Traces of Carnian volcanic activity in the Transdanubian Range, Hungary

István Dunkl[1], Éva Farics[2], Sándor Józsa[3], Réka Lukács[4], János Haas[5], Tamás Budai[2]

[1] University of Göttingen, Geoscience Center, Department of Sedimentology and Environmental Geology, Göttingen, Germany

[2] University of Pécs, Department of Geology and Meteorology, Pécs, Hungary

[3] Eötvös Loránd University, Department of Petrology and Geochemistry, Budapest, Hungary

[4] MTA-ELTE Volcanology Research Group, Budapest, Hungary

[5] MTA-ELTE Geological, Geophysical and Space Science Research Group, Budapest, Hungary

corresponding author: Éva Farics, eva.gyorfy@gmail.com, +36-306590625

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Abstract

The South Alpine–Dinaridic realm was affected by igneous activity in the Middle Triassic; the marine carbonate platforms and the adjacent basins contain highly variable intrusive-volcanic assemblages. We studied the petrography and determined the zircon U–Pb ages of the Triassic volcanic products in the Transdanubian Range. The geochemical features and thus the geodynamic context of the magmatism is badly known, as the rocks experienced variable chemical alteration. The exact duration of the igneous activity is also poorly constrained, as the geochronological data of the former studies were obtained mostly by the weathering-sensitive K–Ar and Rb–Sr methods and thus some data even being younger than the age of the stratigraphic cover. The presence of andesite dikes and of pebbles and cobbles (< 20cm) of basalt, andesite, rhyolite and of rhyolitic tuff in the Triassic carbonate platform deposits indicate that within the Transdanubian Range formed a volcanic complex in Triassic. The major mineralogical and geochemical features of the Transdanubian igneous suite is similar to the Triassic formations in the Southern Alps. However, dissimilar zircon composition excludes the immediate relationship of the zircon-bearing silicic formations in the two tectonic units. New U–Pb ages show that the beginning of the volcanic activity is probably coeval with the eruption of the widespread "pietra verde" trachytic tuffs in the Upper Anisian–Ladinian successions, but the majority of the ages is younger than those ash layers. The new age constraints give a bench-mark for the termination of the volcanic activity in Carnian time in the Transdanubian Range.

Keywords

Triassic, volcanism, U–Pb geochronology, Transdanubian Range, Southern Alps

Introduction

The Transdanubian Range Unit is a part of the Alcapa Mega-unit (Haas 2013). This fault-bordered terrane – including the Bakony Mountains and Buda Hills – was located close to the Southern Alps at the northwesternmost edge of the opening Vardar ocean during the Middle-Late Triassic and it belonged to the wide carbonate shelf of the western Tethys (e.g. Kázmér and Kovács 1985, Haas et al. 1995, Vörös 2000). Presence of volcanic tuffs in the Triassic succession of the Transdanubian Range had been recognised already by Böckh (1873) in the Bakony Mountains (Fig. 1). According to Lóczy (1916), the Ladinian "Buchenstein beds" are made up of siliceous limestones, marls and "pietra verde" tuffs. These pyroclastic layers have trachytic composition and they consist of mainly sanidine, biotite, few quartz and secondary minerals (Szabó and Ravasz 1970; Ravasz 1973). Literature data and the present study provide evidence that, in addition to the late Anisian–Ladinian "pietra verde" pyroclastic fall deposits present in the Southern Alps and derived from an unknown, remote volcanic centre, a Middle to Late Triassic volcanism also occurred within or close to the Transdanubian Range. This volcanic activity was documented by Raincsák (1980) and Budai et al. (2001) in the Middle Triassic succession of the Bakony Mountains. A comparison of the Middle Triassic volcanic successions of the Bakony Mountains, Bükk Mountains, Southern Alps and Northern Calcareous Alps was presented by Bechstädt and Mostler (1976), Cros and Szabó (1984), Szoldán (1990) and Harangi et al. (1996). They concluded that the Transdanubian Range may have been relatively close to the South Alpine volcanic centres, whereas the area of the Northern Calcareous Alps was located in a more distal position.

This igneous activity – similarly to those of the Southern Alps – is slightly enigmatic, as it is localized in a passive margin settings during the development of carbonate platform successions. The geodynamic evaluations based on the geochemical character of the Southern Alpine and Dinaridic occurrences yielded ambiguous results, showing signs for both, continental rift and magmatic arc settings (e.g. Bébien et al. 1978; Beltrán-Triviño et al. 2016). Harangi et al. (1996) linked the Middle to Late Triassic volcanism to early extensional events that were followed by a more developed rifting phase in the Bükk Mountains, Bakony Mountains and Buda Hills.

The aim of this paper is to complete the information about the puzzle of the dissected parts of the former carbonate platform by new petrographical and geochemical data from the Triassic volcanogenic formations of the Bakony Mountains and Buda Hills and to supply new time constraints by U–Pb ages for the duration of the volcanic activity.

Geological setting and traces of Triassic volcanism in the Transdanubian Range

The Transdanubian Range is the uppermost unit of the Austroalpine Nappe System forming a syncline structure (e.g. Tari et al. 1992). The development of its Upper Permian to Lower Cretaceous formations shows close affinity with that of the Southern Alps (Lóczy 1916; Haas and Budai 1995). The thickest part of the sequence is made up of Triassic shallow marine carbonates (Haas 2013). The Triassic magmatic dikes, volcanic pebbles and cobbles occur in three formations in the Bakony Mountains and in the vicinity of the Buda Hills (Fig. 2).

(i) The Upper Anisian Vászoly Formation contains distal, several cm to max 2 dm thick, bentonitised trachytic, sometimes graded, primary fallout tuff layers (Budai et al. 1999, 2001, 2015). These strata are equivalent to the slightly thicker "pietra verde" layers in the Dolomites (Mojsisovics, 1879), and they are widespread in the entire Southern Alpine–Dinaridic realm (e.g. Obenholzner 1991; Jelaska et al. 2003). The biostratigraphic assignment of these ash layers is well constrained by ammonoid, conodont and radiolarian data to be in the Reitzi Zone (Vörös 1993; Dosztály 1993; Kovács 1994; Pálfy et al. 2003). The zircon content of the ash and bentonite layers of mostly trachytic chemical character allowed highly precise U–Pb geochronology (see details below). According to the accurate biostratigraphic, isotope geochronologic and paleomagnetic constraints (Márton et al. 1997) the Felsőörs section was even proposed as a candidate for a Global Stratotype Section and Point for the base of the Ladinian stage (Vörös et al. 1996, 2003).

(ii) Andesite dikes are known in the quarry of Szár Hill at Polgárdi and they have been detected by the Budaörs-1 and Budafok-1 cored deep drillings of the Buda Hills (Kubovics 1985; Dunkl et al. 2003; Haas et al. 2017). The well exposed, gray porphyritic dikes in the Szár Hill quarry, are 5 to 10 m thick, while the apparent thicknesses of the partly fault-bounded dikes in the boreholes are between 60 to 186 m (Budaörs-1 and Budafok-1, respectively).

(iii) Pebbles of volcanic rocks were recognized in the Middle Triassic sequence of the Bakony Mountains (Raincsák 1980). This volcanoclastic sandstone (Inota Fm.) was correlated with the Wengen Group of the Southern Alps (Mojsisovics, 1879; Budai and Vörös 1993; Budai et al. 2001). Clasts of volcanic rocks were also found at the base of the Upper Eocene transgressive sequences of the Buda Hills (Wein 1977; Horváth and Tari 1987; Farics et al. 2015). As will be discussed below, the "pietra verde" tuff originated from remote sources, while the (ii) and (iii) type formations are local volcanic products within the Transdanubian Range (Budai et al. 2001).

With the exception of a single U–Pb age (Haas et al. 2017), only whole-rock, biotite and hornblende K–Ar data are available from the dikes and pebbles (Balogh et al. 1983; Horváth and Tari 1987). The dated aliquots contain highly variable amounts of potassium and radiogenic argon, and they yielded a wide age range from 240 to 25 Ma. The isotopic systems have been strongly influenced either by the interaction of the dikes with the carbonate host rocks or by the weathering of the pebbles. Thus, their significance for the timing of eruptions and on the duration of the volcanic activity is weak.

Triassic igneous activity in the South Alpine realm and their geochronological constraints

According to the palaeogeographic reconstructions, the Transdanubian Range was located in the neighbourhood of the Southern Alps before the Alpine orogeny (Kázmér and Kovács 1985; Haas et al. 1995; Schmid et al. 2008). Thus, it is necessary to insert a short review of the well exposed and studied Triassic igneous formations of the Southern Alps before the evaluation of our new results from the Transdanubian Range.

The "pietra verde" tuff layers (e.g. Obenholzner 1991) were dated both in the Alps and in the Bakony Mountains by high precision and accuracy and those data were contributed even to the global calibration of the Triassic chronostratigraphic scale (Mundil et al. 1996, 2010; Pálfy et al. 2003; Brack et al. 2005; Furrer et al. 2008; Stockar et al. 2012; Wotzlaw et al. 2018). The ID-TIMS data reveal that these trachytic eruptions took place between 242 and 237 Ma.

The Predazzo Complex is the largest of the Triassic intrusive igneous bodies of the Eastern Southern Alps. The intrusive rocks show wide variation in composition: monzonite is the dominant rock type, but monzodiorite, monzogabbro, gabbro with pyroxenite, granite, quartz-syenite and syenite, also occur (Lucchini et al. 1982; Menegazzo et al. 1995; Visonà 1997; Carraro and Visonà 2003; Casetta et al. 2018). The dike rocks are also highly diverse: latibasalt, latiandesite, K-basanite, monzosyenite, aplite and lamprophyre were reported by Gallitelli and Simboli (1971). Some of the carbonate platforms of the Dolomites are covered by subaerial basaltic flows (e.g. Monte Agnello), but submarine formations like pillow lavas and hyaloclastite-rich volcano-sedimentary formations are more common in the intra-platform basin fill (Gaetani et al. 1981; Preto et al. 2001; Bosellini et al. 2003; Budai et al. 2005; Németh and Budai 2009). In the western Southern Alps the Montecampione subvolcanic complex shows slightly more alkaline character, but the sodium, potassium and trace element contents were probably influenced by intense fluid circulation (Armienti et al. 2003).

The geodynamic interpretation of this magmatism is debated because beyond the obvious traces of Triassic syn-sedimentary extensional tectonics manifested e.g. by half-grabens (Bertotti et al. 1993; Budai and Vörös 1993, 2006; Velledits 2006), strike-slip and compressional tectonics make the image more complex (Castellarin and Rossi 1981; Blendinger 1984; Castellarin et al. 1988). However, the wide spectrum of rock types and their trace elements and Hf-isotope systematics would fit to an extensional regime. Beltrán-Triviño et al. (2016) related the Triassic magmatism to an asymmetrical continental rifting process that affected the entire Southern Alps and the adjacent areas. The geodynamic evaluation of the Triassic volcanism in the Dinarides resulted in similar dilemma; the compositional spectrum of the lithologies (from basalt to rhyolite) and their geochemical features match neither to the rifting nor to the arc settings (Bébien et al. 1978).

Evaluating the age constraints from the Predazzo Complex and from other Triassic volcanic formations we should distinguish between weathering/alteration-sensitive and more robust geochronometers. The Rb–Sr and K–Ar ages scatter between 230 and 204 Ma (Borsi and Ferrara 1967; Borsi et al. 1968; Ferrara and Innocenti 1974; Webb 1982; Crisci et al. 1984; Laurenzi et al. 1994; Visonà 1997; Balogh and Németh 2005). Similarly to the Bakony Mountains, some of these ages clearly post-date the stratigraphically proven age range of the volcanic activity. U–Pb and Sm–Nd ages (246 to 224 Ma) are available only from a few igneous bodies of the Southern Alps (Zanetti et al. 2013; Storck et al. 2018), Eisenkappel pluton (Lippolt et al. 1974; Miller et al. 2011), Western Carpathians (Putiš et al. 2000), Bükk Mountains (Haas et al. 2011; Kövér et al, 2018), Eastern Alps, and northwestern Dinarides (Neubauer et al. 2014).

Samples

We collected "pietra verde" tuff, volcanogenic sandstone and conglomerate drilling core and outcrop samples from Triassic strata and from the base of the Eocene transgressive sequence that unconformly covers the partly eroded Triassic successions. Actually, all known and accessible volcanic formations (Vászoly Fm., Inota Fm.) were sampled in the Bakony Mountains and Buda Hills. Additionally, we have taken seven pilot samples for geochronology and zircon geochemistry from the Triassic igneous formations of the eastern Southern Alps. The localities of the dated samples are listed in Table 1, and a list of petrographically analysed samples is given in the Electronic Supplementary Material (ESM_1.xls). In order to represent properly the sources of the coarse volcanic fragments we performed pebble population dating (PPD-method; Dunkl et al. 2009) on selected and amalgamated andesite, and acid volcanite + ignimbrite pebbles. These "PPD" samples were composed of a representative selection of 16 to 54 equal-sized volcanic rock pebbles or pebble fragments.

Analytical method

For the petrographic investigation of the volcanic rocks Olympus BH2 polarization microscope was used. The composition of feldspar, pyroxene, amphibole was determined with AMRAY 1830 scanning electron microscope with EDAX PV 9800 ED spectrometer at the Eötvös University, Budapest. Major, trace and rare earth elements of the whole rock samples were measured at the University of Göttingen by X-ray fluorescence analysis, and by ICP-AES & ICP-MS techniques in ACME Labs (Vancouver).

Zircon crystals were fixed on a double-side adhesive tape stuck on a thick glass plate and embedded in a 25 mm diameter epoxy mount. The crystal mounts were lapped by 2500 mesh SiC paper and polished by 9, 3 and 1 micron diamond suspensions. Cathodoluminescence images were obtained using a JEOL JXA 8900 electron microprobe at the University of Göttingen in order to study the internal structure of the zircon crystals and to select homogeneous parts for in-situ age determination.

The U-Pb dating was performed by laser-ablation single-collector sector-field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS). The method employed for our analyses has been described in details by Frei and Gerdes (2009). We used a Thermo Element 2 mass spectrometer coupled to a Resonetics excimer laser with Laurin Technic 155 constant geometry ablation cell. All age data presented here were obtained by single spot analyses with a laser beam diameter of 33 µm and a crater depth of approximately 10 µm. The laser was fired at a repetition rate of 5 Hz and at nominal laser energy output of 25 %. The data reduction is based on the processing of ca. 50 selected time slices (corresponding ca. 14 seconds) starting ca. 3 sec. after the beginning of the signal. If the ablation hit zones or inclusions with highly variable actinide concentrations or isotope ratios then the integration interval was slightly resized or the analysis was discarded (~1% of the spots). The individual time slices were tested for possible outliers by an iterative Grubbs test (applied at P=5% level). The age calculation and quality control are based on standard-sample bracketing using GJ-1 zircon reference material (Jackson et al. 2004). For further control the Plešovice zircon (Sláma et al. 2008), the 91500 zircon (Wiedenbeck et al. 1995) and the FC-1 zircon (Paces and Miller 1993) were analysed as "secondary standards". The results obtained on the zircon reference materials express the precision and the accuracy of the dating method applied (see details in Electronic Supplementary Material ESM_2.pdf). Drift- and fractionation corrections and data reductions were performed by our in-house software (UranOS; Dunkl et al. 2008). The concordia plots were constructed by the help of Isoplot/Ex 3.0 (Ludwig 2012).

Results

Petrography of the Triassic volcanic products of the Transdanubian Range

Dike rocks

The Triassic volcanic formations are often altered, most of the phenocrysts are replaced by secondary minerals and we can observe only pseudomorphs after them. Due to strong alteration, it is often not possible to achieve a reliable geochemical classification. In these cases, we characterized the samples according to their petrographic features.

The lava and dike rocks are mostly comprised of andesite. The unaltered porphyritic andesite contains large zoned labradorite-andesine and small andesine-basic oligoclase crystals, hypersthenic orthopyroxene, and subordinately augitic clinopyroxene and biotite. The amphibole is hornblende in composition and it was found only in the andesite dikes of the Szár Hill (Fig. 3a). Ilmenite, apatite, garnet, magnetite, zircon and monazite are the accessory minerals. The phenocrysts are often replaced by clay and opaque minerals, chlorite, chalcedony, carbonate, and sericite (Figs. 3b and 3c). In the fine-grained groundmass thin laths of plagioclase, and variable amounts of partly altered (chloritized) glass are present. In the samples from the lower part of the dike in Budaörs-1 well intense K-metasomatism was detected, the plagioclase altered to K-feldspar (Fig. 3d). Complete alteration of the groundmass to secondary silica is observed, especially in the volcanic clasts of the Eocene conglomerates. The vesicles are filled mostly by chalcedony and glauconite. The andesite often contains microdiorite inclusions.

Triassic volcanogenic sandstones and conglomerates

In the Bakony Mountains and in the Strázsa Hill quarry (Zsámbék), the volcanogenic sandstones and conglomerates form clast-supported, polymict deposits. Subangular to subrounded mafic–intermediate volcanic clasts are usually much larger (up to 20 cm) and more common than the subrounded acidic volcanic clasts (≤ 3 cm). The phenocrysts are completely altered to secondary minerals, but three types of mafic lithologies can be distinguished. One type contains abundant vesicles and a few pseudomorphs after plagioclase, pyroxene and olivine phenocrysts (Fig. 3e). The other type has an intersertal texture with plagioclase microliths in the groundmass and few pseudomorphs after plagioclase and mafic phenocrysts. The third type is microgabbro with intergranular texture; the xenomorphic mafic minerals occur in the spaces among the plagioclase laths. Some of the andesites are characterized by the presence of porphyric labradorite-andesine plagioclase, hypersthenic orthopyroxene and few biotite as well as laths of andesine-basic oligoclase plagioclase in the groundmass (Figs. 3f and 3g). In several pebbles the plagioclase has been replaced by K-feldspar due to intense K-metasomatism. The latite-trachyte pebbles are characteristically different from the andesite, they contain primary alkali feldspar (K-feldspar) and less plagioclase. Another type of basaltic/andesitic clasts is vesicle-rich and contains only plagioclase phenocrysts (Fig. 3g). The acidic volcanic pebbles consist of quartz, K-feldspar and biotite. Rhyolite contains dark and light flow banding and has poorly developed micropoikilitic texture (Fig. 3h). Three types of devitrificated rhyolite lava and rhyolite tuff can be found. The first one consists of mostly pumice and few glass shards with very few labradorite phenocrysts and more acidic plagioclase microliths. The second one has perlitic texture, and the third one has spherulitic texture. Acidic tuff clasts (only in the Strázsa Hill quarry) contain pumice and Y-shaped glass shards, pseudomorphs after K-feldspar and biotite flakes, as well as lithic fragments (Fig. 3i). Besides the lithoclasts, the labradorite-basic oligoclase, hypersthenic orthopyroxene, hornblende amphibole, biotite, augitic clinopyroxene and altered olivine crystal fragments are in the volcanogenic sandstone layers of the Bakony

Mountains, as well as strongly altered plagioclase (mostly altered to K-feldspar), biotite, pyroxene, quartz in the volcanogenic sandstones of the Strázsa Hill quarry.

Volcanic clasts from the base of Eocene conglomerates

In the basal layers of the Eocene conglomerate of the Buda Hills we found mostly andesite and acidic lava and tuff pebbles (Fig. 3j).

Geochemistry

The volcanic rocks showing mafic petrographical characters are strongly altered and are not suitable for geochemical analysis (LOI up to 20%; Electronic Supplementary Material ESM_3.xls). However, there are some less altered intermediate and felsic volcanic samples from Buda Hills, Strázsa Hill quarry and Bakony Mountains that yielded useful major and trace element data. Nevertheless, these rocks still have some significant LOI content, therefore their compositions should be evaluated with caution. All samples are plotted on the total alkali versus silica (TAS) diagram after recalculation to anhydrous basis (Fig. 4). They fall mostly into the andesite field, whereas a few samples are rhyolite. The samples showing trachyandesite to trachyte compositions could have experienced some alkali enrichment during alteration, whereas alkali leaching can not be excluded in case of a few samples. Immobile trace elements can be effectively used as indicators for rock types (Pearce 1996) even for altered and slightly metamorphosed rocks. Based on the Nb/Y vs. Zr/TiO_2 diagram the analysed rocks are mainly andesite in spite of their TAS classification.

The immobile trace elements suggest subalkaline affinity (Fig. 4), and they plot in the active continental margins field in the tectonomagmatic setting discrimination diagram of Gorton and Schandl (2000) for felsic and intermediate rocks (Fig. 5). The samples having andesitic petrographical character usually show enrichment in LIL elements (Ba, Rb, Th, U) and negative anomalies for certain HFS elements (Nb, P, Ti), although the latter ones are not always pronounced (Fig. 6). The REE patterns of most andesite samples are similar with negative Eu anomaly, suggesting plagioclase fractionation. Notably the samples classified as rhyolite and trachyte based on their petrographic character show much larger compositional distribution, having lower and higher values for LREE. This compositional variation can be traced also on the multivariate trace element diagrams (Fig. 6).

Mineral chemistry

The strongly altered character of the studied volcanic rocks is reflected in their mineral assemblage, since only a few samples contain detectable mafic minerals, such as pyroxene and amphibole. Pyroxene is present only in a few mafic and intermediate volcanic samples of the Transdanubian Range. The orthopyroxene has a composition from En57 to 53 mol%, while clinopyroxene is of augitic composition. Amphibole can be found only in the samples from Szár Hill quarry and wells of Bakony Mountains, they are Mg-hornblende and tschermakite. Plagioclase shows a wide compositional range with An content ranging from 10 to 70 mol% (ESM_4.xls and ESM_5.pdf).

Zircon U–Pb Geochronology

Laser-ablation ICPMS U–Pb geochronology was performed on 485 separated, CL-mapped zircon crystals in the GÖochron Laboratories of the University of Göttingen. Some samples have poor zircon yield, due to either their mafic character, or due to the small amount of the available drilling cores. Ca. 20% of the obtained ages were much older or younger than Triassic; these spots were measured probably on xenocrystals of the Triassic magmatites or on

Cenozoic igneous pebbles that were mixed into the PPD samples pooled from the Eocene strata. A synopsis of the results is listed in Table 2, the detailed analytical data are given in the Electronic Supplementary Material (ESM_6.xls and ESM_7.pdf). Where possible, the ages were calculated as concordia age, otherwise we considered only those analyses that are 100 ± 10% concordant and applied the Isoplot "ZircAge" algorithm in order to express a mean age for the crystallization of the most reliable zircon population according to Ludwig (2012). The age data are grouped according to major types of the samples and the mean values with the uncertainty intervals are plotted in Fig. 7.

Before the presentation of the results from Transdanubian Range we should consider the U–Pb data obtained on the Eisenkappel intrusion. This narrow granitoid body is situated along the Periadriatic Line and was dated already by several methods and yielded 227 ± 7 Ma biotite and 244 ± 8 Ma hornblende K–Ar ages, 230 ± 5 Ma titanite U–Pb age and 238.4 ± 1.9 Ma and 242.1 ± 2.1 Ma garnet-whole rock Sm–Nd ages (Lippolt et al. 1974; Miller et al. 2011). Our new laser ablation zircon U–Pb ages (234.1 ± 2.5 and 231.2 +5.8 -2.2 Ma) are close to the formerly measured titanite U–Pb ages and obviously younger than the Sm–Nd data.

Component analysis was performed on the ± 10% concordant single-crystal $^{206}Pb/^{238}U$ ages determined in the volcanoclastic formations. The individual samples contain relatively low number of single-crystal ages, thus their component analyses do not result in a reliable image on the substantive age components of the entire volcanic activity. That is why we evaluated the pooled data composed from the single-crystal ages of all samples from the Transdanubian Range by the component analysis methods. This pooled dataset does not contain the ages obtained on the distal "pietra verde" ash layers, as the aim of the dating and component analysis were to characterize the local volcanic sources. Two different algorithms were used to identify the age components: "PopShare" (Dunkl and Székely 2002) and "DensityPlotter"

(Vermeesch 2012). The former procedure assumes Gaussian distribution of the age components and uses the simplex algorithm (Cserepes 1989), while the "Density Plotter" uses the normal mixture modelling algorithm of Galbraith (2005). Beyond the Triassic age components Paleogene and Permian age components were also isolated from the Eocene conglomerates, but these are not in the scope of the current study. The Triassic age spectra could be decomposed to two major age components (Fig. 8). The two procedures resulted in identical mean values: 238.1 ± 4.0 (s.d.) and 238.2 ± 0.9 (s.e.) for the older, and 228.1 ± 3.4 (s.d.) and 229.4 ± 1.1 (s.e.) for the younger age component ("PopShare" and "DensityPlotter", respectively). The isolated older age component corresponds to the younger TIMS ages of the "pietra verde" ash layers (e.g. Pálfy et al. 2003; Mundil et al. 2010; Wotzlaw et al. 2018) and indicates that coarse-grained younger volcaniclastic sediments contain reworked fragments also from this slightly older volcanic event. The younger age component is an obvious proof on a distinct period of volcanic activity in Carnian time.

Discussion

The dikes and pebbles are mineralogically and chemically strongly transformed, thus the petrographical character of the volcanic rocks should be deduced mostly from the preserved mineral assemblages. The spectrum is wide, beyond quartz and K-feldspar both calcic and sodic plagioclase occur, and the mafic minerals reflect also the highly variable composition: olivine, pyroxene, amphibole and biotite were recognised. Only andesite dikes were hit by the deep drillings and exposed in the quarries, and in the pebbles and cobbles the most dominant lithologies are andesite, basaltic andesite, latite-trachyte, rhyolite and rhyolite tuff. One should consider the selective decomposition; the preserved pebble spectra are biased by the loss of mechanically and chemically more sensitive lithologies like weakly welded tuffs and foid-bearing rocks.

A part of the volcanic rocks have altered chemical composition, as shown by the elevated LOI and the large variation in alkaline contents. In addition, even the relatively immobile HFS trace elements appear to show some secondary modification which makes the rock classification difficult. Nevertheless, most of the analysed samples can be classified as andesites based on fluid-immobile incompatible trace element ratios. The classification of the silicic volcanic rocks is more problematic, since fractionation of accessory minerals strongly affects these element ratios. The revised Th/Yb – Ta/Yb diagram (Gorton and Schandl, 2000 after Pearce 1982, 1983) is used to infer the tectonic affinity of the volcanic rocks. All of them fall into the active continental margin field based on the relatively low Ta/Yb ratios. This geochemical character is similar to the rocks from the Dolomites (Castellarin et al. 1988) and confirm their common petrogenesis. According to our point of view the negative Nb-Ta anomaly in the trace element pattern and thus a lower Ta/Yb ratio could also originate from lithospheric mantle metasomatized by subduction related fluids in the past and remobilization during a lithospheric extension event (Sloman 1989 and Bonadiman et al. 1994). Together with the presence of the dikes penetrating platform carbonate and basinal carbonate successions, the abundance and large size of the Triassic volcanic pebbles and cobbles indicates that their source was within the Transdanubian Range. Long transport distance is not a plausible scenario for the provenance of the pebbles. A longer river could not develop on the passive margin that was dominated by the patchy arrangement of carbonate reefs and basins. Longer, wave-driven sediment transport alongshore or between the reef bodies is also not a feasible scenario due to the coarse size and partly angular shape of the detritus and the sensitivity of the volcanic lithologies to weathering. Pebbles of intrusive rocks are present only in minor amount in the Triassic and in the Eocene conglomerates, thus we assume a volcanic centre, but the intrusive-subvolcanic root is less developed than in the case of the Predazzo Complex, or the erosion has not exhumed the subvolcanic level yet.

The new U–Pb ages indicate that in the Transdanubian Range the deposition of the Anisian–Ladinian "pietra verde" tuff was followed by Carnian volcanism with variable, mafic to acid character. Remarkable, that the Triassic volcaniclastic successions in the central and eastern Southern Alps (Garzanti 1985) do not contain a distinct Carnian age group. The youngest U–Pb data of Beltrán-Triviño et al. (2013) form just a diffuse tail of "pietra verde" age components. Our U–Pb ages from the Eisenkappel granite confirms its Carnian emplacement age. As these ages are missing from the siliciclastic formations studied by Beltrán-Triviño et al. (2013) we can assume that this pluton was not yet exhumed to the surface and eroded in the Triassic or its contribution in the sediment was strongly diluted due to its minor size.

Outside of eastern Southern Alps Carnian U–Pb ages or age components around 235–220 Ma were reported in the western Southern Alps (Crisci et al. 1984; Cassinis et al. 2008; Zanetti et al. 2013), in the Dinarides (Neubauer et al. 2014), in the Bükk Mountains (Haas et al. 2011; Kövér et al. 2018) and in Asia Minor in clastic sediments and also in a rhyolitic–andesitic volcanic succession (e.g. Ustaömer et al. 2016; Özdamar et al. 2013).

It is useful to consider the actinide content of the dated zircons as a kind of diagnostic "proxy" for provenance purposes. The U content and the Th/U ratio of the dated zircon crystals indicate an obvious difference between the Triassic volcanic rocks of the Transdanubian Range and the pilot samples from the Southern Alps (Fig. 9). Thus, the immediate derivation of the volcanic pebbles found in the Transdanubian Range the silicic formations of Predazzo and Eisenkappel is rather unlikely.

Conclusions

- The presence of dikes and the proximal volcaniclastic material indicate volcanic eruptions in the Transdanubian Range in the Middle to Late Triassic.
- The composition of volcanic products covers a wide range from basalt to rhyolite. Although andesites are common, it is possible that the character of volcanism is bimodal, but the selective weathering/alteration biases the initial lithological variation. Volcanic textures are dominating, the intrusive and subvolcanic lithologies are scarce among the pebbles.
- The character of the igneous activity in the Transdanubian Range is similar to the South Alpine one. The local half-graben basins developed coevally with the volcanism indicating that the trigger of the magmatism was the extensional tectonics affecting the passive margin of the Adria plate, however their geochemistry shows also active margin character.
- Zircon U–Pb ages were determined on andesite dikes, tuff layers and on variable volcanic fragments from different clastic sediments. The sample-mean ages are between 239 and 228 Ma. We could identify two age components by the evaluation of the pooled single-grain ages determined on detrital zircons and on pebble-population samples. Thus the volcaniclastic formations records two major periods of activity of zircon-bearing volcanism at 238 Ma and around 229-228 Ma, indicating well the presence Carnian magmatic activity within the Transdanubian Range.
- The geochemical character of the dated zircons differs from the composition of the zircon pilot samples from the Dolomites and Carnic Alps, and that rules out the origin of the pebbles and cobbles from the sensu stricto South Alpine igneous formations.
- The new zircon U–Pb age of the Eisenkappel granite approves the formerly published titanite U–Pb age and thus the emplacement age can be considered also as Carnian.

References

Armienti P, Corazzato C, Groppelli G, Natoli E, Pasquarè G (2003) Geological and petrographical study of Montecampione Triassic subvolcanic bodies (Southern Alps, Italy): preliminary geodynamic results. Bollettino della Società geologica italiana, spec vol 2:67-78

Balogh K, Németh K (2005) Evidence for the Neogene small-volume intracontinental volcanism in western Hungary; K/Ar geochronology of the Tihany Maar volcanic complex. Geologica Carpathica 56:91-99

Balogh K, Árva-Sós E, Buda Gy (1983) Chronology of granitoid and metamorphic rocks of Transdanubia (Hungary). Anuarul Institutului de Geologie şi Geofizică 61:359-364

Bébien, J, Blanchet R, Cadet J-P, Charvet J, Chorowicz J, Lapierre, H, Rampnoux J-P (1978) Middle Triassic volcanism in the Dinarides of Yugoslavia: its place in the peri-Mediterranean geotectonic evolution (Le volcanisme triasique des Dinarides en Yougoslavie: SA place dans l'évolution géotectonique péri-méditerranéenne, in French with English abstract). Tectonophysics 47:159-176

Bechstädt T, Mostler H (1976) Middle-Triassic reef-basin-development in the western part of the Northern Limestone Alps (Riff-Becken-Entwicklung in der Mitteltrias der westlichen Nördlichen Kalkalpen, in German with English abstract). Zdt. Geol. Ges. 127:271-289

Beltrán-Triviño A, Winkler W, von Quadt A (2013) Tracing Alpine sediment sources through laser ablation U-Pb dating and Hf-isotopes of detrital zircons. Sedimentology 60:197-224

Beltrán-Triviño A, Winkler W, von Quadt A, Gallhofer D (2016) Triassic magmatism on the transition from Variscan to Alpine cycles: evidence from U-Pb, Hf, and geochemistry of detrital minerals. Swiss Journal of Geosciences 109:309-328

Bertotti G, Picotti V, Bernoulli D, Castellarin A (1993) From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geology 86:53-76

Blendinger W (1984) Late Ladinian strike-slip tectonics of the Marmolada-Costabella area (Dolomites). Jahrbuch Geologische Bundesanstalt B-A, Wien, 127:307-319

Böckh J (1873) The geological conditions of the southern part of the Bakony I (Die geologischen Verhältnisse des südlichen Theiles des Bakony, I, in German). Mittheilungen aus dem Jahrbuche der königlichen ungarischen geologischen Anstalt, 2 (2): 27-182

Bonadiman C, Coltorti M, Siena F (1994) Petrogenesis and T-fO_2 estimates of Mt. Monzoni complex (Central Dolomites, Southern Alps): a Triassic shoshonitic intrusion in a transcurrent geodynamic setting. European Journal of Mineralogy 6:943-966

Borsi S, Ferrara G (1967) Age determination of the intrusive rocks of Predazzo with Rb/Sr and K/Ar methods (Determinazione dell'eta delle rocce intrusive di Predazzo con i metodi del Rb/Sr e K/Ar, in Italian with English Abstract). Mineralogica et Petrographica Acta 14:171-183

Borsi S, Ferrara G, Paganelli L, Simboli G (1968) Isotopic age measurements of the M. Monzoni intrusive complex. Mineralogica et Petrographica Acta 14:171-183

Bosellini A, Gianolla P, Stefani M (2003) Geology of the Dolomites. Episodes 26:181-185

Brack P, Rieber H, Nicora A, Mundil R (2005) The Global boundary Stratotype Section and Point (GSSP) of the Ladinian Stage (Middle Triassic) at Bagolino (Southern Alps, Northern Italy) and its implications for the Triassic time scale. Episodes 28:233-244

Budai T, Vörös A (1993) The Middle Triassic events of the Transdanubian Central Range in the frame of the Alpine evolution. Acta Geologica Hungarica 36:3-13

Budai T, Vörös A (2006) Middle Triassic platform and basin evolution of the Southern Bakony mountains (Transdanubian Range, Hungary). Rivista Italiana di Paleontologia e Stratigrafia 112:359-371

Budai T, Császár G, Csillag G, Dudko A, Koloszár L, Majoros Gy (1999) Geology of the Balaton Highland : explanation to the Geological map of the Balaton Highland, 1:50 000., Geological Institute of Hungary

Budai T, Csillag G, Vörös A, Lelkes Gy (2001) Middle to Late Triassic platform and basin facies of the Eastern Bakony Mts. (Transdanubian Range, Hungary). Bulletin of the Hungarian Geological Society 131:71-95

Budai T, Németh K, Piros O (2005) Middle Triassic platform carbonates and volcanites in the Latemar area (Dolomites, Italy). Annual Report of the Geological Institute of Hungary on year 2004: 175-188

Budai T, Haas J, Piros O (2015) New stratigraphic data on the Triassic basement of the Zsámbék Basin - tectonic inferences. Bulletin of the Hungarian Geological Society 145:247-257

Carraro A, Visonà D (2003) Mantle xenoliths in Triassic camptonite dykes of the Predazzo Area (Dolomites, Northern Italy): petrography, mineral chemistry and geothermobarometry. European Journal of Mineralogy 15:103-115

Casetta F, Coltorti M, Marrocchino E (2018) Petrological evolution of the Middle Triassic Predazzo Intrusive Complex, Italian Alps. International Geology Review 60:977-997

Cassinis G, Cortesogno L, Gaggero L, Perotti CR, Buzzi L (2008) Permian to Triassic geodynamic and magmatic evolution of the Brescian Prealps (eastern Lombardy, Italy). Boll Soc Geol It 127:501-518

Castellarin A, Rossi RML (1981) The Southern Alps: an aborted Middle Triassic mountain chain? Ecl Geol Helv 74:313-316

Castellarin A, Lucchini IF, Rossi PL, Selli L, Simboli G (1988) The Middle Triassic magmatic-tectonic arc development in the Southern Alps. Tectonophysics 146:79-89

Cohen KM, Finney SC, Gibbard PL, Fan J-X (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36:199-204 http://stratigraphy.org/ICSchart/ChronostratChart2017-02.pdf. Accessed February 2017

Crisci GM, Ferrara G, Mauzzoli R, Rossi PM (1984) Geochemical and geochronological data on Triassic volcanism of the Southern Alps of Lombardy (Italy): Genetic implications. Geol Rundschau 73:279-292

Cros E, Szabó I (1984) Comparison of the Triassic volcanogenic formations in Hungary and in the Alps. Paleogeographic criteria. Acta Geologica Hungarica 27:265-276

Cserepes L (1989) Numerical mathematics - for geophysicist students (in Hungarian). Tankönyvkiadó, Budapest

Csontos L, Vörös A (2004) Mesozoic plate tectonic reconstruction of the Carpathian region. Paleogeography Paleoclimatology Paleoecology 210:1-56

Dosztály L (1993) The Anisian/Ladinian and Ladinian/ Carnian boundaries in the Balaton Highland based on Radiolarians. Acta Geologica Hungarica 36: 59-72

Dunkl I, Horváth I, Józsa S (2003) Andesite dikes and skarn formations of Szár Hill, Polgárdi, Hungary. In: Szakáll S, Fehér B (eds) Minerals of Szár Hill. Herman Ottó Museum, Miskolc, pp 55-86, (in Hungarian)

Dunkl I, Frisch W, Kuhlemann J, Brügel A (2009) Pebble population dating as an additional tool for provenance studies - examples from the Eastern Alps. Geological Society, London, Special Publications 324:125-140

Dunkl I, Székely B (2002) Component analysis of detrital FT ages - with visualization of the fitting. Salamanca, International Workshop on Fission Track Analysis, Cádiz, 4-7 June 2002. Geotemas 4:63

Dunkl I, Mikes T, Simon K, von Eynatten H (2008) Brief introduction to the Windows program Pepita: data visualization, and reduction, outlier rejection, calculation of trace element ratios and concentrations from LA-ICP-MS data. In: Sylvester P (ed) Laser ablation ICP-MS in the Earth Sciences: Current practices and outstanding issues. Mineralogical Association of Canada, Short Course 40:334-340

Farics É, Józsa S (2017) Petrographic investigation of the Triassic volcanogenic formations of the Eastern Bakony and interpretation of their genesis (in Hungarian with English abstract). Földtani Közlöny, Bulletin of the Hungarian Geological Society 147:25-38

Farics É, Józsa S, Haas J (2015) Petrographic features of lava rock and tuff clast-bearing sedimentary rocks at the base of the Upper Eocene succession in the Buda Hills. Földtani Közlöny, Bulletin of the Hungarian Geological Society 145:331-350

Ferrara G, Innocenti F (1974) Radiometric age evidence of a Triassic thermal event in the Southern Alps. Geologische Rundschau 63:572-581

Frei D, Gerdes A (2009) Precise and accurate in situ U-Pb dating of zircon with high sample throughput by automated LA-SF-ICP-MS. Chemical Geology 261:261-270

Furrer H, Schaltegger U, Ovtcharova M, Meister P (2008) U-Pb zircon age of volcaniclastic layers in Middle Triassic platform carbonates of the Austroalpine Silvretta nappe (Switzerland). Swiss Journal of Geosciences 101:595-603

Gaetani M, Fois E, Jadoul F, Nicora A (1981) Nature and evolution of Middle Triassic carbonate Buildup int he Dolomites (Italy). Marine Geology 44:25-57

Galbraith RF (2005) Statistics for Fission Track Analysis. Chapman and Hall/CRC, Interdisciplinary Statistics Series, London

Gallitelli P, Simboli G (1971) Petrological and Geochemical Research on the Rocks of Predazzo and Monzoni (North Italy). Verhandlungen der Geologischen Bundesanstalt 2:326-343, Vienna

Garzanti E (1985) The sandstone memory of the evolution of a Triassic volcanic arc in the Southern Alps, Italy. Sedimentology 32:423-433

Gorton MP, Schandl ES (2000) From continents to island arcs: a geochemical index of tectonic setting for arc-related and within-plate felsic to intermediate volcanic rocks. Canadian Mineralogist 38:1065-1073

Haas J (2013) Geology of Hungary, Springer

Haas J, Budai T (1995) Upper Permian–Triassic facies zones in the Transdanubian Range. Rivista Italiana Paleontologia Stratigrafia 101:249-266

Haas J, Kovács S, Krystyn L, Lein R (1995) Significance of Late Permian-Triassic facies zones in terrane reconstructions in the Alpine-North Pannonian domain. Tectonophysics 242:19-40

Haas J, Budai T, Csontos L, Fodor L, Konrád Gy (2010) Magyarország pre-kainozoos földtani térképe 1:500000 (Pre-Cenozoic geological map of Hungary, 1:500000). Hungarian Geological Survey, Budapest.

Haas J, Kovács S, Pelikán P, Kövér Sz, Görög Á, Ozsvárt P, Józsa S, Németh N (2011) Remnants of the accretionary complex of the Neotethys Ocean in Northern Hungary. Földtani Közlöny, Bulletin of the Hungarian Geological Society 141:412-66

Haas J, Budai T, Dunkl I, Farics É, Józsa S, Kövér Sz, Götz AE, Piros O, Szeitz P (2017) The Budaörs–1 well revisited: Stratigraphic and tectonic implications. Central European Geology. https://doi.org/10.1556/24.60.2017.008

Harangi Sz, Szabó Cs, Józsa S, Szoldán Zs, Árva-Sós E, Balla M, Kubovics I (1996) Mesozoic igneous suites in Hungary: Implications for genesis and tectonic setting in the northwestern part of Tethys. International Geology Review 38:336-360

Horváth E, Tari G (1987) Middle Triassic volcanism in the Buda Mountains. Annales Universitas Scientiarum Budapestiensis de Rolando Eötvös Nominatae, Sect Geol 27:3-16

Jackson S, Pearson N, Griffin W, Belousova E (2004) The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. Chemical Geology 211:47-69

Jelaska V, Kolar-Jurkovšek T, Jurkovšek B, Grušić I (2003) Triassic beds in the basement of the Adriatic-Dinaric carbonate platform of Mt. Svilaja (Croatia). Geologija 46:225-230

Kázmér M, Kovács S (1985) Permian–Paleogene paleogeography along the eastern part of the Insubric–Periadriatic lineament system: evidence for continental escape of the Bakony–Drauzug unit. Acta Geologica Hungarica 28:71-84

Kiss J (1954) Andesite from Szabadbattyán and its importance concerning the genesis of ores (Szabadbattyáni andezit és ércgenetikai jelentősége, in Hungarian with English abstract). Földtani Közlöny, Bulletin of the Hungarian Geological Society 84:183-189.

Kovács S (1994) Conodonts of stratigraphical importance from the Anisian/Ladinian boundary interval of the Balaton Highland, Hungary. Rivista Italiana di Paleontologia e Stratigrafia 99: 473-514

Kövér S, Fodor L, Kovács Z, Klötzli U, Haas J, Zajzon N, Szabó C. (2018) Late Triassic acidic volcanic clasts in different Neotethyan sedimentary mélanges: paleogeographic and geodynamic implications. International Journal of Earth Sciences 107:2975-2998

Kubovics I (1985) Mesozoic magmatism of the Transdanubian Mid-Mountains. Acta Geologica Hungarica 28:141-164

Laurenzi MA (1994) High resolution Ar/Ar chronology of Predazzo magmatic complex (Southem Alps, Italy). US. Geological Survey, circular 1107, ICOG pp 8

Leake BE, Wolley AR, Arps CES, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG, Linthout K, Laird J, Mandarino J (1997) Nomenclature of Amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. Mineralogical Magazine 61:295-321

Le Bas MJ, Le Maitre RW, Streckeisen A, Zanettin B (1986) A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27:745-750

Lippolt HJ, Pidgeon R (1974) Isotopic mineral ages of a diorite from the Eisenkappel intrusion, Austria. Z Naturforsch 29a:966-968

Lóczy L (1916) The geology and tectonics of the Balaton Highland (Die geologische Formationen der Balatongegend und ihre regionale Tektonik, in German). In: Resultate der wissenschaftlichen Erforschung des Balatonsees 1, pp 716

Lucchini F, Rossi PL, Simboli G (1982) Triassic magmatism in the Predazzo area (Il magmatismo triassico dell’area di Predazzo, in Italian). In: Castellarin A, Vai GB (eds) Guida alla Geologia del Sudalpino centro-orientale. Società Geologica Italiana, Guide Geologiche Regionali, Roma, pp 221-229

Ludwig KR (2012) User's manual for Isoplot 3.75: A geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication 4:70

Márton E, Budai T, Haas J, Kovács J, Szabó I, Vörös A (1997) Magnetostratigraphy and biostratigraphy of the Anisian–Ladinian boundary section Felsőörs (Balaton Highland, Hungary). Albertiana 20:50-57

McDonough WF, Sun S (1995) The composition of the Earth. Chemical Geology 120:223-253

Menegazzo Vitturi L, Visonà D, Zantedeschi C (1995) Amphibole composition of Predazzo volcano-plutonic complex (Southern Alps, Italy) Sciences Géologiques – Memoires. 47:87-94

Miller C, Thöni M, Goessler W, Tessadri R (2011) Origin and age of the Eisenkappel gabbro to granite suite (Carinthia, SE Austrian Alps). Lithos 125:434-448

Mojsisovics E (1879) The dolomite reefs of South Tyrol and Veneto: contributions to the develeopment of the Alps (Die Dolomit-Riffe von Südtirol und Venetien: Beiträge zur Bildungsgeschichte der Alpen, in German). Wien, Hölder

Morimoto N (1988) Nomenclature of pyroxenes. Mineralogy and Petrology 39:55-76

Mundil R, Brack P, Meier M, Rieber H, Oberli F (1996) High resolution U-Pb dating of middle Triassic volcaniclastics: time-scale calibration and verification of tuning parameters for carbonate sedimentation. Earth and Planetary Science Letters 141:137-151

Mundil R, Pálfy J, Renne PR, Brack P (2010) The Triassic timescale: new constraints and a review of geochronological data. In: Lucas SG (ed) The Triassic Timescale. Special Publications, Geological Society (London) 334:41-60

Németh K, Budai T (2009) Diatremes cut through the Triassic carbonate platforms in the Dolomites? Evidences from and around the Latemar, Northern Italy. Episodes 32:74-83

Neubauer F, Xiaoming L, Borojević Šoštarić S, Bianca H, Yunpeng D (2014) U-Pb zircon data of Middle-Upper Triassic magmatism in Southern Alps and NW Dinarides: Implications for the Southeast Mediterranean tectonics. Buletini i Shkencave Gjeologjike, Proceedings XX Congress of the Carpathian-Balkan Geological Association, Tirana, Albania

Obenholzner JH (1991) Triassic volcanogenic sediments from the Southern Alps (Italy, Austria, Yugoslavia) - a contribution to the "Pietra verde" problem. Sedimentary Geology 74:157-171

Özdamar S, Billor MZ, Sunal G, Esenli F, Roden MF (2013) First U-Pb SHRIMP zircon and $^{40}Ar/^{39}Ar$ ages of metarhyolites from the Afyon-Bolkardag Zone, SW Turkey: Implications for the rifting and closure of the Neo-Tethys. Gondwana Research 24:377-391

Paces JB, Miller JD (1993) Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: geochronological insights into physical,petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga midcontinent rift system. Journal of Geophysical Research 98:13997-14013

Pálfy J, Parrish RR, David K, Vörös A (2003) Middle Triassic integrated U-Pb geochronology and ammonoid biochronology from the Balaton Highland (Hungary) Journal of the Geological Society (London) 160:271-284

Pearce JA (1982) Trace elements characteristics of lavas from destructive plate boundaries. In: Thorpe RS (ed) Andesites. Wiley, New York, N.Y., pp. 525-548

Pearce JA (1983) Role of the sub-continental lithosphere in magma genesis at active continental margins. In: Hawkesworth CJ, Norry MJ (eds) Continental Basalts and Mantle Xenoliths. Shiva, Nantwich, pp. 230-249

Pearce J A (1996) A Users guide to basalt discrimination diagrams. In: Wyman DA (ed) Trace element geochemistry of volcanic rocks: Applications for massive sulphide exploration 12, Geol. Ass. Canada Short Course Notes, pp. 79-113

Preto N, Hinnov LA, Hardie LA, De Zanche V (2001) Middle Triassic orbital signature recorded in the shallow-marine Latemar carbonate buildup (Dolomites, Italy) Geology 29:1123-1126

Putiš M, Kotov AB, Uher P, Salnikova JB, Korikovsky SP (2000) Triassic age of the Hrončok Pre-Orogenic A-type granite related to continental rifting: A new result of U-Pb isotope dating (Western Carpathians). Geologica Carpathica 51:59-66

Raincsák Gy (1980) The structure of the Triassic formations at Várpalota-Iszkaszentgyörgy. Annual Report of the Geological Institute of Hungary 1978:187-196

Ravasz Cs (1973) Mineralogical-petrographical studies on Middle Triassic tuffs of the Transdanubian Central Mountains, Hungary. Acta Mineralogica Petrographica, Szeged 21:123-139

Schmid SM, Bernoulli D, Fügenschuh B, Matenco L, Schefer S, Schuster R, Tischler M, Ustaszewski K (2008) The Alpine-Carpathian-Dinaride-orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences 101:139-183

Sircombe KN (2004) AgeDisplay: an EXCEL workbook to evaluate and display univariate geochronological data using binned frequency histograms and probability density distributions. Computers & Geosciences 30:21-31

Sláma J, Košler J, Condon DJ, Crowley JL, Gerdes A, Hanchar JM, Horstwood MSA, Morris GA, Nasdala L, Norberg N, Schaltegger U, Schoene B, Tubrett MN, Whitehouse MJ (2008) Plešovice zircon - A new natural reference material for U-Pb and Hf isotopic microanalysis. Chemical Geology 249:1-35

Sloman LE (1989) Triassic shoshonites from the Dolomites, Northern Italy: alkaline rocks in a strike-slip setting. Journal Geophysical Research 94:4655-4666

Stockar R, Baumgartner PO, Condon D (2012) Integrated Ladinian bio-chronostratigraphy and geochronology of Monte San Giorgio (Southern Alps, Switzerland). Swiss Journal of Geosciences 105:85-108

Storck JC, Brack P, Wotzlaw JF, Ulmer P (2018) Timing and evolution of Middle Triassic magmatism in the Southern Alps (Northern Italy). Journal of the Geological Society, https://doi.org/10.1144/jgs2018-123

Szabó C et al. (1996) Mineralogy and geochemistry of magmatic rocks of Budafok-1 borehole (Budafok-1 (Bf-1) fúrás magmás összletének ásványkőzettani és geokémiai vizsgálata, in Hungarian). Department of Petrology and Geochemistry, Eötvös Loránd University, Hungary, 27 p.

Szabó I, Ravasz Cs (1970) Investigation of the Middle Triassic volcanics of the Transdanubian Central Mountains, Hungary. Ann Hist Natur Mus Nat Hung 62:31-51

Szoldán Zs (1990) Middle Triassic magmatic sequences from different tectonic settings in the Bükk Mts., NE Hungary. Acta Mineralogica-Petrographica, Szeged 31:25-42

Tari G, Horváth E, Rumpler J (1992) Styles of extension in the Pannonian Basin. Tectonophysics 208:203-219

Ustaömer T, Ustaömer PA, Robertson AHF, Gerdes A (2016) Implications of U-Pb and Lu-Hf isotopic analysis of detrital zircons for the depositional age, provenance and tectonic setting of the Permian–Triassic Palaeotethyan Karakaya Complex, NW Turkey. International Journal of Earth Sciences 105:7-38

Velledits F (2006) Evolution of the Bükk Mountains (NE Hungary) during the Middle–Late Triassic asymmetric rifting of the Vardar-Meliata branch of the Neotethys Ocean. International Journal of Earth Sciences 95: 395-412

Vermeesch P (2012) On the visualisation of detrital age distributions. Chemical Geology 312-313:190-194

Visonà D (1997) The Predazzo multipulse intrusive body (Western Dolomites, Italy). Field and mineralogical studies. Memorie di Scienze Geologiche 49:117-125

Vörös A (1993) Redefinition of the Reitzi Zone at its type region (Balaton area, Hungary) as the basal zone of the Ladinian. Acta Geologica Hungarica 36:15-38

Vörös A (2000) The Triassic of the Alps and Carpathians and its interregional correlation. In: Hongfu Yin, Dickins JM, Shi GR, Jinnan Tong (eds) Permian–Triassic Evolution of Tethys and Western Circum–Pacific. Elsevier, 412 p. http://dx.doi.org/ 10.1016/s0920-5446(00)80011-4

Vörös A, Szabó I, Kovács S, Dosztály L, Budai T (1996) The Felsőörs section: a possible stratotype for the base of the Ladinian stage. Albertiana 17:25-40

Vörös A, Budai T, Haas J, Kovács S, Kozur H, Pálfy J (2003) A proposal for the GSSP at the base of the Reitzi Zone (sensu stricto) at Bed 105 in the Felsőörs section, Balaton Highland, Hungary. Albertiana 28:35-47

Webb JA (1982) A Carnian age from the Mt. Monzoni intrusive complex, western Dolomites, Italy. In: Odin GS (ed) Numerical dating in stratigraphy. Wiley, New York, pp 875-876

Wein Gy (1977) Tectonics of Buda Hills. Geological Institute of Hungary, Budapest, pp 76

Wiedenbeck M, Allé P, Corfu F, Griffin WL, Meier M, Oberli F, von Quadt A, Roddick JC, Spiegel W (1995) Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. Geostandards Newsletters 19:1-23

Wotzlaw JF, Brack P, Storck JC (2018) High-resolution stratigraphy and zircon U–Pb geochronology of the Middle Triassic Buchenstein Formation (Dolomites, northern

Italy): precession-forcing of hemipelagic carbonate sedimentation and calibration of the Anisian–Ladinian boundary interval. Journal of the Geological Society 175:71-85

Zanetti A, Mazzucchelli M, Sinigoi S, Giovanardi T, Peressini G, Fanning M (2013) SHRIMP U-Pb zircon Triassic intrusion age of the Finero mafic complex (Ivrea-Verbano Zone, Western Alps) and its geodynamic implications. Journal of Petrology 54:2235-2265

Captions

Figure 1: Simplified structural map of the Southern Alps, the Transdanubian Range (TR) and the surrounding areas with the major occurrences of the Triassic igneous formations (map base after Csontos and Vörös 2004; Schmid et al. 2008). Square represents the geological map of TR (Fig. 2). Abbreviations of the most significant intrusive complexes and tuff/volcanic occurrences: Re - Recoaro, Pr - Predazzo, Dr - Drauzug, Ek - Eisenkappel, Ba - Bakony Mts., Bu - Buda Hills, Bü - Bükk Mts., Ve - Vepor Mts.).

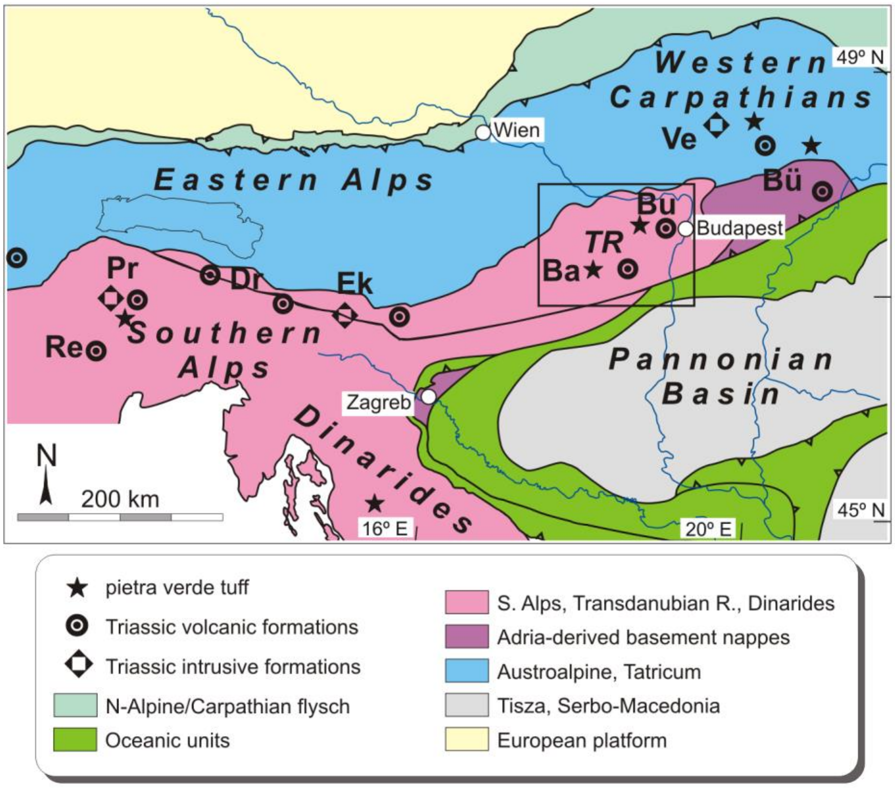

Figure 2: Simplified geological map of the Transdanubian Range without Cenozoic sedimentary cover (after Haas et al. 2010). Codes of boreholes are in italics (for explanation of abbreviations see Table 1).

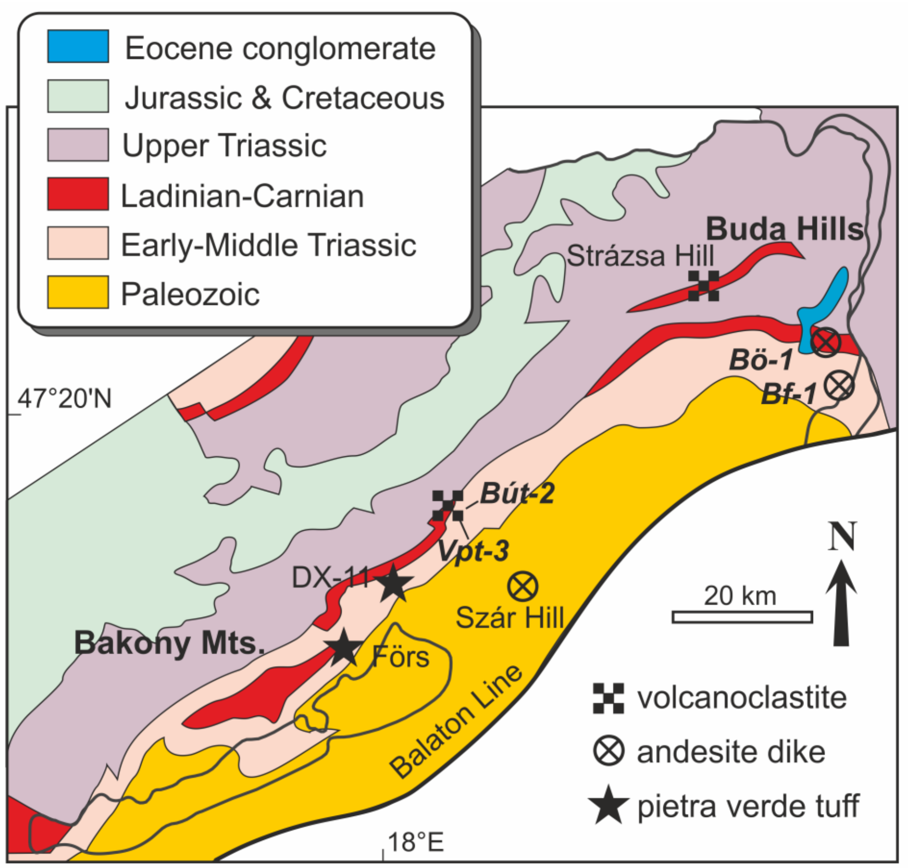

Figure 3: Characteristic photomicrographs showing the textures of Middle-Late Triassic volcanic rocks from the Transdanubian Range. Bö-1: Budaörs-1 borehole, Bút-2: Bakonykúti-2 borehole; for the localities see Fig. 2.

a: Texture of fresh andesite (crossed N), Bö-1, 773 m (from Farics et al. 2015). b: Texture of weakly altered andesite. The pyroxene is altered to secondary minerals, but the plagioclase is fresh (1N), Bö-1, 775.9 m. c: Strongly altered andesite clast in Eocene conglomerate with pseudomorphs of phenocrysts (1N), Budakeszi. d: Texture of K-trachyte - rims of K-feldspar along altered plagioclase (by K-metasomatism) and pseudomorph after pyroxene (1N), Bö-1, 808.6 m. e: Strongly vesiculated texture of a basalt clast in the volcanogenic sandstone/conglomerate (1N), Hideg Valley, Inota. f: Texture of andesite clast (1N), Bút-2, 62 m (from Farics and Józsa 2017). g: Texture of basalt/andesite clasts in volcanogenic rock (1N), Bút-2 62 m. h: Texture of flow banding rhyolite clast (1N), Hideg Valley. i: Texture of moderately welded ignimbrite clast (1N), Strázsa Hill. j: Texture of acid tuff clast in Eocene conglomerate (1N), Kő Hill (Farics et al. 2015).

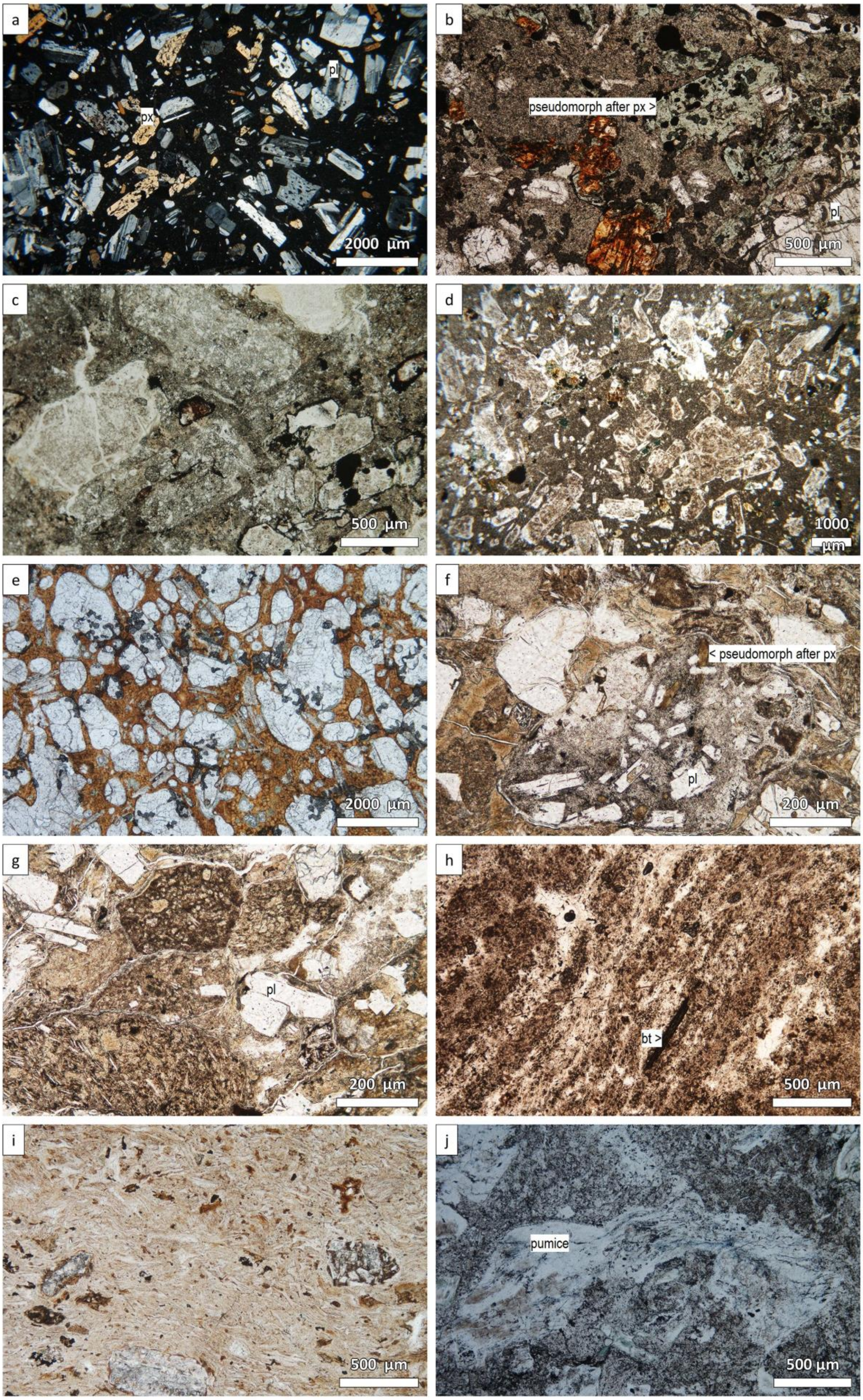
a
pl
px
2000 µm
b
pseudomorph after px >
pl
500 µm
c
500 µm
d
1000
µm
e
2000 µm
f
< pseudomorph after px
pl
200 µm
g
pl
200 µm
h
bt >
500 µm
i
500 µm
j
pumice
500 µm

Figure 4a: Total alkali vs. silica (TAS) classification diagram (Le Bas et al. 1986) and b: Zr/TiO_2 vs. Nb/Y classification diagram (Pearce 1996) for the Triassic volcanic rocks of Transdanubian Range. Data from Kiss (1954), Harangi et al. (1996), Szabó et al. (1996), Dunkl et al. (2003) and own data. The raw analytical data can be found in the Electronic Supplementary Material (ESM_3.xls).

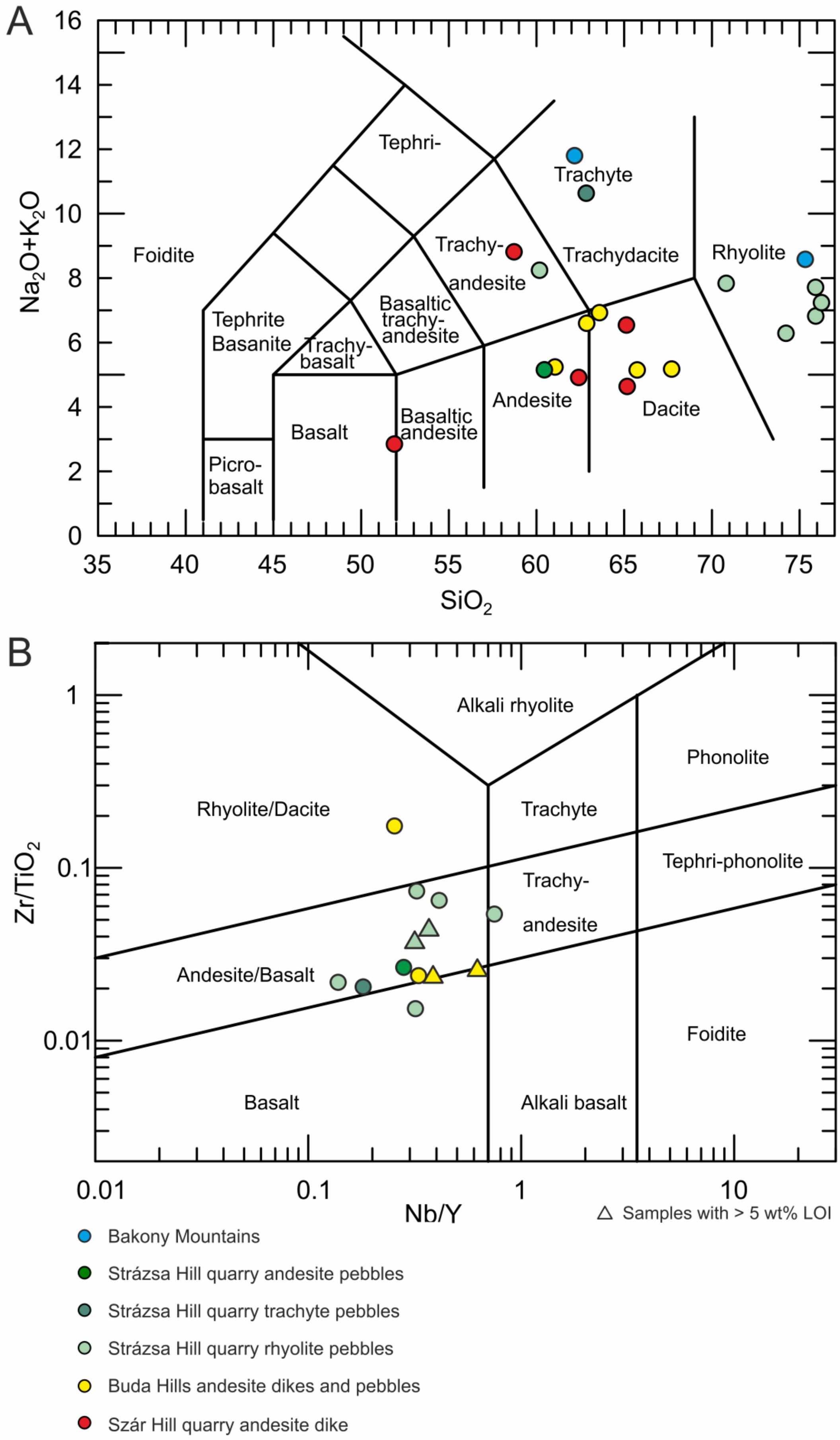
A
16
14
12
10
8
6
4
2
0
35
40
45
50
55
60
65
70
75
Na_2O+K_2O
SiO_2
Tephri-
Trachyte
Foidite
Trachy-
andesite
Trachydacite
Rhyolite
Basaltic
trachy-
andesite
Tephrite
Basanite
Trachy-
basalt
Andesite
Dacite
Basalt
Basaltic
andesite
Picro-
basalt
B
1
0.1
0.01
10
Zr/TiO_2
Nb/Y
Alkali rhyolite
Phonolite
Rhyolite/Dacite
Trachyte
Tephri-phonolite
Trachy-
andesite
Andesite/Basalt
Foidite
Basalt
Alkali basalt
△ Samples with > 5 wt% LOI
Bakony Mountains
Strázsa Hill quarry andesite pebbles
Strázsa Hill quarry trachyte pebbles
Strázsa Hill quarry rhyolite pebbles
Buda Hills andesite dikes and pebbles
Szár Hill quarry andesite dike

Figure 5: Implications for the original tectonomagmatic settings of the Triassic volcanic rocks of the Transdanubian Range by the discrimination of Gorton and Schandl (2000). Triangles represent samples with more than 5% LOI. ACM = active continental margins; WPVZ = within-plate volcanic zones; WPB = within-plate basalts. The legends are the same as in the Figure 4.

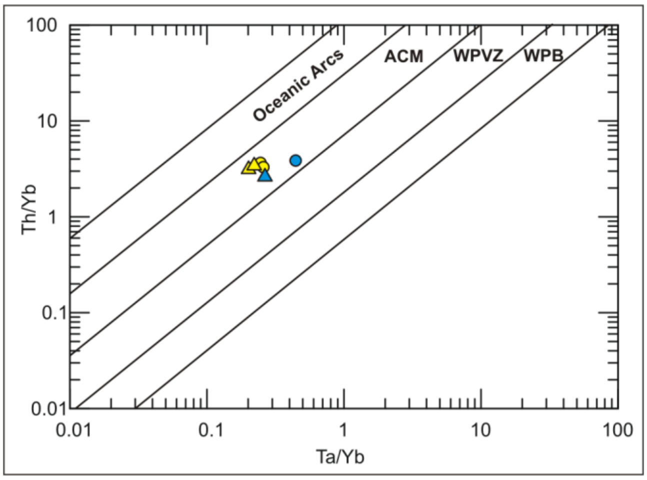

Figure 6: Multi-element variation diagram for the Triassic volcanic rocks of Transdanubian Range. Data from Harangi et al. (1996) and own data. The detailed data are in the Electronic Supplementary Material (ESM_3.xls). The legends are the same as in the Figure 4.

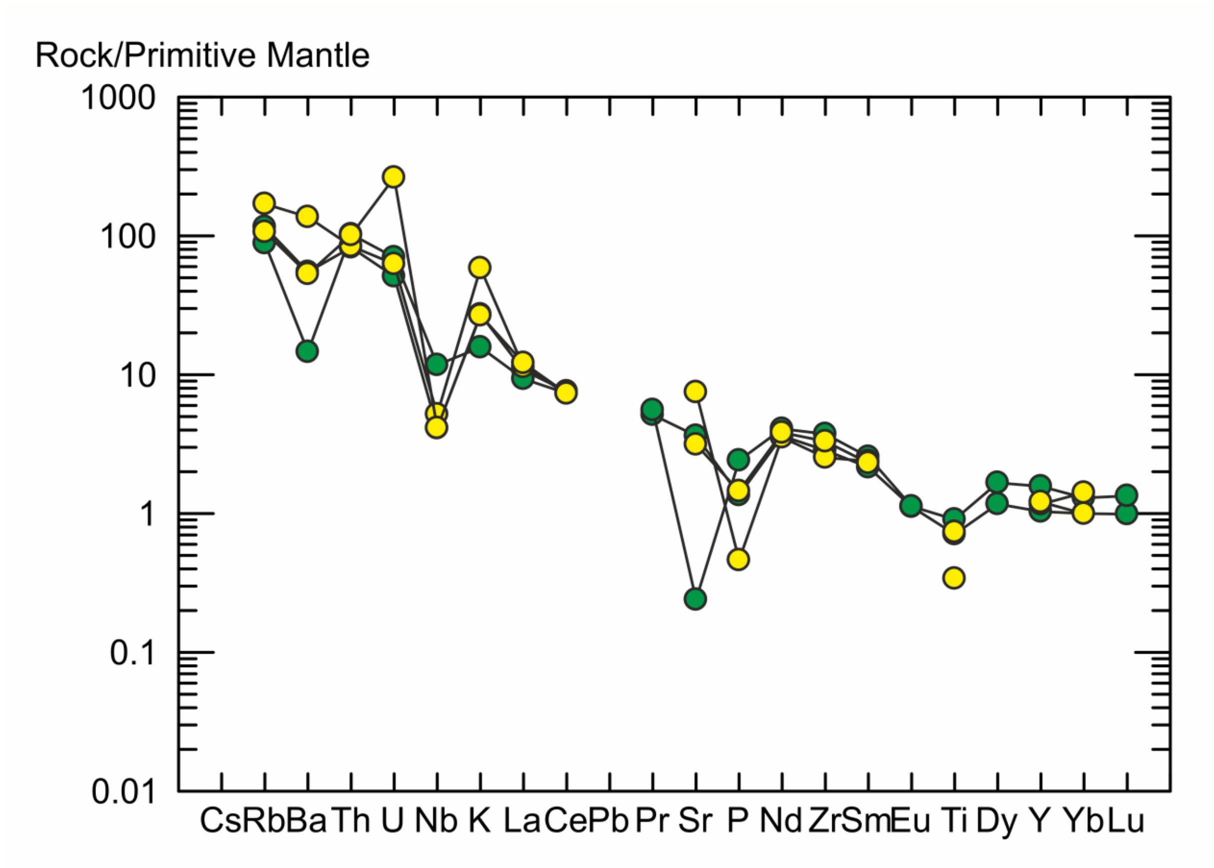

Figure 7: Compilation of the new LA-ICPMS U-Pb ages obtained on the different Triassic volcanic formations of the Transdanubian Range and Southern Alps. PPD: pebble population samples compiled from andesite and rhyolite fragments from the Eocene base conglomerate covering the denudation surface of the Triassic in the Buda Hills. PV (TIMS): Range of 'pietra verde' volcanic activity by high resolution U-Pb dating (see text for sources). Right panel shows the most recent Triassic time scales; [1]: Mundil et al. (2010), [2]: Cohen et al. (2013, updated).

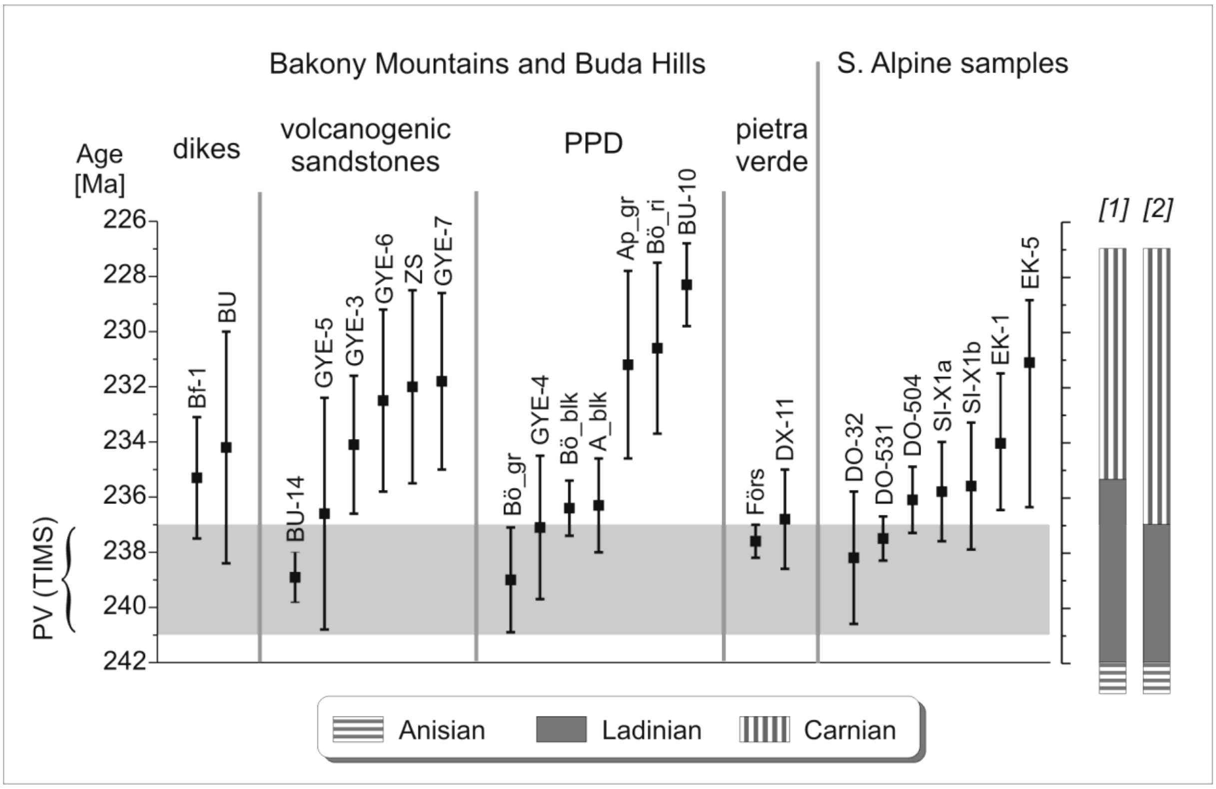

Figure 8: Compilation of all Triassic zircon U-Pb single-grain ages obtained on the volcanic and volcanoclastic formations of the Bakony Mountains and Buda Hills - without the data measured on the 'pietra verde' tuff layers. N=274, the Tertiary ages and the inherited, pre-Triassic ages are not displayed; bin width=2.5 Myr.

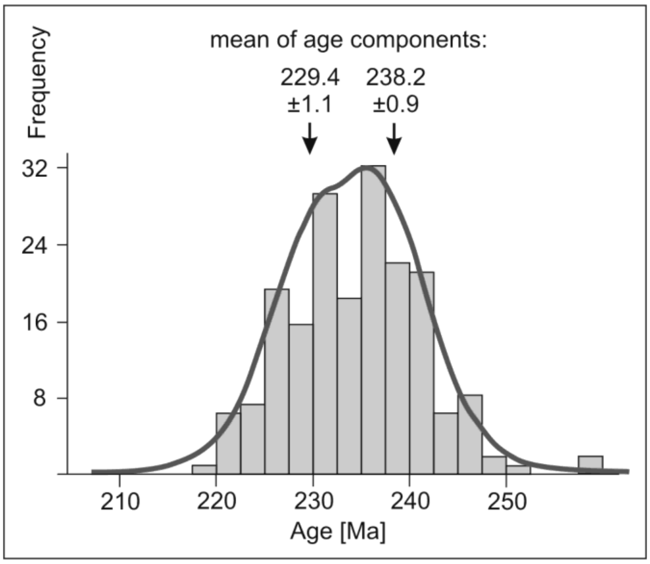

Figure 9: Actinide composition of the dated zircon samples: median of uranium concentration vs. median of Th/U ratio measured in single crystals. Zircons from the Triassic volcanic

formations from the Bakony Mountains and Buda Hills form a tight cluster, and it is obvious that the samples from the Southern Alps with acid-intermediate composition have different actinide element concentrations.

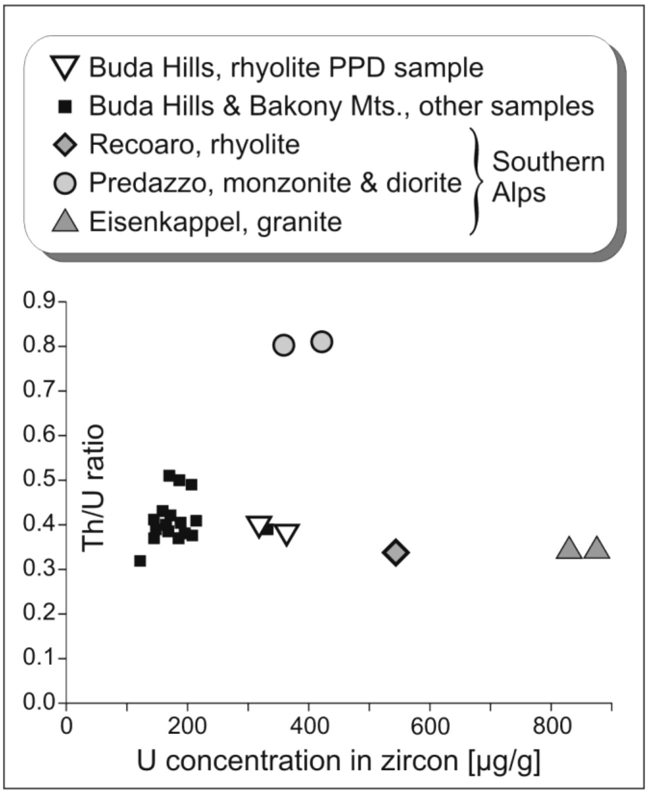

Table 1: Locality and petrography of the samples that yielded usable geochronological results. The entire sample list used for petrographical study is in the Electronic Supplementary Material (ESM_1.xls). PPB indicates pebble population dating according to Dunkl et al. (2009).

Table 2: Synopsis of the U–Pb data obtained on the Triassic igneous formations of Bakony Mts. and Southern Alps. The raw data can be found in the Electronic Supplementary Material (ESM_6.xls and ESM_7.pdf).

Electronic Supplementary Material

Online Resource 1 (ESM_1.xls): List of samples used for petrographical investigation.

Online Resource 2: (ESM_2.pdf): U-Pb ages measured on the zircon reference materials.

Online Resource 3 (ESM_3.xls): Whole rock geochemistry of Triassic volcanic formations from the Transdanubian Range. Oxides and LOI are in wt%, trace elements are in ppm; missing data: not analysed or below the level of detection.

Online Resource 4 (ESM_4.xls): Composition of phenocrysts of the Transdanubian Triassic volcanic formations determined by electron microprobe analyses.

Online Resource 5 (ESM_5.pdf): Composition of phenocrysts of the Transdanubian Triassic volcanic formations on feldspar (a), pyroxene (b) and amphibole (c) classification diagrams. The pyroxene and amphibole classifications are based on Morimoto (1988) and on Leake et al. (1997), respectively. The detailed data can be found in the Electronic Supplementary Material (ESM_4.xls).

Online Resource 6 (ESM_6.xls): Detailed results of the single-grain U-Pb geochronology.

Online Resource 7: (ESM_7.pdf): Age spectra of the individual volcanoclastic samples plotted by the AgeDisplay software (Sircombe 2004).

Table 1: Locality and petrography of the samples yielded usable geochronological results.
The entire sample list used for petrographical study is in the Electronic Supplementary Material (ESM_1.xls).
PPB indicates pebble population dating according to Dunkl et al. (2009).

Type	Code	Long. [°]	Lat. [°]	Elevation [m]*	Locality / Borehole, depth [m]	Area	Petrography
Andesite dikes							
	BU	18,974	47,471	-577,4	Budaörs-1, 790.4 m	Buda Hills	andesite dike
	Bf-1	19,021	47,409	-1047	Budafok-1, 1147 m	Buda Hills	andesite dike
Volcanogenic sandstones							
	ZS	18,702	47,542	222	Strázsa Hill quarry	Zsámbék basin	volcanoclastite layer
	GYE-5	18,183	47,208	134	Várpalota-3, 37 m	S. Bakony Mts.	volcanoclastite layer
	GYE-6	18,196	47,225	164	Bakonykút-2, 21 m	S. Bakony Mts.	volcanoclastite layer
	GYE-7	"	"	123	Bakonykút-2, 62 m	S. Bakony Mts.	volcanoclastite layer
	GYE-3	18,950	47,463	155	Budaörs, Kálvária Hill	Buda Hills	volcanogenic sandstone
	BU-14	18,952	47,462	150	Budaörs, Kálvária Hill	Buda Hills	volcanogenic sandstone
Pebble-population samples from the base of the Eocene transgressive sequence							
	Bö_blk	18,955	47,464	193	Budaörs, Kő Hill	Buda Hills	black andesite PPD-1
	A_blk	"	"	"	"	"	black andesite PPD-2
	Bö_gr	"	"	"	"	"	green acid volcanic PPD-1
	AP_gr	"	"	"	"	"	green acid volcanic PPD-2
	Bö_ri	"	"	"	"	"	rhyolite tuff PPD
	BU-10	18,931	47,523	332	Budakeszi sanatorium	Buda Hills	andesite PPD
	GYE-4	19,036	47,590	225	Róka Hill	Buda Hills	andesite PPD
Pietra verde							
	Förs	17,943	47,018	230	Felsőörs	S. Bakony Mts.	bentonitic trachite tuff
	DX-11	18,020	47,134	195	Hajmáskér	S. Bakony Mts.	bentonitic trachite tuff
Triassic igneous samples from the eastern Southern Alps							
	DO-531	11,589	46,314	1310	Predazzo W	Dolomites	monzonite
	DO-504	11,603	46,307	1052	Predazzo-Bellamonte	Dolomites	mela-diorite
	DO-32	11,221	45,721	660	Recoaro N	S. Alps	rhyolite
	SI-X1a	13,653	46,596	1110	Nötsch im Gailtal	Drauzug	tuffite
	EK-1	14,590	46,477	610	Eisenkappel	Drauzug	granite
	EK-5	14,614	46,475	733	Eisenkappel	Drauzug	granite

*: at boreholes the true elevation of the sample relatively to sea level is indicated

Table 2: Synopsis of the U–Pb data obtained on the Triassic igneous formations of Bakony Mts. and Southern Alps.
The raw data can be found in the Electronic Supplementary Material (ESM_6.xls and ESM_7.pdf).

Type	Sample	Locality & lithology	No. of data	U* [ppm]	Th/U* ratio	Concordia Age [Ma]	± **	TuffZirc Age [Ma]	+	-
Andesite dikes										
	BU	Budaörs-1 borehole, 790.4 m, andesite dike	18	147	0,39			**234,2**	4,2	2,9
	Bf-1	Budafok-1 borehole, 1147 m, andesite dike	18	162	0,40	**235,3**	2,2			
Volcanogenic sandstones										
	ZS	Strázsa Hill quarry, volcanoclastite layer	20	332	0,39			**232,0**	3,5	1,4
	GYE-5	Várpalota-3 borehole, 37 m, volcanoclastite	6	186	0,50	**236,6**	4,2			
	GYE-6	Bakonykút-2 borehole, 21 m, volcanoclastite	11	144	0,41	**232,5**	3,3			
	GYE-7	Bakonykút-2 borehole, 62 m, volcanoclastite	9	158	0,43	**231,8**	3,2			
	GYE-3	Budaörs, Kálvária Hill, volcanoclastic sandstone	19	185	0,37	**234,1**	2,5			
	BU-14	Budaörs, Kálvária Hill, volcanoclastic sandstone	88	207	0,38			**238,9**	0,9	0,9
Pebble-population samples from the base of the Eocene transgressive sequence										
	A_blk	Budaörs, Kő Hill, black andesite PPD-2	18	168	0,42	**236,3**	1,7			
	Bö_blk	Budaörs, Kő Hill, black andesite PPD-1	9	145	0,37	**236,4**	1,0			
	AP_gr	Budaörs, Kő Hill, green acid volcanic tuff PPD-2	26	165	0,40			**231,2**	3,4	2,9
	Bö_gr	Budaörs, Kő Hill, green acid volcanic tuff PPD-1	26	317	0,40			**239,0**	1,9	2,4
	Bö_ri	Budaörs, Kő Hill, rhyolite tuff PPD	23	363	0,38	**230,6**	3,1			
	BU-10	Budakeszi sanatorium, andesite PPD	20	195	0,38	**228,3**	1,5			
	GYE-4	Róka Hill andesite PPD	8	186	0,40			**237,1**	2,6	2,6
Pietra verde samples from the Bakony Mountains										
	Förs	Felsőörs, pietra verde tuff	20	121	0,32			**237,6**	0,6	1,6
	DX-11	Hajmáskér, pietra verde tuff	20	170	0,51			**236,8**	1,8	2,7
Triassic igneous samples from the eastern Southern Alps										
	DO-531	Predazzo W, monzonite	22	421	0,81	**237,5**	0,8			

DO-504	Predazzo E, mela-diorite	18	357	0,80			**236,1**	1,2	1,3
DO-32	Recoaro, rhyolite	23	543	0,34			**238,2**	2,4	2,5
SI-X1a	Nötsch, tuffite	26	214	0,41			**235,8**	1,8	2,1
SI-X1b	Nötsch, tuffite	16	206	0,49			**235,6**	2,3	1,7
EK-1	Eisenkappel, granite	12	877	0,34	**234,1**	2,5			
EK-5	Eisenkappel, granite	14	825	0,34			**231,2**	5,8	2,2

The U concentration and the Th/U ratio are calculated as median.

*: calculated only for the crystals yielding Triassic U-Pb age

**: uncertainty of concordia ages as 95% confidence