Precise U-Pb age constrains on the Ediacaran biota in Podolia, East European Platform, Ukraine

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The Neoproterozoic Era was characterized by rapidly changing paleogeography, global climate changes and especially by the rise and fall of the Ediacaran macro-biota. The correlation between disparate Ediacaran fossil-bearing localities and the tentative reconstruction of their paleoenvironmental and paleogeographic contexts are usually complicated by the lack of precise and accurate age data. For this reason, Neoproterozoic sedimentary sections associating Ediacaran biota fossils and fresh volcanic material are especially valuable for radioisotopic dating. Our research in the Podolya Basin, southwestern Ukraine, revealed the presence of four Neoproterozoic volcanic ash deposits (potassium-bentonite layers) within Ediacaran fossil-bearing siliciclastic rocks of the Mohyliv-Podilskyi Group. We used zircon U-Pb LA-ICPMS and CA-ID-TIMS methods to date two of those layers. The results indicate that a diverse assemblage of body and trace Ediacaran fossils occurred as early as 556.78 ± 0.18 million years (Ma) ago. By combining morphological evidence and new age determinations, we suggest a closer paleobiogeographical relationship between the Ukrainian Ediacaran assemblage and the Avalon paleocontinent than previously estimated.

The Neoproterozoic Era corresponds to a period of global changes related to the breakup of the supercontinent Rodinia and to protracted global glacial events1. In terms of biological evolution, it is associated with deep innovations likely related to the so-called ‘second great oxygenation event’ (NOE)2, and is marked by the rise and fall of the Ediacaran biota4–8. As revealed by over thirty sites inventoried worldwide9–14, the soft body imprints of the Ediacaran macro-organisms have been preserved in various marine environments and related deposits, such as carbonate rocks15–17, turbidites and volcanoclastic successions18,19, as well as siliciclastic deposits20–22.

Several species forming the Ediacaran biota - e.g., Charnia (575–545 Ma), Dickinsonia (560–541 Ma), Onega (558–543 Ma), Rangea (558–545 Ma), Palaeopascichnus and Tribrichidium (558–541 Ma) - are long-lived taxa without substantial morphological change10, and their presence/absence thus does not represent a useful indicator for reliable biostratigraphical assessment. Additionally, the common lack of datable ash beds interlayered with the sedimentary sequences is the major obstacle for geochronological correlations between different Ediacaran fossil bearing sections6,8,13. In most contexts, the only way Ediacaran biostratigraphy could be appropriately placed into reliable chronological order is by high-precision radioisotopic dating of zircons from the products of large explosive volcanic eruptions such as ash, tuff or ignimbrite interlayered within Ediacaran fossil bearing strata19,23–25. In some Proterozoic terrains, ash deposits are altered and transformed into bentonite, whose chemical composition and mineralogy depend on the alteration processes and diagenetic history26.

In southwestern Ukraine, the siliciclastic deposits of the Mohyliv-Podilskyi Group outcropping in the Podolya Basin have revealed an abundant Ediacaran macrofauna27, but the preservation conditions of the fossil assemblages do not systematically grant secure biostratigraphic correlations at macro-regional scale across different sedimentary basins. For now, only one bentonite bed has been described in the Yarishyska Formation28. However, the only available date for this context of 553 Ma28 is from the tuffaceous level without related information on its stratigraphical position as well as petrological description. Therefore, with the aim of constraining the

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chronological span of the Ediacaran fossils from the Podolya Basin, we have specifically investigated two among the four bentonite beds identified so far in the Mohyliv-Podilskyi Group.

By using LA-ICPMS and ID-TIMS dating methods, here we report U-Pb ages of two ash beds of the Mohyliv-Podilskyi Group interlayered with siliciclastic deposits where nearly the totality of the Ediacaran remains are embedded. Our results allow for the first time the integration of the paleobiological record from the Podolya Basin into a general Ediacaran biostratigraphic framework, which is a fundamental condition for more finely assessing the spatiotemporal relationships of the Ukrainian record with respect to the evidence from other Neoproterozoic basins in the context of the still debated paleogeographical location at that time of the paleocontinent Baltica27.

Geological setting
The Podolya Basin (Fig. 1) is located at the southwestern margin of the East European Platform, on the western flank of the Archean Ukrainian Shield27,29. It drains the hydrological basin of the Dniester River that cuts the Quaternary deposits overlaying the Neoproterozoic strata with an angular unconformity. In the studied area, the East European Platform is built on the continental shelf forming the edge of the Archean basement. The Neoproterozoic siliciclastic deposits represent the main part of the sedimentary column, while the considerably thinner Paleozoic (Cambrian-Silurian) strata are restricted to the southwestern part of the Podolya Basin. All these are unmetamorphic deposits.

The late Neoproterozoic sedimentary deposits of the Ukrainian Podolya Basin belong to the Mohyliv-Podilskyi and Kanilivska Groups. Imprints and fossil remains of representatives of the Ediacaran biota and bentonite beds are observed in the Mohylivska (FM) and Yarishyvska (FY) Formations forming the lower part of Mohyliv-Podilskyi Group (Fig. 2; a more detailed stratigraphic column of the late Neoproterozoic of the Podolya Basin is provided as Supplementary Information Fig. 1).

In the lower part of the late Neoproterozoic sedimentary pile, at the transition between the two formations, four bentonite deposits (B1 to B4) have been identified (Figs 2, 3). Local examples of variably-sized Ediacaran macrofossils include Gareevella elliptica, Intrites punctatus, Cyclomedusa plana and Nemiana simplex22,30, ranging from a few millimeters to a few decimeters in diameter. Thin layers of microbial mats have preserved the discoidal forms in grouped (Fig. 4A,B) or isolated morphological units (Fig. 4C,D). Both “flinders-style” and “death mask-style” preservation forms are represented31. Discoidal forms and trace fossils have maximum abundance in the coarse-grained facies at the base of the sedimentary pile. Most of the soft-bodied imprints occur between the B1 and B2 bentonite levels of the Mohylivska Formation. The sandy level underlying the first bentonite contains well-preserved imprints of Nemiana simplex (Fig. 3A). No evidence of Ediacaran fauna were found above and below the second dated B4 layer (Fig. 3D). At the Mohylivska-Yarishyvska transition, the facies deposits change from sandstone (upper part of FM - V2lyad sequence) to clayey siltstone (basal part of overlying FY - V2bern) (Fig. 2). Except for some rare rounded macrofossils observed immediately above the B4-layer, the Ediacaran-type forms disappear in the upper silty-shaly sediments of the section.

Results

Lithostratigraphy. From the bottom of the Mohylivska (FM) to the base of the Yarishyvska (FY) Formations, lithofacies are fine-to-medium grained (clayey silts to massive sandstone facies), whereas the transition from FM to FY is more clays22,27,29.

Figure 1. Synthetic geological map showing the relations between the Paleozoic-Precambrian sedimentary cover and the Archean basement rocks of the Ukrainian Shield and the position of the bentonite outcrops.
Four bentonite beds were sampled in three locations: the two lower ones, B1 and B2, are associated with the top part of FM in the Novodnistrovsky quarry (48°3′N, 27°2′E) - B1 (a, b) and B2 beds (Fig. 3A,B). The two upper levels, B3 and B4, which correspond to the base of FY, were discovered in a ravine near the locality of Bernashevka (48°1′N, 27°1′E) - B3 (a, b) bed (Fig. 3C), and in the Borshive ravine near the city of Moguilive-Podilsky (48°1′N, 27°2′E) - B4 bed (Fig. 3D), respectively. The bentonite beds were clearly identified due to their clayey character and bright color26, which distinctly contrasts with the generally grey to greenish-gray sediments in which they are intercalated.

Geochemistry. Compared to the immediately below and above siliciclastic sediments (Fig. 5A), the major elemental composition of all four bentonite beds show important differences (Fig. 5A). According to the absence of detrital quartz and feldspars, the contents in SiO₂ and Na₂O are less than 51% and nearly zero, respectively, which is much lower than those of their host sediments (Table 1). On the contrary, the contents in Al₂O₃ (>24%) and MgO (>1.65%) are higher because of the high abundance of clays. Small amounts of iron can be incorporated in the crystalline lattice of I:Si clay minerals in the bentonite, but most of it is contained in iron-bearing phases, such as hematite or poorly crystallized oxides, which indicate oxidizing conditions during alteration of primary volcanic ash32. Indeed, the iron content in the bentonite beds varies from 1.86% to 6.98%, except for an anomaly of 14.99% in the B3 (a) sample. The bentonite content in K₂O is lower than those recorded in the host siliciclastic rocks, which in turn contain detrital muscovite and K-feldspar. None of these inherited minerals are present in the bentonite, where the potassium is exclusively related to illite/smectite mixed-layer minerals (Supplementary Fig. 2). The chemical and mineralogical compositions of each bentonite level are hence typical of K-bentonites33.

Compared to their host sediments, the alkaline earth metals distribution (Table 1) of the bentonite beds normalized to primitive mantle (PRIMA)34 exhibit a systematic depletion of Ba and Sr contents related to the scarcity of micas and feldspars. These two elements are concentrated in the lower and upper sedimentary deposits where their mineral phases form the bulk of the detrital input. In contrast, Cs content is higher in bentonite material because this immobile element33 is easily absorbed by the newly formed clay minerals. Likewise, other elements, such as Nb, Ta, Zr, Hf and REEs (especially La, Ce, Nd, Sm and Y), which were immobile during the surficial alteration processes of volcanic ashes35,36, are enriched in bentonite products37. The slight Nb-Ta negative anomalies in bentonite beds indicate their volcanic origin in subduction setting.

The normalized chondrite REE spectra of bentonite beds and host sediments are significantly different (Fig. 5C). Average ∑REE values (1960 ppm), Y contents (73 ppm) and ∑LREE/∑HREE ratios (5.2) are, respectively, 6, 3 and 2 times higher than those of the silty sediments in the same units. Therefore, bentonite beds exhibit a specific geochemical signature. The absence of a positive Ce anomaly (at most concentrated REE, 420 ppm), which is probably an indication of suboxic water conditions during ash alteration. On the other hand, the Eu depletion in bentonite is indicative of plagioclase fractionation in a magmatic source, while in the host sediments plagioclase is absent due to its sensitivity to weathering before sedimentation. Immobile components of the composition in each bentonite bed were plotted in a Nb/Y - Zr/Ti diagram48, and used to discriminate the compositional fields of...
common volcanic rocks (Fig. 5D). They all plot into the rhyolite or rhyodacite fields, an evidence which confirms trace elements distribution previously observed for this material (Fig. 5B) and typical of rhyolitic material41,42.

Geochronology.

The geochemical analyses show that B4 K-bentonite is almost exclusively illite/smectite mixed-layer without inherited minerals (Supplementary Fig. 2). This indicates no reworking and in situ ash-bentonite transformation. In these conditions, U-bearing minerals can be confidently used for absolute dating this volcanoclastic deposits. The correlative high concentrations of Zr and U suggest that zircon is the main carrier of uranium in B4 K-bentonite.

Zircon crystals from the granular fraction (<4.5% weight) have a maximum size from 50 to 80µm (Fig. 6). They are characterized by three typologies: mainly elongated acicular, euhedral, and subhedral. Regardless of shape, sharp edges indicate the absence of corrosion and transport. The needle-shaped acicular zircon crystals (Fig. 6A,B) indicate rapid zircon crystallization, while euhedral crystals exhibit some vesicles (Fig. 6C,D) possibly interpreted as fluid inclusions43 and/or gas bubbles44 trapped in their crystalline lattice.

While needle-shaped acicular zircons are weakly zoned, other subhedral zircons display very regular fine-scale oscillatory zoning without solid inclusions. Moreover, complex growth associated to superimposed or disrupted zonings, or local recrystallizations, were never observed. Consequently, we suggest that these zircons crystallized within one episode, without zircon reworking from previous magmatic products. A total set of forty-three zircon crystals from bentonite B4 were analyzed by LA-ICP-MS and plotted in a Tera-Wasserburg 238U/206Pb vs. 207Pb/206Pb diagram45 (Fig. 7). Twenty-five concordant analyses yield a Concordia age of 555.4 ± 2.9 Ma (MSWD(C+E) = 1.2) (Table 2). Five zircon crystals revealed 1.3–2.2 Ga Meso and Paleoproterozoic inherited ages. The occurrence of such old zircons inherited in the magma chamber or scavenged from the basement during the volcanic eruption is frequently recorded46. The remaining three analysed zircons were not considered in

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**Figure 3.** Field pictures of the bentonite beds occurring in FM (A and B) and FY (C and D) formations of the Podolya Basin. (A) bed B1 a (reddish) and b (greenish) from the Novodnistrovsky quarry with underlying sandstones including imprints of *Nemiana simplex* and overlying silty shales; the sample for zircon U-Pb CA-ID TIMS analyses is taken from bed B1 (greenish); (B) bed B2 from the Novodnistrovsky quarry with underlying silts and overlying massive sandstones; (C) bed B3 with two interbeds of bentonite - purple (a) and pink (b) - from the ravine near the Bernasheva village, with underlying and overlying massive silts; (D) bed B4 from the Borshiv ravine with underlying clayey silts and overlying sandy silts; the sample for zircon U-Pb LA-ICP-MS analyses is taken from bentonite B4.
the calculations owing to a small common Pb contribution. We interpret this age of 555.4 ± 2.9 Ma as dating the crystallization of the volcanic zircons.

Zircons from bentonite B1 bed was analysed by CA-ID-TIMS method. All data are interpreted in terms of weighted mean 206Pb/238U dates by defining the youngest coherent population which yields statistically acceptable MSWD (Table 3). The highest temperature of chemical abrasion (210 °C) and a 13 h duration have been proven to eliminate the residual lead loss effect in the zircon crystals. Accordingly, we are confident that the reported weighted mean dates represent the age of the ash deposition.

All five analysed zircons from bentonite B1 (Fig. 7) are concordant, yielding a statistically equivalent weighted mean 206Pb/238U age of 556.78 ± 0.10/0.18/0.62 Ma (MSWD = 2.2, n = 5).

Discussion

Supported by our field observations, the mineralogical and geochemical analyses of the four Neoproterozoic clayey beds of the Mohylivska (FM) and Yarishivska (FY) Formations sampled in the Podolya Basin show that these levels derive from volcanic ash deposits altered into K-bentonites. The difference in illite layer proportions in I-S mixed layers of investigated bentonite beds (Supplementary Fig. 2) (70/30) and the host sediments (85/15) is identical to the diagenetic conditions reported in other sedimentary basins (e.g., the Slovak basin47). Illitization kinetics seems to be slower in bentonites than in detrital sediments. It is noticeable here that the chemical composition of the diagenetic mineral assemblage in the bentonite beds is consistent with a mixture of quartz, kaolinite and a single I-S phase (Fig. 8a).

The distribution of REE elements in the bentonite beds after chondrite- and Al-normalizations shows a significant similarity, which confirm the common source of all these altered igneous materials (Fig. 8b). The composition of initial eruptive material corresponds to alkaline rhyolite-type, e.g., from a calc-alkaline magmatism series related to an arc setting. Moreover, the B4 K-bentonite layer contains zircon grains with sharp edges, which exclude the possibility of secondary transport and reworking. Therefore, our zircon-based chronological assessment of the bed can be considered as the absolute age of the ash deposition and thus be used to constrain the chronological span of the Ediacaran fossils of the Podolya Basin.

Only one previous age measure of 553 Ma exists for the Podolya Basin19. However, so far it has been difficult to assess its degree of accuracy because the analyses were not accompanied by a lithostratigraphical characterisation of the context, nor by mineralogical, petrographical or geochemical data. The age of the bentonite B4 bed, which is stratigraphically 40–45 m above the bentonite B1 from the Mohylivska (FM) Formation, is 555.4 ± 2.9 Ma. The age of the uppermost bentonite B1 of FM is 556.78 ± 0.10/0.18/0.62 Ma. On the basis of these two dates, we can now confidently infer that the transition between the Mohylivska and the Yarishivska Formations is within the uncertainty of the LA-ICP-MS method and can be constrained between 556.78 Ma and 555.4 Ma.
During this relatively short period of ~1.38 Ma, the Ediacaran macrobiota distribution at the Neoproterozoic Podolya Basin experienced notable changes: from abundant, spread and characterized by a variety of morphotypes (e.g., Nemiana simplex, Beltanelliformis, Cyclomedusa plana, Intrites punctatus), it experienced progressive depletion, until its disappearance in the fossil record. Perhaps, such preservation bias of the Ediacaran fauna can be also associated with changes occurred in the sedimentary regimes determining less favourable conservation conditions.

The Ediacaran biota from the Podolya Basin has great potential relevance in terms of litho-biostratigraphic correlation with other occurrences observed in similar siliciclastic successions worldwide variably rich in volcanic ash deposits representing potential sources of nutrients affecting bioproductivity48–51. Such Ediacaran-type assemblages have been preserved in similar geodynamic52 and sedimentary contexts also in several geographical areas of the ancient microcontinent Baltica, notably the White Sea, Urals, or its neighbourhood.

Following the prevalent morphotypes in the preserved fossil record and the progressive integration of refined U-Pb dates of the Ediacaran facies, three time-related major assemblages were established for this biota: the “Avalon” (579–559 Ma), the “White Sea” (558–550 Ma) and the “Nama” (549–542 Ma) assemblages. In this context, the Ediacaran macrofossils of the Podolya Basin distinctly exhibit closer affinities with some morphotypes forming the Avalon assemblage12,13. Indeed, one of the most common representatives in both assemblages is the taxon Intrites punctatus12 (Fig. 4B), which is typical of an early stage of the Ediacaran development because devoid of any complex structural feature. Conversely, more complex forms, such as Kimberella, Charnia, Ovatoscutum, have been reported in the assemblage from the Zimnie Gori Section of the White Sea53.

Accordingly, the differences in composition observed between the Ediacaran fossil remains represented in the Podolya Basin and in the Zimnie Gori Sections could be related to the rifting dynamics of the Rodinia-Pannotia supercontinent occurred across the Ediacaran-Paleozoic52.

Based on its morphological similarities with the Avalon assemblage and on its constrained chronological context, the Ediacaran macrobiota of the FM Formation of the Ukrainian Podolya Basin can be now directly compared to similar penecontemporary evidence from the Chernyi Kamen Formation, in Central Urals (Russia), dated to 557 ± 13 Ma54, and to the Welsh Wrekin Terrane (southern UK), dated to 559.3 ± 2 Ma55, the latter forming part of the East-Avalonia terrane close to Baltica around the end of the Neoproterozoic12,13 (Table 4).

**Conclusion**

Present new U-Pb-based dates of zircons from two (B1 and B4 K-bentonites) bentonite layers of the Mohylivska and Yarishyvska Formations of the Podolya Basin constrain the local presence of the Ediacaran biota between 556.78 ± 0.18 Ma and 555.4 ± 2.9 Ma. From a phylogenetic point of view, the Podolya's macrofauna consists of relatively primitive forms compared to those from the White Sea assemblage where, approximately at the same
|  | Bentonites | Siliclastic sediments |
|---|---|---|
| SiO₂ | 49.17 | 50.12 |
| Al₂O₃ | 25.95 | 26.23 |
| Fe₂O₃ | 3.13 | 2.22 |
| MnO | 0.00 | 0.00 |
| MgO | 2.04 | 2.08 |
| CaO | 0.62 | 0.66 |
| Na₂O | 0.10 | 0.11 |
| K₂O | 6.46 | 6.68 |
| TiO₂ | 0.22 | 0.24 |
| P₂O₅ | 0.08 | 0.00 |
| P₂O₅ | 12.49 | 11.74 |
| Total | 100.18 | 100.08 |

| ppm | Rb | 34.45 | 44.40 |
|---|---|---|---|
| Cs | 30.70 | 32.79 | 69.17 |
| Ba | 62.06 | 69.09 | 592.28 |
| Sr | 77.41 | 79.40 | 66.34 |
| Zr | 305.18 | 378.18 | 308.29 |
| Hf | 11.95 | 14.71 | 11.07 |
| U | 4.34 | 5.97 | 10.51 |
| Th | 39.83 | 48.70 | 52.39 |
| Y | 17.55 | 20.76 | 6.94 |
| Nb | 20.34 | 22.52 | 28.72 |
| Ta | 2.87 | 3.40 | 3.81 |
| Cr | 5.02 | 3.19 | 1.63 |
| Mo | <L.D. | <L.D. | <L.D. |
| W | 0.98 | <L.D. | 3.32 |
| Co | 9.35 | 12.70 | 2.68 |
| Ni | 15.71 | 23.19 | 4.87 |
| Cu | 3.43 | 5.05 | 9.37 |
| Zn | 7.66 | 8.06 | 15.45 |
| Cd | 0.06 | 0.07 | 0.05 |
| In | 0.11 | 0.13 | 0.11 |
| Ga | 33.55 | 34.58 | 38.02 |
| Pb | 22.63 | 25.25 | 5.20 |
| Sn | 7.87 | 8.17 | 12.12 |
| Ge | 1.89 | 1.57 | 2.61 |
| As | 3.78 | 7.96 | 0.54 |
| Sb | 0.91 | 1.08 | 0.17 |
| Bi | 0.57 | 0.80 | 0.68 |
| Sc | 19.56 | 22.37 | 13.78 |
| Y | 50.48 | 61.18 | 132.44 |
| La | 33.17 | 33.66 | 47.06 |
| Ce | 109.87 | 112.91 | 190.54 |
| Pr | 15.53 | 15.95 | 32.24 |
| Nd | 64.88 | 66.69 | 154.80 |
| Sm | 11.43 | 12.09 | 34.53 |
| Eu | 1.87 | 2.02 | 5.03 |
| Gd | 7.47 | 8.37 | 24.65 |
| Tb | 1.25 | 1.48 | 3.85 |
| Dy | 9.07 | 10.99 | 23.82 |
| Ho | 2.11 | 2.54 | 4.77 |
| Er | 6.27 | 7.53 | 12.33 |
| Tm | 0.94 | 1.20 | 1.78 |
| Lu | 0.96 | 1.20 | 1.70 |

Continued
time (555.3 ± 0.3 Ma), bilaterians were identified. Paleoover the late Neoproterozoic indicate a position of the paleocontinent Baltica in the immediate vicinity of the Avalon system, which may explain why the Ediacaran fossils from the Podolya Basin display a closer resemblance with some Avalon-type

### Table 1. Chemical composition of the K-Bentonite beds with lower and upper siliciclastic sediments.

| %   | Bentonites | Siliciclastic sediments |
|-----|------------|-------------------------|
| Yb  | B1a 8.18   | B1b 11.72               |
|     | B3a 16.31  | B3b 16.31               |
|     | B3b 13.78  | B4a 6.54               |
|     | B4b 6.52   | FM3 1.78               |
| REE | 271.43     | FM5 1.01               |
|     | 284.82     | FM8 2.56               |
|     | 548.82     | FY1 3.36               |
|     | 1203.41    | FY3 3.49               |
|     | 478.09     | FY6 1.78               |
|     | 885.18     |                         |
|     | 811.46     |                         |
|     | 277.20     |                         |
|     | 112.67     |                         |
|     | 133.57     |                         |
|     | 117.93     |                         |
|     | 187.71     |                         |
|     | 183.55     |                         |

Figure 6. Morphological features of zircon crystals from the B4 bentonite bed.

Figure 7. Concordia diagrams for U-Pb zircon dating of bentonites in the Podolia Basin. (A) Terra-Wasserburg concordia diagram showing the U-Pb age on the dated B4 bentonite sample. Analyses acquired using LA-ICP-MS; (B) concordia plot showing the result of high precision CA-ID-TIMS dating of zircons from the B1b bentonite sample NOV-ccg. All single error ellipses are in 2σ; the age is given as weighted mean 206Pb/238U age within 2σ x/y/z error systematics.
macro-organisms. Accordingly, the new chronostratigraphic evidence weakens the traditional hypothesis of a temporal sequence of the Avalon and White Sea assemblages and rather points to the need of additional research for furtherly refining the paleogeographic scenarios at the end of the Neoproterozoic Era.

Table 2. Zircon U-Pb data obtained by in situ Laser Ablation ICP-MS. 1: concentration uncertainty c. 20%; 2: data not corrected for common-Pb; a - Th contents calculated from radiogenic 208Pb and 230Th-corrected 206Pb/238U date of the sample, assuming concordance between U-Pb Th-Pb systems; b - Total mass of radiogenic Pb; c - Total mass of common Pb; d - Ratio of radiogenic Pb (including 208Pb) to common Pb; e - Measured ratio corrected for fractionation and spike contribution only; f - Measured ratios corrected for fractionation, tracer and blank; g - Isotopic dates calculated using $\lambda_{238} = 1.55125E-10$ (Jaffey et al. 1971) and $\lambda_{235} = 9.8485E-10$ (Jaffey et al. 1971); h - Corrected for initial Th/U disequilibrium using radiogenic 208Pb and Th/U[magma] = 3.50000. 1concentration uncertainty c. 20%, 2data not corrected for common-Pb, 3(206Pb/238U age)/(207Pb/206Pb age) * 100.
Methods

Mineralogical compositions of the bulk bentonite samples and their clay fraction (<2 µm) have been compared to that of under- and overlying deposits using X-ray diffraction. Bulk analyses were carried out on the material previously crushed and sieved at 50 µm and mounted in randomly ordered powder mode in order to characterize (hkl) reflections. The <2 µm fractions have been separated by sedimentation after dispersion and centrifugation at 20 °C − 1000 rpm during 120 s using a JOUAN GR 422 centrifuge. After drying, 15 mg of clay were dispersed in 1.5 mL of osmosed water. The solution was deposited on a glass slide to study position of (00 l) reflections in

| Table 3. Zircon U-Pb data obtained by the ID-TIMS method. |
|----------------------------------------------------------|
| Locality | Type of dating materials | Age | Dating method | Type of enclosing facies | Biota (prevailing morphotypes) |
|----------------------------------------------------------|
| Podolya (Ukraine) Bentonite* | 555.4 ± 2.9 Ma | LA-ICP-MS | Clayey siltstone with sandy lenses |
| Podolya (Ukraine) Bentonite* | 556.82 ± 0.2 Ma | ID-TIMS | Interbedded fine-grained sandstone and sandy siltstone |
| Podolya (Ukraine) Volcanic tuff* | 553 Ma | Methodology non precised by authors* | Not precised by authors* |
| Wrekin Terrane (Wales) Tuff** | 559.3 ± 2 Ma | SHRIMP | Interbedded siltstone and medium-grained sandstone |
| Ural (Russia) Volcanic tuff*** | 557 ± 13 Ma | SHRIMP | Volcanic tuff12,49 559.3 ± 2 Ma SHRIMP | Interbedded siltstone and medium-grained sandstone |
| White Sea (Russia) Volcanic ash** | 555.3 ± 0.3 Ma | ID-TIMS | claystones |

| Table 4. Summary of different ages obtained by previous works from several Neoproterozoic localities (*data from this study). |
|----------------------------------------------------------|
| Locality | Type of dating materials | Age | Dating method | Type of enclosing facies | Biota (prevailing morphotypes) |
|----------------------------------------------------------|
| Podolya (Ukraine) Bentonite* | 555.4 ± 2.9 Ma | LA-ICP-MS | Clayey siltstone with sandy lenses |
| Podolya (Ukraine) Bentonite* | 556.82 ± 0.2 Ma | ID-TIMS | Interbedded fine-grained sandstone and sandy siltstone |
| Podolya (Ukraine) Volcanic tuff* | 553 Ma | Methodology non precised by authors* | Not precised by authors* |
| Wrekin Terrane (Wales) Tuff** | 559.3 ± 2 Ma | SHRIMP | Interbedded siltstone and medium-grained sandstone |
| Ural (Russia) Volcanic tuff*** | 557 ± 13 Ma | SHRIMP | Volcanic tuff12,49 559.3 ± 2 Ma SHRIMP | Interbedded siltstone and medium-grained sandstone |
| White Sea (Russia) Volcanic ash** | 555.3 ± 0.3 Ma | ID-TIMS | claystones |

Figure 8. (A) Major element compositions plotted in 4Si-M^+−R^2+− system showing a proximity of bentonite to montmorillonite field; (B) REE distribution of altered volcanoclastic deposits of Podolya after chondrite- and Al-normalizations demonstrating similar element distribution characteristics for each K-bentonite bed.
different states: air-dried and ethylene-glycol solvatation\textsuperscript{56,57}. The obtained diffraction profiles were compared to ones calculated with NEWMOD software for illite-smectite mixed layer minerals.

The major, trace and rare earth elements (REE) were analyzed by spectrometry of inductively coupled plasma emission (ICP) at the department of Rocks and Minerals analysis (SARM) in the Petrographic and Geochemical Research Center (CRPG) of Nancy, France.

Bentonites B1 and B4 were subjected to radioisotopic dating using single zircon grains that were separated after dispersion of 200 g of bentonite in sodium solution (1 N NaCl).

U-Th-Pb isotope data from bentonite B4 were measured by laser ablation inductively coupled mass spectrometry (LA-ICP-MS) at the Laboratoire Magmas & Volcans of Clermont-Ferrand, France. Zircons were ablated using a Resonetics Resolution M-50 laser system operating at a wavelength of 193 nm coupled to a Thermo Element XR ICP-MS. Helium carrier gas was supplemented with N\textsubscript{2} prior to mixing with Ar for sensitivity enhancement\textsuperscript{58,59}. The laser was operated with a spot diameter of 20 μm, a repetition rate of 3 Hz and a fluence of 2.5 J/cm\textsuperscript{2}. Instrumental operating conditions and data acquisition parameters are basically similar to that reported in Hurlu et al.\textsuperscript{44} and Moyen et al.\textsuperscript{99}. Reduction of raw data was carried out using the GLITTER\textsuperscript{89} software package of Macquarie Research Ltd\textsuperscript{90}. Isotope ratios were corrected for laser-induced and instrumental mass fractionation via sample-standard bracketing using the GJ-1 zircon (206Pb/238U age of 601 Ma\textsuperscript{61}). Data were not corrected for common Pb. 206Pb/207Pb vs. The 238U/206Pb diagram was generated using the Isoplot/Ex v. 2.49 software of Ludwig\textsuperscript{46}. Error ellipses for each point are shown at the 2\textsigma level and incorporate both internal and external uncertainties. Data points were pooled to calculate a date and associated 2\textsigma error. The 91500 zircon reference material – 1065 Ma\textsuperscript{65} – was analyzed along with the samples to independently monitor the external precision and accuracy of the measurements. The Concordia age for 132 analyses of 91500 conducted over the course of the study was 1063.9 ± 2.4 Ma (2\textsigma including decay constant errors). All data are reported in Table 1.

Zircons from bentonite B1 were analyzed by high precision U-Pb Chemical Abrasion Isotope Dilution Thermal Ionisation Mass-Spectrometry (CA-ID-TIMS) at University of Geneva, Switzerland. After initial dissolution of the clay minerals, the remaining sample was subjected to methylene iodide heavy liquid separation. The retrieved zircons were predominantly long prismatic, with clear pyramids and sharp prisms. Selected grains were subjected to annealing and chemical abrasion (CA) following Mattinson\textsuperscript{91}. The annealing conditions were 900 °C for 48 h, while the chemical abrasion was done by placing each individual zircon into a pre-cleaned Savillex capsule with HF + trace HNO\textsubscript{3} at 210 °C for up to 13 h in a Parr bomb. After the partial dissolution step, each zircon together with the leachate was again transferred into a 3 ml screw-top Savillex vial. The leachate was completely pipetted out and the remaining zircons were rinsed in ultrapure water and then flushed for several hours in 6 N HCl on a hotplate at a temperature of ca. 80 °C. After removal of the acid, the zircon fragments were again rinsed several times in ultra-pure water and 7 N HNO\textsubscript{3} in an ultrasonic bath. Each single zircon grain was loaded for dissolution into pre-cleaned Savillex capsules, spiked with approximately 5 mg of the EARTHTIME 202Pb-205Pb tracer solution\textsuperscript{94}. The isotopic analyses were performed at University of Geneva on a TRITON mass spectrometer equipped with a MasCom discrete dynode electron multiplier. The linearity of the multiplier was calibrated using U500, Sr SRM987, and Pb SRM982 and SRM983 solutions. The deadtime for the SEM was determined to be constant at 22.5 ns for up to 1.3 Mcps and at a Faraday/SEM yield between 93 – 94%. Lead and uranium isotope fractionation were corrected using the ratios 206Pb/207Pb (0.9992391 ± 0.0265%, 1σ) and 235U/233U (0.99506 ± 0.01%, 1σ) of the double spike solution. The average Pb and U fractionation factors determined were 0.13 ± 0.02%/amu and 0.09 ± 0.02%/amu (1σ), respectively. Pb and U (as UO\textsubscript{2}) isotope compositions were measured on the electron multiplier. Isobaric interference of 231\textsuperscript{U} and 235\textsuperscript{U} on 237\textsuperscript{U} was corrected using an 18O/16O ratio of 0.00205. The measured uranium isotopic ratios were corrected assuming a sample 238U/235U ratio of 137.818 ± 0.045\textsuperscript{65}. All common Pb in the zircon analyses was attributed to the procedural blank with the following lead isotope composition: 206Pb/204Pb = 17.62 ± 0.09, 207Pb/204Pb = 14.73 ± 0.06, 206Pb/207Pb = 35.77 ± 0.99 (1-sigma %). The initial statistics, data reduction and age calculation were done using the TRIPOLI and Redux software\textsuperscript{66}. All 208Pb/238U and 206Pb/207Pb ratios were corrected for initial disequilibrium in 230Th/238U using Th/U (magma) assuming Th/U of the magma = 3.5. The accuracy of the measured data was assessed by repeated analysis of the 100 Ma synthetic solution\textsuperscript{65} and the international R33 zircon standard\textsuperscript{95}, which was pre-treated by chemical abrasion. Both yielded an internal reproducibility in 206Pb/238U dates of better than 0.05%. All uncertainties reported are at the 2 sigma level, following x/y/z systematic of Schoene et al.\textsuperscript{99}. All data are reported in the Table 2 with internal errors only, including counting statistics, uncertainties in correcting for mass discrimination, and the uncertainty in the common (blank) Pb composition. The MSWD value of weighted mean from the sample is within the range of acceptable values at 95% confidence level and for (n - 1) degrees of freedom.

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A.E.A. conceived the project. Y.S. and A.E.A. designed research. Y.S. A.E.A., V.N. and M.R. performed field research. Y.S., A.E.A. C.F. and V.N. performed sedimentological analyses. Y.S., C.F., A.E.A. and M.A. performed mineralogical and petrographical analyses. J.L.P. and M.O. performed geochronological analyses. Y.S., C.F., A.E.A. and A.M. performed mineralogical and petrographical analyses. J.L.P. and M.O. performed geochronological analyses. Y.S., A.E.A. C.F. and M.O. wrote the main part of the manuscript with the inputs from all co-authors.

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