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Tracing multiple resedimentation on an isolated karstified plateau: The bauxite-bearing Miocene red clay of the Southern Bakony Mountains, Hungary

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A B S T R A C T

The Vöröstó (=Red Lake) Formation, located in the Southern Bakony Mountains and the Balaton Highlands (Hungary), is a red, clayey continental assemblage containing hard, up to fist-sized bauxite pebbles, occurring in a large apparent stratigraphic gap between underlying karstified Triassic carbonates and mid' Miocene to Quaternary cover. The origin and the exact stratigraphic position of the assemblage have been controversial for a long time. In this study, petrographic observations on the bauxite pebbles revealed common features with Cretaceous bauxite deposits known in the region, whereas heavy mineral composition of the red clay matrix is similar to those known from the Eocene bauxite horizon of the region. Single grain zircon U–Pb ages obtained from the bauxite pebbles and their red clayey matrix show similar late Archean to Jurassic age components. Additionally, Cenozoic U–Pb ages are well represented in the mostly euhedral zircon crystals separated from the red clays, whereas this volcanogenic contribution completely missing from the bauxite pebbles. SEM morphology and related EDX chemical analysis of clay minerals indicate polygenetic, detrital origin for the red clays. The main source material of the bauxite bearing Vöröstó Formation is most probably local Cretaceous and Eocene bauxite deposits exposed during the middle-late Miocene. These tropical weathering products were partly decomposed and degraded, but dilution by siliciclastic contribution is negligible. We suggest a transport mechanism dominated by local redeposition of mostly pelitic and allitic material through seasonal muddy debris flows within a karstic landscape.

1. Introduction

The Vöröstó Formation (VF) is a continental red clay assemblage that is exposed in the Southern Bakony Mountains and the Balaton Highlands between Diszel and Vörösberény (Fig. 1). This area belongs to the Transdanubian Range (Fig. 1). The Transdanubian Range (TR) is situated in the western part of the Pannonian Basin and belongs to the 'ALCAPA' composite terrane (Fig. 1). This terrane was amalgamated during Paleogene to early Miocene time and consists of (i) the Eastern Alps (various Paleozoic formations and mainly carbonatic Mesozoic sequences), (ii) Carpathian elements of dominantly low to medium grade metamorphic rocks and (iii) Neogene sedimentary sequences of the Pannonian Basin (Haas, 2013).

The Vöröstó Formation essentially consists of a red clayey matrix, which contains up to 15 cm sized mostly well rounded, hard bauxite-pebbles. It was deposited during Miocene time and mainly comprises the fillings of karstic dolinas and sinkholes within Triassic Carbonates. It thus represents a huge stratigraphic gap giving rise to several contrasting evolutionary models for the VF. The main controversy relates to the question whether the entire sequence is recycled from older Cretaceous and Paleogene bauxite levels or the deposits reflect some bauxitic sediment and/or bauxite pebbles formed in-situ at the time of the Middle Miocene Climatic Optimum (e.g. Bárdossy, 1982; Knauer and Mindszenty, 1987; Bárdossy and Dercourt, 1990; Budai et al., 1999; Tóth and Varga, 2014). Given the high relevance of ferrallitic paleosoils and related bauxitic sediments for terrestrial paleoclimate reconstructions (e.g. Kovács et al., 2013; Mindszenty, 2016), providing a solution to this controversy is important for the paleoclimatic and paleoenvironmental interpretation of bauxitic deposits in general.

To shed light on this controversy we present a multi-proxy provenance approach to the VF bauxitic continental deposits, including thin

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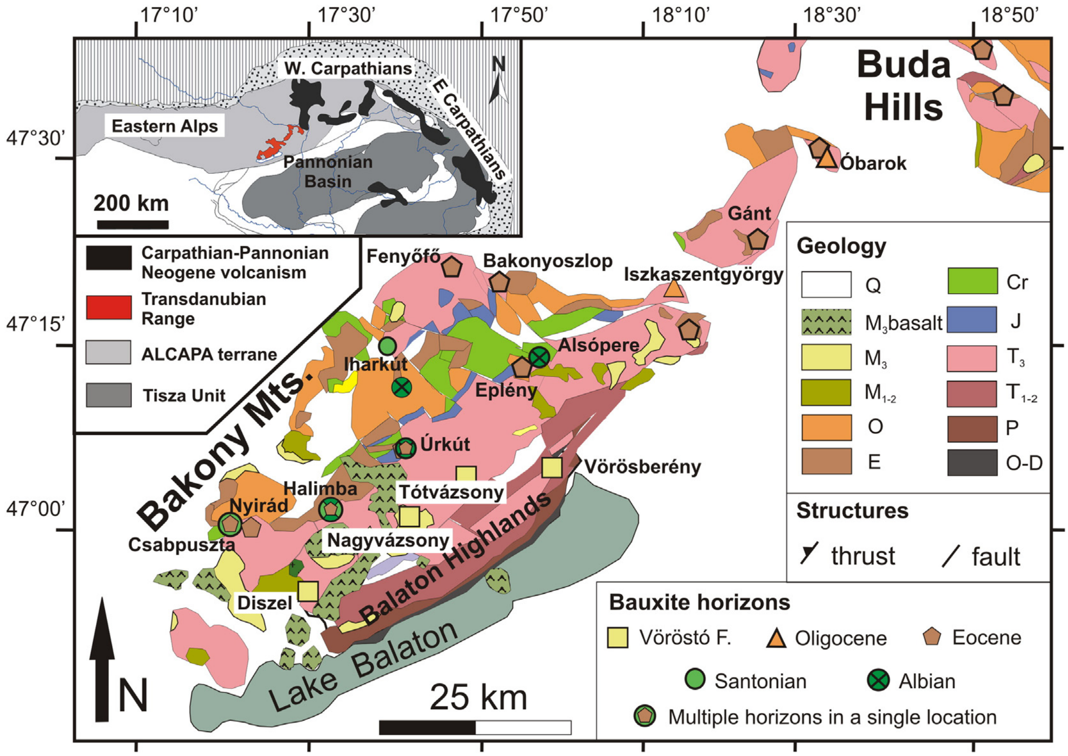

Fig. 1. Simplified geological map of the Transdanubian Range showing the main occurrences of the Vöröstó Formation and bauxites (base map: Gyalog, 2005, 1:100,000). Abbreviations: O-D: Ordovician to Devonian mostly low-grade quartz phyllite and slate. P: Permian continental red sandstone. T_{1-2}: Early to middle Triassic carbonates and the "pietra verde" tuff (Horváth and Tari, 1987; Pálfy et al., 2003). T_3: Late Triassic carbonates, dominantly Dachstein Limestone and Main Dolomite. J: Jurassic carbonates. Cr: Cretaceous in general. E: Eocene in general. O: Oligocene in general. M_{1-2}: Early and middle Miocene in general. M_3: Late Miocene in general. M_3basalt: Late Miocene to Pliocene basalts. Q: Quarternary in general. For detailed lithology see Haas (2013). The Carpathian-Pannonian Neogene volcanism is described in details in Harangi and Lenkey (2007) and Lukács et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

section petrography, phase analysis by X-ray powder diffraction (XRD), bulk-rock geochemical analysis by X-ray fluorescence spectrometry (XRF), microscale morphological observations on clay minerals by scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM-EDX), quantitative heavy mineral analysis and U–Pb geochronology of detrital zircon grains. Because VF was most likely never buried deep enough to undergo significant diagenetic alteration, these data are considered to record primary information on the Mesozoic to Paleogene rocks exposed at the surface in the surroundings of the karstic depocenters. Especially if outcrop conditions are poor, such approach is considered most promising for (i) the regional comparison to other, eventually better preserved archives, (ii) deciphering (multiple) recycling of older bauxitic levels, and (iii) constraining the timing of deposition and bauxite formation.

2. Geological setting

The main occurrences of the Vöröstó Formation are located in the Southern Bakony Mountains and the Balaton Highlands within the Transdanubian Range (TR, Fig. 1). The TR sensu stricto is bounded by major strike-slip faults and dominated by sedimentary successions, which are part of a major NE-SW striking synclinal structure formed within the Alpine nappe system during the Aptian to early Albian (Tari, 1994; Kiss and Fodor, 2005). The Transdanubian Range detached from the Alpine zone during Paleogene times and moved eastwards along a major dextral strike-slip fault system to the Pannonian Basin from Paleogene to Neogene times. In the early Miocene the hitherto separated ALCAPA and Tisza terranes (Fig. 1) were already located close to each other and their final amalgamation finished during the middle Miocene and created the modern tectonic framework for landscape evolution (Kázmér, 1984; Tari, 1994; Márton and Fodor, 2003; Csillag and Sebe, 2015). For the purpose of this paper we divided the Palaeozoic to Cenozoic successions into six sedimentary cycles (Fig. 2).

The first cycle is the Ordovician to lower Carboniferous, mostly dominated by slates, which experienced Variscan low-grade to medium grade metamorphism. They are exposed at the southern margins of the syncline only. The second, Permian to Aptian cycle starts with massive, several hundred meters thick continental clastic red sandstone-type Permo-Triassic sediments covered by up to 3 km thick, mostly shallow marine carbonates of Mesozoic age. Mid-Cretaceous compression triggered syncline formation, uplift, subaerial exposure, partial erosion and concomitant karstification of the predominantly carbonate landscape. The Albian greenhouse climate conditions (Ufnar et al., 2004) provided the preferable circumstances for the formation of the oldest, Albian "Alsópere" bauxite horizon of the region (Fig. 1). The bauxites are traditionally dated by the age of their immediate cover. The Albian bauxites fill shallow karstic features of either upper Triassic or sometimes lower Jurassic limestones and are covered by Albian freshwater or brackish marls (Fig. 2). Towards the end of the third, Albian to Turonian sedimentary cycle, subaerial exposure and bauxite formation occurred again, resulting in the erosion of all Turonian sediments and the accumulation of commercial-grade bauxite deposits. These are covered mostly by upper Cretaceous sediments. The major occurrences of this younger Late Cretaceous (Santonian) bauxite horizon can be found at Halimba, Iharkút and at Csabpuszta (Fig. 1). Their bedrock is also mostly upper Triassic dolomite and limestone and they are covered by Coniacian to Maastrichtian sediments of the fourth cycle (Fig. 2). The next erosional event resulted in the formation of the Eocene bauxite horizon. Considerable deposits can be found, for instance, at Nyirád,

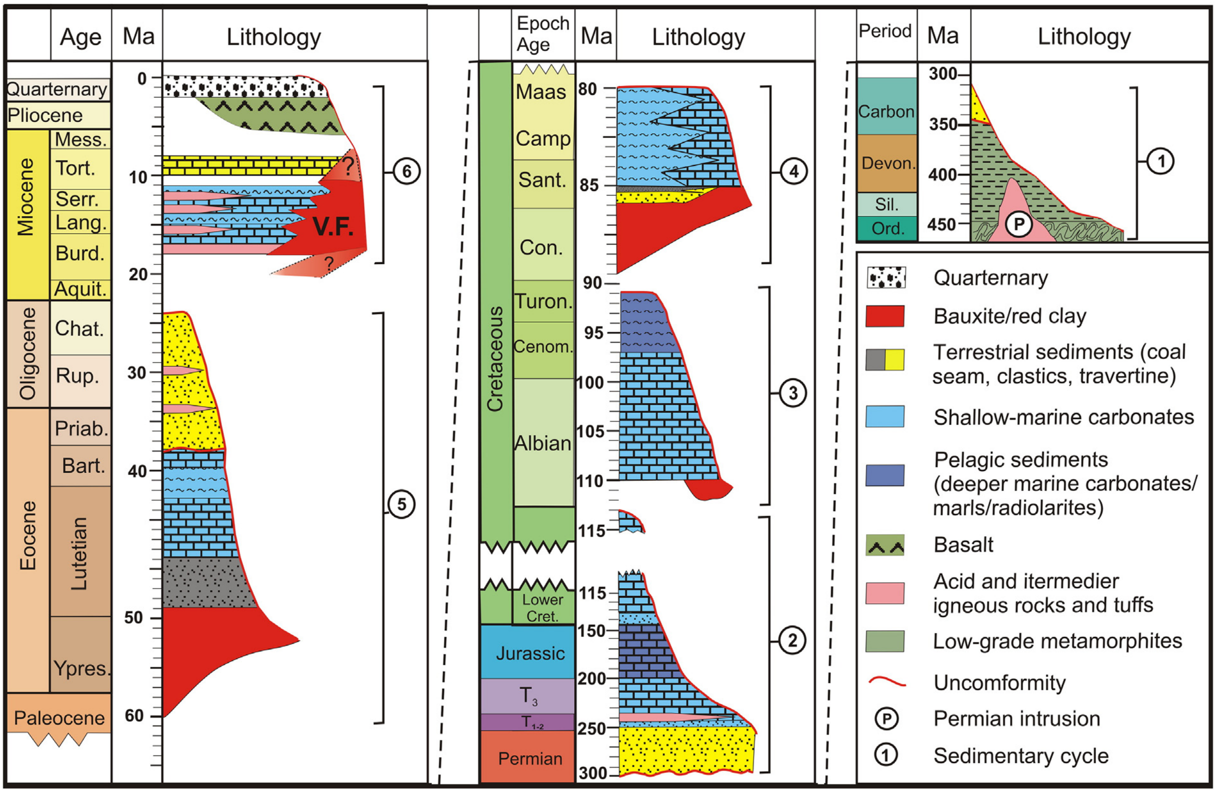

Fig. 2. Simplified stratigraphy of the Bakony Mountains. For the purpose of this paper, we divided it into 6 major sedimentary cycles. The end of each cycle is characterized by large scale erosion events and in some cases bauxite formation. The deposition of the Vöröstó Formation (VF) has started approximately at the beginning of the last cycle. For detailed lithology see Haas (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Eplény, Iszkaszentgyörgy, Gánt, Fenyőfő and Bakonyoszlop (Fig. 1). In some cases, for example at Csabpuszta, both the Cretaceous and the Eocene bauxite horizons are recorded at the same locality forming two bauxite levels separated by a late Cretaceous "Urgonian-type" limestone layer. At these locations both the Eocene (upper level) and the underlying Cretaceous (lower level) bauxite horizon provided commercial grade deposits (Mindszenty et al., 1988). The fifth, Eocene to Oligocene cycle consists of alternating sequences of carbonate and terrestrial sediments including the youngest Oligocene bauxite horizon of the TR (Óbarok, Mindszenty et al., 2002).

The strata of the sixth cycle composed of various carbonate and terrestrial sediments deposited from early Miocene to Quaternary times (Fig. 2). After the Oligocene, the TR suffered multiple erosional events (e.g. Csillag and Sebe, 2015). As a result, several hundred meters thick early Jurassic to late Oligocene strata have been eroded in the Southern Bakony Mountains. The original areal extent of these formations is unknown, but they are locally preserved and rough estimations can be given for their thicknesses (Korpás, 1981; Tari and Horváth, 2010). Simultaneously with the erosional events in isolated basins sedimentation was still ongoing as indicated by various carbonate and siliciclastic deposits of the sixth cycle (Budai et al., 1999; Haas, 2013). The accumulation of the Vöröstó Formation was possibly related to the local "Serravallian exhumation event" of the middle Miocene (Tóth and Varga, 2014). This interval is also described by Bulla (1958) and Csillag and Sebe (2015) as the last tropical period in the Pannonian basin characterized by deep tropical weathering and related sinkhole and dolina formation in the karstified regions. These morphological features reach up to 30 m in diameter and 100 m in depth. Jiménez-Moreno (2006) performed detailed palynological study in the Pannonian Basin and verified the warm-humid low altitude subtropical climate conditions for early to mid-Miocene times ("the Middle Miocene Climatic Optimum") followed by a progressive cooling period started at Serravallian times ("Monterey cooling event").

According to the low number of borehole data available in the study area, namely Nzt-6, Nzt-16, Nzt-18 and K-41 (Fig. A.1) and some field observations, the up to 85 m thick assemblage unconformably lies on the karstified surface of Triassic carbonates and the oldest cover here is upper Miocene freshwater limestone. The exact age, stratigraphic position and in-situ or redeposited origin of the Vöröstó Formation are highly debated mainly due to the large stratigraphic gap between bedrock and cover formations and also to the lack of good outcrops (Budai et al., 1999).

Based on field observations and the size and shape of the bauxite pebbles Bertalan (1953), Jaskó (1957), Bárdossy (1982) considered the VF as a redeposited assemblage formed by only short, <1 km long, seasonal fluvial transportations. In contrast, Knauer and Mindszenty (1987) and Budai et al. (1999) suggested that some of the pebbles could have an in-situ origin and that they were very likely formed during the Middle Miocene Climatic Optimum and can be related to an in-situ paleo-weathering crust. This assumption was based on thin section observations by Knauer and Mindszenty (1987). However, they also concluded that the bauxite pebbles could have been resedimented from Cretaceous bauxite levels.

In the area of Diszel (Fig. 1) the VF was considered as a potentially economic bauxite deposit and therefore detailed prospection was carried out. These data and their interpretations were summarized by Tóth and Varga (2014). The VF at Diszel rests on the surface of upper Triassic bedrock and is covered by various mid-Miocene formations. It fills karstic features, dolinas and even up to 70 m deep sinkholes, formed on upper Triassic carbonates. Based on the changes in size, amount and distribution of the bauxite pebbles in the clayey matrix Tóth and Varga (2014) divided the Diszel deposits into four sedimentary cycles, each separated from the others by erosional boundaries. According to thin section analysis, the lowermost cycle could be the remnant of a former Eocene bauxite deposit thus not part of the VF. Tóth and Varga (2014) greatly strengthened the former hypothesis of a redeposited fluvial

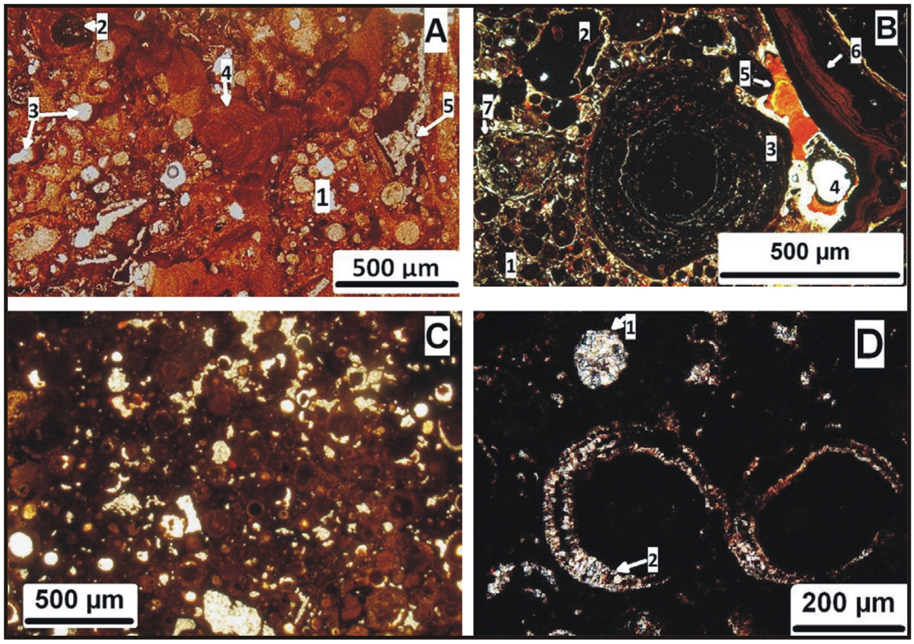

Fig. 3. (A): The typical microscopic texture of Tótvázsony bauxite pebbles. (1) Microclastic matrix. (2) Opaque intraclast. (3) is an artifact (open hole formed during thin section preparation). 4) Rhythmic alternation of light and dark laminae, a characteristic feature of collomorphous Fe-oxide-clay illuviation. (5) Gibbsitic vein filling. (B): Typical texture of Nagyvázsony bauxite pebbles. (1) Oolithic matrix composed of Al-oxide-hydroxide minerals. (2) Opaque intraclast. (3) Oolithic intraclast. (4) Open hole formed probably during thin section preparation. (5) Rhythmic alternation of light and dark laminae, a characteristic feature of collomorphous Fe-oxide-clay illuviation. (6) Goethitic coating. (7) Intraclast with complex inner texture. (C): Oolithic bauxite clast in a Sátor-hegy bauxite pebble. (D): Cross-polarized microscopic image of pore filling gibbsite crystals (1) and grown-up tabular crystals around grains (2) in a Vízvöröstó bauxite pebble (VV_b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

origin. They confirmed the seasonal fluvial deposition mechanism by reconstructing the size distribution pattern of the pebbles based on the data provided by the numerous boreholes. Based on the fining upward trend of the bauxite pebbles and increasing amount of clay they suggested that the relief energy was highest when the accumulation of the VF started and then decreased gradually. They concluded that the age of deposition was Serravallian based on the continuity towards and interfingering with the cover sequences. They were also able to define a main transport direction trend from N to S and E to W.

In this study, we essentially rely on the model established for the Diszel area by Tóth and Varga (2014). This is because our study area neither provides a sufficient number of borehole data nor sufficient outcrops with respect to both quantity and quality to make reliable sedimentological observations on sorting, fabric type, bedding style or vertical clast size trends. The use of the Diszel area as analog is supported by the fact that it represents the same formation with similar lithological characteristics, formed in an essentially similar geological setting.

3. Materials and methods

The samples were collected in two areas from within the same large apparent stratigraphic gap (between Triassic and late Miocene): Nagyvázsony and Vörösberény (Fig. A.1). A summary table is provided with the sample names, locations, and methods used (Table A.1). The Nagyvázsony area belongs to the Southern Bakony Mountains and the locations within are situated at different topographic elevations. The structural tilt of the Vöröstó Formation deposits is negligible and elevations can be directly used to constrain relative stratigraphic positions. However, due to poor outcropping conditions, a reliable stratigraphic column cannot be constructed. The lowermost sampling site is the Vízvöröstó (VV_b; 272 m NN) and above it situated the Nagyvázsony sampling site (NV_c and NV_b; 276 m NN). On the top is Kab-hegy (289 m NN), where the red clay of the Vöröstó Formation (KH_c) and its probably pedogenically altered equivalent (KH_c_s) is covered by late Miocene-Pliocene basalt lava. KH_c_s has been collected directly from below the basalt. KH_c and KH_c_s were collected from the same

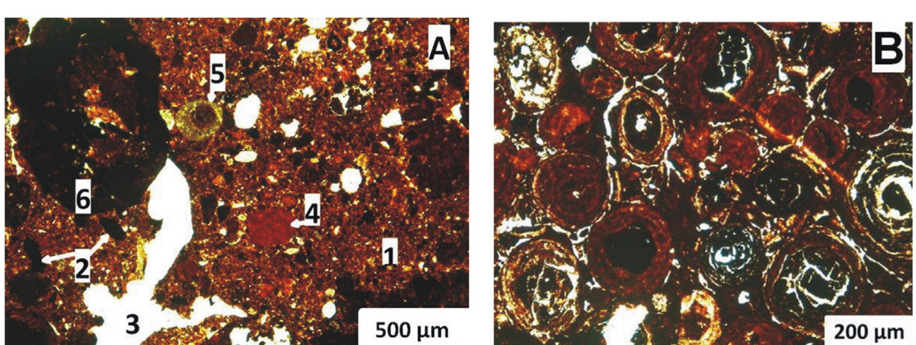

Fig. 4. Thin section images of representative textures of Transdanubian bauxites (collection of the Department of Applied Geology of the Eötvös Loránd University, Budapest). (A): Sample Pe7; typical thin section image of the Albian Alsópere bauxite. (1) Microclastic matrix. (2) Opaque intraclasts. (3) Open hole formed probably during thin section preparation. (4) Homogenous red intraclast. (5) Ooid (round-shaped and of concentric structure). (6) Intraclast with complex inner texture. (B): Sample Nb183; typical grain supported oolithic texture of Santonian bauxites.

Table 1
Major element composition of the bauxite pebbles indicates their good quality close to the economic ore cut-off grade. The composition of the bauxite pebbles is in line with the composition of well-known economic bauxite deposits of the TR. The NV_b_XRF sample is probably a ferricrust-bauxite with high Fe2O3 content. For other major and trace element data see Table A.3.

Reference	Al_2O_3% (min.–max.)	SiO_2% (min.–max.)	TiO_2% (min.–max.)	Fe_2O_3% (min.–max.)	
Alsópere (Albian)	37.75–58.95	6.01–16.68	1.8–3.1	14.58–20.31	Knauer, unpublished
Iharkút (Santonian)	43.9–60.7	1.4–9.8	1.3–3.1	12.9–28.7	Bárdossy and Mindszenty, 2013
Halimba (Santonian)	31.9–65.7	0.9–15.0	1.1–6.3	2.0–38.2	Bárdossy, 2009
Eplény (Cretaceous? bauxite pebbles in Eocene matrix)	52.58	0.51	2.39	26.88	Bárdossy, 1968
Sample	**Al_2O_3%**	**SiO_2%**	**TiO_2%**	**Fe_2O_3%**	
NV_b_XRF	33.51	1.24	1.76	50	
TV_b_XRF	45.63	1.46	2.17	24	
VV_b_XRF	41.32	1.47	2.37	26	
SH_b_XRF	40.79	1.13	2.61	29	

elevation. KH_c could have been pedogenically altered as it is abundant in ca. 0.5 cm sized iron oxide nodules. This phenomenon is resembling redoximorphic features in water-saturated soils (e.g., Stoops et al., 2010). The Vöröstó area belongs to the Balaton Highlands and includes Sátor-hegy (SH_c and SH_b) and Festékföld-bánya (FF_c) locations. Bauxite pebbles (NV_b, VV_b, TV_b, SH_b) and their red clay matrix (KH_c, NV_c, FF_c, SH_c) were collected at six locations close to Nagyvázsony and Vörösberény (Fig. A.1). Sample SH_c was collected from loose debris close to Sátor-hegy location. It contains dolomite and limestone clasts as well as mica flakes. Based on its lithologic features, it may represent locally reworked Vöröstó Formation.

All samples were split by a diamond saw for the preparation of thin sections. From the bauxite fragments we generated pebble-population samples (Dunkl et al., 2009). The pebbles were pooled into composite samples for bulk mineral separation in order to get a sufficient number of detrital grains for heavy mineral study and zircon geochronology.

3.1. Petrography

Based on the macroscopic observation of >300 bauxite pebbles five representative samples were selected for microscopic study. Additionally, the thin section archive of the Department of Physical and Applied Geology of the Eötvös Loránd University (Budapest) from key bauxite occurrences of the Transdanubian Range was used for comparison to the bauxite pebbles from the Vöröstó Formation.

3.2. Phase analysis by X-ray diffraction (XRD)

Mineral phase identification has been carried out on representative, powdered samples from each locality. XRD analysis was performed on altogether 9 samples: 4 bauxite pebble samples (NV_b, VV_b, TV_b, SH_b), 4 red clay samples (KH_c, NV_c, FF_c, SH_c) and the on the Kab-hegy paleosol sample (KH_c_S). Standard powder diffractograms were acquired with 45-minute duration on a 65° 2θ range. For the red clay samples we carried out 3 additional measurements on oriented, dry and glycolated preparations. In the case of KH_c_S sample, we used ZnO as internal standard and 9 and half hours analysis time to achieve quantitative evaluation. The instruments used were a Siemens D5000 Kristalloflex at the Department of Mineralogy of Eötvös Loránd University, Budapest and a X'Pert MPD Phillips device at the Geoscience Centre of the Georg-August University, Göttingen. We used EVA and X'Pert as evaluation software.

3.3. Bulk rock chemical composition by X-ray fluorescence analysis (XRF)

The bulk chemical composition of 4 bauxite pebbles was analyzed at the Geoscience Center, Department of Geochemistry of the Georg-August University, Göttingen with an AXIOS-Advanced PANalytical XRF spectrometer. The data processing was controlled by the SuperQ 4 software package. The analytical precision for major elements was 0.5 to 2% and 2 to 5% for trace elements. Detection limits varied from 0.1 to 3 ppm for the majority of the measured elements. To ensure the best accuracy and precision values glass disks were made of 3900 mg of lithium tetraborate, lithium metaborate, lithium fluoride composite flux and 1750 mg powdered samples. The TW 45 clay was used as standard.

3.4. Microscale morphology of clay minerals

The micromorphological study of the clay minerals was carried out by an AMRAY 1830I scanning electron microscope coupled with

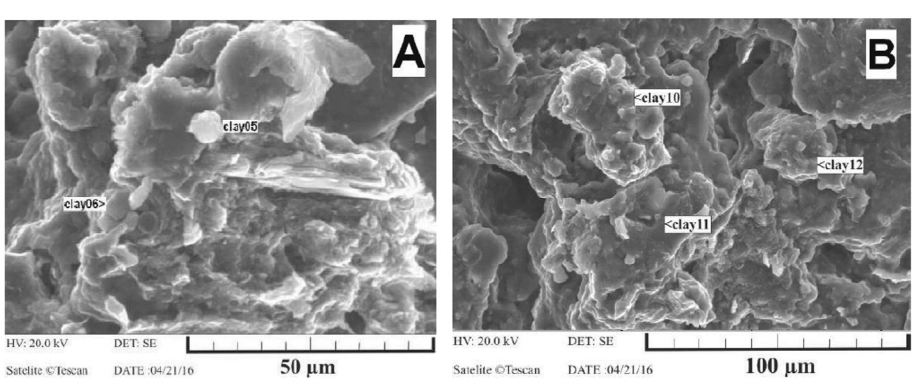

Fig. 5. Scanning electron microscopic images indicating the fine structure of red clays from Nagyvázsony and Festékföld-bánya sampling sites (NV_c and FF_c samples, A and B, respectively). The clay flakes are forming silt-sized aggregates at this magnification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

PV9800 type EDX spectrometer at the Department of Petrology and Geochemistry of the Eötvös Loránd University, Budapest. The micromorphological features of the clay minerals were examined on freshly broken surfaces of ~5 mm pieces of red clays from the Kab-hegy (KH_c), Nagyvázsony (NV_c) and Festékföld-bánya (FF_c) locations. EDX analysis was performed on altogether 16 clay mineral grains and an additional 3 on homogenous surfaces representing the bulk chemical composition of the matrix of each sample: (i) 7 analysis on the KH_c sample (6 grains + matrix); (ii) 6 analysis on the NV_c sample (5 grains + matrix); (iii) 6 analysis on the FF_c sample (5 grains + matrix). All chemical

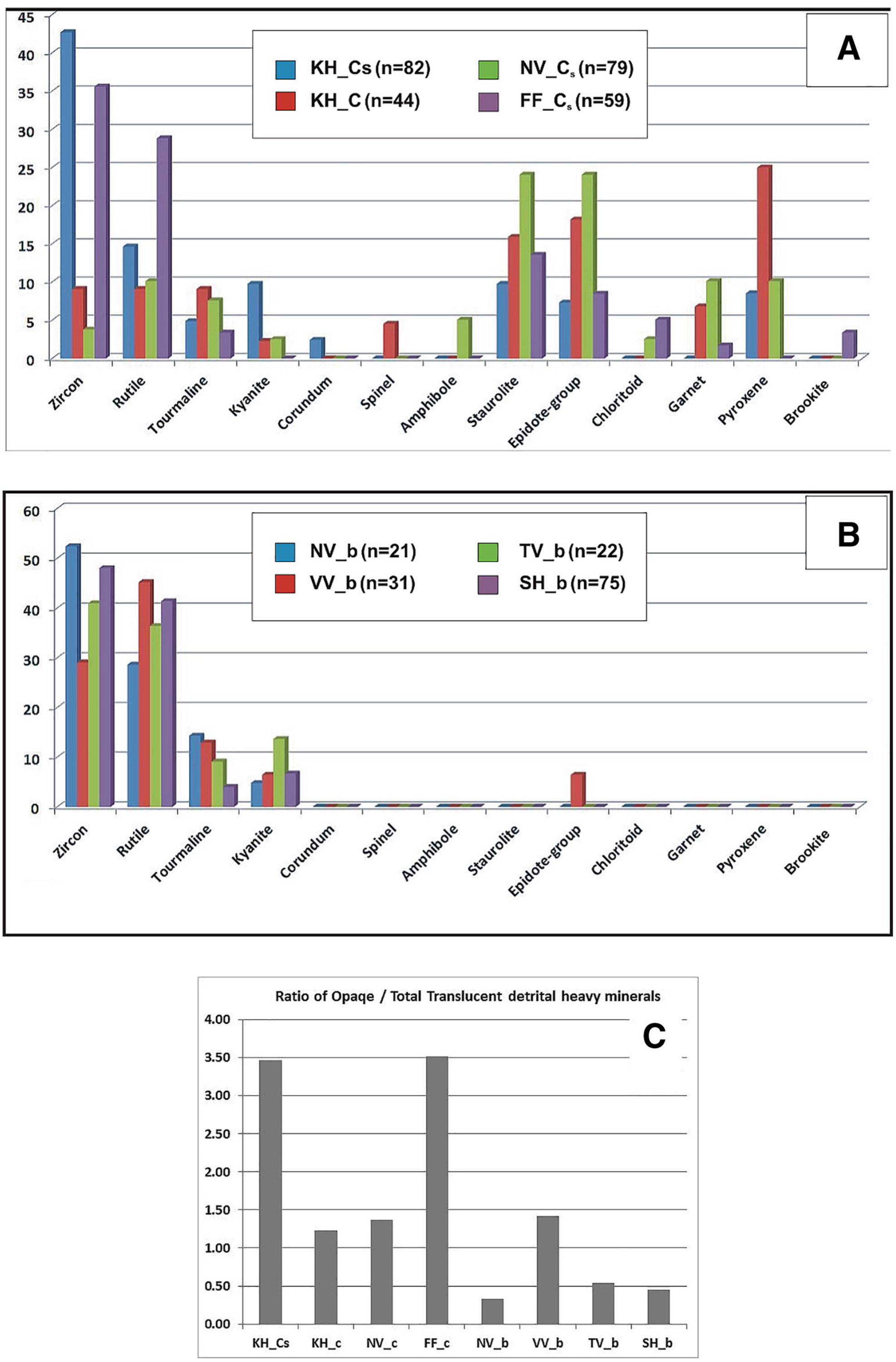

Fig. 6. Heavy mineral composition in the Vöröstó Formation red clays (A) and in the bauxite pebbles (B). Number of non-opaque grains is marked with (n). Raw data is provided in Table A.5. The red clays generally have higher detrital opaque mineral content than the bauxite pebbles (C). The occurrence and high variety of metamorphic minerals in the red clay samples are very similar to those observed in the Eocene bauxites of the Transdanubian Range. The dominance of the ultrastable heavy minerals in the bauxite pebbles is similar to those observed in the Cretaceous bauxite levels. See details in Mindszenty et al. (1991). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

data was evaluated by the Moran Scientific 2.3 software. Applied tools were ZAF correction and internationally verified standards.

3.5. Heavy mineral analysis

For quantitative heavy mineral analysis and U–Pb dating, we used 1 to 2 kg representative material from each red clay and bauxite pebble populations except NV_b where we could only collect about 100 g sample material. Bauxite pebbles were crushed in a disc mill and a jaw crusher, whereas red clays were soaked in warm water. Approximately 100 g from each sample type has been used for quantitative heavy mineral analysis. The 63 to 125 μm sieve fractions were studied using the ribbon counting method (Mange and Maurer, 1992). Exact number of grains analyzed by ribbon counting are provided in the caption of the relevant figures (Fig. 6A, B). For embedding, we used Cargille Meltmount immersion medium of $n = 1.66$ refractive index. For geochronological purpose, zircon crystals were concentrated from the <250 μm sieve fraction by shaking table and heavy liquid treatment (sodium polytungstate, 2.85 to 2.89 g/cm^3). The heavy fraction was treated with 5% acetic acid and ultrasonic agitation to remove carbonate, while authigenic iron oxides and hydroxides were removed by the DCO method (Varadachari et al., 2006). This method has no effect on the detrital, well crystalline iron-oxide minerals, like ilmenite or magnetite. Finally, a Frantz L-1 magnetic separator was used to remove the paramagnetic minerals.

3.6. U–Pb geochronology

U–Pb geochronology was performed on altogether 693 individual zircon grains: (i) 294 analysis on red clays; (ii) 289 on bauxite pebbles and 110 on the KH_c$_s$ paleosol. Note that these analyses contain results later on excluded from the data set because they gave false results for various reasons. For in situ single grain U–Pb dating, we used a Resonetics type excimer laser ablation system coupled to a Thermo Element2 sector field ICP-MS following the techniques described by Frei and Gerdes (2009). The laser was fired at 5 Hz with 80 mJ energy and 25% transmission. The carrier gas was He. Usually, 33 μm spot size was applied, but in the case of small zircon crystals, it was set to 23 μm. The ablation time was 20 s per spot; the ^{202}Hg, mass204, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U and ^{238}U isotopes were detected by variable dwell times. The primary reference material was GJ1 zircon and FC1, 91 500, Plešovice zircons were used as secondary standards for U–Pb dating (Paces and Miller, 1993; Wiedenbeck et al., 1995; Jackson et al., 2004; Sláma et al., 2008). For instrument calibration, the NBS 612 glass standard was applied (Schultheis et al., 2004).

We applied two approaches to the selection of zircon crystals for detrital U–Pb geochronology. The aliquots formed from the randomly selected grains aim to represent the entire, unbiased sample. By the analysis of the aliquots composed of the selected euhedral, intact, mostly clear zircon crystals we aimed to increase the probability to identify the youngest – probably volcanogenic – zircon population. Cathodoluminescence (CL) images of polished grains were used as maps to select the proper positions of laser ablation spots and avoiding any fractures, inclusions or inhomogeneities. Laser spots were positioned on the outermost mantle of the grains to date the latest crystallization event and to avoid inherited older cores. The CL images were taken with a JEOL JXA 8900 electron microprobe. Data reduction was performed with UranOS 2.06a software (Dunkl et al., 2008). The CL mapping and the ICP-MS geochronology have been carried out at the Geoscience Center, Department of Geochemistry of the Georg-August University, Göttingen (Germany). If the ^{206}Pb/^{238}U age was younger than 1.5 Ga, we considered this age for further data analysis, otherwise above this threshold the ^{207}Pb/^{206}Pb age was used (Spencer et al., 2016). The concordia plots and age spectra were constructed with the help of Isoplot/Ex 3.0 and AgeDisplay software (Sircombe, 2004; Ludwig, 2012).

4. Results

4.1. Petrography

The Vöröstó Formation is composed of a clayey, silty to fine-grained sandy matrix with usually 1 to 10 mm rounded to subrounded clasts (Fig. 3A). The clasts are generally opaque but complex clastic or oolithic inner textures can also be observed (Fig. 3B and C). Well crystallized, pore-filling gibbsite is common as tabular crystals grown perpendicular to pore walls or scattered in the matrix (Fig. 3D). The observed collomorphous Fe-oxide-clay illuviations are characterized by the rhythmic alternation of light and dark laminae (Fig. 3A). The Sátor-hegy bauxite pebbles (SH_b) often show pore filling calcite.

The textures of the Nagyvázsony (NV_b) bauxite pebbles are different as they frequently show oolitic features (Fig. 3B). Larger (~200–500 μm) ooids are embedded in an oolitic packstone matrix consisting of smaller (~10–20 μm) ooids. However, like in the case of the other Vöröstó Formation bauxite pebbles, opaque intraclasts, collomorphous Fe-oxide-clay illuviations and occasionally intraclasts with complex textures are found in the Nagyvázsony pebbles, too (Fig. 3B).

Among the bauxites of the TR, the Albian Alsópere type shows similar characteristics to the bauxite pebbles of Vízvöröstó (VV_b), Tótvázsony (TV_b) and Sátor-hegy (SH_b_1) samples (Figs. 3A, C, D and 4A). The typical oolithic texture of the Santonian Iharkút type bauxite is very similar to those collected from Nagyvázsony (Figs. 3B and 4B). On the contrary, none of the studied bauxite pebbles show pelitomorphous "aggregate-like" textures characteristic for the Eocene bauxites (Mindszenty et al., 1988).

4.2. Phase analysis by X-ray diffraction (XRD)

The identified mineral phases are summarized in the Appendix (Table A.2) and the diffractogram of each sample is also provided (Figs. A.2, A.3). In red clays, quartz and kaolinite are always present. Illite was also identified in the red clay samples, except in the Kab-hegy sample (KH_c). Smectites have been also detected in the Sátor-hegy (SH_c), Kab-hegy (KH_c) and Festékföld-bánya (FF_c) samples. Hematite and goethite were detected in the majority of

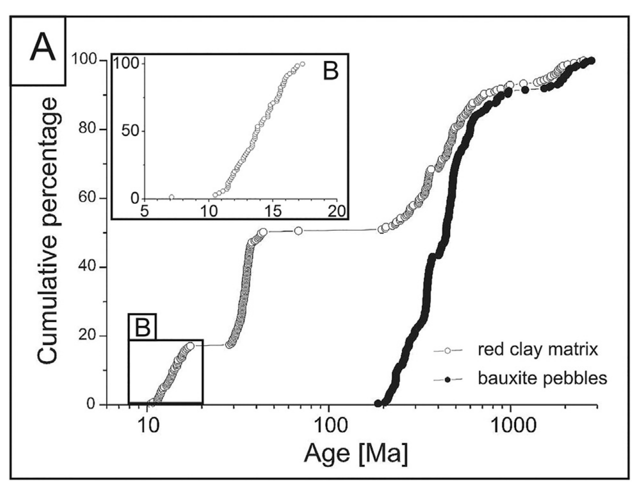

Fig. 7. (A) Summary of all zircon U–Pb ages obtained on red clay samples and bauxite pebble populations. Both types of samples show wide age ranges from Archean to Triassic, but Cenozoic ages are present only in the red clays. The Cenozoic ages from the clay matrix can be further divided into Paleogene and Miocene age components. (B) The wide range of Miocene ages is representing almost the entire Neogene Carpathian-Pannonian volcanism (Harangi and Lenkey, 2007; Lukács et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

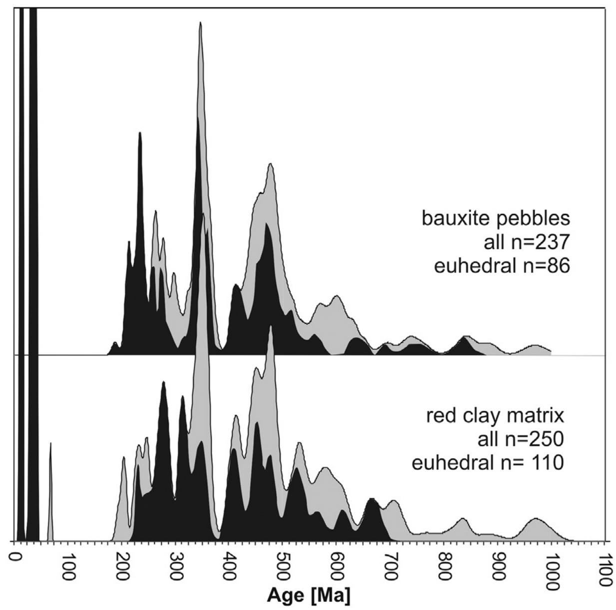

Fig. 8. Probability density plot of the Vöröstó Formation zircon U–Pb data (only data with concordance between 90 and 110%). Ages older than 1.1 Ga are mostly diffuse and represent only ca. 10% of the entire data sets, see Fig. 7. The age distribution of the euhedral grains of the red clays tends to show younger ages, whereas the age distribution of the bauxite pebbles is more or less similar (except Proterozoic and older ages). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

red clay samples and bauxite pebbles. Gibbsite, boehmite and anatase are present in most bauxite pebbles.

4.3. Bulk rock chemical composition by X-ray fluorescence analysis

The complete major and trace element composition is provided in the Appendix (Table A.3). The composition of the bauxite pebbles is in line with the composition of well-known economic bauxite deposits of the TR (Table 1). The Al_2O_3 content of sample NV_b is below 40%; it is characterized by a high Fe_2O_3 to Al_2O_3 ratio when compared to the other samples.

4.4. Microscale morphology on clay minerals

The clay minerals are mostly iron-coated kaolinite, illite and their transitional phases. The red clay samples consist of 1–100 μm sized anhedral grains with corroded edges suggesting detrital origin (Fig. 5). This micromorphology indicates obviously that the authigenic clay growth is lacking in the matrix of the VF. Detailed chemical analysis of clay minerals is provided in Table A.4.

4.5. Heavy mineral composition

Each identified heavy mineral species are photo documented and verified by SEM-EDX chemical phase analysis (Figs. A.4, A.5, A.6).The heavy mineral spectra of the red clays and the bauxite pebbles show a remarkable difference. Generally, the bauxite pebbles contain much less amount and variety of heavy minerals than the red clay samples (Fig. 6). The common features are the presence of the "ultrastable" species (rutile, zircon, tourmaline), kyanite and opaque minerals. The heavy mineral composition of the bauxite pebbles is similar to that of the Cretaceous bauxites, whereas the red clays show more diverse spectra like the Eocene bauxites of the TR (Mindszenty et al., 1991). The detailed results of this study are listed in the Appendix (Table A.5).

4.6. U–Pb geochronology

According to Cathodoluminescence (CL) images, the zircon crystals are generally zoned (Fig. A.7). In the red clays intact, euhedral crystals are frequently present (Fig. A.7.A), whereas zircon crystals extracted from the bauxite pebbles are mostly damaged and metamict (Fig. 7.B). We accepted 276 concordant ages from the red clays and 259 from the bauxite pebbles and additional 97 ages from the Kab-hegy palaeosol sample (KH_c_s). For detailed data see Appendix (Table A.5). The zircon U–Pb ages show a wide range from Archean to middle Miocene (Fig. 7).

In the case of the Kab-hegy and Nagyvázsony red clay samples (KH_c and NV_c) and the Vízvöröstó and Sátor-hegy bauxite pebble population samples (VV_b and SH_b), there was no significant difference between the age components of the euhedral and the randomly selected grains. However, the Festékföld-bánya red clay sample (FF_c), the Nagyvázsony and Tótvázsony bauxite pebble samples (TV_b) tend to show younger euhedral grains than their randomly selected equivalents. The young Cenozoic ages are present only in the red clays, whereas, the bauxite pebbles show only Jurassic and older ages (Fig. 7). The pre-Cenozoic age distributions in the red clay samples and the bauxite pebble-populations are similar (Fig. 8).

In order to isolate geologically significant ages from the mass of single-grain data, we performed component identifications using ages with concordance from 90 to 110% only. Two methods were applied to identify the age components: the "Density plotter" (Vermeesch, 2012) and the "PopShare" software (Dunkl and Székely, 2002). The two procedures are based on different algorithms, but they identified very similar major age components (Table 2).

Table 2
Age components identified in the concordant zircon U–Pb ages by Popshare procedure (Dunkl and Székely, 2002). The Jurassic and younger age components are very well defined and appear in the red clay matrix only. The age components observed in both sample types are very similar.

Red clay matrix Mean ± s.d.	Bauxite pebble population Mean ± s.d.	Associated igneous event	References
14.0 ± 2		Miocene volcanism in the Carpathians	Harangi and Lenkey, 2007; Lukács et al., 2015
34.6 ± 2		"Periadriatic" Paleogene volcanism	Benedek et al., 2004; Bergomi et al., 2015; Danišík et al., 2015
42.4 ± 1		Early phase of "Periadriatic" volcanism	Bergomi et al., 2015; Danišík et al., 2015
196 ± 4		Early Jusrassic magmatism	Blackburn et al., 2013
244 ± 26	224 ± 14	"Pietra verde" volcanism	Horváth and Tari, 1987; Pálfy et al., 2003
279 ± 3	271 ± 27	Permian volcanism	Lelkes-Felvári and Klötzli, 2005
328 ± 18		Variscan magmatism	Gerdes et al., 2003
352 ± 5	347 ± 10	Early Variscan magmatism	Gerdes et al., 2003
461 ± 30	465 ± 26	Ordovicain magmatism	Guillot et al., 2002
570 ± 120	578 ± 113	Cadomian magmatism	Košler et al., 2014
1699 ± 365	1827 ± 273		

5. Discussion

5.1. Interpretation of U–Pb ages

For the interpretation, we use mean ages and standard deviations of the age components isolated by the Simplex algorithm of "PopShare" software (Table 2). Since the age components show distinct similarities (Fig. 8) we evaluate the results obtained on the red clays and bauxite pebbles together.

The "Cadomian" igneous formations are relatively widespread in the region (e.g. Košler et al., 2014), thus these age components have minor diagnostic value. The Ordovician age components can be originated from the TR or from the Internal - Southern Alps, its former immediate neighbor (Kázmér, 1984). The zircon-bearing formations of the Palaeozoic basement of the Internal and Southern Alps are dominated by acid volcanics in the upper Ordovician strata (Albani et al., 1985; Schönlaub, 2000; Guillot et al., 2002). Regarding the age signatures of the Variscan and Permian magmatism, the results of this study are slightly complex. The early Variscan and Permian zircon ages are present both in the clay and bauxite samples. The ca. 330 Ma old age component was detected only in the red clay matrix. This age is close to the typical ages of the widespread early Carboniferous magmatism (e.g. the South Bohemian Batholith; Gerdes et al., 2003). We assume that these age components derived probably not from the s.s. TR as early Variscan igneous formations are not known from the ALCAPA tectonic block. Permian volcanite complex is known in the Transdanubian Range (Lelkes-Felvári and Klötzli, 2005). According to its 291.4 ± 4 Ma U/Pb age, this formation can be a possible source for some of the Permian zircons of the Vöröstó Formation red clays and bauxite pebbles.

A part of the Paleozoic and older zircons more likely not derived directly from their primary source, they rather represent recycled material from siliciclastic sediments of Carboniferous or Permian age (Figs. 1 and 2). The widespread Permian red sandstone (Fig. 1) frequently contains acidic volcanic rock fragments (Szakmány and Nagy, 2005). However, their exact origin is yet unknown. This formation can be a possible candidate as a source for the Permian and Variscan zircons.

The middle Triassic zircons are also present both in the red clay and in the bauxite samples. These can be associated to the "Pietra verde" tuff layers of Ladinian age, which is the only zircon-bearing member of the Mesozoic carbonate platform sequence of the Southern Tethyan (African) margin (Horváth and Tari, 1987; Pálfy et al., 2003;). Upon denudation and karstification of the carbonates, the zircons from the middle Triassic tuff layers were accumulated locally in the bauxite deposits of the karstic area (Dunkl, 1992).

The early Jurassic age component is represented only by 4 grains, but it can be well distinguished from the middle Triassic one and was derived therefore from a distinct source. Igneous formations of such age are not known from the TR, but in the Tisza Unit the upper Triassic to lower Jurassic sequences contain both dispersed volcanogenic material and well-preserved ash layers (Némedi Varga, 1998; Pozsgai et al., in press). Alternatively, they can be the distal depositions of the pyroclastic products of the Central Atlantic Magmatic Province (CAMP, e.g. Blackburn et al., 2013).

The minor age component at ca. 42 Ma and the dominant one at 35 Ma are clearly related to the significant Alpine, Palaeogene "Periadriatic" magmatic activity that is mostly localized in the Southern Alps (e.g., Bergel, Adamello and Riesenferner plutons and numerous dikes; Bergomi et al., 2015). Volcanic edifices of the same age (ca. 44 to 28 Ma) are preserved in the TR (Benedek et al., 2004). Fission track ages of euhedral zircon crystals of the Eocene-covered deposits reflect that Eocene ash fall events contributed to the bauxite formation (Dunkl, 1990, 1992).

The presence of the euhedral zircons with Miocene age indicates that red clay matrix received volcanic material from the Carpathian volcanism (e.g. Lukács et al., 2015).

5.2. Bauxite pebbles

Based on petrographic features the bauxite pebbles of the Vöröstó Formation can be divided into two major types: (i) The majority belong to the "Albian type" characterized by wackestone texture with various intraclasts and gibbsite macrocrystals embedded in a microclastic matrix. This type is well represented at all localities investigated in this study. (ii) The bauxite pebble found in the Nagyvázsony area and formerly described in chapter 4.1 as of grain supported oolithic texture was considered to be representative of the "Santonian type". However, small pebbles similar to the latter one were also discovered as bauxitic extraclasts within the "Albian type" bauxite pebbles of the Vörösberény area. This phenomenon – namely a supposedly younger clast embedded in an older matrix – implies that petrographic features alone are not sufficient to discriminate between the Santonian and the Albian bauxite levels. They only indicate differences of the fundamental formation processes, i.e. differences within the depositional environment of a single bauxite deposit, and thus can only be used to designate textural types rather than the age of the pebbles.

According to XRD data, the bauxite pebbles have comparable gibbsite-boehmite-hematite-goethite-anatase mineral composition at all the examined localities. XRF bulk chemical analysis revealed that their high, 40–45% Al_2O_3 content is close to that of the traditional Hungarian industrial cut-off grade (46%; HUNGALU, Hungarian Aluminium Corporation). The exceptionally low SiO_2 content is close to the composition of the Santonian deposits. The Albian Alsópere deposit has much higher SiO_2 values (Table 1). The exceptionally low Al_2O_3 content in the Nagyvázsony bauxite pebbles can be attributed to its high Fe_2O_3 content, which may indicate a later "iron impregnation" event.

The heavy mineral composition of the pebbles in the Vöröstó Formation is similar to those described from the Cretaceous bauxites of the TR (Mindszenty et al., 1991), They are characterized by low heavy mineral amount and low variability as compared to the Cenozoic ones (Fig. 6B). Although kyanite is present in every bauxite pebble sample and is considered to be a characteristic heavy mineral of the Albian and also the Eocene bauxites (Mindszenty et al., 1991) the origin of some pebbles from the Santonian bauxite level cannot be excluded. The U–Pb age data support the Cretaceous origin since all bauxite pebbles contain only Jurassic or older zircon crystals (Fig. 7, Table A.6). According to the entire image composed by the heavy mineral and detrital age data, the bauxite pebbles of the Vöröstó Formation were derived from areas where Albian and/or Santonian bauxite deposits were exposed and eroded in Miocene times.

5.3. Pebble-bearing red clay matrix

The large variety in the mineral composition according to XRD and heavy mineral analysis show that the Vöröstó Formation comprises materials from multiple sources. Kaolinite, hematite, and goethite may be either degradation products of pre-existent bauxite deposits or indicators of strong (at least ferallitic) weathering under warm and humid climate. In the present study a detritic bauxitic origin of the red clay is verified only in Vörösberény by the presence of diaspore. Since diaspore, as a bauxite constituent, is exclusively known from Eplény in the TR (Bárdossy, 1968), its presence in the investigated samples is considered to indicate provenance from the Eplény deposits. Illite is relatively common in the Paleozoic low-grade schists and the Triassic to Oligocene clayey sediments of the wider surroundings thus considered as a source-specific clay mineral rather than a carrier of climate-related information (e.g., Korpás, 1981; Kecskeméti and Vörös, 1986; Budai et al., 1999). Illite is missing from the Kab-hegy location, which is the upper part of the Nagyvázsony area. A possible explanation for its absence may be that the basaltic cover has protected the red clay from any significant illite contribution in this specific sample, resulting in an undetectably low amount of illite. Quartz grains derive mostly from other sedimentary sources but some grains could have volcanic origin as well. Calcite is most probably postgenetic to the accumulation of the bauxite pebbles at the Sátor-hegy location. It may be related to the covering limestone or to some calcrete type pedogenesis. SEM images of anhedral and corroded clay mineral flakes forming chaotic textures and silt- to sand-sized aggregates clearly support the redeposited nature of the red clayey matrix of the Vöröstó Formation in the whole study area (Fig. 5). Therefore, their apparent ferrallitic nature may be inherited from previous periods of weathering. Consequently, they cannot be used as direct climate indicators for the Miocene. The high amount and great variability in the heavy mineral composition of the Vöröstó Formation red clays are strikingly similar to that of the Eocene bauxites (Fig. 6.A; Mindszenty et al., 1991) suggesting that a part of the red clay is the alteration product of those bauxites. However, the probably volcanogenic pyroxenes are unknown in the Eocene bauxites; they derived from post-Eocene eruptions. They are present in high abundance in the Nagyvázsony area whereas missing in the Vörösberény samples (Fig. 6.A). Detrital chloritoid generally indicates low to medium grade metamorphic rocks in the source area (Mange and Maurer, 1992), but there is no evidence in the literature for chloritoid bearing rocks in the TR (Korpás, 1981; Bérczi and Jámbor, 1998; Budai et al., 1999; Dávid, 1991; Haas, 2013). The heavy mineral composition of the red clays is the result of the mixing of individual grains eroded from the disintegrated Cretaceous and Eocene bauxites (identified also in the hard bauxite pebbles) and additionally, individual grains were derived from various post-Eocene formations of the TR.

The U–Pb zircon age distributions of the red clays and the bauxite pebbles show diagnostic differences (Figs. 7, 8). Cenozoic ages are completely missing from the bauxite pebbles. We thus preclude a Cenozoic origin of the pebbles. The “old”, Pre-Cenozoic zircons found in the red clays and in the bauxite pebbles are showing strikingly similar age components, which means that their common source is highly likely (Fig. 8). The late Eocene to Oligocene zircons represent most probably the eroded cover sequences of the various bauxite levels of the TR (Danišík et al., 2015). Miocene U–Pb ages measured on euhedral zircon crystals could have originated in the Carpathian-Pannonian Neogene volcanism (Harangi and Lenkey, 2007; Lukács et al., 2015).

5.4. Possible sources of the Vöröstó Formation

The results of the current study combined with the already known geological background provide sufficient data to reconstruct the possible sources of the Vöröstó Formation. To sum up the previous discussion, the bauxite pebbles represent the eroded material of the Cretaceous – Albian and/or Santonian – bauxite horizons. The red clay matrix contains additional components reworked from Eocene bauxite deposits and their Eocene to Oligocene cover. The triggering mechanism of this large scale erosion, which removed several hundred meters (Tari and Horváth, 2010) of Paleogene sedimentary cover from the Balaton Highlands and caused their resedimentation is most likely related to the post-Eocene uplift, and the formation of the predecessor of the current topography in late Miocene time.

The Vöröstó Formation – formed via uplift-related erosional events – can be considered as one of the earliest representatives of this chain of events creating the topography of today's Southern Bakony Mountains and Balaton Highlands. Beside the above mentioned detrital sources, the Vöröstó Formation subordinately also received airborne volcanic ash material during the Miocene and contribution from other sediments. It can thus be considered as a polygenetic continental accumulation, which integrates the signature of earlier sedimentary

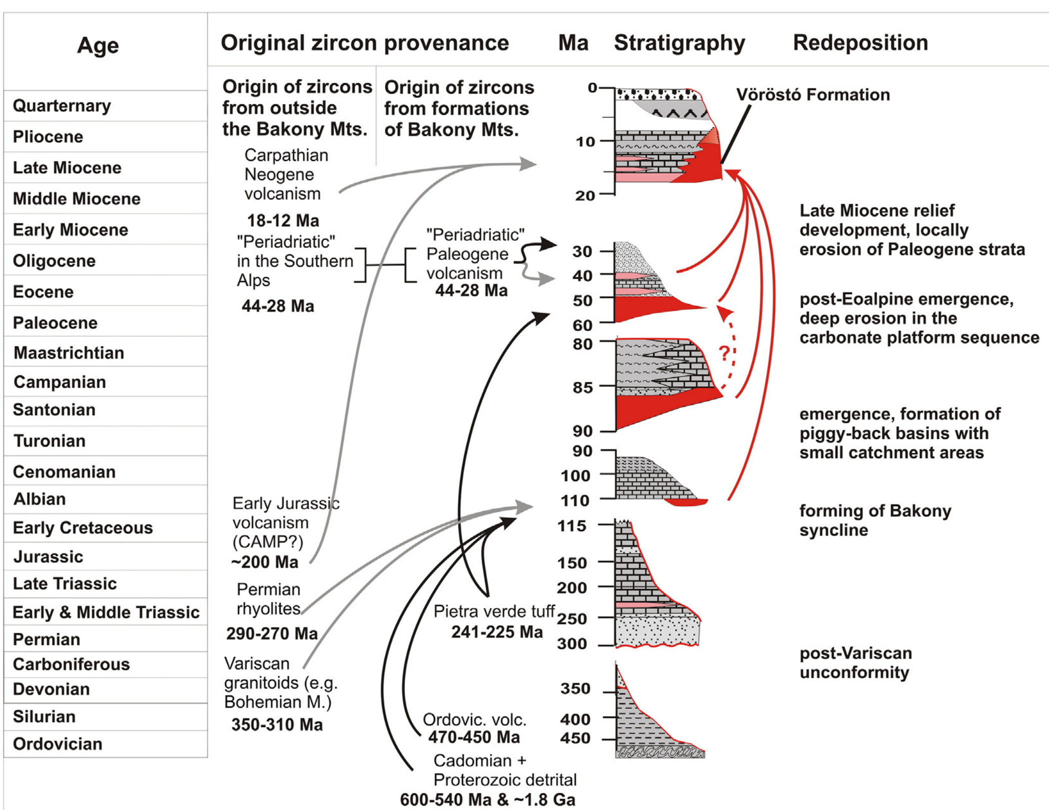

Fig. 9. Synopsys of the provenance of the zircon grains. Left side demonstrates the transport of the zircons from the source formations into the bauxite deposits. Consider that the Santonian bauxite level received zircon crystals probably from the same sources as the Albian bauxite level. Right side shows the documented/assumed redeposition within the karstic area of Southern Bakony Mountains. The Vöröstó Formation is a polygenetic assemblage. The hard bauxite pebbles were eroded from some of the older Cretaceous bauxite deposits. A significant part of the matrix is derived from the Paleogene bauxite deposits. The cover sequences of Eocene bauxites could be also part of the source material. The continental red clay landscape in the Bakony Mts. accumulated air-born ash material during the entire period of the Carpathian-Pannonian Neogene volcanic activity. The reference of the main zircon producing events is summarized in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

events. Fig. 9 presents a synopsis on the primary provenance of zircon grains into the bauxite deposits and their most probable scheme of redeposition within the karstic area of the Miocene TR.

In the immediate surroundings of the study area, the Jurassic to Oligocene successions are completely eroded. Their nearest representatives can be traced in a zone from Halimba to Eplény, approximately 15 to 20 km to the NW from the Nagyvázsony and Vörösberény area (Fig. 10). This zone is characterized by a relatively elevated topography and variegated geology. Remnants of Albian to Eocene bauxites and their cover sequences are all preserved here. We thus suggest that the Halimba-Eplény zone was the main source area of the Vöröstó Formation, i.e. it was exposed on the surface at the time of the deposition of the Vöröstó Formation. The wide range of Miocene U–Pb ages indicates that the continental red clay landscape of the Southern Bakony Mountains received airborne volcanic ash material during the entire period of the Neogene volcanism of the Carpathian-Pannonian Basin (Fig. 7; Pécskay et al., 2006; Harangi and Lenkey, 2007; Lukács et al., 2015).

5.5. Accumulation mechanism

Based on the study of the bauxite pebbles and red clays and on the areal distribution of the supposed source areas it is suggested that the accumulation of the Vöröstó Formation was the result of temporary fluvial and partly aeolian processes. The only definite representatives of the aeolian contribution are the above described euhedral, Neogene zircon crystals in the heavy mineral suite. This is suggested by the fact that the closest large-scale Miocene volcanic edifices, potentially delivering zircon grains to the exposed Nagyvázsony karst plateau can be found hundreds of km away, in the Carpathian Volcanic Arc (Fig. 1; Harangi and Lenkey, 2007; Lukács et al., 2015), and there is no evidence of fluvial connection of that scale between the Bakony Mts. and that volcanic area in Miocene times.

Local fluvial transportation, by ephemeral water-flows is, however, a very likely mechanism of sediment transport, since the Nagyvázsony area could have been a transitional zone between the eroding highlands and the adjoining less elevated karstic plains of the TR where the Vöröstó Formation deposited in local depressions. The surface uplift of the bauxitic hinterlands could have been triggered by the Langhian-Serravallian dextral transpression events affected the whole region (Márton and Fodor, 2003; Kiss and Fodor, 2007) and also the Diszel area (Tóth and Varga, 2014). If so, as a consequence of the surface uplift, the high relief of the elevated hinterlands enhanced the erosional processes providing the source material to the Vöröstó Formation and supposedly removing hundreds of meters of the Jurassic to Oligocene strata. Most of the more vulnerable carbonates probably underwent rather chemical then physical erosion, whereas the more resistant allitic and siliciclastic material formed debris and transported towards the lower topography areas. The Vöröstó Formation is thus considered as the result of a muddy debris-flow, which could efficiently spread coarse conglomeratic material within a fine-grained matrix over the area. In our case, the coarse fraction is represented mostly by the Cretaceous bauxite pebbles whereas the fine-grained matrix is the red clay with the younger, clay to silt-size Cenozoic components. The source material could have been restricted to the former Cretaceous to Palaeogene bauxite deposits and subordinately their immediate siliciclastic cover. The Eocene bauxites probably did not form pebbles because of their less consolidated nature (Knauer and Mindszenty, 1987). They apparently fell apart into fine-grained particles during transportation and contributed to the red clay matrix. The material came from a predominantly bauxitic source area, which reflects humid-warm climate conditions at the time of formation of the bauxites, but not necessarily at the time of the deposition of VF. Kaolinite, gibbsite, hematite as major constituents may remain stable even under non-tropical climatic conditions. The clay matrix of the Vöröstó Formation being also of redeposited nature fits into this model supporting the idea of both the bauxite pebbles and the red clay matrix having been deposited in the late Miocene as a polygenetic mixture originating from a source area built up by dominantly ferralitic weathering products of Mesozoic to Cenozoic age.

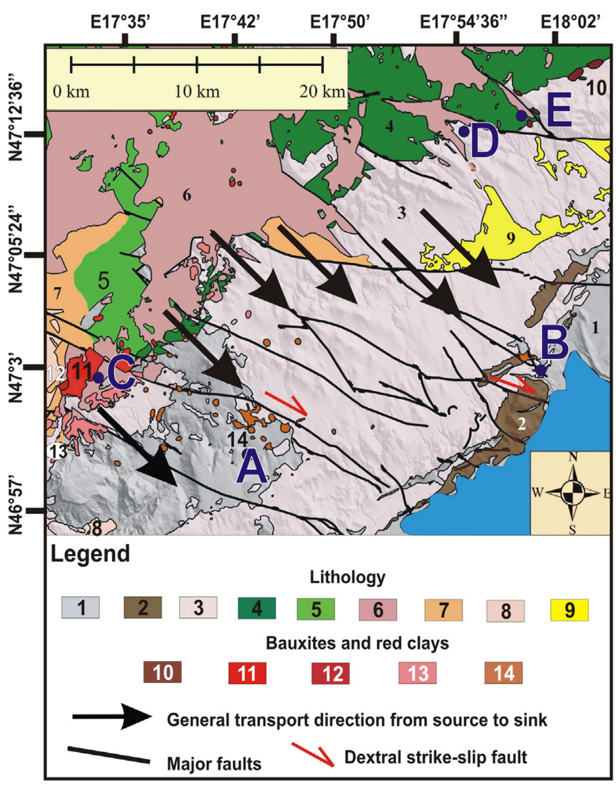

Fig. 10. Arrows represent the assumed provenance of the re-deposited pelitic-bauxitic material from the Cretaceous and Paleogene deposits of the slightly elevated areas towards the current occurrences of Vöröstó Formation. The recent topography reflects the late Miocene situation. This map is based on Budai et al. (1999, 2000a, 2000b), Császár and Csereklei (1982), Haas and Jocháné-Edelényi (1980) and Tóth and Varga (2014). A: Nagyvázsony, B: Vörösberény, C: Halimba, D: Eplény, E: Alsópere. 1. Pre-Cretaceous covered with upper Miocene, 2. Paleozoic, 3. Triassic and Jurassic, 4. Lower Cretaceous, 5. Upper Cretaceous, 6. Paleogene, 7. Preserravallian Miocene, 8. Serravallian marine sediments; 9. Serravallian continental sediments; 10. Lower Cretaceous (Albian) bauxites; 11. Upper Cretaceous (Santonian) bauxites; 12. Upper Cretaceous and Eocene bauxites; 13. Eocene bauxites; 14. Vöröstó Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusions

(1) The Vöröstó Formation shows similar characteristics from the southwest (Nagyvázsony) to the northeast (Vörösberény); therefore it is considered in all investigated locations as one unit. The continental red clay deposit is a polygenetic accumulation where both fluvial and aeolian transport mechanisms acted together and/or consecutively.

(2) The petrography, heavy mineral composition and zircon U–Pb age spectra of the bauxite pebbles show obvious similarities to the Transdanubian Range Cretaceous bauxite horizons and the pebbles are interpreted as their eroded remnants. Despite redeposition, the quality of the bauxite pebbles is in line with the composition of the well-known economic bauxite deposits of the TR. The extraclast composition and the zircon U–Pb age spectra of the Vöröstó Formation red clays indicate a mixed character from different source materials: Cretaceous and Eocene bauxite horizons and their mid-Eocene to Oligocene cover sequences, early Miocene continental sediments, and ashes of the Carpathian-Pannonian Neogene volcanic activity at the time of accumulation of the Vöröstó Formation.

(3) The youngest U–Pb zircon ages verify the Tortonian age of the Vöröstó Formation although accumulation most probably started already in the Burdigalian (oldest Miocene zircons) or even earlier.
(4) The micromorphology of clay minerals indicates transport features, no evidence for authigenic formation was detectable. The presence of kaolinite and allite minerals is thus not diagnostic for paleoclimate interpretation due to their most likely redeposited origin.
(5) Based on the size of the biggest bauxite pebbles (5 to 15 cm) and the geology of the surrounding area the Vöröstó Formation was derived from local sources, from less than ca. 20 km distance (except the aeolian contribution).

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.sedgeo.2017.07.005.

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