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ORIGINAL PAPER

Provenance of the Upper Triassic siliciclastics of the Mecsek Mountains and Villány Hills (Pannonian Basin, Hungary): constraints to the Early Mesozoic paleogeography of the Tisza Megaunit

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Abstract The Tisza Megaunit in the Southern Pannonian Basin formed part of the southern margin of the European Plate in the Early Mesozoic era. Its exact paleo-position and relation to other structural blocks is disputed for a long time. Detrital zircon U–Pb dating, heavy mineral analysis and petrographical examination of Carnian to Pliensbachian sandstone members lead to better understanding of the provenance of clastic deposits after the Ladinian–Carnian carbonate to siliciclastic facies shift in the Southwestern Tisza Megaunit. Investigations allow for constraining its paleogeographic relation to adjacent units. The Carnian and Pliensbachian siliciclastics of the Villány Hills derive from inside the Southwestern Tisza Megaunit, i.e. the medium-grade polymetamorphic rocks of the adjacent Slavonian Mountains or similar basement fragments. The Upper Triassic clastic deposits of the Mecsek Mountains most likely derive from Variscan felsic plutonic rocks of the local basement or partially from the Southern/Southwestern Bohemian Massif. About 200 Ma zircon U–Pb ages are tentatively interpreted as traces of synsedimentary distal volcanism in the Central Atlantic Magmatic Province.

Keywords Tisza Megaunit · Upper Triassic · Provenance · Heavy mineral analysis · Detrital zircon U–Pb geochronology

Introduction

The Tisza Megaunit occupies the southern half of the Pannonian Basin and is composed of southwest to northeast oriented tectonic belts, the Mecsek–Szolnok, Villány–Bihor and Békés–Codru Units (e.g. Csontos and Vörös 2004; Fig. 1a). The majority of the megaunit is covered by thick Neogene basin fill; in the west the basement crops out only in the Mecsek Mountains and Villány Hills in Hungary, and in the Eastern Slavonian Mountains in Croatia (Papuk and Krndija Mountains), while in the east it is exposed in the Northern Apuseni Mountains in Romania (Bleahu et al. 1994; Fig. 1a, b).

During the Early Mesozoic the Tisza Megaunit was part of the southern margin of the European Platform and it got separated by the Tethyan rifting in the Jurassic (Géczy 1973). Prior to rifting away from the European margin, Tisza Megaunit was located on the western side of the Neotethyan shelf south of the Bohemian Massif in the late Triassic, according to Csontos and Vörös (2004) and Haas and Péró (2004) (Fig. 2). In contrast to these views, Tari (2015)

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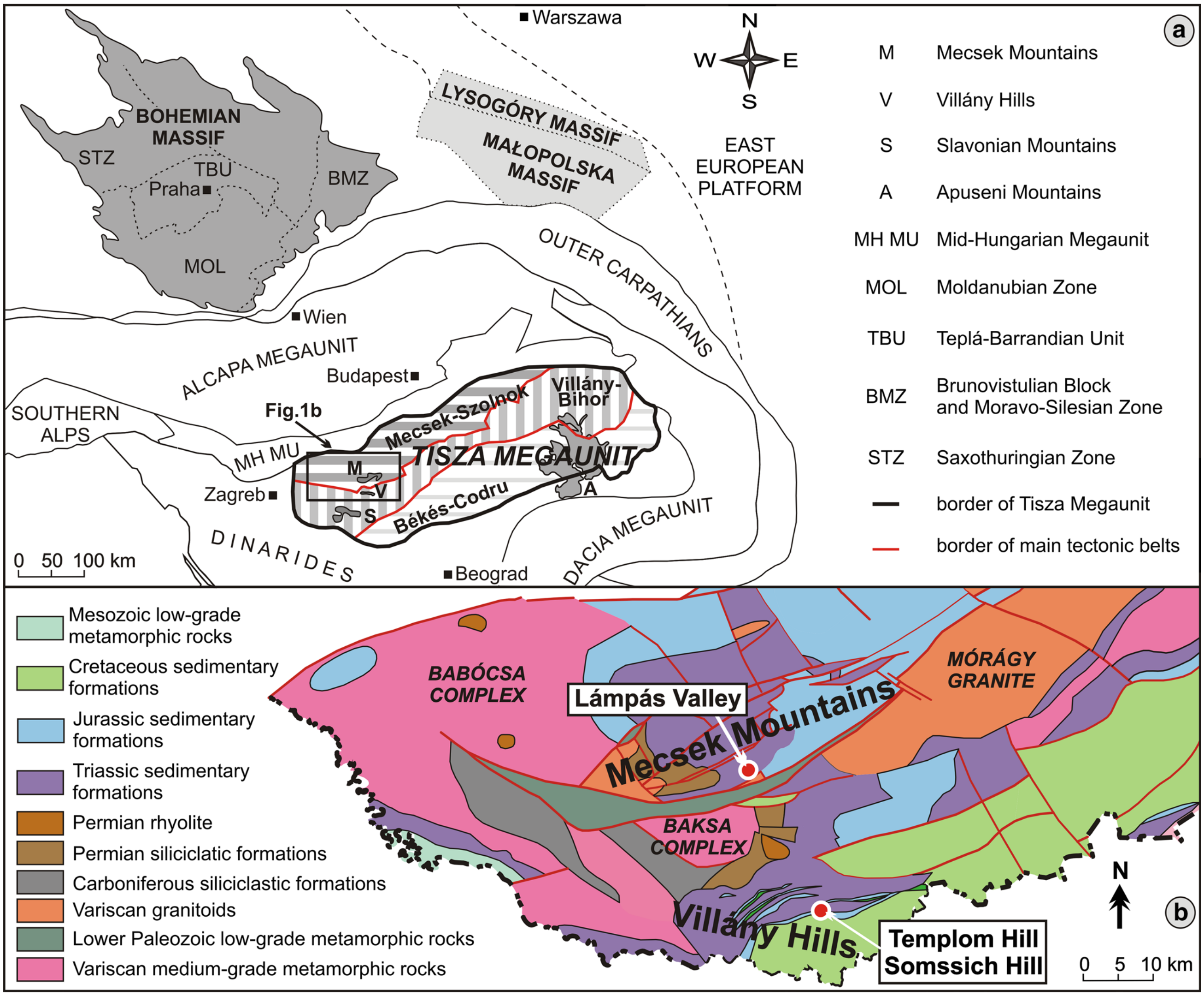

Fig. 1 **a** Location of the Tisza Megaunit in the Pannonian Basin and its relation to the Bohemian, Małopolska and Lysogóry Massifs (compiled after Belka et al. 2000; Haas et al. 2010; Klomínský et al. 2010; Schmid et al. 2008). **b** Geological sketch map of the Hungarian part of the western Mecsek–Szolnok and Villány–Bihor Units (simplified after Haas et al. 2010). Sampling sites are marked with *red dots*. *Red lines* indicate major faults

places the Tisza Megaunit to the west of the Bohemian Massif, while Szulc (2000) and Götz and Török (2008) suggest a position east of the Bohemian Massif and even east of the Silesian Gate, in the proximity of Fennoscandia. Because Tisza Megaunit forms an important structural unit for paleogeographic and geodynamic reconstructions of the western Neotethyan region (e.g. Schmid et al. 2008; Stampfli and Borel 2002), it is necessary to constrain its paleogeographic position.

In this paper the composition and possible sources of the Upper Triassic and Lower Jurassic clastics are examined in the two northwestern units within the Tisza Megaunit, the Mecsek–Szolnok and Villány–Bihor Units. The goal is to better understand which rock varieties were eroded and transported into the Upper Triassic clastic successions from the European passive margin. In addition, we aim to better constrain the paleogeography and recognize connections and barriers between uplifted source areas and subsided sedimentary basins.

Geological setting

The study area is situated in the Southern Pannonian Basin of Hungary and includes the Mecsek Mountains, which belong to the Mecsek–Szolnok Unit, and the Villány Hills, part of the Villány–Bihor Unit (Haas and Péró 2004). The pre-Permian crystalline basement of the study area is

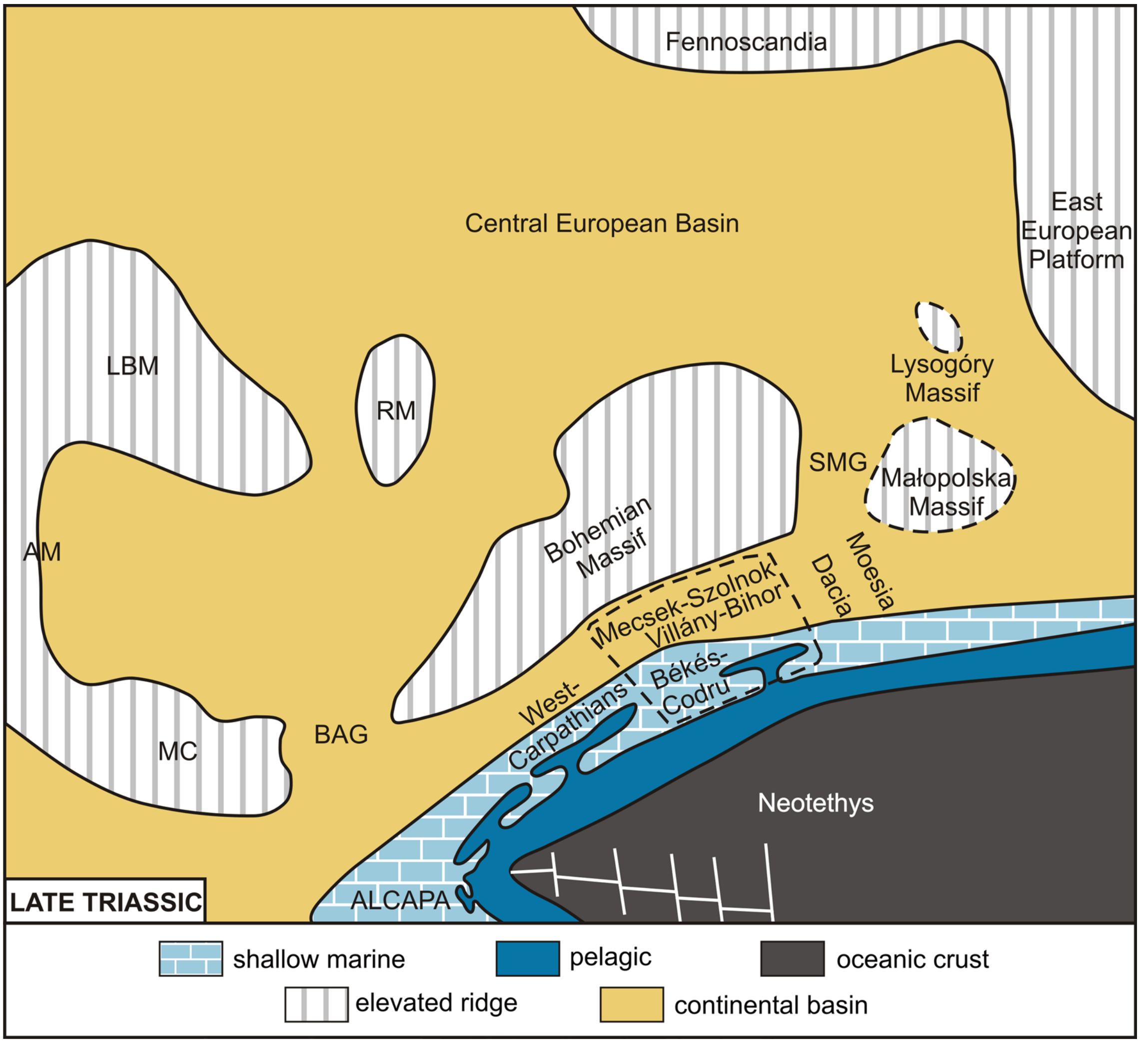

Fig. 2 Paleogeographic setting of the Tisza Megaunit in the Late Triassic (simplified after Haas and Péró 2004; Schmid et al. 2008; Szulc 2000). *AM* Armorican Massif, *BAG* Burgundy–Alemannic Gate, *LBM* London–Brabant Massif, *MC* Massif Central, *RM* Rhenish Massif, *SMG* Silesian–Moravian Gate

constituted by the Baksa and Babócsa Complexes, which consists of dominantly medium-grade parametamorphic sequences of Early Paleozoic protoliths, and the Carboniferous Mórágy Granite Complex (Szederkényi 1998). The basement is covered by a thick Upper Paleozoic–Lower Mesozoic clastic–carbonatic sequence, which is considerably thicker in the Mecsek Mountains than in the Villány Hills (Bérczi-Makk et al. 2004; Figs. 1b, 3).

The Lower and Middle Mesozoic sequences show evidently European affinities based on paleontological data, such as the Germanic-type ammonite fauna (Géczy 1973). In addition, the clastic Lower Triassic (Buntsandstein), evaporitic Röt and carbonatic Middle Triassic (Muschelkalk) deposits are similar to the Germanic-type Triassic in both units (Török 1997). In contrast, the clastic Upper Triassic (Keuper) shows closer affinities to the Carpathian Keuper (Bleahu et al. 1994). Initial Tethyan rifting resulted in the fragmentation of the extensive Middle Triassic carbonate ramp and thus in the divergence of sedimentation in the Mecsek and Villány facies belts (Konrád 1998). From the Ladinian onwards the sedimentation was continuous in the Mecsek Unit; however, in the Villány Unit well-developed hiatuses were documented, indicating multiple breaks in sedimentation (Haas and Péró 2004). These facies differences are recognized along the entire length of the Tisza Megaunit (Bleahu et al. 1994).

Due to tectonic fragmentation since the Late Ladinian, the former uniform basin geometry with a homoclinal ramp changed markedly. In the Mecsek Unit, a rapidly subsiding half-graben developed, with maximum subsidence in the south (Nagy 1968). The main direction of sediment transport was from the north, north-northeast or northwest,

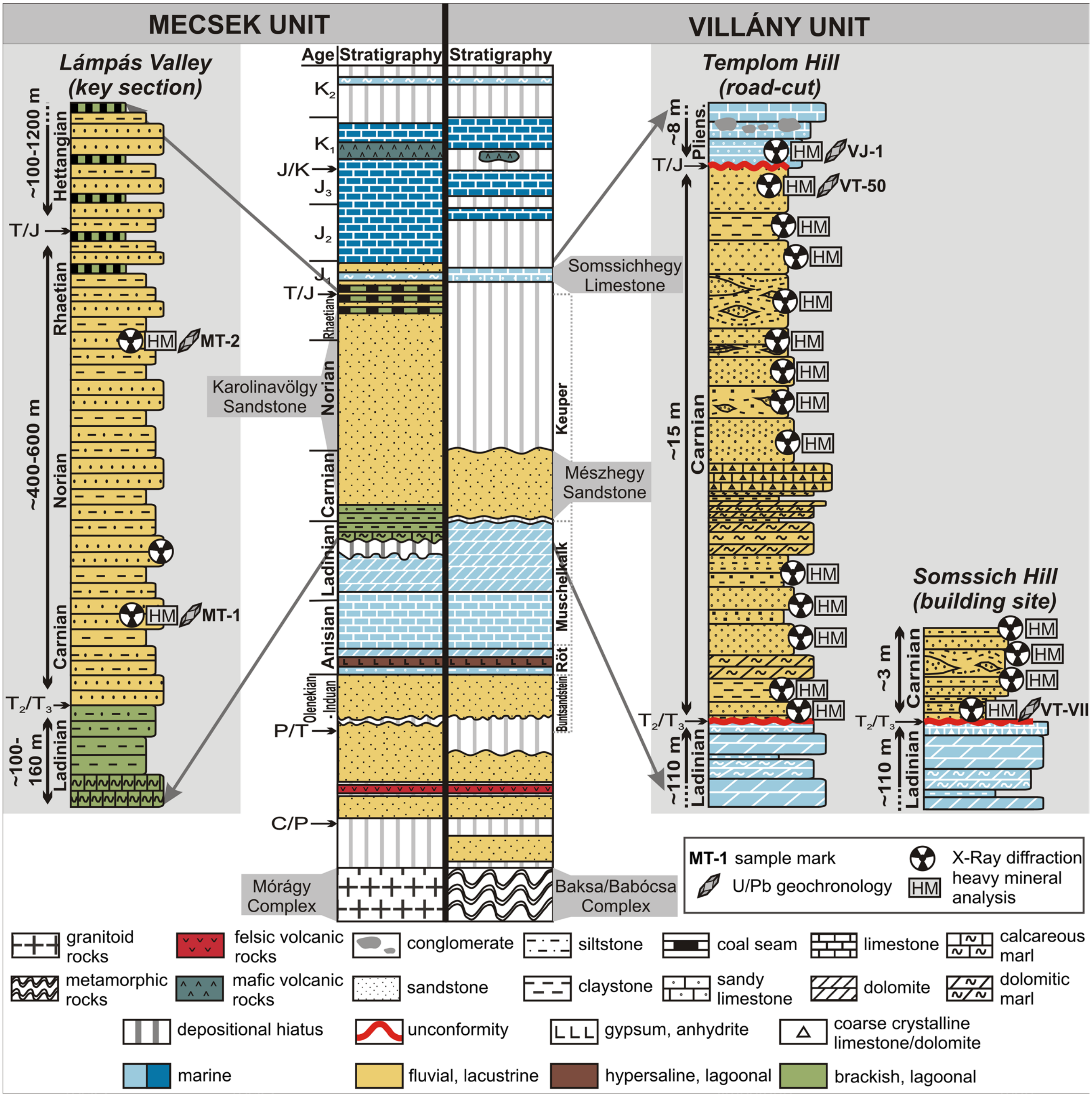

Fig. 3 Simplified lithostratigraphic columns of the Pre-Cenozoic formations of the Mecsek Mountains and the Villány Hills. *Left* stratigraphic column of the Lámpás Valley in the Mecsek Mountains with estimated thickness data. *Right* stratigraphic column of the Templom Hill and Somssich Hill in the Villány Hills with measured thickness data. Sampled strata are marked with *symbols* of analytical methods

with mainly granitoid and metamorphic rocks exposed in the provenance area (Császár et al. 2013; Győrfy 2012; Nagy 1968; Nagy et al. 2008). Along the southern boundary of the subsiding basin carbonate debris was intercalated, indicating erosion of uplifting blocks in the south (Nagy 1968; Császár et al. 2013). In the current study, we focus on the Late Carnian–Rhaetian Karolinavölgy Sandstone Formation (Fig. 3), which is a 400–600 m thick fluvial–lacustrine–lagoonal sequence consisting of dark gray, grayish green and grayish red conglomerates, sandstones, pelites, with coal intercalations in the upper part (Nagy 1968; Wéber 1984).

During the same time interval, the Villány Unit represented a more elevated belt within the Tisza Megaunit (Vörös 2012) with only episodic sedimentation. The first member of this succession is the relatively thin (maximum

20 m) Carnian Mészhegy Sandstone Formation (Fig. 3), composed of variegated conglomerate, sandstone, pelite and cellular dolomitic limestone, deposited in a nearshore, coastal plain or fluvial–lacustrine setting (Ősi et al. 2013; Bérczi-Makk et al. 2004; Vörös 2009). This thin siliciclastic unit, which interrupts the carbonate succession, has been correlated with the "Carnian Pluvial Event" (Simms and Ruffel 1989). Besides this, we studied the basal clastic layers of the overlying shallow marine Pliensbachian Somssichhegy Limestone Formation (Vörös 2009; Fig. 3) in order to detect possible changes in provenance.

Samples and methods

Unweathered rock samples were taken from Mészhegy and Somssichhegy Formations in the Eastern Villány Hills, along a road cut (Templom Hill; Fig. 1b) and at a construction site (Somssich Hill; Fig. 1b), and from the Karolinavölgy Sandstone in the Central Mecsek Mountains (Lámpás Valley; Fig. 1b). We aimed to select samples of varying grain sizes (pelite to conglomerate) in accordance with the grain size requirements of the methods. Electronic Supplementary Material (ESM Table 1) indicates the localities, and Fig. 3 presents the detailed successions with the sampled levels and applied methods. In the sample codes, V and M indicate Villány and Mecsek, and T and J Triassic and Jurassic, respectively.

The framework composition of sandy pelites to coarse sandstone samples was studied by thin sections using point counting of 300 to 400 grains. Grains of 1–2 and >2 mm in diameter were investigated in grain mounts. Whole-rock mineralogical composition was determined on pulverized bulk samples by X-ray diffraction using a Rigaku Miniflex 600 (40 kV, 15 mA) at the University of Pécs. XRD scans were evaluated for quantitative mineralogy with a full profile fit method using XDB Phase Analytical Software (ESM Table 2). The X-ray diffraction results are especially helpful when determining fine-grained matrix and/or cement phases of the arenitic samples. Pelites were investigated by using X-ray diffraction for their mineralogical composition.

Samples were soaked in sodium acetate solution, wet sieved and deslimed. Heavy minerals were separated from the 63–125 and 125–250 µm fractions using sodium polytungstate solution with an average density of 2.78 g/cm^3. Heavy mineral grains were mounted on microscope slides by Meltmount ($n = 1.66$), quantified by ribbon counting of 300–400 grains under the polarizing microscope (Mange and Maurer 1992). The heavy minerals in the 63–125 µm grain size fraction were systematically evaluated (ESM Table 3). The 125–250 µm fractions were also checked for heavy mineral abundance to avoid significant bias in heavy mineral assemblages due to grain-size effects (Garzanti et al. 2009). In order to verify the optical identification of heavy minerals, Raman spectroscopy and scanning electron microscopy were used. Raman spectra of heavy minerals were obtained at the University of Göttingen, using a Horiba Jobin Yvon HR800-UV spectrometer (488 nm, 20 mW) with an Olympus BX-41 microscope and a 100 × long working distance objective. At least 300 to 350 grains were measured in four samples. The Raman spectra were evaluated using the software CrystalSleuth. The SEM-EDX (AMRAY 1830 with EDAX PV9800 energy dispersive spectrometer; 20 kV, 1 nA, 50 nm) was used at the Eötvös Loránd University. At least 50–100 mineral grains were checked in every 9 samples.

For U–Pb geochronology of detrital zircon grains five fine-grained sandstone samples were selected, crushed and sieved using 63 and 125 µm mesh size. The carbonate content was removed with 5% acetic acid. Heavy minerals were separated using sodium polytungstate heavy liquid and magnetic separation. At the choosing the zircon grains for geochronology we carefully applied an unbiased selection avoiding any personal preferences or any kind of fractionation of a given grain size or shape. The crystals were spread randomly on a double-side adhesive tape stuck on a thick glass plate and embedded in a 25 mm diameter epoxy mount. These crystal mounts were lapped by 2500 mesh SiC paper and polished by 9, 3 and 1 micron diamond suspensions. For all zircon samples and standards used in this study cathodoluminescence (CL) images were obtained using a JEOL JXA 8900 electron microprobe at the Geozentrum Göttingen in order to study their internal structure and to select homogeneous parts for the in-situ age determinations. The mounts were cleaned by diluted HCl, ethanol and deionized water in an ultrasonic bath to remove surface lead contamination before introduction into the sample cell.

The in-situ U–Pb dating was performed by laser-ablation single-collector magnetic sector-field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS). The method employed for analysis is described in detail by Frei and Gerdes (2009). A Thermo Finnigan Element 2 mass spectrometer coupled to a Resonetics Excimer laser ablation system was used. All age data were obtained by single spot analyses with a laser beam diameter of 33 µm and a crater depth of approximately 12 µm. The laser was fired at a repetition rate of 5 Hz and at nominal laser energy output of 25%. Two laser pulses were used for pre-ablation. The carrier gas was He and Ar. Analytes of ^{238}U, ^{235}U, ^{232}Th, ^{208}Pb, ^{207}Pb, ^{206}Pb, ^{204}Hg and ^{202}Hg were measured by the ICP-MS. The data reduction is based on the processing of 100 time slices (corresponding to ca. 10.5 s) starting ca. 1 s after the beginning of the signal. The possible outliers were tested by the iterative Grubbs test (applied at $P = 5\%$ level). The age calculation is based on the drift and fractionation correction by standard-sample bracketing using GJ-1 zircon reference material (Jackson et al. 2004). For further control Plešovice, FC-1 and 91500 zircons were analysed as "secondary standards" (Paces and Miller 1993; Wiedenbeck et al. 1995; Sláma et al. 2008). The age results of the standards were consistent within 1σ of the published ID-TIMS values. Drift and fractionation corrections and data reductions were performed by our in-house software (UranOS; Dunkl et al. 2008). The level of Hg-corrected ^{204}Pb signal was very low, thus no common lead correction was required. The number of single-grain ages per sample ranges between 94 and 109. If the ^{206}Pb/^{238}U age was younger than 1.2 Ga we considered this age, while above this threshold the ^{207}Pb/^{206}Pb age was used. The concordia plots and age spectra were constructed by the help of Isoplot/Ex 3.0 (Ludwig 2003) and AgeDisplay (Sircombe 2004).

Results

Petrography

The major lithologies of Mészhegy Sandstone Formation (Villány Hills) are micaceous sandstones and pelites, while pebbly horizons occur rarely. The prevailing sandstone varieties are quartzose, quartzofeldspathic and quartzolithic (Figs. 4a, 5a–c). The fine-grained matrix is usually argillaceous and sericitic with considerable hematite and goethite content. Argillaceous cement is common, dominated by montmorillonite and kaolinite with less illite. The cement of some coarse sandstones is coarse crystalline calcite. Predominantly angular to subangular quartz grains occur. Monocrystalline quartz frequently shows undulose extinction. Very rarely resorbed monocrystalline quartz grains were found. Polycrystalline quartz usually contains more than three subcrystals with primarily sutured subcrystal boundaries. Orthoclase and microcline are usually unweathered or weakly altered. The lithic fragments are typically metapelites: fine-grained, quartz-rich, muscovite-schist and biotite-schist, muscovite- or biotite-bearing gneiss, and undulose quartzite fragments are common. A staurolite-bearing mica schist fragment was also detected. Sandstone, siltstone and slate fragments are abundant. Subordinately granitoid lithoclasts and volcanic rock fragments are also present. Pebbly sandstone horizons of the sequence include angular to rounded polycrystalline quartz, sandstone, pelite, limestone, dolomite and dolomarl granules, pebbles or even cobbles.

Sandstones from the base of the Somssichhegy Limestone Formation (Villány Hills) are poorly sorted quartzarenites and sublitharenites cemented by microcrystalline calcite (Fig. 4a). The fine-grained carbonate mud matrix is weakly argillaceous (montmorillonite, illite). Angular to subangular monocrystalline and polycrystalline quartz grains are common; resorbed monocrystalline quartz fragments also occur. Microcline and orthoclase are present in subordinate amounts. Mica-bearing gneiss and schist fragments are frequent. Bioclast-rich pelites constitute a high proportion of the lithic fragments. Conglomerate beds overlying the psammites contain polycrystalline quartz, gneiss, sandstone, limestone, and dolomite pebbles with a diameter of 0.5–3 cm.

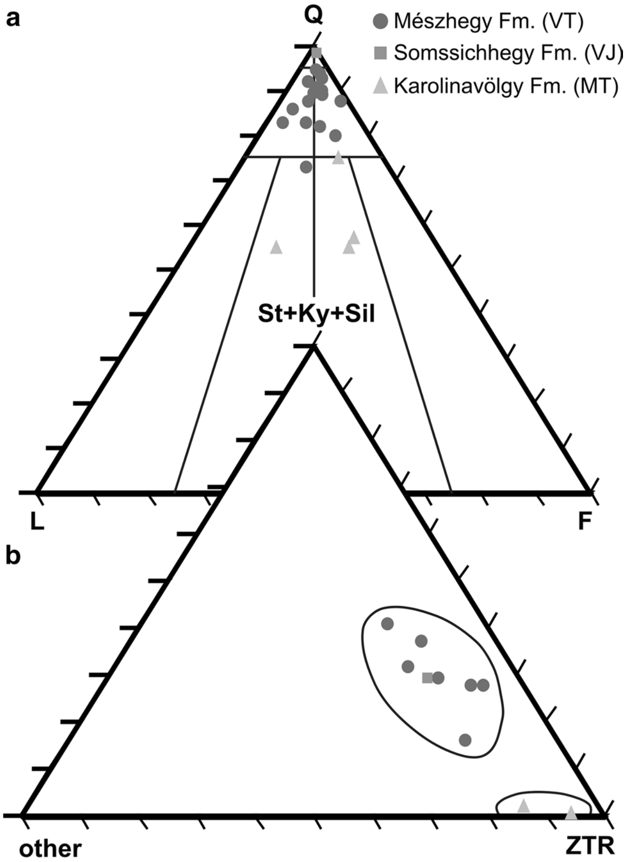

Fig. 4 **a** Framework composition and **b** heavy mineral distribution of the samples from the Mecsek Mountains and Villány Hills. *Q* quartz, *F* feldspar, *L* lithic fragment, *ZTR* zircon + tourmaline + rutile ultrastable minerals, *St* + *Ky* + *Sil* staurolite + kyanite + sillimanite medium-grade metamorphic minerals, *other* all other detrital heavy minerals

The Karolinavölgy Sandstone Formation (Mecsek Mountains) is composed of poorly sorted subarkoses, sublitharenites, lithic arkoses or feldspathic litharenites, with grain-supported fabric and syntaxial overgrowth on the quartz grains (Figs. 4a, 5d–f). The matrix and cement contain various proportions of silica, clay minerals, sericite, calcite and chlorite. Quartz grains are dominantly polycrystalline, usually composed of more than three subcrystals; the contact of subcrystals is sutured. The weathering

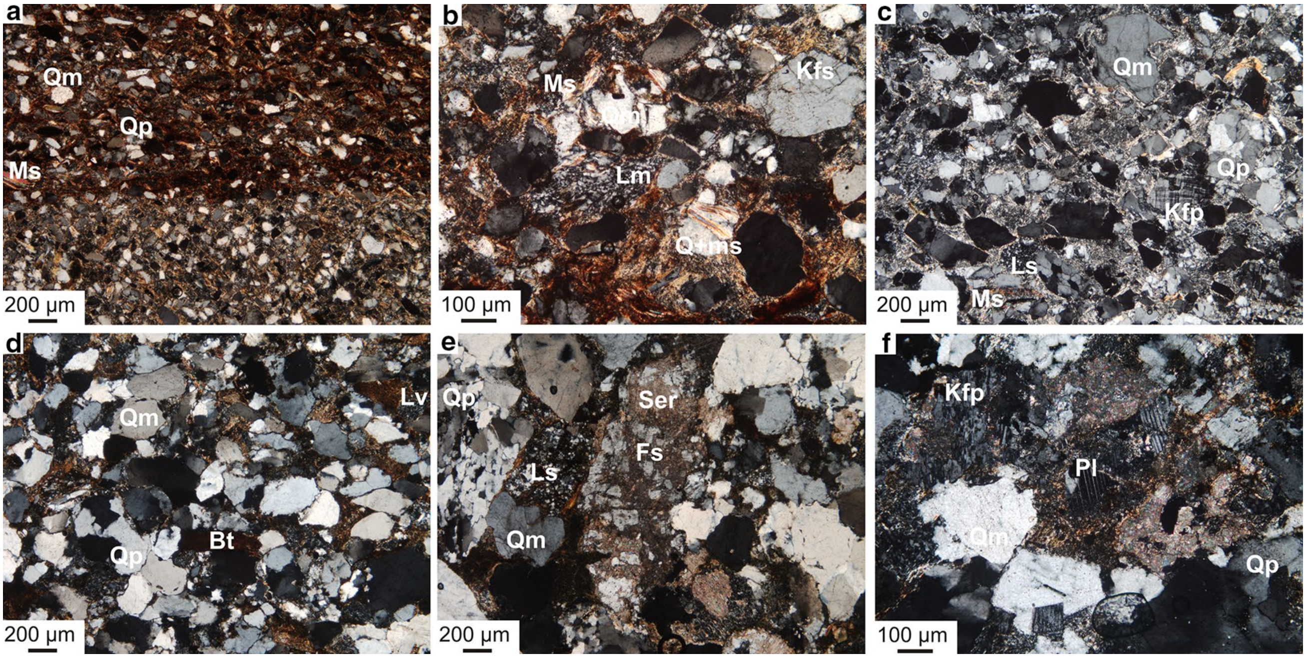

Fig. 5 Cross-polarized microphotographs of typical rock varieties of the Mészhegy Sandstone (VT samples) (**a**–**c**) and Karolinavölgy Sandstone (MT samples) (**d**–**f**). **a** Graywacke with oriented mica flakes and iron oxide content, with higher proportion of sericite in the matrix at the base; **b** lithic graywacke; **c** micaceous graywacke; **d** arenite with syntaxial overgrowth of quartz; **e** arkose with sericitic feldspar remnants; **f** calcareous arkose. *Qm/Qp* mono- and polycrystalline quartz, *Kfs* potassium feldspar, *Pl* plagioclase, *Ms* muscovite, *Bt* biotite, *Ser* sericite, *Lm/Ls/Lv* metamorphic/sedimentary/volcanic lithic fragment

of abundant feldspar grains is advanced, mainly sericitic, perthitic microcline and orthoclase occur, albite is less frequent. Gneiss, mica schist and phyllite fragments are abundant. Sandstone, siltstone, slate, felsic volcanic and granitoid fragments were indentified.

In summary, the petrofacies of the Karolinavölgy Sandstone of the Mecsek Unit is more diverse due to a more abundant feldspar and lithic fragment assemblage compared to the two formations from the Villány Unit. The Mészhegy Sandstone differs from the Somssichhegy Limestone in the higher proportion of feldspars and lithic fragments (Fig. 4a).

Heavy mineral spectra

The characteristic opaque mineral of the Mészhegy and Somssichhegy Formations (Villány Hills) is ilmenite, and leucoxene and hematite were observed as well. Biotite and muscovite occur in remarkable proportions in each studied formation but they are not considered in the heavy mineral evaluations, because we focus the observations on the non-micaceous transparent minerals (Fig. 6; ESM Table 3).

The dominant heavy minerals of the Mészhegy Sandstone are zircon, TiO_2-polymorphs and staurolite. In lower amounts garnet, tourmaline, apatite and chromite, while in traces monazite, xenotime, kyanite and sillimanite occur. The zircon grains are mainly rounded. Euhedral zircons are rich in inclusions, often showing a zoning structure. The most frequent form of TiO_2-polymorphs is angular or subrounded rutile, less anatase and brookite were observed. Staurolite is typically angular, often showing advanced etching with rugged outlines and deeply etched, brownish-spotted facets (Fig. 7a). Evidence of etching was detected on angular garnet grains as well (Fig. 7b). Dark brown, brownish yellow and light yellow tourmalines occur euhedral, angular or subangular grains, but slightly corroded grains are also present. Apatites are angular or subrounded, rarely euhedral. Dark brown, angular chromite; almost colorless, rounded monazite; and grayish, angular kyanite and fibrous sillimanite occur very seldom.

The heavy mineral spectrum of the sandy horizon at the base of the Somssichhegy Limestone resembles those of the Mészhegy Sandstone: it contains a large amount of zircon, TiO_2-polymorphs and staurolite, with minor amounts of tourmaline, apatite, garnet, chromite and monazite. Beside the yellowish brown, euhedral, angular or subangular tourmalines, in subordinate amounts occur greenish and bluish tourmaline.

The heavy mineral assemblage of the Karolinavölgy Sandstone is characterized by a high amount of zircon, tourmaline and TiO_2-polymorphs, whereas less apatite and garnet, occasionally staurolite, sillimanite, chromite and

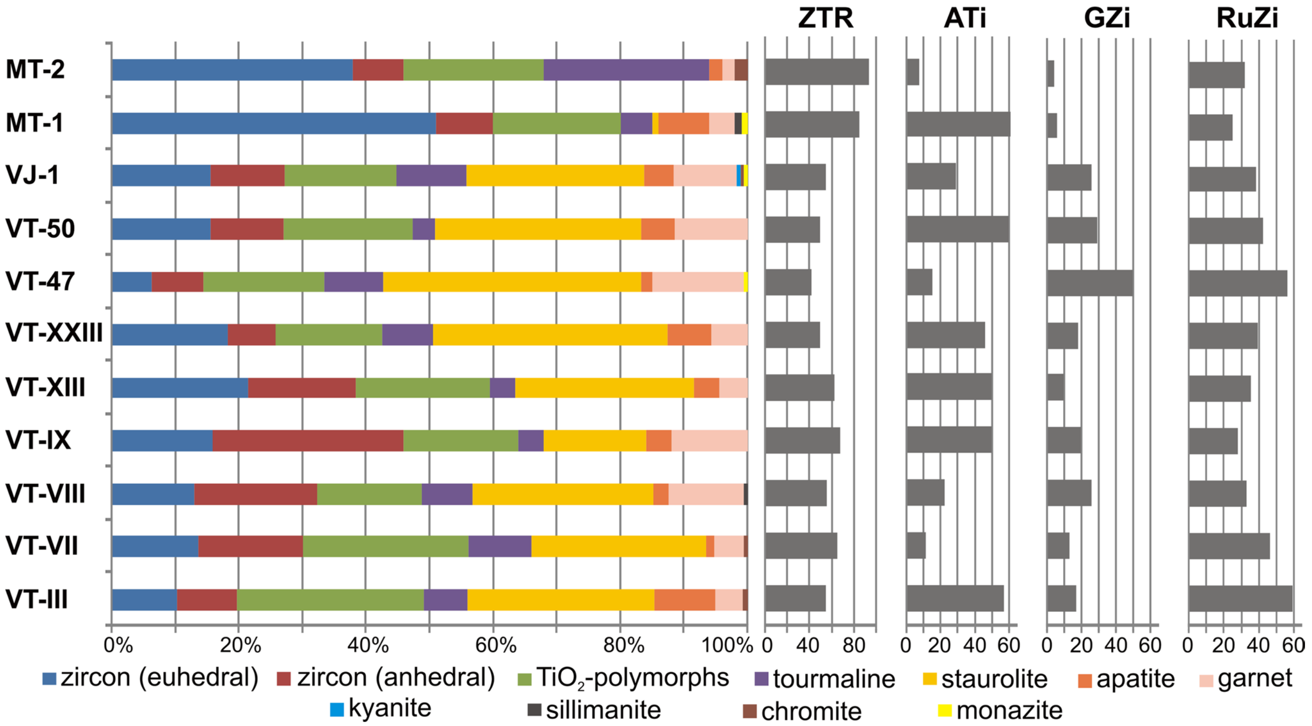

Fig. 6 Transparent heavy mineral distributions of the studied formations with the presentation of zircon–rutile–tourmaline index (*ZTR* index) and provenance-sensitive index values (*ATi* apatite–tourmaline index, *GZi* garnet–zircon index, *RuZi* rutile–zircon index)

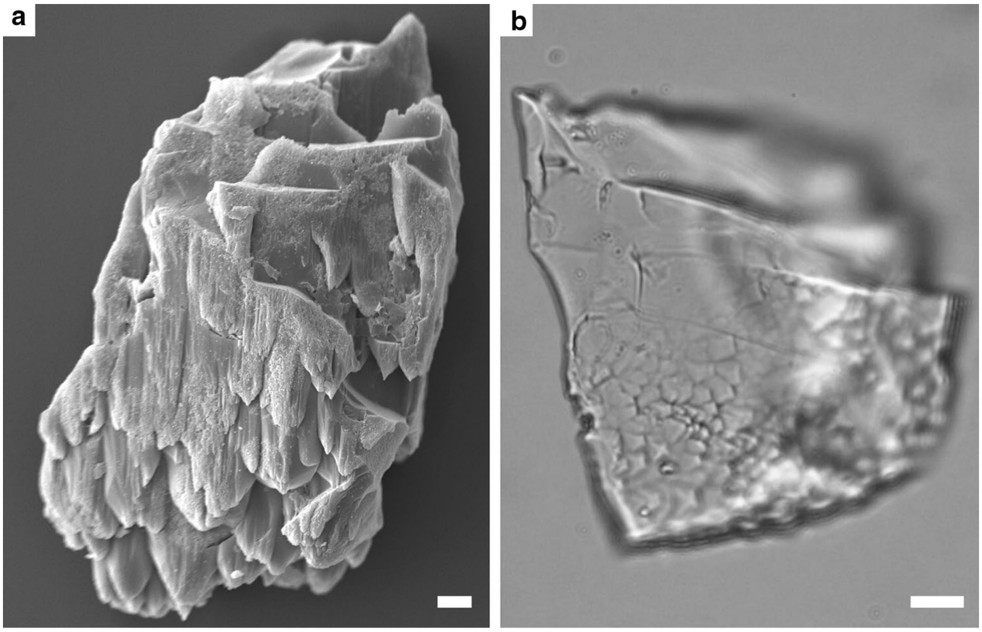

Fig. 7 Features of advanced stage of etching of the mineral facets. **a** Staurolite grain (scanning electron microscopic image) and **b** garnet grain from the Mészhegy Sandstone (optical microphotograph). *Scale bars* 10 µm

monazite were observed. The presence of euhedral, coarse-grained zircons with abundant inclusions or with zoned internal structure is much higher than the subrounded or rounded zircons. Rutile is mostly euhedral and coarse-grained (>100 µm), rarely subrounded. The coarse, euhedral tourmalines are yellow–brown, light green–dark green

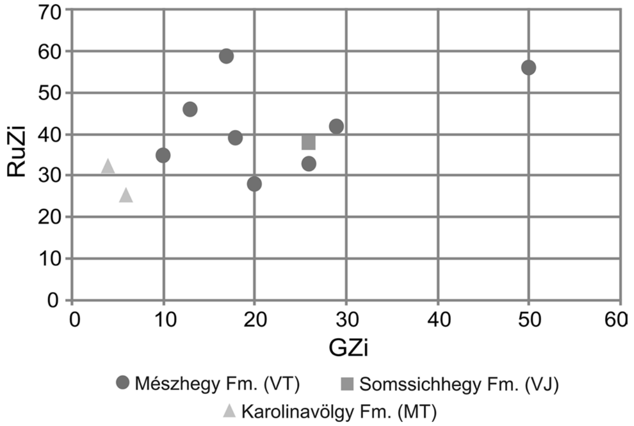

Fig. 8 Heavy mineral ratios RuZi (rutile–zircon index) and GZi (garnet–zircon index) show obvious difference between the provenance of the sandstones from Mecsek and Villány Units. The Mecsek samples indicate higher degree of mineralogical maturation

or green–black. Apatites occur as euhedral, slightly broken grains and frequently show dissolution features. Grayish garnets are angular. Rounded monazite and dark brown, angular chromite occur rarely, while a broken prism of sillimanite was observed.

Collectively, the most obvious difference compared to the Mészhegy and Somssichhegy Formations of the Villány Unit is that coarser, euhedral ultrastable mineral grains occur and the metamorphic index minerals are almost missing in the Karolinavölgy Sandstone of the Mecsek Unit. The mineral assemblage of the sandstone layers in the Somssichhegy Limestone closely resembles that of the Mészhegy Sandstone.

To evaluate several factors that may have overprinted the heavy mineral assemblages due to processes operating during the sedimentary cycle (weathering, mechanical breakdown, hydraulic processes, burial diagenesis), we calculated provenance-sensitive heavy mineral ratios (Morton and Hallsworth 1994, 1999; Morton et al. 2005) and the zircon–tourmaline–rutile (ZTR) index (Hubert 1962), shown in Figs. 6 and 8. The Karolinavölgy Sandstone shows particularly high ZTR values (85–94) in contrast to the Mészhegy (42–68) and Somssichhegy Formations (55). ATi values range from 7 to 61 in the Karolinavölgy Sandstone, while ATi indices have a similarly wide range in the Mészhegy Sandstone (11–60) and the sandstone sample from the Somssichhegy Limestone (29). GZi indices show somewhat smaller dispersion than the ATi values, displaying very low values (4–6) in the Karolinavölgy Sandstone, low or moderate amounts (10–50) in the Mészhegy Sandstone and 26 in the Somssichhegy Limestone. Binary plots of provenance-sensitive index values demonstrate that there is remarkable variation not only between the three formations studied, but within each formation as well (Fig. 8). Despite rather uniform heavy mineral assemblages of the Mészhegy Sandstone including RuZi (28–59) and GZi (10–29) values with relatively low scatter (with the exception of the VT-47 sample with high values of both RuZi (56) and GZi (50), respectively), ATi values show pronounced contrasts from about 11 to 60 (Fig. 6).

We combined the ZTR index with the proportion of medium-grade metamorphic minerals (staurolite, kyanite, sillimanite) in Fig. 4b. In all samples the ultrastable minerals prevail the spectra. In case of the samples from the Mészhegy and Somssichhegy Formations, the total amount of the "other minerals" group does not reach the cumulative amount of metamorphic minerals (staurolite, kyanite, sillimanite), in some cases it is only half of the metamorphic ones. Samples from the Karolinavölgy Sandstone are separated from the latter by (1) higher proportion of ultrastable minerals (zircon, tourmaline, rutile) and (2) higher ratio of "other minerals" and medium-grade metamorphic minerals. This comparison reflects the fundamental difference between the Mecsek and Villány Units and caused the multiple differences in the provenance-sensitive indices.

Detrital zircon U–Pb ages

More than 500 zircon crystals from five sandstone samples (Fig. 3) were dated. The age spectra are displayed in Fig. 9, while the raw data with the concordia diagrams can be found in the Electronic Appendix (ESM Table 4). Around 80% of the single-grain ages are concordant (filtering between 90 and 110%, e.g., Eglington and Harmer 1993). In the Phanerozoic ages the concordant data have considerably higher proportion than the Precambrian ones. A part of the zircon grains experienced alteration, this modification in the isotopic composition is the most pronounced in sample VT-VII from the Mészhegy Sandstone (Fig. 10). The degree of shift from the concordia curve correlates well with the effective uranium content ($\mathrm{eU} = U$ [ppm] + Th [ppm] × 0.235). Obviously the more damaged crystals experienced more leaching by diagenetic pore fluids that corroded also the detrital garnet and staurolite crystals (see above and Fig. 7a, b). Remarkably, the ca. 450 Ma ages cluster along the concordance curve, they were less influenced than the ca. 320 Ma ages, due to their low eU content (ca. 500 ppm). The youngest concordant ages of ca. 200 Ma were detected in the MT-1 sample. We assume that some of the discordant grains having 200 to 224 Ma $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ ages and eU higher than 1000 ppm are also related to this youngest age group.

Figure 11 illustrates the cumulative single-crystal age distributions of the samples. In order to express numerically the similarity/dissimilarity of the U–Pb age spectra we applied the Kolmogorov–Smirnoff (K–S) test using the Excel spreadsheet of J. Guynn (University of Arizona,

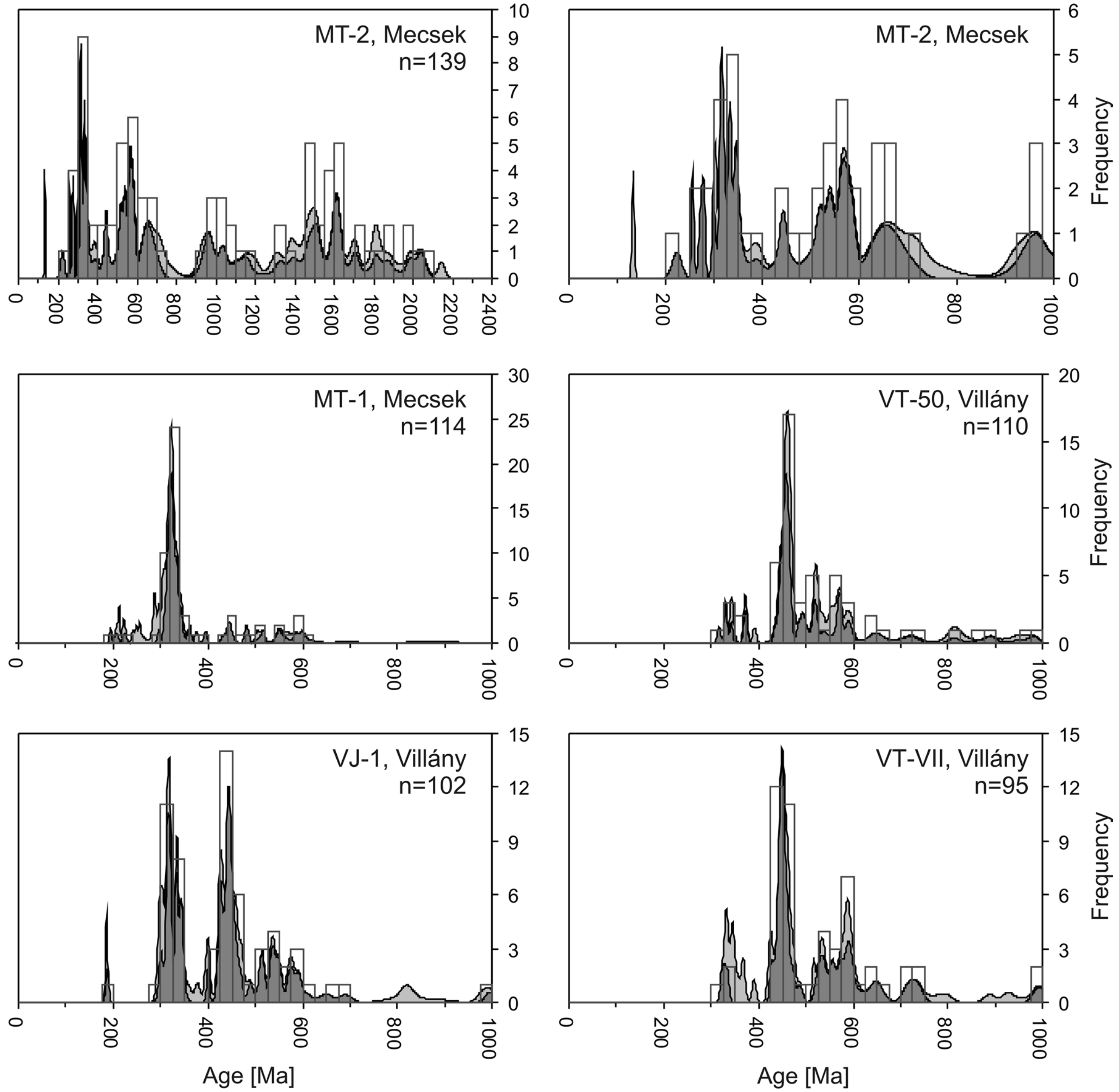

Fig. 9 U–Pb age spectra of detrital zircon crystals. The plots are constructed by AgeDisplay (Sircombe 2004); the *light gray* areas on the probability density plots represent the data of exceeding 10% discordance

letter comm., 2014). The test was performed both on the entire age range detected in the samples (up to 3 Ga) and also on a selected age range containing the ages younger than 1 Ga only. With the latter selection we minimize possible bias caused by the sporadic age data between 2 and 3 Ga. The test resulted in K-S *P*-values less than 0.002 for all but one sample pairs, thus the age distributions are distinct. The only exception is the VT-VII and VT-50 sample pair, which are not significantly different ($P = 0.52$).

Two methods were applied to identify the age components in the single-grain ages with concordance from 90 to 110%. The "*Density plotter*" (Vermeesch 2012) and the "*PopShare*" software (Dunkl and Székely 2002) are based on different algorithms, but they found very similar major age components (Table 1). The most common age components cluster around 320 (~350 in sample VT-50) Ma, around 450 Ma and around 590 Ma. They are present in almost each sample in dominant or in subordinate amount. For the sake of simplicity

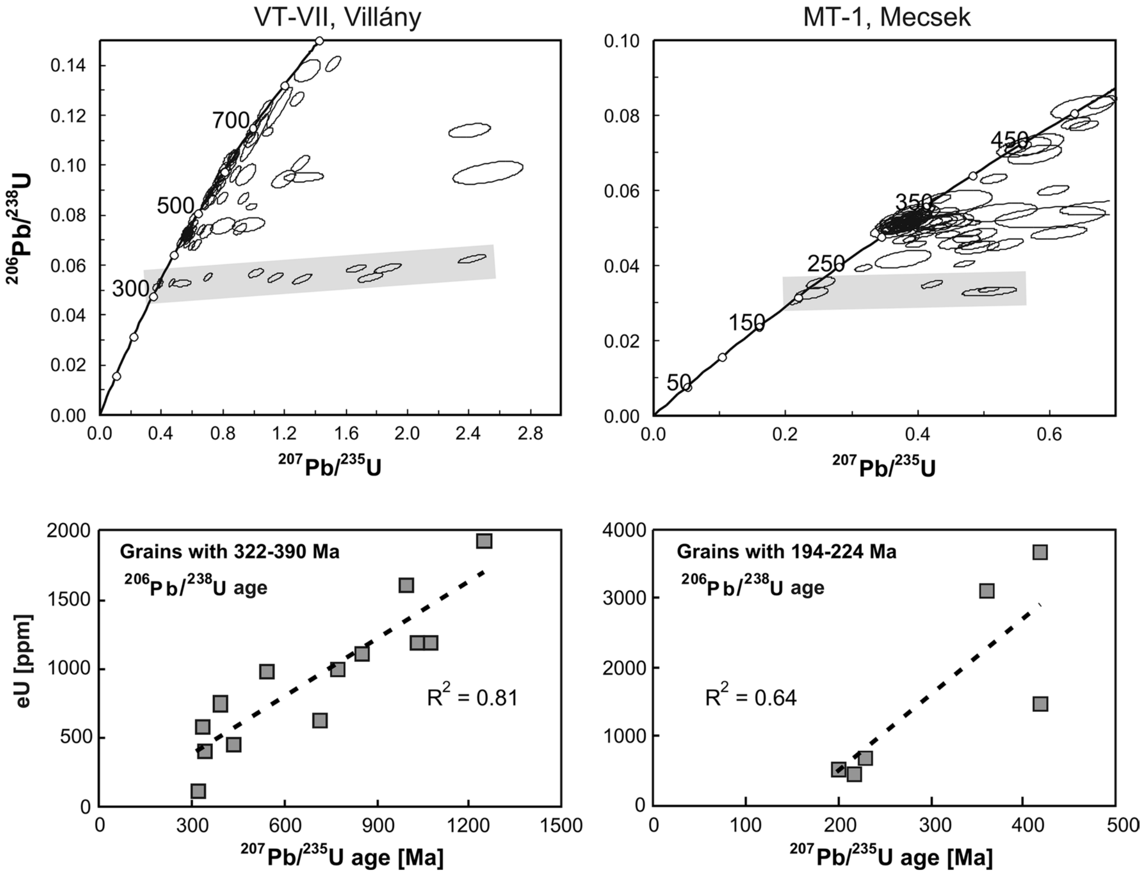

Fig. 10 Youngest parts of the U–Pb concordia plots of samples VT-VII and MT-1 (*upper panel*). The degree of discordance correlates well with the effective uranium content of the individual grains (*lower panel*; eU is calculated as U [ppm] + 0.253 * Th [ppm])

we will call the ca. 320 (350) Ma age components "Variscan," the ca. 450 Ma age components "Ordovician" and the slightly broader component between 540 and 600 Ma "Cadomian." Less constrained and slightly diffuse age components are found around 1000, 1500 and 2000 Ma. The youngest isolated age component is around 200 Ma (Table 1). The Variscan ages dominate the age spectrum of one sample in the lower part of the Karolinavölgy Sandstone (MT-1), but their proportion is also significant in the upper part of the Karolinavölgy Sandstone (MT-2) and in the lower part of the Somssichhegy Limestone (VJ-1). In contrast, Variscan ages are present only in subordinate amounts in samples VT-50 and VT-VII of the Mészhegy Sandstone. Ordovician ages have a dominating role in the two rather similar samples of the Mészhegy Sandstone and the sample of the Somssichhegy Limestone Formation. Cadomian ages are present in all samples, their highest proportion occurs in the upper part of the Karolinavölgy Sandstone (MT-2). The two study areas (Mecsek and Villány) differ mostly in the Ordovician age component, which is characteristic of the Villány Hills and present only in traces in the Mecsek Mountains.

Discussion

Unequivocal differences appear in the composition and the provenance of the examined sediments of Mecsek Mountains and Villány Hills. The clastic deposits of both areas were derived mostly from metamorphic and magmatic rocks, but their mineral composition show significant differences, therefore different source formations can be assumed. The U–Pb age distributions contain principally similar age components, but their proportions are highly different. In order to clarify the provenance, we briefly summarize the possible source units in the southwestern part of Tisza Megaunit, with regard to the mineral content (ESM Table 5) and age data (Fig. 11). We extend the comparison to more distal potential source areas like the Bohemian, Małopolska and Lysogóry Massifs, since certain Triassic paleogeographic reconstructions assume their proximity to the Tisza Megaunit in the Triassic (Csontos and Vörös 2004; Götz and Török 2008; Haas and Péró 2004; Szulc 2000; Tari 2015).

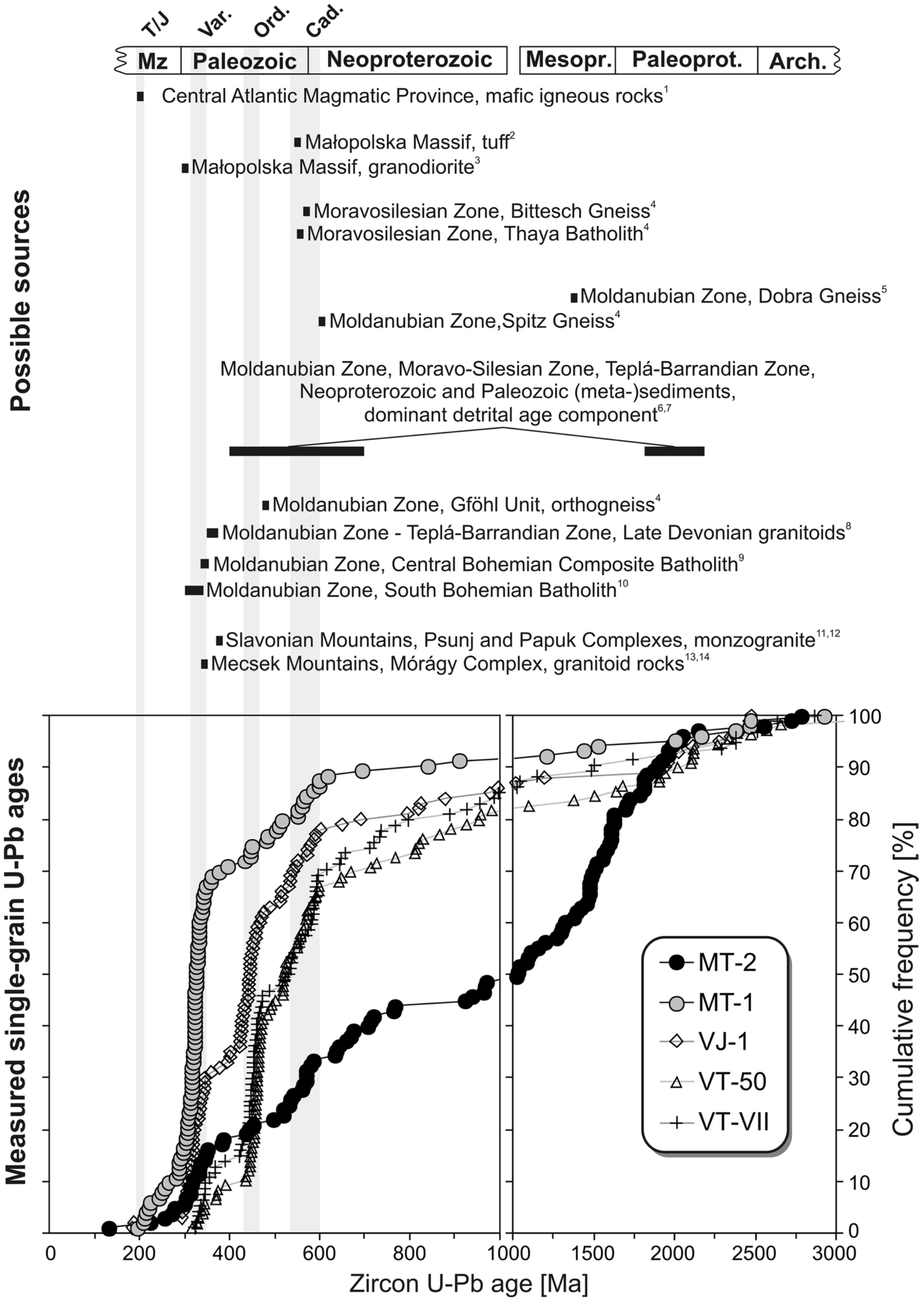

Fig. 11 Cumulative frequency diagram of the single-crystal U–Pb ages from Upper Triassic and Lower Jurassic sandstones of the Mecsek Mountains (MT-1, MT-2) and Villány Hills (VT-VII, VT-50, VJ-1) and comparison with the U–Pb age spectra of possible sources. *Grayish* columns indicate age clusters, which present in all samples (*Var.* Variscan, *Ord.* Ordovician, *Cad.* Cadomian) and the Triassic/Jurassic boundary (T/J). Data sources: [1]Blackburn et al. (2013); [2]Compston et al. (1995); [3]Żelaźniewicz et al. (2008); [4]Friedl et al. (2004); [5]Gebauer and Friedl (1994); [6]Košler et al. (2014); [7]Drost et al. (2011); [8]Žák et al. (2011); [9]Janoušek and Gerdes (2003); [10]Gerdes et al. (2003); [11]Horvat et al. (2015a); [12]Horvat et al. (2015b); [13]Klötzli et al. (2004); [14]Koroknai et al. (2010)

Review of the potential source formations and their role: Southwestern Tisza Megaunit

Baksa and Babócsa Metamorphic Complexes

Both polymetamorphic complexes are situated in the Mecsek and Villány Units (Fig. 1a), composed of paragneisses, orthogneisses, mica schists and amphibolites, in case of the Baksa Complex further intercalations (marble, calc-silicate rocks, chlorite schist, eclogite, serpentinized ultramafic lenses) are present (Szederkényi 1998). Gneisses and schists comprise a medium-grade, greenschist to amphibolite facies mineral paragenesis. This basement yielded mostly Variscan mica cooling ages (ca. 275–356 Ma; Lelkes-Felvári and Frank 2006).

The major elements of the studied samples derive from metamorphic rocks, for instance, the deformed quartz varieties, mica schist and gneiss fragments, and the metamorphic index minerals such as staurolite, kyanite, sillimanite, the rounded zircon, and tourmaline. Some orthoclase,

Table 1 Age components (in Ma) of the samples were identified by two different procedures implemented in software DensityPlotter (Vermeesch 2012) and in the PopShare (Dunkl and Székely 2002)

Sample code	Method		Major age components					
			VAR.	ORD.	CAD.			
MT-1	DensityPlotter	**198**	**326**	**459**	**580**	916		2700
	s.e.	1.1	0.4	1	1.5			
	PopShare	**201**	**322**	**444**	**538**	600		2700
	s.d.	15	8	5	69	3		
MT-2	DensityPlotter	**307**		**605**	1034	**1453**	**2009**	
	s.e.	0.9		1.4	3	3.7	8	
	PopShare	**322**		**595**		**1478**	**1899**	
	s.d.	40		65		193	640	
VT-50	DensityPlotter	**345**	**465**	**601**	802			2304
	s.e.	1	0.7	1.3	2.2			
	PopShare	**350**	**458**	**582**		1687		
	s.d.	40	7	103				
VT-VII	DensityPlotter		**430**	**597**	**858**		1980	2676
	s.e.		0.5	0.7	1.8			
	PopShare	329	**450**	**582**	**849**			2366
	s.d.	10	8	69	136			
VJ-1	DensityPlotter	**318**	**449**	600	1021		1952	
	s.e.	0.6	0.7	1.1				
	PopShare	**324**	**444**	542			1934	
	s.d.	14	9	152				

DensityPlotter yields the mean of the age components and indicates the error of the mean (s.e.), while PopShare yields beyond the mean the standard deviation (s.d.) of the age components, thus the presented errors are not comparable.

Bold values indicate when the two procedures resulted in similar mean ages for an isolated component, and it represents more than 5% of the single-grain ages of the sample

VAR Variscan, *ORD* Ordovician, *CAD* Cadomian

microcline, muscovite, biotite, rutile, garnet and monazite can also be originated from metamorphic rocks. Due to the proximity of these basement units to the Mecsek Mountains and Villány Hills (ca. 30–50 km, present-day) and the proper match to the metamorphic mineral assemblages found in our samples we consider these units as a possible dominant source of the studied clastic deposits.

Psunj and Papuk Metamorphic Complexes

The southwesternmost metamorphic units of the Tisza Megaunit are situated in the Slavonian Mountains (Fig. 1a). Two of them, the Psunj and Papuk Metamorphic Complexes represent regionally metamorphosed associations with felsic plutonic intrusions (Balen et al. 2006). The Psunj Complex consists of greenschist facies series (mica schist, chlorite schist) and amphibolite facies rocks like paragneiss, mica schist, amphibolite, metagabbro, marble, locally meta-granodiorite and plagiogranite. The Papuk Complex consists of granitoids and migmatites, amphibolites, paragneisses and mica schists. Gneisses and schists are characterized by low- to high-grade metamorphic index minerals. The oldest phase of medium-grade metamorphism took place in the Ordovician–Silurian (ca. 428–448 Ma), but a Variscan low-grade metamorphic event (ca. 350 Ma) is also detected (Balen et al. 2006; Horváth et al. 2010).

The medium-grade metamorphic mineral assemblage of mica schists and paragneisses is identical to those from the Mészhegy and Somssichhegy Formations. The Ordovician–Silurian and Carboniferous monazite metamorphic ages of the complexes (Horváth et al. 2010) fit well to the detected Ordovician and Variscan zircon U–Pb age component of the studied formations.

Mórágy Granite Complex

This intrusion constitutes the basement of the Mecsek Mountains and extends to the east of them (Fig. 1a). It consists of monzogranite, syenogranite, quartzdiorite, associated with mafic microgranular enclaves and leucocratic dykes (Király 2010). Zircon U–Pb dating on this

K-Mg-rich granitoid assemblage yielded Variscan emplacement age at ca. 337–354 Ma (Klötzli et al. 2004; Koroknai et al. 2010; Fig. 11).

The detected monocrystalline quartz grains, microcline phenocrysts, euhedral zircon, apatite and titanite can be derived from such felsic plutonic rocks. The Carboniferous age of the Mórágy Granite fits well to the Variscan age component of the examined samples. Particularly in case of the Mecsek Mountains, if the sedimentary basin was opened to the north-northeast (Nagy 1968), a derivation of clastic material from the Mórágy Complex would be reasonable. In case of the Villány Hills, if the major source of the metamorphic material were the Slavonian Mountains, then a contribution from the Mórágy Complex is questionable.

Granitoids of the Papuk and Psunj Complexes

Two types of granitoids are present in the crystalline basement of the Slavonian Mountains (Horvat and Buda 2004; Balen et al. 2006). Monzogranite and granodiorite intrusions characterize the Psunj Complex. Granodiorite and plagiogranite intrusions are preserved in the Papuk Complex. Their mineralogical composition closely resembles to the Mórágy Granite (ESM Table 5), but the zircon U–Pb dating yielded Late Devonian intrusion ages at ca. 380 Ma (Horvat et al. 2015a, b; Fig. 11).

The Papuk and Psunj Complexes could be another possible source of the granitoid-related detritus. However, the oldest Early Carboniferous (ca. 350 Ma) age cluster is present only in small amount in the VT-50 sample, which is approximately 30 Myr younger than the age of the Slavonian granitoids. In other samples Early to Late Carboniferous ages present. Thus the contribution from Slavonian plutonites is unsubstantiated.

Low-grade metamorphic series

Traces of Lower Paleozoic sedimentation were found in the Mecsek Unit (Szederkényi 1998) such as Silurian low-grade metapelite–metasandstone series (Szalatnak Slate Formation) are located in the northern Mecsek. Another very low- to low-grade metamorphic occurence is the Devonian Ófalu Formation in the Southern Mecsek, which consists of metapelites, metapsammites, metaconglomerates, metabasic rocks, enclaves of crystalline limestone bodies, amphibolite and serpentinite. Very low-grade metapelites, metapsammites, intercalating marls and tuffs occur in the northern foreland of the Villány Hills as well (Carboniferous–Permian Turony Formation; Jámbor 1998). In the Slavonian domain, the Carboniferous Radlovac Complex (Bisevac et al. 2013) overlying the Psunj Complex consists of very-low to low-grade metamorphic series of metapelites, metapsammites and metaconglomerates, associated with metadiabase and metagabbro bodies.

A part of the low-grade metapelitic rock fragments as well as tourmaline and rutile detected in the examined sediments can be associated with these metamorphic formations. In case of the Villány Hills, if the dominant source is the Slavonian medium-grade metamorphic series, a contribution from the Radlovac Complex is likely.

Ultramafic bodies in the metamorphic Complexes

Serpentinites or partly serpentinized ultramafic bodies are preserved in the Paleozoic basement of the western and eastern part of the Mecsek Mountains and between the Mecsek Mountains and Villány Hills (Szederkényi 1998). Similar serpentinites with relics of peridotite occur in the Papuk Complex (Pamić et al. 2002).

The occurence of serpentinite fragments (detected in the Karolinavölgy Sandstone by Nagy et al. 2008) and chromite grains (this study) may suggest the presence of ultramafic rocks exposed in the provenance area. Detrital chrome spinel or chromite grains, however, might be recycled from older siliciclstic units (e.g. von Eynatten 2003).

Felsic volcanic occurrences

Extended occurence of Permian felsic volcanic formations is known from the basement both of the Mecsek Mountains and the area between the Mecsek and Villány Hills (Barabás and Barabás-Stuhl 1998). The Lower Permian Gyűrűfű Rhyolite Formation is composed of mostly broken quartz and feldspar phenocrysts and opaque pseudomorphs after biotite, while the overlying Cserdi Formation is interpreted as volcanoclastic deposit mostly from felsic volcanic lithic fragments (Hidasi et al. 2015).

The felsic volcanic rock fragments detected in our samples and the resorbed monocrystalline quartz grains of the Mészhegy Sandstone most likely derive from the Gyűrűfű and Cserdi Formations.

Upper Paleozoic–Lower Mesozoic siliciclastics

The crystalline basement of the SW Tisza Megaunit remained subaerially exposed for a long time and was the major source for the Late Paleozoic–Early Mesozoic clastic sedimentation (Bérczi-Makk et al. 2004). The thick siliciclastic sequence of the Mecsek–Villány area is composed of mostly granitoid, metamorphic and felsic volcanic fragments. In case of these clastic sediments, any detailed heavy mineral study is accessible. However, petrographical studies suggest that the heavy mineral spectra of these formations should be rather mature than complex (ESM Table 5).

In case of the Mészhegy and Somssichegy Formations, resedimentation of older siliciclastics is not supported exclusively due to the much broader range of detrital accessory minerals found in the examined samples. Based on the mostly euhedral shape of accessory minerals in the Karolinavölgy Sandstone resedimentation of older siliciclastic series is considered negligible.

Review of the potential source formations and their role: autochthonous European terranes

The Tisza Megaunit formed a part of the European Plate but its exact position in the Late Triassic is disputed. According to existing paleogeographical reconstructions (Csontos and Vörös 2004; Haas and Péró 2004; Götz and Török 2008; Szulc 2000; Tari 2015), the Mecsek–Villány Units were situated south, east or maybe west of the Bohemian Massif, which behaved as an elevated regional basement high since the beginning of the Mesozoic (Szulc 2000). Thus the Bohemian Massif could also contribute to the Triassic clastic sediments of Mecsek and Villány. Similarly, east of the Bohemian Massif, the Małopolska and Lysogóry Massifs could have been situated in the proximity of the Tisza Megaunit and could have provided material. Without providing an exhaustive list, we briefly summarize the most important potential European source areas and their relevant geochronological data.

Southern Bohemian Massif

The Moldanubian Zone is a nappe complex including Proterozoic basement fragments (Klomínský et al. 2010). The lowermost part of the polymetamorphic basement sequence is the granitic or granodioritic–tonalitic Dobra Orthogneiss with a Mesoproterozoic protolith age at ca. 1.3 Ga (Gebauer and Friedl 1994; Fig. 11), while the granodioritic to quartz dioritic Spitz Orthogneiss yielded Neoproterozoic ages at ca. 610 Ma (Friedl et al. 2004; Fig. 11). Lower to Mid-Paleozoic metasediments are widespread, the Monotonous Series composed of paragneisses and leucocratic orthogneisses, the Variegated Series composed of paragneisses, orthogneisses, intercalating metaquartzites, graphite schists, marbles and amphibolites, and the high-grade metamorphic Gföhl Unit comprises granitoids, peraluminous orthogneisses, granulites, eclogites, pyroxenites and serpentinized garnet-peridotites (Friedl et al. 2004; Finger et al. 2007). Zircon U–Pb dating of metasediments resulted in Neoproterozoic and Paleoproterozoic age maxima and sparse Neo- and Mesoarchean ages (Košler et al. 2014; Fig. 11). In the Moldanubian Zone abundant Lower Carboniferous plutons occur (e.g. the South Bohemian Batholith at ca. 300–330 Ma; Gerdes et al. 2003), moreover, along the suture of the Moldanubian and the Teplá-Barrandian Zone, Late Devonian (ca. 375 Ma) plutons were preserved (Klomínský et al. 2010; Žák et al. 2011; Fig. 11). Post-Variscan flysch sedimentation produced a Carboniferous and Permian local sedimentary cover (Nehyba et al. 2012).

Proterozoic zircon U–Pb ages (ca. 1, 1.5 and 2 Ga), which dominate a sample of the Karolinavölgy Sandstone (MT-2) and occur sparsely in all samples, are possibly related to old cratonic fragments and metasediments exposed in the Bohemian Massif. The Neoproterozoic age of granitoids and associated rocks resembles the slightly diffuse Cadomian peak discovered in all formations. The higher metamorphic grade of the Early-Mid-Paleozoic sequence and the scarce medium-grade mineral paragenesis contradicts a possible relation to the medium-grade mineral association of Villány. The basements of the Bohemian Massif and the SW Tisza Megaunit show very similar composition in several aspects, e.g. Variscan potassium feldspar-rich durbachites (ca. 335–340 Ma; e.g. von Raumer et al. 2014) are very similar to the Variscan Mórágy Granite. The Carboniferous age of granitoids of the Southern Bohemian Massif fits the significant age element of the samples of the Karolinavölgy and Somssichhegy Formations, and also occurs in the samples of the Mészhegy Sandstone in traces. However, clastic material derived from the Bohemian plutons or from the Mórágy Granite cannot be distinguished without further isotopic and geochemical investigations. The euhedral shape of many granitoid-related accessory minerals such as zircon and apatite contradicts transport from the distal Bohemian Massif compared to the more proximal Mórágy Complex.

Central Bohemian Massif

The Teplá-Barrandian Unit consists of unmetamorphosed or low-grade Late Neoproterozoic and Early Cambrian to Middle Devonian volcano-sedimentary (mostly siliciclastic) assemblage, indicating almost similar ages of protoliths to the Moldanubian metasediments (Drost et al. 2011; Košler et al. 2014; Fig. 11). Plutonic rocks occur subordinately and were emplaced during Late Devonian (ca. 375 Ma) and Variscan (ca. 350 Ma, Central Bohemian Composite Batholith at the boundary of the Teplá-Barrandian and Moldanubian Zones) magmatic events (Janoušek and Gerdes 2003; Žák et al. 2011; Fig. 11). In the western part of this unit, between the high-grade metamorphic units of the Moldanubian and Saxothuringian Zones, medium-grade (greenschist to amphibolite facies) Ediacaran–Cambrian metasedimentary rocks are preserved, which were overprinted by Cadomian and Variscan regional metamorphic events (Timmermann et al. 2006).

The medium-grade mineral paragenesis of metasedimentary rocks in the western part of this unit is similar to the composition of the studied samples of Villány. Their Variscan metamorphic age excludes this source based on the prominent Ordovician age of the suggested metamorphic protolith. However, the Early Carboniferous age (ca. 350 Ma) of the Central Bohemian Composite Batholith is similar to the minor youngest age cluster of one sample of Villány (VT-50).

Eastern Bohemian Massif

In the Brunovistulian Block and Moravo-Silesian Zone Neoproterozoic (ca. 565–595 Ma) granitoids, ophiolites and associated orthogneisses, metabasites and metasediments are preserved mostly without Variscan metamorphic overprint (Schulmann et al. 2005; Friedl et al. 2004; Fig. 11). Weakly metamorphosed Silurian to Devonian metasediments are preserved, which derived mainly from the local Cadomian granitoids (Košler et al. 2014; Kröner et al. 2000; Schulmann et al. 2005). Traces of Silurian magmatic activity (ca. 430 Ma) were discovered as lenticular bodies of granites intruding into the Cadomian granitoids (Leichmann et al. 2013). Permo-Carboniferous flysch deposits also occur in the area (Nehyba et al. 2012). At the boundary of the Moldanubian and Moravo-Silesian Zones Ediacaran rocks suffered Variscan metamorphism. This amphibolite facies metamorphic sequence (staurolite–sillimanite zone decreasing to chlorite zone) is composed of various granitic orthogneisses, metapelites and calc-silicate rocks locally associated with high-grade granulite and eclogite remnants and partly anatectic amphibolite (Kröner et al. 2000; Schulmann et al. 2005; Štípská et al. 2015).

Cadomian rocks could have contributed material to the study area. The marginal medium-grade metamorphic sequence of the suture zone of the Moravo-Silesian and Moldanubian Zones is most closely comparable to the heavy mineral and U–Pb age spectra of the siliciclastics of Villány. However, this marginal domain in the west was reset by Variscan metamorphism, what excludes contribution to the Villány deposits, for which primarily Ordovician metamorphic protoliths supplied material.

Małopolska and Lysogóry Massifs

The basement of the Małopolska Massif comprises Ediacaran–Cambrian low-grade metapelites presumably linked to the Cadomian active continental margin (Belka et al. 2000; Compston et al. 1995; Żelaźniewicz et al. 2009; Fig. 11). It is overlain by Ordovician to Carboniferous clastic and carbonate rocks, which characterize the Lysogóry Massif as well. Granodiorite occurence was described in the Małopolska Massif, which yielded a Carboniferous/Permian age at ca. 300 Ma (Żelaźniewicz et al. 2008; Fig. 11).

Only a part of the Neoproterozoic ages fit to the age components identified in the studied sandstone samples; those could principally derive from these basement units.

Implications on the Triassic provenance

In case of the Carnian Mészhegy Sandstone of the Villány Unit, the most common metamorphic minerals and rock fragments and the most frequent Ordovician zircon U–Pb ages indicate the dominance of Ordovician metamorphic rocks in the source area. Since the average mineralogical composition and maturity of the Pliensbachian Somssichhegy Limestone remained similar to that of the Mészhegy Sandstone, both exposed in the Villány Hills, the same source area is suggested for these two formations. The moderate maturity of the sediment, the abundant angular clastic components and the complex but rather uniform heavy mineral spectra across all samples suggest that the source area was located relatively close and it has remained largely unchanged during the entire sedimentation period. The broad range of metamorphic index minerals and rock fragments indicates a primary source of metamorphic rocks, because older siliciclastics of the Tisza Megaunit do not comprise such a diverse metamorphic mineral assemblage as the studied samples. Distal source areas like the Southwestern or the Southeastern Bohemian Massif could not have provided the medium-grade metamorphic debris of similar metamorphic mineral content due to the contradictory Variscan age of the Barrovian-type metamorphism of metasedimentary and associated rocks (Štípská et al. 2015; Timmermann et al. 2006). The only evidence of separate Ordovician and Variscan metamorphic phases along with a medium-grade metamorphic mineral paragenesis was described from the Psunj Complex (Balen et al. 2006; Horváth et al. 2010). Here Late Devonian plutons are preserved but the traces of Variscan and Cadomian magmatic activity are missing. Thus we assume that the Cadomian and Proterozoic zircons originate from the recycling of older sedimentary rocks. A metamorphic sequence similar to the Slavonian basement in several aspects like the dominant rock types and the metamorphic grade are the Baksa and Babócsa Complexes. However, the scarcity of U–Pb age data from the Baksa and Babócsa Complexes hampers further comparison. On the other hand, transport direction in the Villány Upper Triassic cannot be determined due to tectonic overprint, which hinders the reconstruction of the position of the source area.

We conclude that the clastic material of the Mészhegy Sandstone was derived from inside the Tisza Megaunit; however, it remains unconstrained where exactly the polymetamorphic basement was exhumed. Today the Slavonian Mountains are located close (ca. 30–50 km) to the southwest of the Villány Hills (Fig. 1a). The Upper Paleozoic and

Lower Mesozoic sedimentary cover is poorly preserved, areally restricted, and the depositional environment considered to be more seaward than the Mecsek and Villány Units (Bleahu et al. 1994). In the Mecsek and Villány Units, paleogeographic reconstructions highlight that Upper Paleozoic molasse sediments were deposited in local basins, while the overlying Lower Triassic siliciclastics and Middle Triassic shallow marine carbonates represent an overstep sequence. The latter were distributed over the entire Tisza Megaunit including the Mecsek, Villány and Slavonian Mountains (Bleahu et al. 1994). Thus exposure of the crystalline basement would require tectonic differentiation of the region. Vertical movements along faults between the Mecsek and Villány Units have been suggested for the Anisian (Konrád 1998), for the Late Triassic (Császár et al. 2013) and for the Jurassic (Vörös 2012). Exhumation of the Slavonian Mountains or nearby crystalline basement would mean considerable vertical displacement within the Villány Unit. Although this idea is not in accord with the traditional views on the Mesozoic evolution of the area, it is tectonically possible and should therefore not be discarded but requires further consideration.

In case of the Upper Triassic Karolinavölgy Sandstone, the dominant euhedral zircon varieties and the abundant feldspar assemblage including potassium feldspar and plagioclase grains call for derivation from felsic igneous rocks. Further contribution from metamorphic and clastic sedimentary rocks is evident. Based on its composition the detritus was sourced either from the proximal igneous (Mórágy Complex), metamorphic (Babócsa Complex) and Upper Paleozoic–Early Mesozoic sedimentary sequences, or even from the more distant units of the Bohemian Massif, where very similar rock types occur. The dominance of ultrastable minerals and their frequent euhedral shape suggest a relatively short transport distance. Petrological and geochronological data show that the clastic material is dominated by Variscan granitoid debris. Variscan plutons are common in the Southern Bohemian Massif (Moldanubian Zone), thus the derivation from that area is possible. The higher frequency of the Neoproterozoic and Cadomian zircon U–Pb ages, which are characteristic for the Moldanubian basement as well, further confirm the possible contribution. The abundance of ultrastable minerals and the absence of less resistant felsic igneous particles (against mechanical and chemical breakdown; Mange and Maurer 1992), e.g. amphibole or titanite suggest a derivation from distal source area as the Southern Bohemian Massif. In contrast, based on the prevailing abundance of the Variscan igneous components, a provenance from the Cadomian basement of the Eastern Bohemian Massif (Brunovistulian Block and Moravo-Silesian Zone) and the Małopolska and Lysogóry Massifs, where Variscan plutons are completely missing, could be excluded. Based on these considerations, the Tisza Megaunit was not situated east of the Bohemian Massif during the Triassic as some paleogeographical reconstructions (Götz and Török 2008; Szulc 2000) suggested. In contrast, the Southern or Southwestern Bohemian Massif, i.e. the Moldanubian Zone could have acted as the source area. At a more regional scale, since Late Permian, rifting processes were active between Gondwana and Laurasia that finally opened the Tethyan ocean basins. The rifting started in the Permian, and progressed rapidly in the easternmost Tethyan areas with the rapid northward drift of the Cimmerian continent and with the active Triassic seafloor spreading that opened the Neotethys Ocean. The rifting expanded westward during the Triassic–Jurassic and generated continental rift basins. During the Jurassic, it was followed by the detachment of microplates (e.g. the "Mesomediterranean Microplate") from the main Europe and Africa plates, and by the opening of wide continental margins and narrow oceanic basins that characterize the Western Tethys region (Perrone et al. 2006; Critelli et al. 2008; Perri et al. 2011, 2013). Despite the different source areas, sandstones of both continental margins have quite similar compositional signatures (present study for European margin and Critelli et al. 2008; Perri et al. 2011, 2013 for the western continental margin).

Late Triassic volcanic contribution

The MT-1 sample contains seven zircon grains around 200 Ma, which are obviously younger than the age range of the widespread Carboniferous–Permian igneous activity. Although the number of grains is small, they are concordant, they cluster well and both component identification algorithms recognized them (Table 1). This magmatic activity might reflect precursors of the Early Jurassic volcanic ashes that are well preserved as tuff intercalations in the coal-bearing clastic sedimentary sequence of the Mecsek Mountains (Lower Jurassic Mecsek Coal Formation, which overlies the Upper Triassic Karolinavölgy Sandstone) (Némedi Varga 1998). The ongoing study of G. Tari (personal communication, 2016) indicates also an age component around 200 Ma in the region. The origin of these zircons can be related to the contemporaneous Central Atlantic magmatic activity (e.g. Blackburn et al. 2013). Although it produced mostly zircon-free mafic lithologies, in some formations zircons are present, which allowed the precise U–Pb dating of this event at ca. 201 Ma (e.g. Blackburn et al. 2013; Fig. 11).

Conclusions

- Distinct dissimilarities occur in the mineralogy and zircon age distribution of the Upper Triassic–Lower Jurassic siliciclastic strata of the Mecsek and Villány Units. The framework composition, the heavy mineral composition and the detrital zircon age components indicate that the major sources were greenschist to amphibolite facies metamorphic rocks for the Villány Hills and granitoid rocks for the Mecsek Mountains.

- The Upper Triassic clastic sequence of the Mecsek Mountains was derived from Cadomian and Variscan igneous and metamorphic rocks, and older siliciclastics contributed material as well. Its major source area was probably the adjacent igneous Mórágy Complex, the metamorphic Babócsa Complex and Upper Paleozoic/Lower Mesozoic clastic sequences, but more distant units of the Bohemian Massif may have also contributed to the sediment supply.
- The Upper Triassic clastic sequence of the Mecsek Mountains contains diluted traces of synsedimentary volcanic activity. These ca. 200 Ma old zircon crystals may indicate the first eruptions of the already well documented earliest Jurassic distal extensions of the Central Atlantic volcanism.
- There is no significant change in the bulk composition from the Carnian Mészhegy to the Pliensbachian Somssichhegy Formations in the Villány Hills; both are sourced mainly from Ordovician medium-grade metamorphic rocks, subordinately from Upper Paleozoic/Lower Mesozoic volcanic and sedimentary assemblages. Greenschist to amphibolite facies polymetamorphic rocks of Ordovician and Variscan age occur in the adjacent basement of the Slavonian Mountains, which could have contributed source material. Derivation from the Baksa and Babócsa Complexes can neither be supported nor neglected because of the absence of U–Pb ages. Exposure of the Slavonian Mountains would mean tectonic differentiation of the Villány Unit in the Late Triassic.
- Our results do not support that the original location for the Tisza Megaunit was east of the Bohemian Massif. In contrast, they suggest a connection to the Southern/Southwestern Bohemian Massif.

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