GEOLOGICA CARPATHICA, APRIL 2022, 73, 2, 173–178 https://doi.org/10.31577/GeolCarp.73.2.5

Short Communication

$^{238}U/^{206}Pb$ age of the fossil sinter crust (flowstone) covering fault walls of a Badenian neptunian dyke (Devín quarry, Western Carpathians)

FRANTIŠEK MARKO[1,✉], JON WOODHEAD[2], DENIS SCHOLZ[3], VRATISLAV HURAI[4] and ALEXANDER LAČNÝ[1,5]

[1]Comenius University in Bratislava, Faculty of Natural Sciences, Department of Geology and Paleontology, Ilkovičova 6, 842 15 Bratislava, Slovakia; ✉frantisek.marko@uniba.sk
[2]School of Geography, Atmospheric and Earth Sciences, University of Melbourne, Victoria 3010, Australia; jdwood@unimelb.edu.au
[3]Institut für Geowissenschaften, Johannes Gutenberg-Universität Mainz, Johann-Joachim-Becher-Weg 21, 55128 Mainz, Germany; scholzd@uni-mainz.de
[4]Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 84528 Bratislava, Slovakia; vratislav.hurai@savba.sk
[5]State Nature Conservancy of the Slovak Republic, Little Carpathians Protected Landscape Area, Štúrova 115, 900 01 Modra, Slovakia; alexander.lacny@sopsr.sk

(Manuscript received December 28, 2021; accepted in revised form February 16, 2022; Associate Editor: Igor Broska)

Abstract: Here, we report on the first radiometric dating of pre-Quaternary sinters covering the ENE–WSW striking vertical faults filled with Upper Badenian sands (neptunian dykes) in Mesozoic carbonates of the Devín quarry in the Malé Karpaty Mountains. The $^{238}U/^{206}Pb$ age of 13.98±0.56 Ma fits well with the former age prediction based on biostratigraphic evidence. Our results provide fault opening age, refine the age of sediments and fossils preserved in the neptunian dykes, and constrain the onset of Badenian sea transgression.

Keywords: fault dating, U/Pb age, fossil sinter, Western Carpathians, Late Badenian.

Introduction

Neptunian dykes with calcareous sinter crusts (flowstones, speleothems respectively) of assumed Badenian age in the Malé Karpaty Mts. were comprehensively described by Mišík (1980) and the Badenian paleokarst of Devín castle hill was further studied by Lehotský (1994, 2012). Within the Mesozoic carbonates of the Devín quarry (Fig. 1), Upper Badenian sands form neptunian dykes – vertical, approximately E–W striking, tensional open faults. The fault walls are covered by up to 1 m thick sinter (flowstone) crust with a stromatolite-like laminated structure (Figs. 2a, b; 3) composed of intercalations of thin carbonate layers deposited during the fault opening. Mišík (l.c.) suggested a Badenian age of these speleothems based on observations of sinter crusts affected by boring marine organism *Lithophaga indet*. (Mišík 1976, 1980) and the occurrence of Badenian sinter pebbles in transgressive sandy gravels. Badenian sands also fill neptunian dykes in the middle open parts of fractures and the age of these sands is also biostratigraphically well-constrained (Švagrovský in Papp et. al. 1978). In the lower parts of the neptunian dykes, loamy infillings with an Upper Karpatian–Lower Badenian vertebrate fauna were observed (Fejfar 1974; Papp et al. 1978). All this evidence suggests an Upper Badenian age of the neptunian dykes. However, the bottom part of the dykes also contains an Upper Karpatian–Lower Badenian fauna. As a result, it is suggested that the age of the fracture should be older than Upper Karpatian, if the fauna is not redeposited. The lowermost theoretical age limit corresponds to that of the Triassic host rock. The age of faults is recorded in calcareous sinter crusts covering the fault walls, which grew simultaneously with the fault opening. Mišík (1980) estimated the age of this fossil sinter crust to ~14–15 Ma (Upper Badenian), but recommended isotopic dating.

To resolve the question of the exact age of neptunian dyke-bearing faults, we dated sinter crust from a fault in the Devín quarry. To test the possible Quaternary rejuvenation, we initially employed the $^{230}Th/U$ method sensitive for the last 500,000 years (e.g. Scholz & Hoffman 2008) with negative result. Hence, we conducted a $^{238}U/^{206}Pb$ dating and obtained reliable and precise numerical age.

Geological setting

The research area is situated in the Inner Western Carpathians (IWC) terrane at the eastern periphery of the Vienna Basin (Fig. 1). The Western Carpathian structure is a result of Neo-Alpine tectogenesis and is composed of Outer and Inner Carpathians (sensu Biely 1989; Bezák et al. 2004). Both superunits have been formed due to an oblique continent–continent Neo-Alpine collision and extrusion and are juxta-

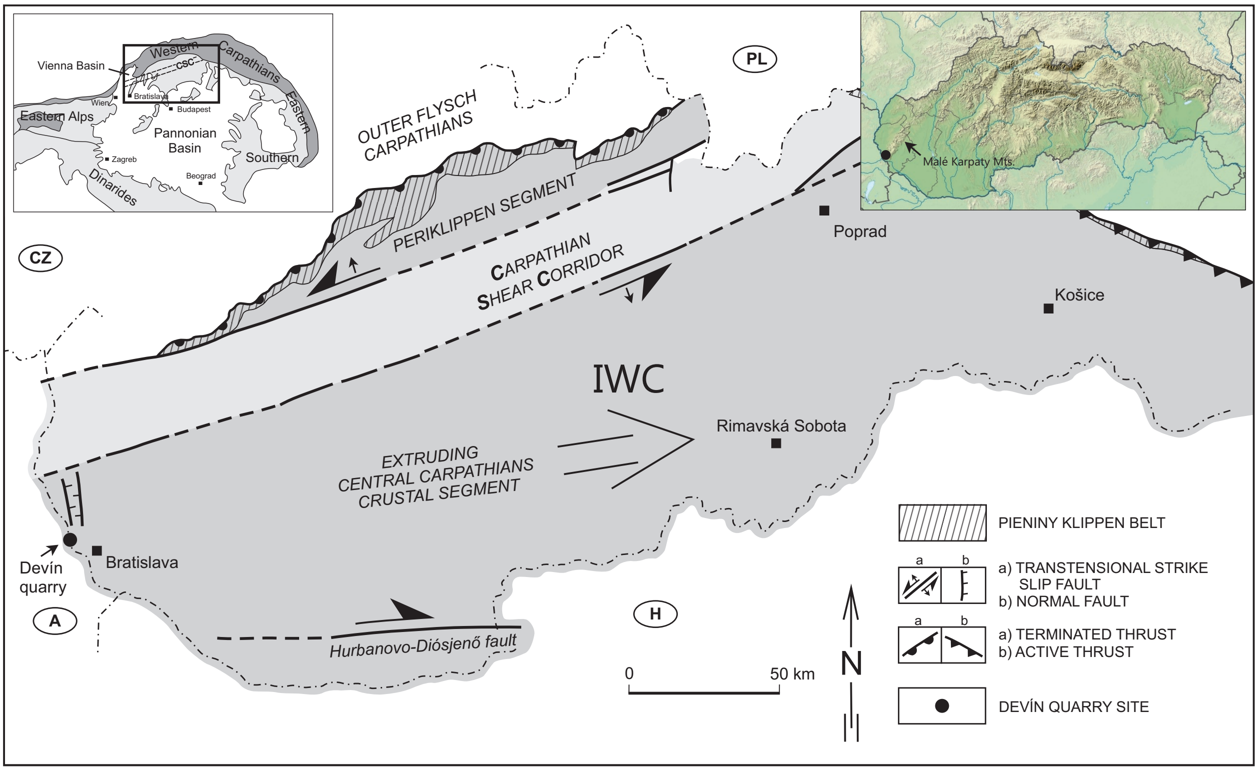

Fig. 1. Localization of the Devín quarry within the Western Carpathian realm with interpretation of the Late Badenian dynamics. Source of DTM: ÚGKK SR ©Geodetic and Cartographic Institute Bratislava.

posed along the Pieniny Klippen Belt zone of extreme shortening and wrenching during Miocene. Hence, the Outer Carpathians represent a Miocene accretionary prism composed of flysch nappes overlain by the Neogene foredeep molasse basin. The Inner Western Carpathians (IWC) represent a rigid crustal segment (microplate) consolidated during Paleo-Alpine orogeny. The IWC consist of Palaeozoic crystalline basement and sedimentary cover exhumed in horsts uplifted during Neogene. Most of the terrane is covered by the Mesozoic cover and Paleo-Alpine nappe units of Cretaceous accretionary wedge. Paleogene and Neogene sedimentary basins with Cenozoic volcanic products are the youngest superposed units. The IWC crustal segment is affected by Neogene faults, reflecting paleostress conditions and dynamics during the Neo-Alpine evolution. In this study, infillings of representative E–W striking faults exhumed at the margin of the Vienna Basin in the Devín quarry near Bratislava are described.

The Devín quarry is situated at the southern edge of the Malé Karpaty horst controlled by NW–SE boundary faults of the Hainburg gate followed by the Danube river bed, and by an NNW–SSE fault system controlling the Morava river flow (Fig. 1). Massive Triassic (Anisian–Ladinian) dolomites and dolomite breccias of the Mesozoic cover unit are exposed in the quarry (Vaškovský et al. 1988; Polák et al. 2011). Several sub-vertical open faults with sinter crusts are exposed at the N–S striking, ca. 6–12 m high, quarry face. Some of the faults are sealed by Upper Badenian sands filling the middle parts of open gashes as neptunian dykes. The faults are almost vertical, with ENE–WSW strike (average attitude 340°/90°). Width of the fault zones is in the range from 10 cm to 1 m. The faults are overlain by well-stratified Upper Badenian marine littoral sediments of the Studienka Formation of the Sandberg Member (Polák et al. 2011). This unconformity of the Upper Badenian transgression described by Andrusov (1969) is well-recognized in the quarry (Fig. 2). The Devín quarry was abandoned many years ago and is recently inactive.

Samples and methods

The Devín quarry is located within Little Carpathians Protected Landscape Area, where the sampling is prohibited due to environmental restrictions. For this reason, we extracted the sinter crust from a loose dolomite block at the quarry floor just below the mining face (Fig. 2a). Although this block is not *in situ*, it is clearly derived from the filling of the ENE–WSW faults, where thick sinter crusts are present. In contrast, the N–S faults also exposed in the quarry are only covered by up to a few cm thick, non-laminated speleothems and calcite crystals.

The dated sinter was extracted from basal part of ca. 10 cm thick flowstone in the basal part of a 60 cm thick sinter crust composed of recurrent thin, colour-contrasting (brown and pale) laminas covering the fault wall surface (Fig. 3). As such, the obtained datum provides an early age limit (oldest age)

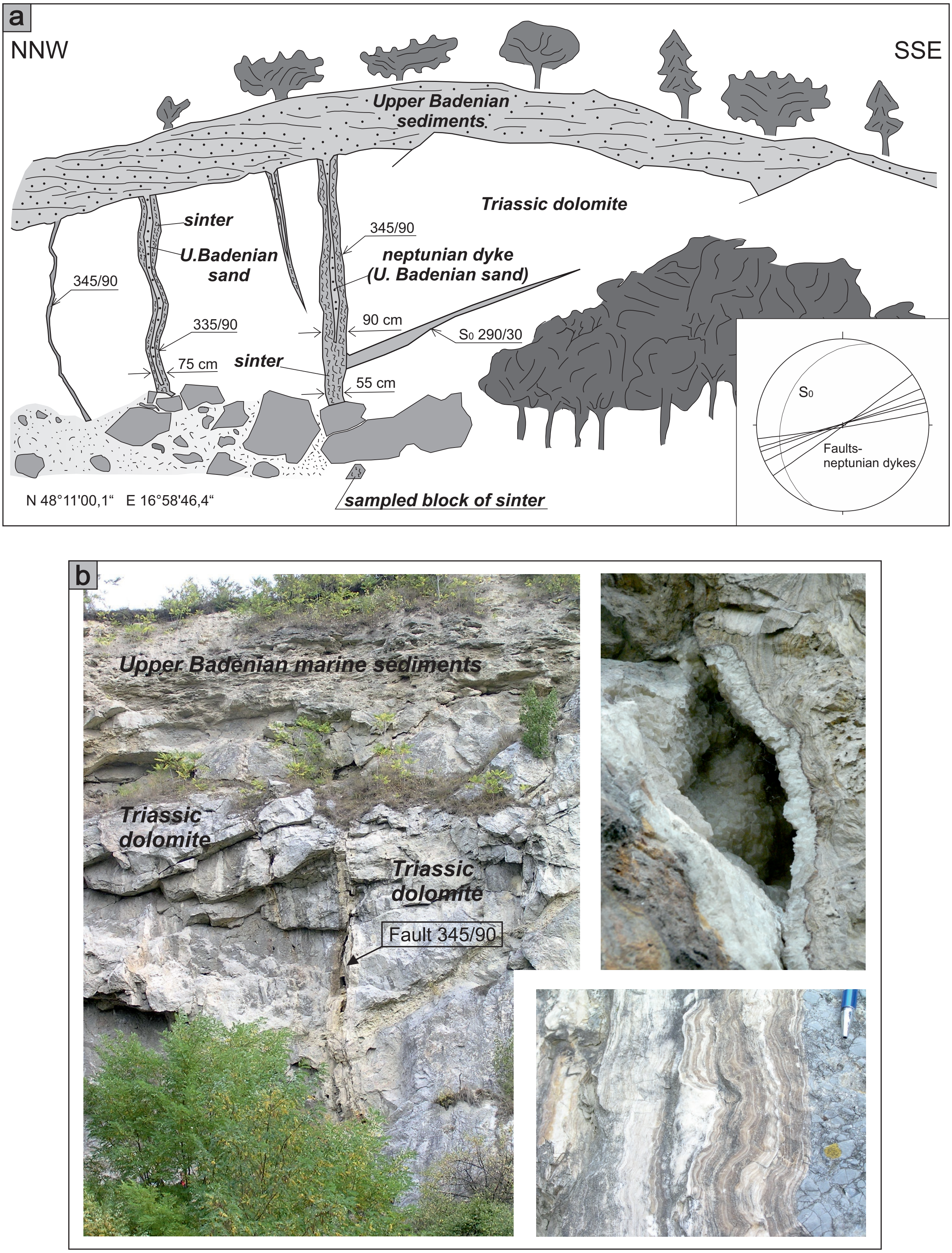

Fig. 2. a — Schematic structural sketch of the geological defilé exposed in the mining face of the Devín quarry with an indication of the sampling point (48°11’00.1”N, 16°58’46.4”E). Stereonet lower hemisphere plot shows ENE–WSW vertical faults – neptunian dykes and bedding of dolomite. **b** — Detailed view of a 345/90° fault (left photo) and its sinter infilling with calcite crystals in drusy cavity (right photos).

for the sinter origin if the fault infill is syntaxial, i. e. growing from the wall towards the centre. The late age limit (youngest age) recorded in the sinter crust in the central part of the fault zone depends upon the rate of the sinter growth and the crust thickness.

^{230}Th/U-dating was performed by multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) at the Institute for Geosciences, University of Mainz, Germany. For a detailed description of the analytical procedures, sample preparation and the calibration of the mixed ^{229}Th–^{233}U–^{236}U spike, the reader is referred to Obert et al. (2016), Yang et al. (2015), and Gibert et al. (2016).

U–Pb dating methods using MC-ICPMS at the School of Geography, Atmospheric and Earth Sciences, University of Melbourne followed procedures described in Woodhead et al. (2006), Woodhead & Petrus (2019), with enhanced chemical separation procedures described in Engel (2020). Analytical accuracy was monitored for each mass spectrometry session using synthetic zircon solutions provided by the EarthTime initiative.

Results and discussion

The ^{230}Th/U-dating was applied to seven sub-samples of the flowstone. The (^{230}Th/^{238}U) and (^{234}U/^{238}U) activity ratios of all aliquots were very close to secular equilibrium. The corresponding ages were >500 ka and thus at the limit of or beyond the dating range of the ^{230}Th/U-method. This suggests that the flowstone is older than 500 ka and did not grow during the Quaternary.

The U–Pb dating method, however, yielded a radiometric age of 13.98±0.56 Ma (Fig. 4, Table 1). The sample aliquots are relatively non-radiogenic and the high MSWD suggests some variation in the initial (common) Pb composition. Nevertheless, given the wide spread of multiple samples projecting along an isochron, we believe that this result provides the reliable age estimate within the specified uncertainty limits.

The calcareous sinters covering fault walls are interpreted as speleothems originated by the precipitation of calcite from phreatic freshwater leaking through beds capping cavities and formed when the cavity, in our case the open fault, was air-filled (Scholz & Hoffman 2008). Alternatively, the sinters could precipitate from hydrothermal solutions. If the sinters are products of freshwater leaking, the Malé Karpaty Mountains must have been above the sea level and deeply eroded already in the Upper Badenian, ~14 Ma ago, before the sea transgression, because the Upper Badenian marine sediments, younger than the fault sinter dated, overlie the exhumed faults.

Fig. 3. Cross-sections of dated sinter crust from the Devín quarry with distinct growth layering.

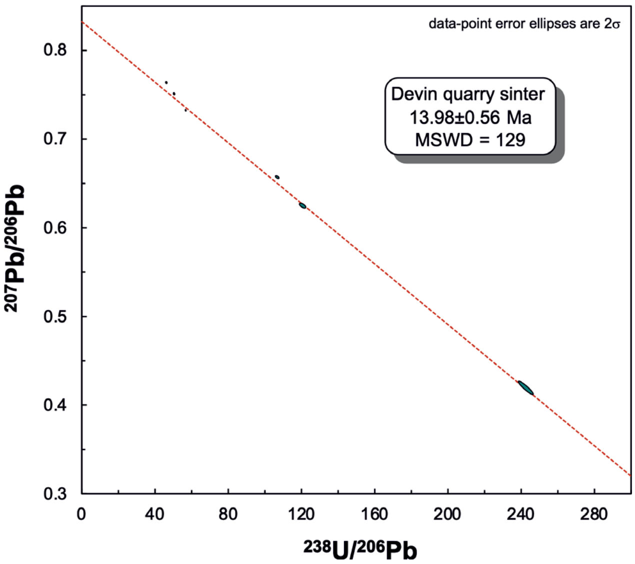

Fig. 4. ^{238}U/^{206}Pb–^{207}Pb/^{206}Pb isochron plot for sinter crust covering ENE–WSW fault walls in the Devín quarry.

Table 1: Measured values of uranium and lead concentrations from six subsamples.

U ppm	Pb ppm	^{238}U/^{206}Pb	2 sigma %	^{207}Pb/^{206}Pb	2 sigma %	error correlation
0.38	0.022	54.36	0.57	0.73287	0.12	−0.34
0.39	0.011	104.96	0.74	0.65713	0.22	−0.60
0.46	0.033	43.67	0.58	0.76377	0.11	−0.26
0.41	0.027	47.76	0.86	0.75109	0.11	−0.25
0.34	0.003	242.51	1.38	0.41938	1.50	−0.93
0.39	0.009	119.03	1.16	0.62521	0.34	−0.64

The hydrothermal origin of the dated sinters cannot be definitely ruled out. Drusy cavities with well-developed calcite crystals occur within E–W faults together with traces of corrosion (sponge-like porous textures) preserved on fault walls (Fig. 2b). These phenomena and emplacement of sinters in open vertical, probably deep range faults are arguments for their hypogene origin (Bella 2016). The calcite sinter crusts from the Devín quarry very probably precipitated from warm hydrothermal, deeply circulating aqueous fluids. Nevertheless, further research based on crystal chemistry, fluid inclusion microthermometry, and stable isotopes is needed to confirm this hypothesis. Recent works described the hypogeneous karst in the Malé Karpaty Mts., particularly in its fault-controlled peripheries (Bella & Bosák 2012; Bella & Gaál 2017; Bella et al. 2019a, b). The Devín quarry within the Devínska Kobyla karst area (Stankoviansky 1982) is also situated nearby the horst-controlled boundary faults and in the vicinity of probably hypogene cave in the Štokerauská Vápenka quarry (Magdolen 2021), as well as hypogene caves of Hainburg hills (Neuhuber et al. 2021). Regarding these facts, the ENE–WSW-trending faults in the Devín quarry seem to serve as conduits for hydrothermal fluids, which karstified limestones in the southern part of the Malé Karpaty Mts.

The determined age of the ENE–WSW faults has several important tectonic implications. Mišík (1980) attributed the origin of the Devín faults and neptunian dykes to the formation of the Lamač fault-controlled graben – a NNW–SSE striking transversal depression crosscutting the Malé Karpaty horst. The ENE–WSW faults filled with sinter crusts are perpendicular to the Lamač graben, so that the origin of these extensional dislocations can rather be connected with eastward extrusion of the IWC crustal segment rimmed by the ENE–WSW shear zone of the Carpathian Shear Corridor and the E–W-trending Hurbanovo-Diósjenő boundary fault (Marko et al. 2017). Both boundaries operated as strike-slip interfaces to the extruding IWC segment. The boundary fault geometry and the IWC movement vectors were suitable for the generation of transtensional regime along boundary faults some 15–13.5 Ma ago (Marko, in prep.). The origin of ENE–WSW-trending fractures and the opening recorded by the growth of sinter crusts is most probably related to this event.

Conclusions

In the Western Carpathian caves, only Quaternary flowstones have thus far been dated using radiometric methods (e.g., Hercman et al. 1997, 2008, 2020; Bosák et al. 2002; Gradziński et al. 2007; Benson et al. 2018; Bella et al. 2019c, 2021; Neuhuber et al. 2021). Generaly, carbonates U/Pb dating is very rare as well in the Western Carpathians. However, lately Majzlan et al. (2021) dated by U/Pb method approximately 24 Ma old vein carbonates from the Nízke Tatry Mts. These are record of Meso-Alpine (Paleogene), while Devín sinter dated herein is record of Neo-Alpine (Neogene) tectonothermal evolution of the Western Carpathians.

In this study, we provide the first isotopic U/Pb dating of pre-Quaternary sinters (flowstones) covering walls of Upper Badenian neptunian dykes in the Devín quarry situated in the Malé Karpaty horst. These flowstones were originally described by Mišík (1980), who estimated their age using biostratigraphic evidence to approximately 15 Ma and recommended radionuclide dating. To address this issue, here we determine the radiometric age of this sinter crust at 13.98± 0.56 Ma, which defines the age of the ENE–WSW fault system opening. The determined age of fault opening has consequences for the interpretation of sediments and fossils filling and overlying the fault zone, and also for the timing of the Upper Badenian marine transgression, which must have started just after the fault sinter deposition. Owing to the Upper Badenian age of faults, the Upper Karpatian–Lower Badenian fossil fauna reported from the base of the neptunian dykes has to be redeposited.

Acknowledgements: This paper is dedicated to the memory of professor Milan Mišík, whose essential and still actual scientific works addressed and inspired us to realize our current research. This work was supported by the Slovak Research and Development Agency Project APVV-16-0146 focused on fault research. D. Scholz thanks DFG for funding the projects SCHO 1274/11-1; INST 247/889-1 FUGG). J. Woodhead thanks the Australian Research Council for funding the grant FL160100028.

References

Andrusov D. 1969: Chaines enterrées, mégaanticlinaux et horsts dans la région des Carpathes occidentales. *Geologický Zborník Geologica Carpathica* 20, 39–45.

Bella P. 2016: Jaskyne na Slovensku – Genetické typy a morfológia. *Verbum Publishers*, *Catholic University*, Ružomberok, 1–124.

Bella P. & Bosák P. 2012: Speleogenesis along deep regional faults by ascending waters: case studies from Slovakia and Czech Republic. *Acta Carsologica* 41, 169–192. https://doi.org/10.3986/ac.v41i2-3.556

Bella P. & Gaál Ľ. 2017: Hypogene caves in Slovakia. In: Klimchouk A., Palmer A., De Waele J., Aurel A. & Audra P. (Eds.): Hypogene Karst Regions and Caves of the World. . Cave and Karts Systems of the World. *Springer*, Cham, 299–311. https://doi.org/10.1007/978-3-319-53348-3_19

Bella P., Bosák P., Braucher R., Pruner P., Hercman H., Minár J., Veselský M., Holec J. & Léanni L. 2019a: Multi-level Domica–Baradla cave system (Slovakia, Hungary): Middle Pliocene–Pleistocene evolution and implications for the denudation chronology of the Western Carpathians. *Geomorphology* 327, 62–79. https://doi.org/10.1016/j.geomorph.2018.10.002

Bella P., Bosák P. & Littva J. 2019b: Hypogénny pôvod jaskyne Pec (Plavecký kras, Malé Karpaty): Tektonická predispozícia a morfologické znaky. *Slovenský kras* 57, 133–146.

Bella P., Bosák P., Mikysek P., Littva J., Hercman H. & Pawlak J. 2019c: Multi-phased hypogene speleogenesis in a marginal horst structure of the Malé Karpaty Mountains, Slovakia. *International Journal of Speleology* 48, 203–220. https://doi.org/10.5038/1827-806X.48.2.2265

Bella P., Gradziński M., Hercman H., Leszczynski S. & Nemec W. 2021: Sedimentary anatomy and hydrological record of relic fluvial deposits in a karst cave conduit. *Sedimentology* 68, 425–448. https://doi.org/10.1111/sed.12785

Benson A., Hoffmann D. L., Bella P., Drury A. J., Hercman H., Timothy C. & Atkinson T. C. 2018: Building robust age models for speleothems – A case-study using coeval twin stalagmites. *Quaternary Geochronology* 43, 83–90. https://doi.org/10.1016/j.quageo.2017.10.004

Bezák V., Broska I., Ivanička J., Reichwalder P., Vozár J., Polák M., Havrila M., Mello J., Biely A., Plašienka D., Potfaj M., Konečný V., Lexa J., Kaličiak M., Žec B., Vass D., Elečko M., Janočko J., Pereszlényi M., Marko F., Maglay J. & Pristaš J. 2004: Tectonic map of Slovak republic 1:500 000. *ŠGÚDŠ*, Bratislava.

Biely M. 1989: The geological structure of the Western Carpathians. In: Maheľ M., Dercourt J. & Nairn A.E.M. (Eds.): Evolution of the Northern Margin of Tethys. Vol. II. *Mémoirs Societé Geologique France*, *Nouvellé Série* 154, 51–57.

Bosák P., Bella P., Cílek V., Ford D. C., Hercman H., Kadlec J., Osborne A. & Pruner P. 2002: Ochtiná aragonite cave (Western Carpathians, Slovakia): morphology, mineralogy of the fill and genesis. *Geologica Carpathica* 53, 399–410.

Engel J., Maas R., Woodhead J., Tympel J. & Greig A. 2020: A single-column extraction chemistry for isotope dilution U–Pb dating of carbonate. *Chemical Geology* 531, 119311. https://doi.org/10.1016/j.chemgeo.2019.119311

Fejfar G. 1974: Die Ecmyiden und Criceritiden (Rodentia, Mammalia) des Miozäns der Tschechoslowakei. *Paleontographica*, *Abt. A* 146, 1–180.

Gibert L., Scott G.R., Scholz D., Budsky A., Ferrandez C., Martin R.A., Ribot F. & Leria M. 2016: Chronology for the Cueva Victoria fossil site (SE Spain): Evidence for Early Pleistocene Afro–Iberian dispersals. *Journal of Human Evolution* 90, 183–197. https://doi.org/10.1016/j.jhevol.2015.08.002

Gradziński M., Hercman H., Nowak M. & Bella P. 2007: Age of black coloured laminae within speleothems from Domica cave and its significance for dating of prehistoric human settlement. *Geochronometria* 28, 39–45. https://doi.org/10.2478/v10003-007-0029-7

Hercman H., Bella P., Glazek J., Gradziński M., Lauritzen S.E. & Lovlie R. 1997: Uranium-series dating of speleothems from Demänová ice cave: A step to age estimation of the Demänová cave system (the Nízke Tatry Mts., Slovakia). *Annales Geologorum Poloniae* 67, 439–450.

Hercman H., Gradziński M. & Bella P. 2008: Evolution of Brestovská Cave based on U-series dating of speleothems. *Geochronometria* 32, 1–12. https://doi.org/10.2478/v10003-008-0023-8

Hercman H., Blasczyk M., Mulczyk A. & Bella P. 2020: Uranium isotopic ratios and their implication for uranium–uranium dating and groundwater circulation studies: A case study from speleothems of the Demänová caves, Nízke Tatry Mts., Slovakia. *Geologica Carpathica* 71, 61–72. https://doi.org/10.31577/GeolCarp.71.1.5

Lehotský R. 1994: Krasové a pseudokrasové jaskyne Devínskych karpát. *Slovenský kras* 32, 23–40.

Lehotský R. 2012: Exhumovaný predvrchnobádenský paleokras brala Devínskeho hradného vrchu (Malé Karpaty). *Slovenský kras* 50, 149–158.

Magdolen P. 2021: Hypogénna jaskyňa v Bratislavskom okrese. *Spravodaj Slovenskej Speleogickej Spoločnosti* 52, 28–32.

Majzlan J., Chovan D., Kiefer S., Gerdes A., Kohút M., Siman P., Konečný P., Števko M., Finger F., Waitzinger M., Biroň A., Luptáková J., Ackerman L. & Hora M.J. 2021: Hydrotermal mineralisation of the Tatric superunit (Western Carpathians, Slovakia): Geochronology and timing of mineralisations in the Nízke Tatry Mts. *Geologica Carpathica* 71, 113–133. https://doi.org/10.31577/GeolCarp.71.2.2

Marko F., Andriessen P.A.M., Tomek Č., Bezák V., Fojtíková L., Bošanský M., Piovarči M. & Reichwalder P. 2017: Carpathian Shear Corridor – A strike-slip boundary of an extruded crustal segment. *Tectonophysics* 703–704, 119–134. https://doi.org/10.1016/j.tecto.2017.02.010

Mišík M. 1976: Geologické exkurzie po Slovensku. *Slovenské Pedagogické Nakladateľstvo*, Bratislava, 1–359.

Mišík M. 1980: Miocene sinter crusts (speleothems) and calcrete deposits from neptunian dykes, Malé Karpaty Mts. *Geologický Zborník Geologica Carpathica* 31, 495–512.

Neuhuber S., Plan L., Gier S., Hintersberger E., Lachner J., Scholz D., Lüthgens C., Braumann S., Bodenlenz F., Voit K. & Fiebig M. 2021: Numerical age dating of cave sediments to quantify vertical movement at the Alpine-Carpathian transition in the Plio- and Pleistocene. *Geologica Carpathica* 71, 539–557. https://doi.org/10.31577/GeolCarp.71.6.5

Obert J.C., Scholz D., Felis T., Brocas W.M., Jochum K.P. & Andreae M.O. 2016: ^{230}Th/U dating of Last Interglacial brain corals from Bonaire (southern Caribbean) using bulk and theca wall material. *Geochimica et Cosmochimica Acta* 178, 20–40. https://doi.org/10.1016/j.gca.2016.01.011

Papp A., Cícha I., Seneš J. & Steininger F. 1978: Chronostratigraphie und Neostratotypen. Miozän der Zentralen Paratethys. Bd. IV, M_4 Badenien. *Veda*, Bratislava, 1–594.

Polák M., Plašienka D., Kohút M., Putiš M., Bezák V., Filo M., Olšavský M., Havrila M., Buček S., Maglay M., Elečko M., Fordinál K., Nagy A., Hraško Ľ., Németh Z., Ivanička J. & Broska I. 2011: Geological Map of the Malé Karpaty Mts. 1:50 000. *ŠGÚDŠ*, Bratislava.

Scholz D. & Hoffman D. 2008: ^{230}Th/U – dating of fossil corals and speleothems. In: Preusser F., Hajdas I. & Ivy-Ochs S. (Eds.): Recent Progress in Quaternary Dating Methods. *E&G Quaternary Science Journal Spec. Issue* 57, 52–76. https://doi.org/10.3285/eg.57.1-2.3

Stankoviansky M. 1982: Geomorfologické pomery krasových území Malých Karpát. In: Geomorfologická konference konaná na počest 100. výročí narození profesora J. V. Daneše, Praha, 3.–5. 6. 1980, 233–242.

Vaškovský I., Kohút M., Nagy A., Plašienka D., Putiš M., Vaškovská E. & Vozár J. 1988: Geologická mapa Bratislavy a okolia 1:25 000. *ŠGÚDŠ*, Bratislava.

Woodhead J.D. & Petrus J. 2019: Exploring the advantages and limitations of in-situ U–Pb carbonate geochronology using speleothems. *Geochronology* 1, 69–84. https://doi.org/10.5194/gchron-1-69-2019

Woodhead J.D., Hellstrom J., Maas R., Drysdale R., Zanchetta G., Devine P. & Taylor E. 2006: U–Pb geochronology of speleothems by MC-ICPMS. *Quaternary Geochronology* 1, 208–221. https://doi.org/10.1016/j.quageo.2006.08.002

Yang Q., Scholz D., Jochum K.P., Hoffmann D.L., Stoll B., Weis U., Schwager B. & Andreae M.O. 2015: Lead isotope variability in speleothems – A promising new proxy for hydrological change? First results from a stalagmite from western Germany. *Chemical Geology* 396, 143–151. https://doi.org/10.1016/j.chemgeo.2014.12.028