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# Tectonic discrimination of siliciclastic sedimentary record of the northern Tethyan margin at the end of the Triassic

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Tectonic setting of both the uppermost Triassic Tomanová and the lowermost Jurassic Dudziniec formations can be characterized by a series of diagnostic discrimination diagrams. High-silica and low-silica multi-dimensional diagrams indicate that the sediments could have been deposited in the continental collision/rift setting. Diagrams of $K_2O/Na_2O$ *versus* $SiO_2$, $SiO_2/Al_2O_3$ *versus* $K_2O/Na_2O$ and Th-Co-Zr/10 as well as Th-Sc-Zr/10 determine an origin from the tectonically active and/or passive continental margin setting. REE parameters indicate predominantly a passive margin tectonic setting of the sediments. The most probable source of clastic admixture in the Scythian to Domerian sediments in the Tatric Unit was situated in a remnant of the Variscan collisional orogen – the Vindelician Highlands. Occasional monsoonal rains occurring in orbitally controlled cycles transported weathered material from the source area down river valleys on the seaward slopes of the Variscan Vindelician Mountains towards the Tethyan Sea. The input of this material influenced also the marginal parts of the Fatricum (e.g., Vysoká or Havran units).

Key words: sedimentology, geodynamics, major and trace elements, palaeogeography.

## INTRODUCTION

**Geographical setting**. The area under study, where the Tomanová Formation crops out on the surface, lies in the Tatra Mountains on both sides of the Slovakia/Poland state border (Jach et al., 2014). The most famous localities are situated in the Tomanová Valley (Červený Úplaz ravine under Goryczkowa Mt. – N 49°266'296", E 19°947'626") (see Michalík et al., 1976) and in the Czerwone Wierchy Mts. (Tomaniarski Twardy Uplaz, Czerwone Żlebki; Fig. 1).

**Geological setting**. The tectonostratigraphic Tomanová Unit is a part of the post-Variscan sedimentary cover of the Tatric Superunit in the Central Western Carpathians (Fig. 2). This cover has been partially detached from its crystalline (mostly granitic) fundament and folded into several folds and digitations. The Tomanová Unit represents one of the deeper structures and used to be considered a para-autochthonous or even an "autochthonous" unit by former authors.

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**Previous studies**. The "Tomanowa beds" have been defined by Raciborski (1890) as a complex of variegated and black fine clastic sediments with abundant palustrine flora, forming a characteristic Upper Triassic member in the homonymous tectonostratigraphic unit. Uhlig (1897) parallelized the lower part of this complex with the Carpathian Keuper and the upper part with the Liassic Gresten Beds. Kotański (1959) considered the Tomanová "beds" to be of Late Norian to Early Rhaetian age. Radwański (1968) regarded them as Rhaetian marine deposits. Michalík et al. (1976, 1988) confirmed the lacustrine/palustrine character of the Tomanová Formation by findings of three dinosaur footprints and by the character of an accompanying plant association. Niedźwiedzki (2011) found several other dinosaur footprints on the Polish side of the High Tatra Mts.

**Rock record**. The Upper Triassic sequence in the Tatric Superunit of the Central Western Carpathians consists mostly of clastic rocks (Michalík, 1994). The Rhaetian Tomanová Formation overlying the Norian Carpathian Keuper in the Červený Úplaz section is built of a cyclic parasequence of argillites and sandstones. Quartz, kaolinite and 2:1 Al dioctahedral phyllosilicates represent the major, slightly diagenetically altered mineral phases. The kaolinite/dioctahedral 2:1 ratio decreasing upward the section (from 4.3 to 0.5) signalizes variability in the weathering/erosion intensity and changing water salinity. The overlying Jurassic sequence starts with the marine Dudziniec

Formation. It consists of sandy limestones to calcareous sandstones (Lintnerová et al., 2013).

**Geochemistry**. Major and trace element (LILE, HFSE, REE) composition of sediment supposes an uniform source composed of felsic rocks (Lintnerová et al., 2013). U, V and Eu were mobilized by oxygen reduced conditions, and the high Fe content resulted in a formation of siderite and berthierine. The C isotope composition indicates a continental character of the organic matter. The relative decrease in $\delta^{13}C_{org}$ values in the Dudziniec Formation carbonates indicates a marine type of organic matter and, in principle, it documents marine transgression (Lintnerová et al., 2013).

**Sedimentology**. The mineralogical maturity of clastic grains has been reached by long and strong chemical weathering of felsic rocks. Kaolinite crusts of the intensely weathered elevated areas were eroded and transported down the river valleys into the basin as supported by lithofacies, mineral homogeneity of sediments, and by their chemical properties. The ratio of kaolinite to dioctahedral 2:1 phyllosilicates in argillite points to changes in erosion intensity and physical differentiation during sedimentation. An event character of sandstone layers containing mixed aeolian and fluvial quartz grains is underlined by the textural immaturity of sediment particles (Lintnerová et al., 2013).

**Environment and palaeoclimate**. Alternation of dry and humid periods was attested by the sedimentary textures and by the maturity of quartz (aeolian *versus* fluvial) grains, content of organic matter and its character ($C_{org}$ and $\delta^{13}C_{org}$). Shales with a high kaolinite content (2:1 phyllosilicates ± chlorite) are typical of the Rhaetian pluvialized climate (Michalík et al., 2010) com-

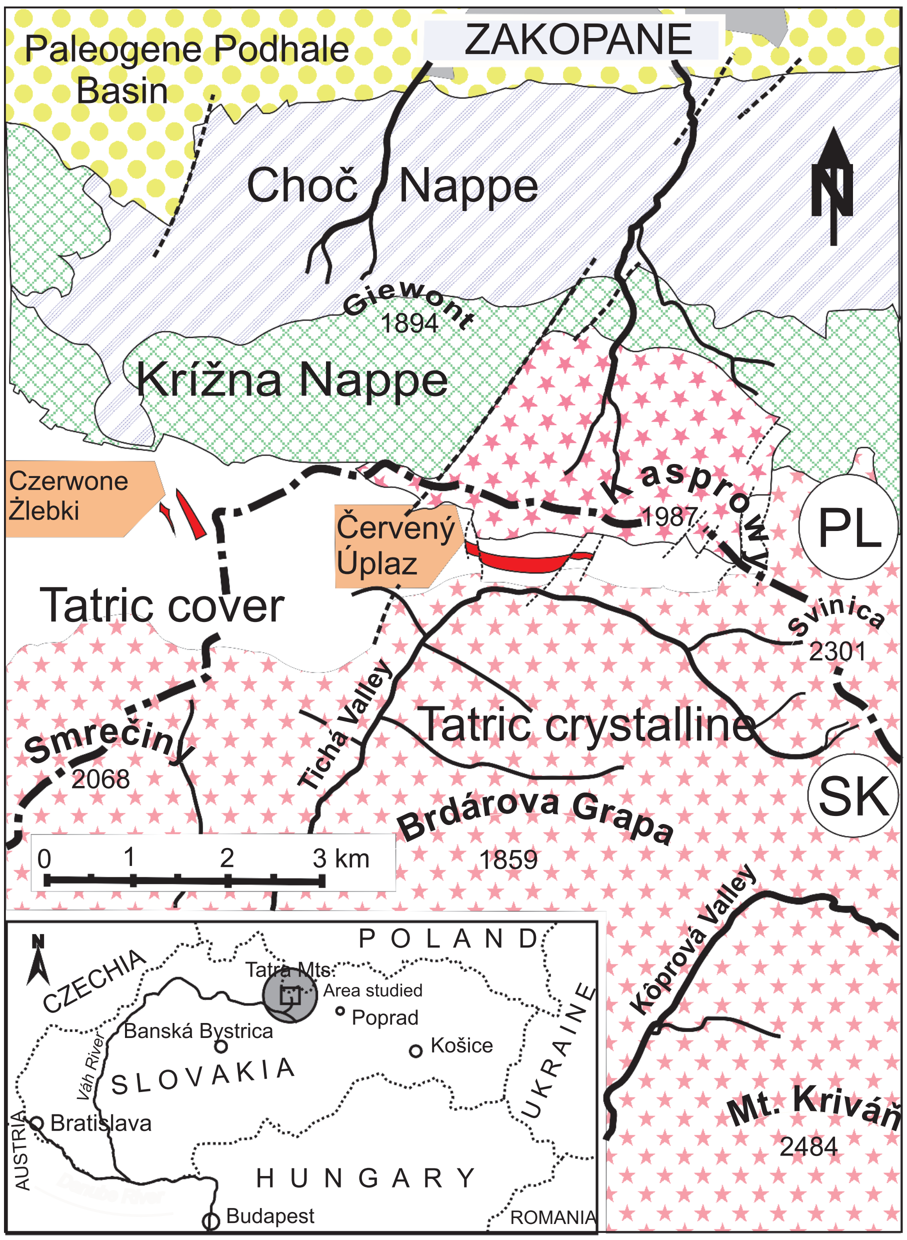


**Fig. 1. Geographical location (lower left corner) and geological situation of the central part of the Tatra Mts., with indication of outcrops of the Tomanová and Dudziniec formations (red areas), which are situated along both sides of the Slovak-Polish border line (after Bezák et al., 2011, adapted)**

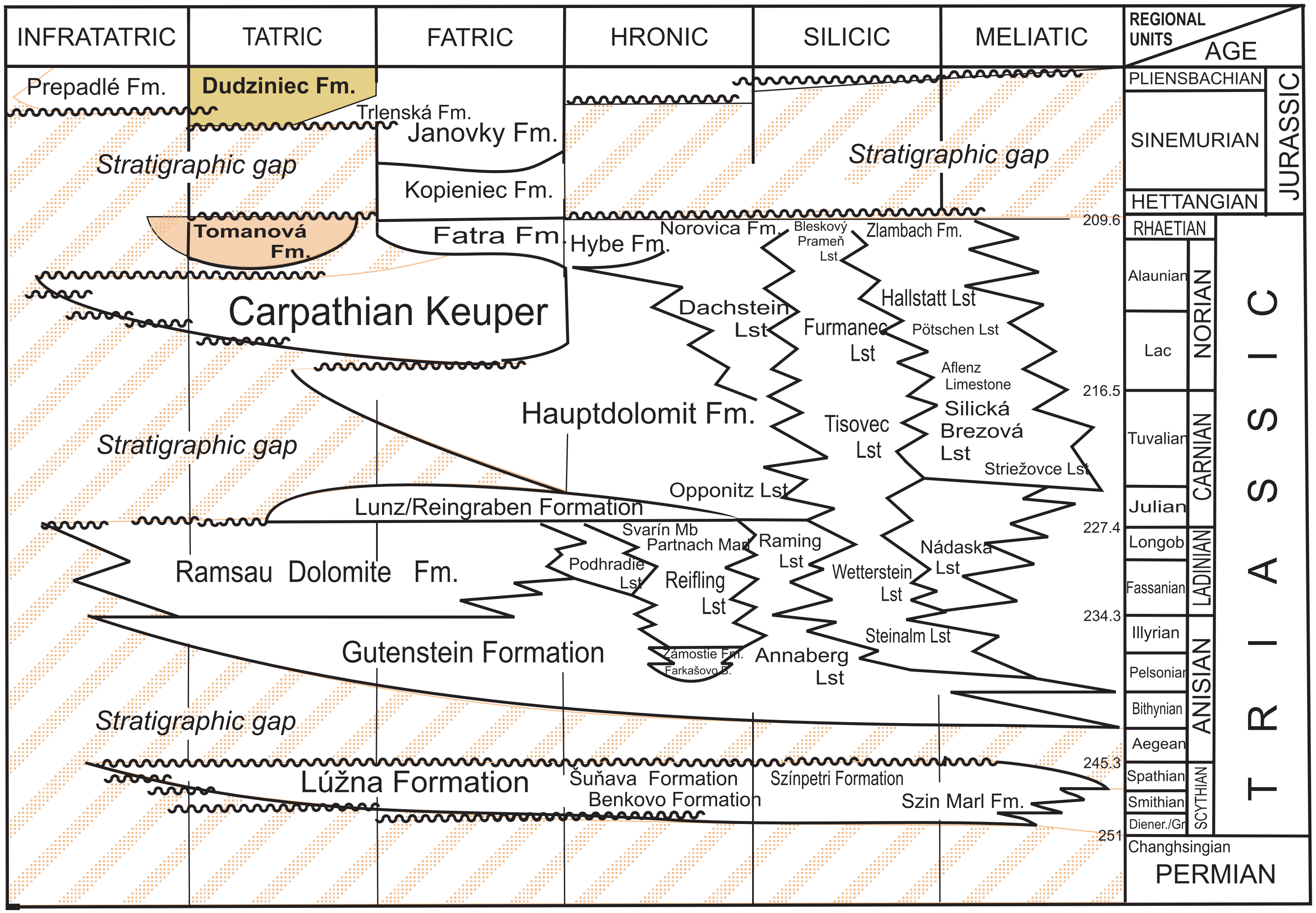


**Fig. 2. Schematic Triassic-lowermost Jurassic lithostratigraphic table of the Central Western Carpathians, with indication of the Tomanová and Dudziniec formations**

Stratigraphic gaps are marked by diagonal hatching (after Michalík, 2003, adapted) parable to conditions governing the entire European continent (Norian-Hettangian kaolinization period). Authigenic siderite or berthierine in the upper part of the Tomanová Formation may also indicate wet (or even brackish) and reducing conditions. The sedimentary rate (83 mm/ky according to the cyclostratigraphic analysis) has been determined by the quantity of precipitations. The production and decay of organic matter were controlled by humidity (Michalík et al., 2007, 2010). The palaeosol formation, transport of eroded material, and enhancement of bioproductivity in a limnic basin were evoked by periodical climatic changes – "megamonsoons" coming from the Tethyan Domain in probably 400-ky-long eccentricity cycles (Lintnerová et al., 2013).

The sedimentary rate of the Hettangian Dudziniec Formation attained 25 mm/ky, and the fining-upward parasequences preserved in the sequence are similar to those of the Tomanová Formation (Lintnerová et al., 2013). However, quite different mineralogy of clays, recycled character of silicates, raised calcite detritus, and carbonate $\delta^{18}O$ (from –9 to –11‰ PDB) and $\delta^{13}C$ (from –25 to –28‰ PDB) values document meteoric re-equilibration within the parasequences. Gradual stabilization of marine biota is recorded by the vertical distribution and environmental significance of benthic foraminifera. Involutinids and spirillinids dominate in the lower part of the Dudziniec Formation, endothyrinids govern its middle part, and nodosariids and *Ammodiscus*-type microfauna occur in the upper part (Lintnerová et al., 2013).

**Palaeogeography and palaeotectonics**. Sandy and argillaceous material of the Tomanová Formation was originated by mechanical and chemical weathering of the Vindelician Highlands. Monsoonal winds coming from the Tethys had been losing their water content above the seaward slopes of these old mountains until they came to the dry Mid-European Basin (Feist-Burkhardt et al., 2008). These slopes were cut by occasional river valleys (Berra et al., 2010). The gradual sea level rise in the Tatric Zone was triggered by the thermal expansion of the Central Atlantic Rift, being also affected by the input of terrestrial clastics via fresh water and wind (Lintnerová et al., 2013).

## METHODS

Nine shale samples from the Tomanová Formation as well as two calcareous sandstone and two sandy limestone samples from the Dudziniec Formation (all obtained from and described in Lintnerová et al., 2013) were analysed for major and trace elements at the Acme Analytical Laboratories (Vancouver) Ltd in Canada. Geochemical analyses were carried out for whole rocks without extracting the clay fraction. Two instrumentation techniques, inductively coupled plasma optical emission spectrometry and mass spectrometry (ICP-OES/MS), were used for the geochemical analyses. The analytical procedures were described in detail by Lintnerová et al. (2013) and are briefly summarized below. The pulverized rock samples were mixed with $LiBO_2/Li_2B_4O_7$ flux. Later, crucibles were fused in a furnace. The cooled beads were then dissolved in ACS grade nitric acid. Finally, these beads were analysed by ICP-OES/MS.

In this study, the major and trace element data from the studied sediments (Table 1) were used to infer the tectonic setting of the sedimentary basin with the help of various diagnostic diagrams proposed by Roser and Korsch (1986), Bhatia and Crook (1986), Verma and Armstrong-Altrin (2013). To apply the multi-dimensional tectonic discrimination diagrams of Verma and Armstrong-Altrin (2013), the DF1 and DF2 function coordinates for the samples were calculated from the respective equations. However, the chemical data were first adjusted to 100% on an anhydrous (LOI-free) basis.

In order to further determine the tectonic setting of the sediments, their most characteristic rare earth element (REE) parameters were compared with those of greywackes of a known tectonic setting (Bhatia, 1985). The sum of all REE determined (La–Lu) is denoted by ΣREE. The ΣLREE/ΣHREE is the ratio of the sum of light REE (La–Sm) to the sum of heavy REE (Gd–Yb). The La/Yb ratio is an index of the enrichment of LREE over HREE, and it is called $La_N/Yb_N$ when expressed as the chondrite-normalized ratio. Chondrite values were taken from Boynton (1984), since this type of chondrite is one of the most commonly used in sedimentary rocks. The value of Eu/Eu* represents the ratio of actual normalized Eu to interpolated normalized Eu for no depletion or enrichment.

Original bulk rock chemical analyses of the samples studied and basic characteristics of their chemical composition were provided by Lintnerová et al. (2013). In addition, chemistry was used as the proxy of source rock weathering, reworking, provenance and sedimentary and climatic conditions. In this paper, we evaluated the same geochemical data to complement and extend the above-mentioned study. New, compared to our previous contribution, was the use of the set of the aforementioned analyses for tectonic discrimination of the source area of clastics. Thus, the present study contributes to the interpretation of geodynamic pattern of the whole northern Tethyan shore.

## MINERAL COMPOSITION AND BURIAL HISTORY OF THE SEDIMENTS

The quantitative mineral composition of the studied sediments was interpreted from XRD patterns by Lintnerová et al. (2013). The major mineral phases in the Tomanová samples were represented by quartz (15–70%), kaolinite (13–46%) and 2:1 Al dioctahedral phyllosilicates (5–39%). The fourth mineral phase included berthierine and probably Fe-chlorite (3–14%). Interestingly, siderite was the dominant phase in sample CU13R (39%), accompanied by other Fe minerals, goethite (11%) and hematite (4%). Goethite was also recorded in other samples, but typically in amounts lower than 2%. Likewise, biotite and K-feldspar were identified in the majority of samples, but their contents did not exceed 3%. Albite, oligoclase, dolomite, anatase, rutile and ilmenite occurred only in trace amounts (<1%). The major mineral phases in the Dudziniec samples were represented by quartz (14–71%) and 2:1 dioctahedral phyllosilicates (3–14%). These samples were also enriched in calcite (24–79%), while chlorite (0–4%) and kaolinite (1%) were determined only in trace amounts.

It is well known that assemblages of clay minerals can elucidate burial history of sediments. The most important phenomenon of burial history of shales includes continuous illitization of smectite *via* intermediate mixed-layer illite-smectite (Kisch, 1983). Although Lintnerová et al. (2013) identified illitic illite--smectite in the samples from the Tomanová Formation, which could be a stage of illitization resulting from a burial temperature of about 180–200°C (Pollastro, 1993), they excluded the possibility that the sediments experienced late diagenesis. Their argumentation was based on the presence of berthierine which is a typical mineral of very early diagenesis, since it is transformed to chamosite at temperatures over 70°C (Hornibrook and Longstaffe, 1996). Moreover, the common presence of disordered kaolinite and the occurrence of detrital illite-smectite and chlorite in the studied samples are strong indications that the rocks were not markedly transformed after deposition. Finally,

Table 1

**ICP-determined major and some trace element abundances for sediments of the Tomanová and Dudziniec formations**

| Sample | CU1 | CU3 | CU5 | CU7 | CU10 A | CU13 | CU13R | CU13 R1 | CU15 | CU37 | CU40 | CU44 | CU55 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Major elements [wt.%] | | | | | | | | | | | | | |
| $SiO_2$ | 57.24 | 62.94 | 56.33 | 54.73 | 58.61 | 63.02 | 23.77 | 43.12 | 51.5 | 75.55 | 20.71 | 70.74 | 63.54 |
| $TiO_2$ | 1.28 | 1.6 | 1.14 | 1.39 | 1.46 | 1.18 | 0.42 | 0.82 | 0.89 | 0.12 | 0.13 | 0.15 | 0.82 |
| $Al_2O_3$ | 25.94 | 23.3 | 19.5 | 26.2 | 21.55 | 21.82 | 7.13 | 13.33 | 25.75 | 2.29 | 2.37 | 2.15 | 11.67 |
| $Fe_2O_3$ | 2.08 | 1.07 | 2.95 | 4.06 | 6.44 | 2.56 | 48.31 | 24.3 | 5.65 | 1.42 | 1.14 | 1.02 | 2.35 |
| MnO | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.51 | 0.18 | 0.01 | 0.08 | 0.1 | 0.03 | 0.03 |
| MgO | 0.49 | 0.38 | 0.23 | 0.65 | 0.65 | 0.75 | 0.98 | 1.92 | 0.81 | 0.15 | 0.73 | 0.22 | 0.98 |
| CaO | 0.05 | 0.1 | 0.03 | 0.19 | 0.09 | 0.13 | 0.19 | 0.77 | 0.32 | 10.79 | 39.55 | 13.41 | 7.66 |
| $Na_2O$ | 0.26 | 0.31 | 0.21 | 0.4 | 0.27 | 0.25 | 0.01 | 0.05 | 0.45 | 0.05 | 0.04 | 0.03 | 0.1 |
| $K_2O$ | 1.32 | 0.63 | 0.78 | 1.21 | 0.93 | 0.89 | 0.21 | 0.41 | 2.83 | 0.43 | 0.7 | 0.54 | 3.24 |
| $P_2O_5$ | 0.03 | 0.03 | 0.04 | 0.04 | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.01 | 0.03 | 0.02 | 0.07 |
| LOI | 11.2 | 9.5 | 18.6 | 11 | 9.8 | 9.2 | 18.4 | 15.9 | 11.6 | 9.1 | 34.4 | 11.6 | 9.3 |
| Trace elements [ppm] | | | | | | | | | | | | | |
| Co | 8.7 | 8.8 | 2.7 | 8.7 | 26.7 | 11.5 | 25.3 | 18.3 | 11.8 | 1.2 | 1.8 | 2.3 | 7.4 |
| Sc | 20 | 18 | 17 | 21 | 20 | 16 | 11 | 20 | 7 | 1 | 2 | 2 | 8 |
| Th | 22.5 | 24.5 | 18.7 | 25.9 | 32.7 | 24.5 | 8.8 | 17 | 14.7 | 3.2 | 4.5 | 5.9 | 16.1 |
| Zr | 245 | 460 | 357 | 207 | 297 | 411 | 180 | 363 | 120 | 99 | 164 | 252 | 730 |
| Rare earth elements [ppm] | | | | | | | | | | | | | |
| La | 48.9 | 41.5 | 70.8 | 88.1 | 71.8 | 34.7 | 18 | 23.5 | 39.5 | 8.5 | 13.7 | 16.5 | 45.4 |
| Ce | 102.6 | 96.2 | 154.2 | 165.5 | 187 | 72.5 | 40.5 | 51.8 | 79.5 | 14.7 | 27.5 | 32.4 | 90.8 |
| Pr | 10.88 | 10.7 | 16.5 | 17.45 | 19.97 | 9.74 | 4.32 | 6.03 | 9.87 | 1.77 | 3.13 | 3.72 | 9.81 |
| Nd | 41.3 | 37.5 | 58.1 | 61.5 | 73.1 | 41.3 | 16.4 | 25.1 | 37 | 5.5 | 11.4 | 15.2 | 34.8 |
| Sm | 7.09 | 6.01 | 10.1 | 10.54 | 12.67 | 9.01 | 3.39 | 4.61 | 7.17 | 1.28 | 2.22 | 2.71 | 5.92 |
| Eu | 1.27 | 1.08 | 1.97 | 1.91 | 2.31 | 2.5 | 1.93 | 1.49 | 1.28 | 0.2 | 0.35 | 0.26 | 0.76 |
| Gd | 6.17 | 5.72 | 9 | 8.18 | 9.04 | 8.27 | 3.69 | 4.6 | 5.42 | 1.02 | 1.67 | 2.06 | 4.98 |
| Tb | 1.07 | 1.19 | 1.6 | 1.38 | 1.47 | 1.31 | 0.73 | 0.94 | 0.89 | 0.13 | 0.26 | 0.29 | 0.77 |
| Dy | 6.15 | 7.22 | 8.41 | 7.44 | 7.71 | 7.18 | 4.41 | 5.92 | 4.93 | 0.95 | 1.36 | 1.61 | 4.69 |
| Ho | 1.23 | 1.58 | 1.68 | 1.51 | 1.59 | 1.46 | 1 | 1.35 | 0.99 | 0.15 | 0.26 | 0.27 | 0.93 |
| Er | 3.52 | 4.65 | 4.54 | 4.21 | 4.5 | 4.16 | 2.84 | 3.74 | 2.97 | 0.49 | 0.7 | 0.87 | 3.21 |
| Tm | 0.5 | 0.71 | 0.66 | 0.61 | 0.67 | 0.63 | 0.43 | 0.57 | 0.45 | 0.07 | 11 | 13 | 48 |
| Yb | 3.34 | 4.66 | 4.09 | 3.76 | 4.43 | 3.94 | 2.69 | 3.67 | 2.92 | 0.42 | 0.81 | 0.93 | 3.44 |
| Lu | 0.51 | 0.71 | 0.62 | 0.55 | 0.66 | 0.62 | 0.4 | 0.55 | 0.45 | 0.05 | 0.13 | 0.15 | 0.54 |

Samples CU1–15 are from the Tomanová Formation and samples CU37–55 are from the Dudziniec Formation; CU1 – black-grey argillite; CU3 – black-grey argillitic shale; CU5 – black-grey argillitic shale; CU7 – black-grey argillite with copper coloured coatings; CU10A – orange-weathering grey argillite with siderite sphaeroids; CU13, CU13R, CU13R1 – grey argillites with siderite bulbs; CU15 – black-grey argillite with copper coloured coatings; CU37 – grey calcareous sandstone; CU40 – black sandy biodetrital limestone; CU44 – shaly calcareous sandstone with bivalve shells; CU55 – dark grey sandy limestone with quartz pebbles; geochemical data were taken from Lintnerová et al. (2013)

also the $\delta^{18}O$ shift to more negative values in siderite suggests a relative weak diagenetic alteration (Lintnerová et al., 2013). Thus, the intensity of diagenetic change of the sediments was notably low and hence these sediments are suitable for tectonic setting deductions based on geochemical data.

## RESULTS

Major and trace element data from the Tomanová and Dudziniec formations were plotted for tectonic setting discrimi-

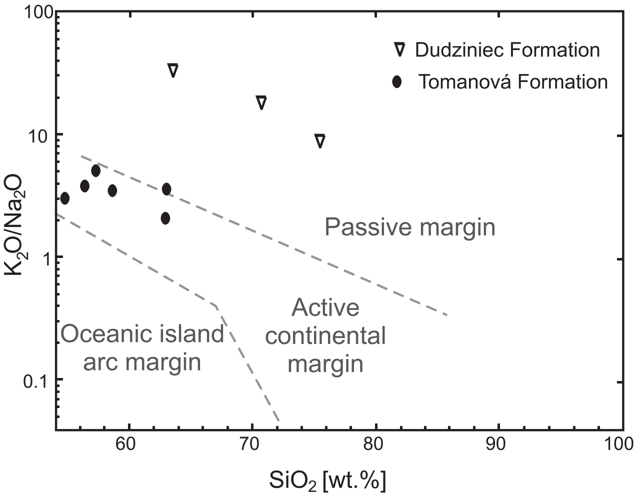


**Fig. 3. Tectonic discrimination diagram (Roser and Korsch, 1986) of sediment samples from the Tomanová and Dudziniec formations**

Some samples were not plotted in the diagram, because their values were out of the discrimination range

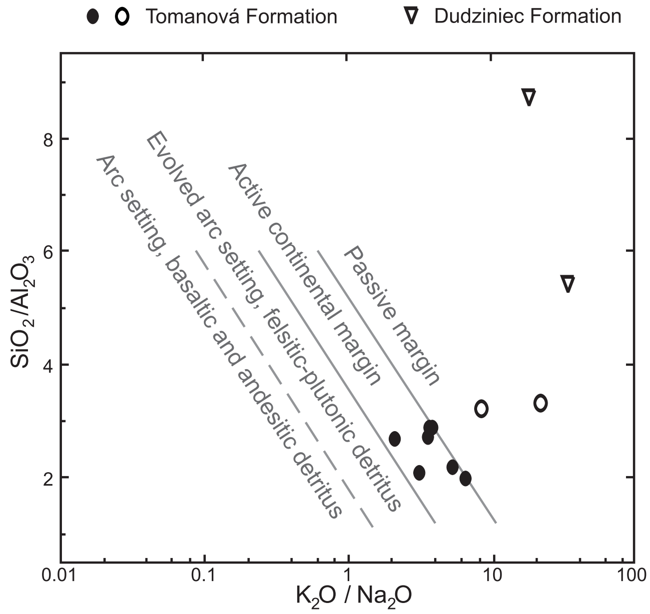


**Fig. 4. $SiO_2/Al_2O_3$–$K_2O/Na_2O$ diagram (Roser and Korsch, 1986) discriminating the tectonic setting of sediments sampled from the Tomanová and Dudziniec formations**

Dashed boundary between arc and evolved arc setting fields emphasizes the transitional nature of these settings; two samples (CU13R and CU13R1) from the Tomanová Formation with more anomalous composition (high $Fe_2O_3$ content) are marked by open circles, while the other Tomanová samples are marked by solid circles

nation. The diagram of $K_2O/Na_2O$ *versus* $SiO_2$ is shown in Figure 3. The fields in this diagram represent oceanic island arc margin (ARC), active continental margin (ACM) and passive margin (PM), as indicated in Roser and Korsch (1986). Inasmuch as the chemistry of siliciclastic sediments is influenced by the grain size, Roser and Korsch (1986) plotted sand-mud couplets for recent sediments to test the validity of their diagram for sands and muds. Generally, they reported that sediments plot where expected. Exceptions are forearc sands that plot in the ARC field, whereas the associated muds plot in the ACM field. Our samples fall predominantly in the ACM field with a considerable overlap into the PM field.

Similarly, four plate tectonic settings, the arc ($A_1$), evolved arc ($A_2$), active continental margin (ACM) and passive margin (PM), have been recognized in the $SiO_2/Al_2O_3$ *versus* $K_2O/Na_2O$ discrimination diagram of Roser and Korsch (1986) (Fig. 4). On this diagram, the samples studied fall again within the ACM field with substantial overlap of both the Tomanová and the Dudziniec sediments into the PM field.

Bhatia and Crook (1986) identified the chemical elements La, Th, Zr, Nb, Y, Sc, Co and Ti as the most useful in discriminating between sediments from different tectonic settings and recognized distinctive fields for four environments – oceanic island arc (A), continental island arc (B), active continental margins (C) and passive margins (D) – on bivariate plots of La *versus* Th, La/Y *versus* Sc/Cr, Ti/Zr *versus* La/Sc and trivariate plots of La-Th-Sc, Th-Sc-Zr/10 and Th-Co-Zr/10. Figure 5 shows the plots of Th-Co-Zr/10 and Th-Sc-Zr/10 for both the Tomanová and the Dudziniec formations. All samples fall within the C and D fields, except for two samples of Fe-rich mudstones (CU13R and CU13R1) which are placed in the B field.

Figure 6 shows two discriminant function-based major-element diagrams for the tectonic discrimination of clastic sediments for high-silica [$(SiO_2)_{adjusted}$ = 63–95%] and low-silica [$(SiO_2)_{adjusted}$ = 35–63%] rocks (after Verma and Armstrong-Altrin, 2013). Fields of three main tectonic settings, island or continental arc (active volcanism), continental rift (extension) and collision (compression), are shown. These two multi-dimensional diagrams can be considered a tool for successful discrimination of the geotectonic setting of older sedimentary basins (Armstrong-Altrin, 2015). On these high-silica and low-silica multi-dimensional diagrams (Fig. 6), the sediments studied are plotted mostly in the collision field with serious overlap into the continental rift field.

In addition to the above, the mean values of REE parameters of the Tomanová and Dudziniec formations were compared to REE parameters in sediments of the oceanic island arc, continental island arc, Andean-type continental margin and passive margins (Table 2). Most values of the REE parameters of the studied sediments are similar to those of sediments from the passive margins. Specifically, the La, Ce, ΣREE and ΣLREE/ΣHREE values from the Tomanová Formation samples and the La/Yb, $La_N/Yb_N$ and Eu/Eu* values from the Dudziniec Formation samples indicate passive margin sediments.

## DISCUSSION

The geochemical composition of clastic sedimentary rocks is especially a function of tectonic setting, provenance, weathering, transportation and diagenesis. Trace elements (Th, Zr, Co, Ti and Sc) are the least mobile elements during weathering, transportation, deposition and diagenesis and are considered the most useful for determination of the nature of tectonic settings of sedimentary rocks (Bhatia and Crook, 1986). Various authors (e.g., Zaid et al., 2015; Maslov et al., 2016; Hernández-Hinojosa et al., 2018) used the major and trace element assemblage from clastic sediments to determine their tectonic settings. Nevertheless, some secondary processes, such as diagenesis and weathering, could affect the geochemical composition. Our previous study revealed that the intensity of diagenetic overprint in sediments from the Tomanová and Du-

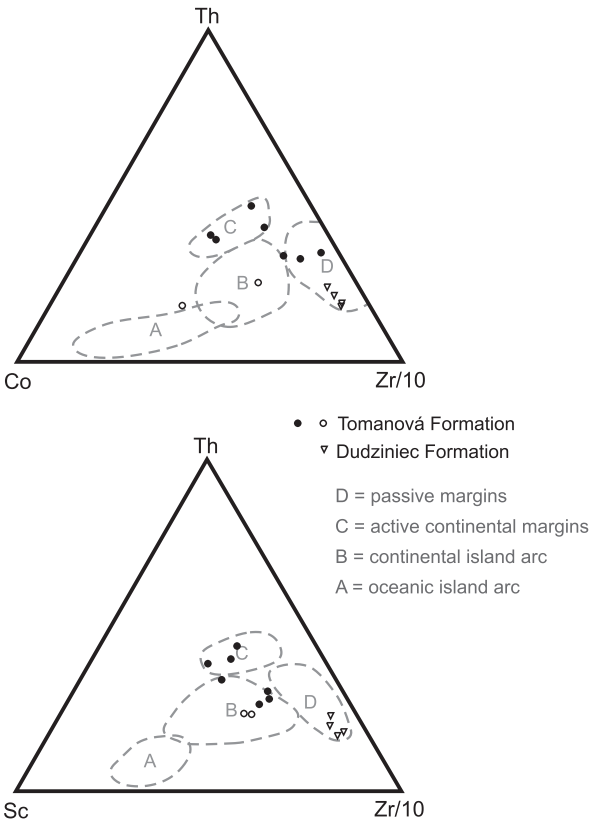


**Fig. 5. Th–Co–Zr/10 and Th–Sc–Zr/10 plots (Bhatia and Crook, 1986) of sediments sampled from the Tomanová and Dudziniec formations, illustrating discrimination of tectonic setting**

Dashed lines represent dominant fields of various tectonic settings; two samples (CU13R and CU13R1) from the Tomanová Formation with more anomalous composition (high $Fe_2O_3$ content) are marked by open circles, while the other Tomanová samples are marked by solid circles

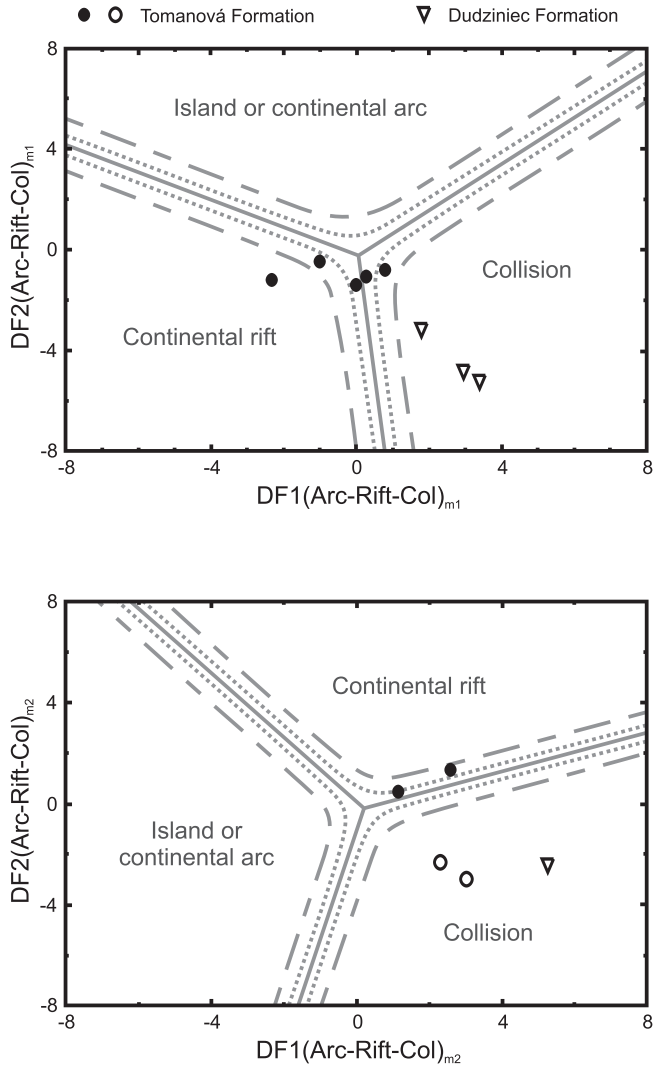


**Fig. 6. Multi-dimensional discriminant function diagram of high-silica sediments of the Tomanová and Dudziniec formations (up) and multi-dimensional discriminant function diagram of low-silica sediments of the Tomanová and Dudziniec formations (down) (Verma and Armstrong-Altrin, 2013)**

The $_{m1}$ subscript in DF1 and DF2 represents the high-silica diagram based on $log_e$-ratios of major elements and the $_{m2}$ subscript in DF1 and DF2 represents the low-silica diagram based on $log_e$-ratios of major elements. The discriminant function DF1 and DF2 equations come from Verma and Armstrong-Altrin (2013). The probability boundaries for 70 and 90% probabilities are also shown as dotted and dashed curves, respectively. Two samples (CU13R and CU13R1) from the Tomanová Formation with more anomalous composition (high $Fe_2O_3$ content) are marked by open circles, while the other Tomanová samples are marked by solid circles

dziniec formations was notably low, but weathering was intense as documented by the high Th/U, CIW and CIA values (Lintnerová et al., 2013). The REE distributions also indicate enrichment during only the weathering process. Enrichment of stable (Si, Al, Ti) and depletion of labile (K, Na, Ca, Mg) major elements are typical features of weathered silicate rocks. Because the major and trace element composition of the Tomanová Formation samples showed chemical homogeneity, we suppose that the weathering process was dominantly isochemical, and elemental redistribution was limited. Consequently, the tectonic setting of the sedimentary basin could be inferred from the chemical composition of the samples studied.

Craigie (2018) pointed that mixing of various sources can significantly change the provenance results, making the application of tectonic setting diagrams misleading. Fortunately, the overall setting of the studied formations restricts any possibility of source mixing. We suppose that recycling was also not so important to affect significantly the chemical composition of the investigated sediments. Consequently, the provenance plots could be applied for the samples from the Tomanová and Dudziniec formations. As indicated in Figures 3–5, our samples can be classified as derived from the passive to (formerly) active continental margin. Figure 6 suggests that they came from the (Variscan) continental collision and the (Palaeoalpine) rift setting. Similarly, the REE characteristics indicate that the samples bear mostly attributes of passive continental margin sediments (Table 2). Moreover, according to Lintnerová et al. (2013), the relative increase in Hf and higher Zr/Sc ratios in these samples suggest only felsic or mixed felsic material from a passive continental source but not from any volcanic rocks. To summarize, these data indicate that the sediments were derived from the passive continental margin. Although the sediments were most likely deposited on the passive continental margin, some samples bear attributes of ac-

Table 2

**Mean values of REE parameters of sediments from the Tomanová and Dudziniec formations, compared to those of sediments from various tectonic settings (after Bhatia, 1985)**

| REE parameters | Tomanová Formation (n = 9) | Dudziniec Formation (n = 4) | Sediments of oceanic island arc | Sediments of continental island arc | Sediments of Andean-type continental margin | Sediments of passive margins |
|---|---|---|---|---|---|---|
| La | 49 | 21 | 8 ±1.7 | 27 ±4.5 | 37 | 39 |
| Ce | 106 | 41 | 19 ±3.7 | 59 ±8.2 | 78 | 85 |
| ΣREE | 244 | 113 | 58 ±10 | 146 ±20 | 186 | 210 |
| La/Yb | 12.9 | 17.0 | 4.2 ±1.3 | 11.0 ±3.6 | 12.5 | 15.9 |
| $La_N/Yb_N$ | 8.7 | 11.5 | 2.8 ±0.9 | 7.5 ±2.5 | 8.5 | 10.8 |
| ΣLREE/ΣHREE | 8.7 | 5.0 | 3.8 ±0.9 | 7.7 ±1.7 | 9.1 | 8.5 |
| Eu/Eu* | 0.79 | 0.45 | 1.04 ±0.11 | 0.79 ±0.13 | 0.60 | 0.56 |

For the sake of simplicity and easy comparison with Bhatia (1985), La, Ce and ΣREE mean values are provided in ppm

tive continental margin provenance (Figs. 3–5), which very likely reflects old inherited information about their origin. Nevertheless, this interpretation of the tectonic setting in the source areas is open to further discussion, because it is based on limited data, and an integrated petrographic-geochemical approach could be more accurate.

A continual supply of clastic material from the continental Palaeo-European foreland onto the Tethyan shelf during the Triassic and Early Jurassic was interrupted during the extremely dry Middle Triassic time interval only. As concerns the origin of this material, Michalík (1993, 1994) calculated the size of the possible source areas vs the size of bodies of Lower Triassic clastics, and he concluded that the Alpine-Carpathian part of the northern Tethyan shelf must have been situated SW of the Bohemian Massif. Mišík and Jablonský (2000) pointed that the Lower Triassic sandstones should have been sourced from the area between the Moldanubic Unit of the Bohemian Massif and the Armorician Massif. Uher (1999) and Bačík and Uher (2007) argued that clasts or tourmaline-rich rocks could have been derived from the western part of the Bohemian Massif, but they excluded their transport from its eastern part. Aubrecht et al. (2017) stated that the transport of the Lower Carnian fine clastics onto the shelf would be possible only through the depression (gate) between the Bohemian and Armorician massifs, and a huge delta of the Lunz Beds must have formed immediately south of it. The Carnian-Norian Carpathian Keuper variegated shales in the Tatricum contain frequent psammitic clastic rocks, in contrast to the more distal areas, typified by dolomite intercalations. Clastic admixture is present in the uppermost Triassic and Lower Jurassic rocks (Baboš Quartzite) in the Tatricum and the marginal Fatricum (McCann, 2008). In contrast, the Upper Jurassic and Lower Cretaceous siliciclastic input came to the Fatric Basin mostly from the south (Michalík, 2007). The origin and transport routes of weathered material onto the Alpine-Carpathian shelf have not been sufficiently explained, especially, at the end of this time, when these ways should have been already cut by the opening of the Penninic Rift (McCann, 2008).

## CONCLUSIONS

The tectonic setting of the Tomanová and Dudziniec formations was illustrated by chemical composition of 13 sediment samples, using a series of various diagnostic discrimination diagrams. As indicated by high-silica and low-silica multi-dimensional diagrams, the analysed sediments bear signs of the continental collision/rift setting. Diagrams of $K_2O/Na_2O$ *versus* $SiO_2$, $SiO_2/Al_2O_3$ *versus* $K_2O/Na_2O$, Th-Co-Zr/10 and Th-Sc--Zr/10 determined their origin from the tectonically active and passive continental margin setting. The majority of the REE parameters suggested the passive margin tectonic setting. The most probable source of clastic admixture in the Scythian to Domerian sediments in the Tatric Unit was the Vindelician Highlands, as a remnant of the Variscan collisional orogen. The input of this material influenced also the marginal parts of the Fatricum (e.g., Vysoká or Havran units).

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