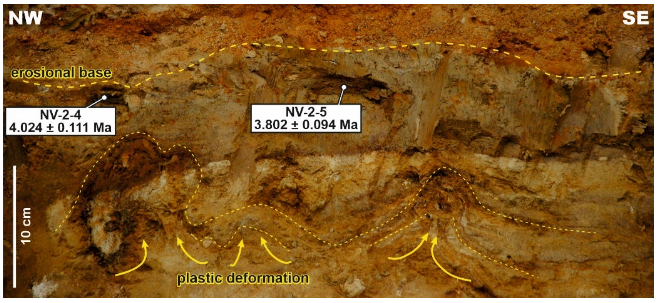

Fig. 11. Basal muds appearing below the base of the river terrace. Note the flame structure plastic deformations. For location of the outcrop, see Fig. 1D,E.

6.3 Sedimentary environment

Thickness of the bars deposited within fluvial channels vary considerably, from 0.4 m (Fig. 8) to the highest observed thickness of 2.5 m, represented by the inclined sedimentary unit in Fig. 5A,B. Thickness of a bar is generally equal to the depth of a channel, hence, the studied succession was likely accumulated by a network of channels with various depth (Bridge and Tye, 2000). Presence of both types of unit bars of downstream accretion and lateral accretion, together with low accommodation to sediment supply ratio indicated by low preservation of muddy overbank and oxbow lake facies, and indication of variable channel sizes all point to the interpretation of sedimentary environment of a wandering river (Forbes, 1983; Miall, 2006; Long and Lowey, 2011)(Fig. 12A), in agreement with the previous sedimentological research performed at the locality by Vlačiky et al. (2008). The river regime was characteristic by a deposition from perennial flow with significant proportion of surge-type flows, indicating some discharge variability was present, potentially linked to climate causes (Fielding et al., 2018; Alexander et al., 2020; Hansford et al., 2020; Herbert et al., 2020).

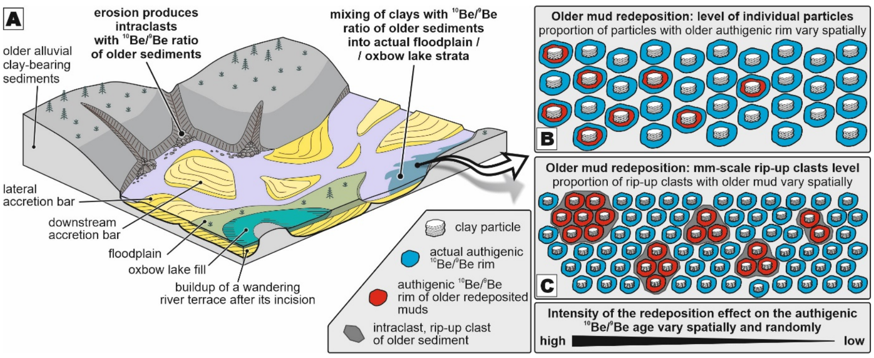

Fig. 12A. Block-diagram, showing a wandering river facies model as a sedimentological interpretation of the studied succession. The model implements incision and redeposition of underlying alluvial succession as a factor affecting the authigenic ^{10}Be/^{9}Be dating. Facies model modified from Miall (2006). B. Schematic hypothesis of redeposition of older mud into younger sediment by mixing at the level of individual particles. Two authigenic rims are formed around the redeposited particles, with inner one preserving the $^{10}Be/^{9}Be$ ratio of the older bed. C. Schematic hypothesis of redeposition of older mud into younger sediment at the level of millimeter-scale intraclasts/rip-up clasts. The redeposition effect on a measured $^{10}Be/^{9}Be$ ratio of a sample is expected to vary spatially, driven by the stochastic character of random distribution of the redeposition intensity in an incising river paleoenvironment.

Considering the geomorphological position of the studied accumulation as a river terrace surrounded by hills composed of older sediments (Fig. 1C), timing of the sedimentation during the basin inversion and base-level fall recorded in the river terrace staircase formation, and abundant occurrence of clay intraclasts composed of floodplain facies, all mentioned features point to the incision, denudation of the older alluvial deposits and their redeposition as an important aspect of sedimentary environment of the Nová Vieska succession (Fig. 12).

7. Depositional age and redeposition as a factor affecting the authigenic $^{10}Be/^{9}Be$ dating

The authigenic ages show a relatively large time span, however, separating them into three groups allows determination of a narrower depositional age interval for the Nová Vieska succession. The two ages 4.024 ± 0.111 Ma and 3.802 ± 0.094 Ma obtained from the muds below the base of the river terrace imply their affinity to the Pliocene Kolárovo Formation. Thus, this formation related to the base-level rise and aggradation in the basin was at least locally preserved after the incision active after ~3 Ma, and it is not always the Volkovce Formation appearing below the river terraces in the area.

The analyzed intraclasts yielded ~0.2–1.4 Myr higher ages than the *in situ* layers, after excluding the sample NV-1-1 considered as an outlier. The depositional model shown on Fig. 12A allows to attribute this difference to a redeposition of older sediment during incision. Mixing of the older muddy sediment into younger strata on a level of individual sediment particles would result in formation of two authigenic rims around a particle, one older with $^{10}Be/^{9}Be$ ratio relevant to the redeposited sediment, and the second outer one formed at the time of deposition with ^{10}Be/^{9}Be ratio of the incising river waters (Fig. 12B). Since it is not possible to separate several authigenic rims during extraction, this effect would result in apparently older authigenic ^{10}Be/^{9}Be age. It is assumed that the older authigenic phase was not exposed to pH<4 and therefore remains intact despite the repeated dispersion of sedimentary particles in a water column (Willenbring and von Blanckenburg, 2010). Another possible way of redeposition of older mud into younger sediment is on the level of millimeter-size rip-up clasts, scattered in the sediment with actual ^{10}Be/^{9}Be ratio (Fig. 12C).

The ratio of both rims forming the resulting isotopic ratio of an analyzed sample should scale to how strong is the input of older redeposited mud to a specific bed, regardless of whether it is achieved at the level of individual particles or rip-up clasts. The input of mixed older mud will vary randomly across a sedimentary environment, especially in such topographically differentiated environment as a wandering river with channels of various depth and hierarchy, and with flows of wide scale of speed, turbulence, and transport capacity. Hence, this effect should widen the range of authigenic ^{10}Be/^{9}Be ratios and ages within a single succession, as has been observed in the studied set of samples.

Erosion of muddy strata, production of rip-up clasts and mixing of mud by traction currents was observed in flume experiments (Schieber et al., 2010; Noack et al., 2015; Van Rijn, 2020). Even if formed from unconsolidated and non-lithified mud, the intraclasts might be prone to be transported on considerable distances (Schieber, 2016). The muddy rip-up clasts attain sub-millimeter to centimeter scale, and their presence in a bed might not be straightforward to recognize visually in the field. Processes of mud redeposition as rip-up intraclasts or a mixture are a common feature observed in fluvial environment (Müller et al., 2004; Li et al., 2017; Perkey et al., 2020; Li et al., 2021). Flows with high erosion potential took place during the deposition of the studied succession (Fig. 12A).

The described effect of mixing of mud with preserved older authigenic $^{10}Be/^{9}Be$ signal is considered as a reasonable hypothesis for explanation of the wide range of authigenic $^{10}Be/^{9}Be$ ages of the *in situ* layers, which mostly do not overlap within σ_1 uncertainties. The analytical uncertainties therefore can't mirror the paleoenvironmental variability caused by the redeposition and mixing. Thus, it is assumed that the most robust approach in determination of the depositional age of the outcrop is to use the full range of the *in situ* layers ages within error bars, what yields 1.390–1.912 Ma. Since the burial $^{26}Al/^{10}Be$ dating provided only minimum burial ages, it agrees with the mentioned age interval and does not allow to constrain it more specifically.

The established depositional age is not in agreement with the age range ~2.58–1.85 Ma indicated by the biostratigraphy of large mammal fossils from the succession. Nevertheless, all fossils are present as clasts in the channel-fill facies, and hence were redeposited. The dated intraclasts do exhibit ages fitting to the mammal biostratigraphic age range, pointing to the possibility of the same source of material during redeposition.

The hypothesis of redeposition of older sediment as a factor affecting the authigenic $^{10}Be/^{9}Be$ dating needs to be further verified. A validation of the hypothesis by petrographic or geochemical proxies remains problematic, as the floodplain muddy facies of the redeposited Volkovce and Kolárovo fms. as well as the Quaternary sediments were deposited by comparable processes and with similar provenance (Šujan et al., 2018; Šujan et al., 2020). An open question remains, whether would different climatic conditions allow to trace the described effect in the muddy layers. Mixing of older mud as a cause of apparently older ages of the $^{10}Be/^{9}Be$ dating was documented by microfossils redeposition in the turbiditic succession deposited on the basin floor of Lake Pannon in the Danube Basin (Šujan et al., 2016), however, this approach is not suitable for terrestrial facies.

Extensive occurrence of cryogenic deformations and their burial point to sedimentation during glacials (Vandenberghe, 2013). Evolution of mean annual temperatures (MAT) in the period of ~2.58–1.80 Ma in the Central Europe (Kahlke et al., 2011; Kovács et al., 2015; Martinetto et al., 2015; Teodoridis et al., 2017) show values not cool enough to produce the observed deformations (Ruszkiczay-Rüdiger and Kern, 2016). Glaciation in Europe was suggested only after 1.8 Ma, and its more significant extension in the Alps and Carpathians even after 1.2–0.9 Ma (Muttoni et al., 2003; Van Husen, 2004; Gibbard and Lewin, 2009; Knudsen et al., 2020). Hence, the extensive presence of cryogenic deformations in the Nová Vieska succession favors the age range of 1.390–1.912 Ma established in this study by the authigenic $^{10}Be/^{9}Be$ dating.

8. Conclusions

This study aimed to investigate suitability of incising river deposits formed under low accommodation and high sediment supply conditions for dating using the authigenic $^{10}Be/^{9}Be$ method. The Nová Vieska river terrace succession, located in the eastern Danube Basin, comprises facies of a wandering river, composed of downstream-accreted unit bars and lateral accretion bars. Facies analysis implied a high variability of flow speed, turbulence and sediment concentration, which resulted in a wide range of lithologies from gravelly sands to *in situ* muddy strata of floodplain and oxbow lake deposits forming minor part of the succession. Redeposition of mud from older eroded strata during incision of the river, related to the ongoing inversion of the basin, was an important feature of the sedimentary environment, as is evidenced by the widespread occurrence of mud intraclasts.

The authigenic $^{10}Be/^{9}Be$ dating yielded ages divided into three groups of samples: (1) two ages of 4.024 ± 0.111 Ma and 3.802 ± 0.094 Ma from the strata below the base of the river terrace; (2) three ages of 2.701 ± 0.093 Ma, 2.484 ± 0.096 Ma and 2.031 ± 0.076 Ma obtained from intraclasts of the redeposited mud; and (3) six ages in the range of 1.852 ± 0.060 Ma to 1.438 ± 0.048 Ma yielded by analysis of in situ muddy strata, with one outlier reaching an age of

2.303 ± 0.093 Ma. Burial $^{26}Al/^{10}Be$ dating of two samples provided minimum burial ages of 1.34 ± 0.32 Ma and 0.45 ± 0.10 Ma.

The pattern of the authigenic $^{10}Be/^{9}Be$ ages distribution is interpreted to be a result of redeposition of older mud derived from the incised substrate, which consists dominantly of muddy alluvial sediments. The hypothesis of redeposition as a factor affecting the authigenic $^{10}Be/^{9}Be$ dating is proposed in three scales: (1) redeposition of decimeter-scale intraclasts with preserved original age of the older substrate, (2) redeposition of millimeter-scale rip-up clasts preserving $^{10}Be/^{9}Be$ ratio of the older substrate, which are mixed into younger strata with random proportion, and (3) redeposition at the scale of individual particles, leading to formation of two authigenic rims, the inner one preserving the older $^{10}Be/^{9}Be$ ratio, and the outer one representing the actual $^{10}Be/^{9}Be$ ratio during deposition. The proportion of particles with preserved older authigenic $^{10}Be/^{9}Be$ rim would also vary randomly across the depositional environment. The stochastic spatial variation of the admixture of older mud particles or rip-up clasts is considered to be the reason of the wide range of the ages obtained from *in situ* muddy layers. Taking into account all mentioned assumptions, the full range of the authigenic $^{10}Be/^{9}Be$ ages yielded by the *in situ* mud samples reaching 1.390–1.912 Ma (within uncertainties) is proposed as the age of deposition of the studied succession.

The established age range differs from the interval ~2.58–1.85 Ma provided by the large mammal biostratigraphy, however, these fossils are accumulated as clasts and likely underwent redeposition from the same source as the similarly aged intraclasts. Extensive occurrence of cryogenic deformations also favors the age range provided by the authigenic $^{10}Be/^{9}Be$ dating, since the climatic conditions needed to attain such deformations appeared in Central Europe only at this later time.

The hypothesis of mud redeposition during incision of a river as an effect affecting the authigenic $^{10}Be/^{9}Be$ dating needs further investigation and verification. This study emphasized the potential influence of this effect on the dating method application in continental environments, which should be considered in future studies.

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