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The importance of parameter selection in studies of detrital zircon provenance: An example from Mesozoic deposits of the Bohemian Massif foreland (Poland)

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ABSTRACT

Detrital zircons are commonly used to identify sediment provenance, but usually only their ages are employed for interpretation. We here test the combination of four data types: crystallization ages, Th/U values, cathodoluminescence-induced internal textures, and grain shapes. Six samples of zircons from Triassic and Cretaceous deposits from the northeastern foreland of the Bohemian Massif (Poland) were used to identify as accurately as possible source rocks and their paleolocations, changes in erosional levels of source areas, and transport directions. The samples contain ten age populations, among which Carboniferous and Neoproterozoic zircons dominate, but the use of four parameters allowed subtle differences between the samples to be recognized; this makes interpretation more accurate and more reliable. A comparative analysis based on over 20,000 data points collected from ~200 contributions allowed us to identify the equivalents of crystalline source rocks, which were high-grade and medium-grade metamorphic rocks of the Bohemian Massif (mostly granulites) in the case of complex-textured zircons, and Bohemian magmatic rocks along with pyroclastics in the case of oscillatory-zoned grains. The source rocks were located in the northeastern and eastern parts of the massif, where the proportions of the specific rocks exposed to erosion have changed significantly from the Mesozoic to the present. We found distinct changes in the erosional levels of source areas caused by removal of sedimentary cover and the erosion of crystalline rocks, combined with tectonic movements, particularly in the Olenekian and Coniacian. The transport of debris from the southwest and west during the Induan–Anisian, as well as from the south and north during the Norian, were largely controlled by paleogeography. The Cretaceous transgression resulted in the supply of grains mainly from the nearest units during the Cenomanian and Coniacian. We strongly recommend using a combination of at least these four parameters in provenance studies.

1. Introduction

Zircon is one of the detrital heavy minerals most commonly used to infer the geological histories of sediments (e.g., Fedo et al., 2003; Cawood et al., 2012; Zhang et al., 2015; Augustsson et al., 2018; Nádaskay et al., 2019; Peng et al., 2020; Wang et al., 2021). However, most of contributions using detrital zircons have focused on their crystallization age, paying less attention to other important features. When examining detrital zircons, the original shapes and types of crystal faces and terminations are usually difficult to identify, due to fragmentation and abrasion of the grains, and may therefore be of minor importance. Nevertheless, the internal textures seen in cathodoluminescence-induced and backscattered electron images, the Th/U values, and other parameters that may be measured using specific analytical equipment can be used as additional essential data sources to improve the identification of primary crystalline source rocks, especially those with a long and complex tectonothermal history.

In this contribution, we apply and test an approach based on the combination of four types of data obtained from measurements taken with a sensitive high-resolution ion microprobe (SHRIMP IIe/MC) and preceded by cathodoluminescence (CL) analysis. These parameters are: (i) ages of crystallization, (ii) Th/U values, and (iii) CL-induced internal textures. In addition, (iv) the overall shapes of the grains are also considered. In this study we examined detrital zircons separated from

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the Lower to Upper Triassic and Upper Cretaceous sedimentary rocks located in the northeastern foreland of the Bohemian Massif (Opole Silesia in southern part of Poland, Central Europe). The choice of research area and samples was motivated by the fact that these zircon populations may be mixtures of grains derived from various igneous and metamorphic rocks (or recycled from sedimentary rocks), and supplied from different source areas and units, due to changes in erosional levels and paleogeography; the grains can thus have very different characteristics. These detrital zircon populations have not been studied before, and there is a large collection of zircon data from the nearby crystalline massifs that may have been eroded at various stages of sedimentary basin development; these data are suitable material for the comparative analysis. In overall, about 20,000 data points from almost 200 contributions were used for the comparative analysis performed here. It should be mentioned that only a few of these contributions have drawn attention to the importance of the internal textures of detrital zircons in the description and interpretation of histories of (meta)sediment (e.g., Žáčková et al., 2012; Žák et al., 2018; Vozárová et al., 2019).

The main objectives of this research are to identify the source rocks and their probable paleolocations as accurately as possible using the four parameters and to assess their suitability. Subsequently, the results allow the identification of temporal and spatial changes in the erosional levels of source areas and directions of sediment transport, and the reasons for these changes. Moreover, we emphasize the importance of age gaps in zircon populations for studies of provenance. We also consider whether these zircon populations recorded the Late Cretaceous uplift of the basement blocks of the Bohemian Massif, due to the regional compression caused by the Alpine Orogeny (cf., Ziegler et al., 1995; Malkovský, 1987; Krzywiec, 2006; Ziegler and Dèzes, 2007).

2. Geological setting of the sampled area

The study area is located in Opole Silesia in the southern part of Poland (Fig. 1A-B). The selected samples of Mesozoic sedimentary rocks come from two adjacent tectonostratigraphic units: the Kraków–Silesian Homocline (the Induan, Olenekian, Anisian, Norian, and Cenomanian samples) and the Opole Trough (the Coniacian sample) (e.g., Aleksandrowski et al., 2011).

The basement of the Kraków–Silesian Homocline is built mainly of lower Carboniferous sedimentary rocks (Culm facies of the Moravo–Silesian Zone) (Aleksandrowski et al., 2011; Szulc et al., 2015a, 2015b). The lower Permian sedimentary cover consists of continental brown–red and brown–grey sandstones and rare conglomerates (Rotliegend facies), which were recognized only in boreholes and are almost 140 m thick (Kotlicki, 1973; Kłapciński, 1993). The Lower Triassic sedimentary rocks, poorly exposed at the surface, are subdivided into the Lower, Middle, and Upper Buntsandstein (Induan and Olenekian) (Fig. 1B). The Lower and Middle Buntsandstein (the Older Buntsandstein or the Świerklaniec Beds) consist of aeolian, fluvial, and brackish inland basin arkoses, subarkoses, wackes, conglomerates, and claystones (Fig. 2); their total thickness reach up to 170 m. The Upper Buntsandstein (Röt facies, Olenekian) is composed of siliciclastics (Fig. 2) followed by sabkha, tidal flat, and shallow-marine beige and grey dolostones (mostly calcitized), which are intercalated with grey anhydrites and marlstones, and overlain by grey limestones and marlstones; the sequence varies in thickness from ~50 m to over 100 m (e.g., Assmann, 1925, 1933; Kowal-Linka and Bodzioch, 2017). These rocks are comfortably overlain by Middle Triassic (Lower, Middle, and Upper Muschelkalk) carbonates (various types of limestones, marly limestones, marlstones, and calcitized dolostones) and siliciclastics (siltstones, mudstones, and sandstones) (Figs. 1B and 2), which originated mostly in carbonate ramps and in sabkhas. These are subdivided into eight formal and informal lithostratigraphic units, with their total thickness ranging from 100 m to 200 m, depending on the area (e.g., Assmann, 1944; Bodzioch, 1997; Niedźwiedzki, 2000; Szulc, 2000; Kowal-Linka, 2008, 2009). The Upper Triassic siltstones, mudstones, sandstones and dolostones (Keuper continental facies, including riverine, swamp, and lacustrine deposits; Carnian–Rhaetian) (Figs. 1B and 2) vary in thickness up to 250 m. They originated in the SE marginal zone of the Central European Basin (e.g., Pieńkowski et al., 2014; Szulc et al., 2015a, 2015b; Kowal-Linka et al., 2019).

The Opole Trough is built of Upper Cretaceous marine deposits (Fig. 1B) that directly overlay the Carboniferous flysch facies of the Moravo–Silesian Zone in the south, and the Triassic sequence of the Kraków–Silesian Homocline in the north and east. The Upper Cretaceous deposits include Cenomanian sandstones and conglomerates, followed by Turonian clayey marlstones, marlstones, marly limestones, and limestones, and lower-to-middle Coniacian marlstones and gaizes; these Cretaceous rocks are up to 300 m thick and are covered by Cenozoic deposits (Fig. 2) (e.g., Assmann, 1925; Tarkowski, 1991; Kotański and Radwański, 1977; Kędzierski, 2008).

All these tectonostratigraphic units were affected by Cenozoic volcanism, and basaltic lavas brought fragments of older rocks to the surface—including xenoliths of Cretaceous sedimentary rocks (Fig. 2) (e.g., Birkenmajer and Pécskay, 2002; Ulrych et al., 2011).

3. Samples and methods

Six samples of Triassic (Induan, Olenekian, Anisian, and Norian) and Cretaceous (Cenomanian and Coniacian) siliciclastic and carbonate sedimentary rocks were selected for the study (Fig. 2). Detailed descriptions of the samples and collection locations are provided in Table 1.

The heavy minerals were separated using a heavy liquid with a density of 2.85–2.86 g/cm^3, prepared from sodium polytungstate granules and distilled water. Zircons representing the following size intervals were used in this study: 63–100 μm for the Anisian, Norian, and Coniacian samples, and 63–125 μm for the Induan, Olenekian, and Cenomanian samples, due to the abundance of the grains; ca. 2700 grains in total were handpicked. Next, the beads were made of randomly selected detrital zircons (cf., Dodson et al., 1988; Vermeesch, 2004); only grains with strong surface imperfections were avoided.

All U-Pb isotopic results reported here were collected on the SHRIMP IIe/MC instrument (the sensitive high resolution ion microprobe) located at the Polish Geological Institute – National Research Institute in Warszawa, using a duoplasmatron as primary ion source. The isotopic ratios were analyzed using a ~ 20–23 μm-diameter primary beam consisting of ionized oxygen molecules (O2)1- purified by a Wien filter. Secondary ions were collected on a single electron multiplier by cycling the magnet through six scans (~16 min) across the mass range of interest: 196Zr2O, 204Pb, 204.1 (as a background), 206Pb, 207Pb, 208Pb, 238U, 248ThO, and 254UO. The reference zircon Temora-2 was used in order to control for the stability and accuracy of the instrument. See also Supplementary Material 1.

SHRIMP U-Pb data were processed using open source SQUID-2 software from Geoscience Australia and plotted using AgeDisplay software (Sircombe, 2004). ^{206}Pb/^{238}U ratios were calibrated using the Temora-2 reference zircon with ^{238}U/^{206}Pb age = 416.8 Ma (416.78 ± 0.33 Ma TIMS age; Black et al., 2004). The single zircon ages used in this contribution are ^{206}Pb/^{238}U for zircon ages <1000 Ma, and ^{207}Pb/^{206}Pb for those >1000 Ma. Discordance (see the "Disc %" column in Supplementary Material 2) is a measure of the internal disagreement of the dates derived from the independent ^{207}Pb/^{206}Pb and ^{238}U/^{206}Pb isotopic systems within a single analysis and was calculated, according to Gehrels (2012), as: [100 - (^{206}Pb/^{238}U age / ^{207}Pb/^{206}Pb age) x100]. The used ages were chosen on the following principle: zircons older than 1000 Ma with a discordance of less than or equal to 10% and zircons younger than 1000 Ma with a discordance of less than or equal to 20% (cf., Sun et al., 2016).

In total, 954 measurements were performed, of which 554 yielded concordant U-Pb dates. The results are presented in Supplementary Material 2. The assumption was to perform measurements mainly in the

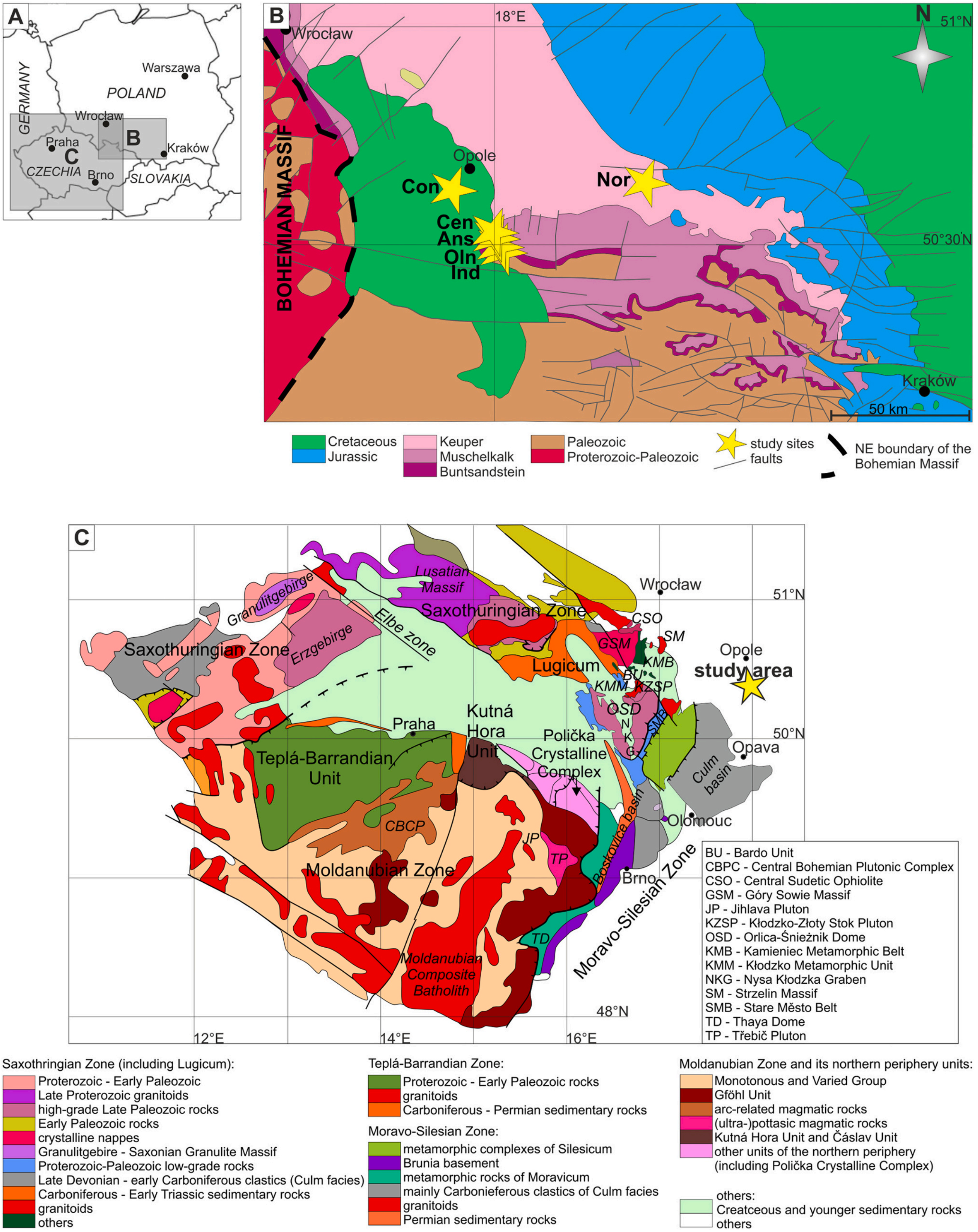


Fig. 1. A: Contour map of Poland, Czechia (the Czech Republic), Slovakia (the Slovak Republic), and adjacent countries. The grey rectangles labeled B and C show the spatial ranges of the maps presented in Figs. B and C. B: Geological map of the study area; simplified fragment after Dadlez et al. (2000). Explanation of abbreviations: Ind – Induan sample; Oln – Olenekian sample; Ans – Anisian sample; Nor – Norian sample; Cen – Cenomanian sample; Con – Coniacian sample (see Table 1 for details). C: Simplified geological map of the Bohemian Massif with its units mentioned in the text, along with location of the study area (juxtaposition based on Chlupáč and Vrána, 1994; Franke and Żelaźniewicz, 2000; Mazur et al., 2006; Cháb et al., 2007; Aleksandrowski et al., 2011).

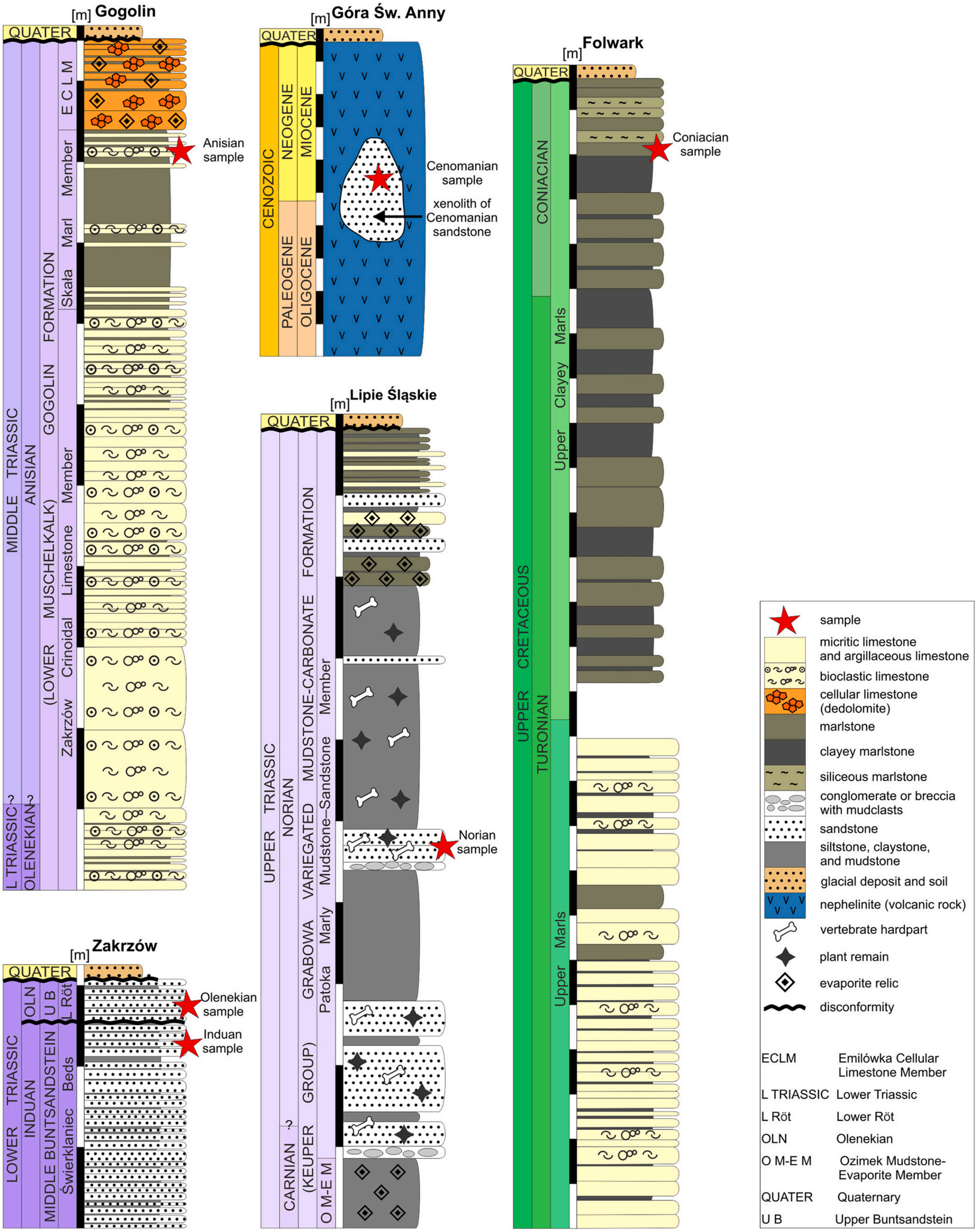


Fig. 2. Lithological columns of the examined sites with marked sampled layers along with chronostratigraphy and lithostratigraphy. The column for the Zakrzów site is a compilation of data from Trzepla (1993), Marek and Pajchlowa (1997), Nawrocki et al. (2003), and own observation. The column for the Gogolin outcrop follows Nawrocki and Szulc (2000) and Kowal-Linka (2008). The column for the Góra Św. Anny outcrop is based on Niedźwiedzki (1994), Birkenmajer and Pécskay (2002), and own observation. The column for the Lipie Śląskie clay-pit is a compilation after Pieńkowski et al. (2014), Szulc et al. (2015a), and Kowal-Linka et al. (2019). The column for the Folwark quarry follows Kędzierski (2008).

Table 1

Description of the samples and sites. Data sources for the sedimentary environments and lithostratigraphical units are as follows: Induan arenite and the Olenekian wacke after Kowal-Linka and Walczak (2018); the Anisian limestone after Kowal-Linka (2008); the Norian wacke after Pieńkowski et al. (2014), Szulc et al. (2015b), and Kowal-Linka et al. (2019); the Cenomanian arenite after Niedźwiedzki (1994); the Coniacian marlstone after Kędzierski (2008). The eastern margin of the Bohemian Massif is assumed at 17°22″E at the present erosional level (based on the geological map after Dadlez et al., 2000); distances were measured in straight lines.

Names of samples (referring to ages of deposition)	Sampled sites	Present distance of the sites to the E margin of the Bohemian Massif	Types of the sampled rocks, sedimentary environments, and units (if established)
Induan sample	cultivated field in vicinity of Jasiona (50°28′15″N, 18°04′29″E)	~51 km	dark red and rusty quartz arenite, the aeolian deposit; the Świerklaniec Beds (Lower Triassic, Middle Buntsandstein)
Olenekian sample	cultivated field in vicinity of Jasiona (50°28′15″N, 18°04′29″E)	~51 km	dirty pink quartz wacke with grey patches, the shallow-marine deposit which originated at the beginning of the late Olenekian transgression; the lower Röt (Lower Triassic, Upper Buntsandstein)
Anisian sample	abandoned quarry near Gogolin (50°29′51″N, 18°02′52″E)	~48 km	quartz grain-rich limestone, the proximal tempestite bed deposited in the middle zone of a carbonate ramp; the Skała Marl Member of the Gogolin Formation (Middle Triassic, Lower Muschelkalk)
Norian sample	Lipie Śląskie clay-pit in Lisowice (50°40′36.05″N, 18°38′41.50″E)	~90 km	calcium carbonate matrix-rich wacke, the deposit of braided to anastomosing river; the Patoka Marly Mudstone–Sandstone Member of the Grabowa Variegated Mudstone–Carbonate Formation (Upper Triassic, Keuper facies)
Cenomanian sample	abandoned quarry in Góra Świętej Anny village (50°27′12″N, 18°10′00″E)	~57 km	quartz arenite; originally it was the shallow-marine deposit, but it was collected from a xenolith contained in Cenozoic volcanic rock; Upper Cretaceous
Coniacian sample	active Folwark quarry near Opole (50°36′54″N, 17°54′22″E)	~38 km	grey marlstone, the deep-marine deposit; the Upper Clayey Marls, Upper Cretaceous (the earliest Coniacian)

outermost parts of the grains, which were uniform in terms of internal textures, and large enough to fit spots, in order to determine ages of the final stages of magmatic or metamorphic events. The Norian sample was the only one to reveal the presence of Triassic zircons in its basic data set. An additional 35 analyzes were performed to find other zircons of such a young age, however, from these additional analyzes only the Precambrian ages were obtained (cf., Kowal-Linka et al., 2019).

Afterwards, we carried out a detailed comparative analysis of the grains under study and zircons contained in the contemporary exposed crystalline and (meta)sedimentary rocks of pre-Mesozoic units adjacent to the studied basins (data collected from literature). In total over 20,000 data points from almost two hundred contributions were collected and used. The compared zircons were required to meet all the following conditions: they had to have similar internal textures, crystallization ages and Th/U values, as well as overall shapes; which, however, was less important due to the possible fragmentation and abrasion of the grains under study. In the absence of published data on Th/U values, the comparative analysis was based on similar textures and ages.

4. Results: features of detrital zircons and age populations

Zircons that yielded concordant ages ($n = 554$) were divided into two main types: (A) grains with complex texture, and (B) grains with plain oscillatory zoning texture. In this work, complex texture is defined as any other than plain oscillatory zoning, including homogenous and patchy internal textures, diffuse and flow patterns, deformed relictic oscillatory zoning, sector zoning, fir-tree zoning, and others (cf., Corfu et al., 2003). Such zircons constitute ~72% of the population ($n = 399$). These grains are usually anhedral, often elongated with rounded terminations, or spherical or nearly spherical. The zircons with plain oscillatory zoning have more or less euhedral shapes and more or less sharp terminations, and constitute ~28% of the population ($n = 155$). All zircons were subdivided into ten age populations (I–X; Fig. 3; Supplementary Material 3; hereafter abbreviated to pop.). The most numerous are Carboniferous zircons, Ediacaran–early-Cambrian zircons, and pre-Ediacaran zircons (Fig. 3; Supplementary Material 3). These age populations are separated by four age gaps, including: (i) the latest Carboniferous gap defined by the absence of the oscillatory-zoned 303–315-Ma-old zircons, (ii) the "middle" Cambrian gap arising from the almost complete absence of 500–520-Ma-old zircons (n = 1), (iii) the lack of grains of 2.13–2.60 Ga and (iv) the lack of grains older than Neoarchean (> 2.8 Ga), regardless of the type of texture. Next, subpopulations of the grains with the most similar ages and Th/U values were separated (Fig. 3; Supplementary Material 4; hereafter abbreviated to subpop.). Populations and subpopulations important for the comparative analysis i.e., those used in Section 6. Discussion, are described below (in order from the most numerous).

4.1. *Zircons from the Induan arenite*

The grains are mostly rounded or well-rounded (Fig. 4). Eighty-two analyses on grains yielded a zircon age spectrum spanning ages between 300 ± 3 Ma and 2070 ± 14 Ma (Fig. 5; Supplementary Material 2). The Carboniferous zircons (pop. VIII) form the largest cluster (46.3%; Fig. 3) with the main peak in the frequency distribution diagram at 339 Ma (Fig. 5). The vast majority of the Tournaisian and Visean zircons (~92%) show complex internal textures, and ~ 73% of them have Th/U values lower than 0.2 or close to this value. They are subdivided into three main types: (1) grains with nonluminescent or weakly luminescent, textureless, circular or bean-shaped cores or central domains (~62% of the grains), (2) grains with varying degrees of resorbed xenocrystic (faint) oscillatory-zoned cores (~20%), and (3) grains without distinct cores (~18%; Fig. 6). The central parts of the first and second types are mantled by relatively thick, usually less luminescent single or double homogenous rims differing in luminescence, or by irregular domains (showing often variable luminesce in the same grain), which are also homogenous or show diffuse patterns, flow patterns, or (rarely) deformed relictic oscillatory zoning (Fig. 6). About 20% of these grains have continuous or discontinuous very thin, bright external rims or domains. The type three grains display sector zoning, irregular and discontinuous concentric zoning, and are patchy or completely homogenous. Two distinct subpop. 1 and 2 of early Carboniferous zircons are separated (Fig. 3). Going further, all Devonian-age zircons (pop. VII; 12.2%) have (deformed) complex textures (subpop. 3, see also 4; Figs. 3 and 6). They are very much like the first and second types of the

Carboniferous grains.

4.2. Zircons from the Olenekian wacke

This sample consists of well-rounded, rounded, and subrounded grains (Fig. 4). One hundred and nine grains yielded ages from 321 ± 5 Ma to 2091 ± 19 Ma (Fig. 5). Considering the Carboniferous zircons (pop. VIII; 54.1%, which is the highest share of all samples; Fig. 3), besides the most numerous grains of Visean age ($n = 37$; the peak at 339 Ma), the sample also contains a significant number of Serpukhovian zircons ($n = 12$; the peak at 327 Ma) (Fig. 5). The Visean (and Tournaisian) zircons show mostly type 1 of internal texture (cf. the Induan sample) (~56% of these grains; Fig. 6). Three zircon twins displaying sector zoning in their rims are found (Fig. 6). Several brightly luminescent zircons are worth noting, as they were not present in the older sample. About 50% of grains have continuous or discontinuous (abraded to various degree) very narrow bright external rims or domains. Approximately 67% of the Serpukhovian zircons are oscillatory-zoned (Fig. 6). Three distinct clusters are separated among the Carboniferous zircons characterized by the complex textures (subpop. 1–3) and two – among the oscillatory-zoned zircons (subpop. 9–10; Fig. 3; Supplementary Material 4).

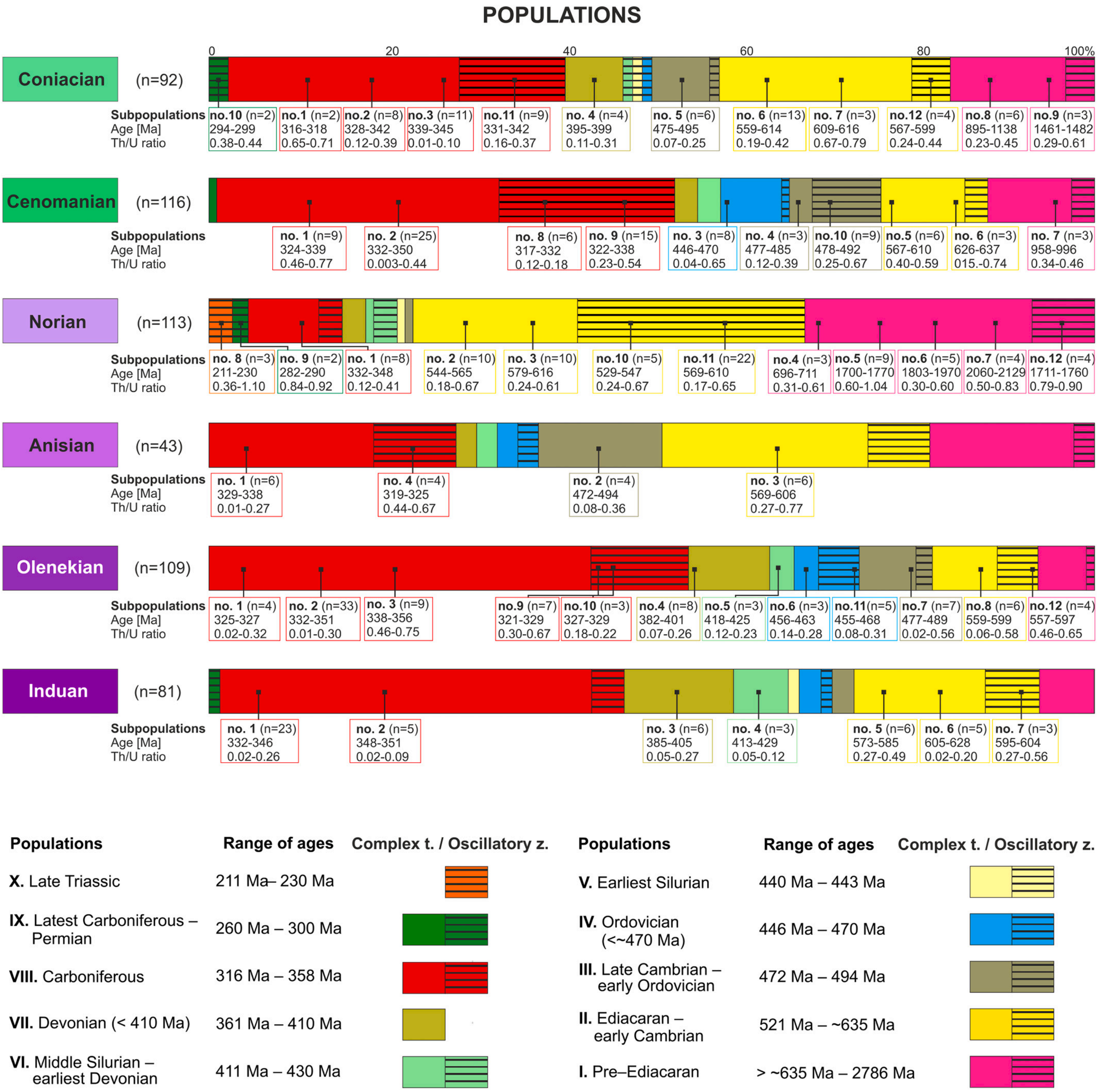


Fig. 3. Bar charts showing the relative abundances of the distinguished age populations I-X (in order from the youngest) with the division into the complex-textured zircons and the oscillatory-zoned zircons. The subpopulations distinguished separately among the complex-textured zircons and the oscillatory-zoned zircons with the number of grains, age ranges and Th/U values are indicated below the bars. (For the colors in this figure, the reader is referred to the online version of this article.)

The zircons with Ediacaran–early Cambrian ages (pop. II; 11.9%) form two small maxima at 593 Ma and 552 Ma (Fig. 5). About 62% of them show complex textures (subpop. 8; Figs. 3 and 6). The Devonian–age zircons (pop. VII; 9.2%) reveal the maximum at 396 Ma (subpop. 4; Figs. 3 and 5). These grains have exclusively complex internal textures and the Th/U values are commonly lower than, or close to, 0.2. The late Cambrian–Early Ordovician zircons (pop. III; 8.3%), with the maximum at 479 Ma, also have complex textures (subpop. 7; Figs. 3 and 5).

4.3. *Zircons from the Anisian limestone*

This sample contains mostly tiny, subangular, angular, subrounded, and rounded grains (Fig. 4). Only forty-three concordant ages were obtained from this sample due to the small sizes and poor quality of the grains. The ages range from 319 ± 5 Ma to 2092 ± 13 Ma (Fig. 5).

The zircons which yielded the Ediacaran–early Cambrian ages (pop. II; 30.2%) show two maxima at 558 Ma and 570 Ma (subpop. 3; Figs. 3 and 5). Only three grains display plain oscillatory zoning (Fig. 6). About 70% of the grains have external, very narrow, brightly luminescent rims or domains. The pre-Ediacaran zircons (pop. I; 18.6%) do not form a coherent cluster, and only a low peak at 1478 Ma is noticeable (Figs. 3 and 5). These zircons show variable and almost exclusively complex textures. Moreover, the late Cambrian-Early Ordovician grains form the distinct cluster (pop. III; 14.0%) with the maximum at 475 Ma and 490 Ma (Fig. 5). These zircons display exclusively complex-textures and subpop. 2 stands out (Fig. 3).

4.4. *Zircons from the Norian wacke*

Zircons are mostly subangular and angular prisms or their fragments, while subrounded and rounded grains occur in subordinate amounts (Fig. 4). The basic data set includes seventy-eight analyses, which yielded a zircon age spectrum spanning the ages between 211 ± 3 Ma and 2105 ± 19 Ma (Fig. 5) (cf., Kowal-Linka et al., 2019). This sample contains the greatest amount of Precambrian zircons (including the Ediacaran grains), i.e. 64.1% (Fig. 3), which makes it clearly different from the all others.

The Ediacaran–early Cambrian zircons (pop. II; 39.7%) form the maxima at 599 Ma, 584 Ma, and 547 Ma (Fig. 5). By adding nineteen ages gained during the extra measurements, we obtained peaks with similar values, i.e., 599 Ma, 580 Ma, and 549 Ma, which justifies the use of these results as well. As many as 63% or 56% of the Ediacaran zircons (considering only the basic set or all data, respectively) show plain oscillatory zoning (subpop. 11; Figs. 3 and 6), which also distinguishes this sample from the others.

The pre-Ediacaran zircons (> 635 Ma) (pop. I; 26.9%; see clusters I.1–I.6 in Supplementary Material 3) form five small maxima at 1736 Ma, 710 Ma, 1875 Ma, 1488 Ma, and 2125 Ma (ordered from the highest peak formed by the largest number of grains). Together with the ages obtained from the additional sixteen analyses, the maxima are as follow: 1736 Ma, 702 Ma, 1865 Ma, 1488 Ma, and 2083 Ma (Fig. 5). These zircons have xenocrystic oscillatory-zoned or homogenous cores mantled by oscillatory-zoned or homogenous bands (Fig. 6). Five distinct subpopulations are isolated within the pre-Ediacaran zircons (subpop. 4–7 and 12; Fig. 3).

The definitely lower shares of the Carboniferous zircons (pop. VIII; 15.4% of the grains; the maximum at 342 Ma; mostly having the type 1 complex textures; Figs. 3 and 5–6), and Devonian zircons (pop. VII; 3.8%) are noticeable. Moreover, the almost complete absence of the late Cambrian-Early Ordovician (pop. III; $n = 1$) zircons is striking, as these were typical of other samples (Fig. 5).

4.5. *Zircons from the Cenomanian arenite*

The sample contains zircons of variable shapes, from well-rounded grains to almost angular prisms (Fig. 4). From 115 analyses, the youngest age obtained was 265 ± 7 Ma and the oldest was 2786 ± 23 Ma (this is the oldest age in the entire examined suite). The Carboniferous zircons (pop. VIII; 51.3%) reveal a maximum at 334 Ma (Figs. 3 and 5). This population is definitely dominated by Visean grains ($n = 34$), which are accompanied by relatively numerous Serpukhovian grains ($n = 15$), Bashkirian zircons ($n = 6$), and Tournaisian zircons ($n = 4$). The Tournaisian and Visean zircons commonly show wide a range of the complex

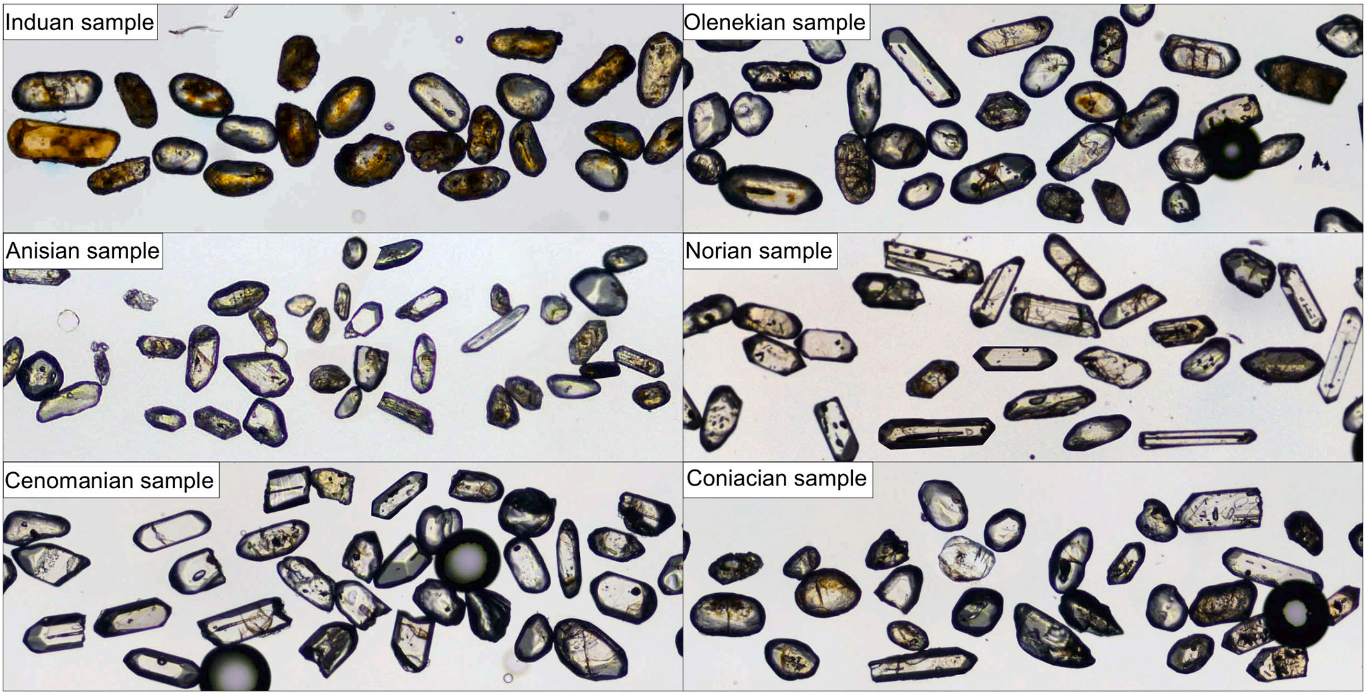


Fig. 4. Photomicrographs of mount fragments taken in transmitted light (before polishing) showing the diversity of the examined detrital zircon samples (all of 63–100 μm size interval) in terms of grain sizes, shapes, and degree of abrasion.

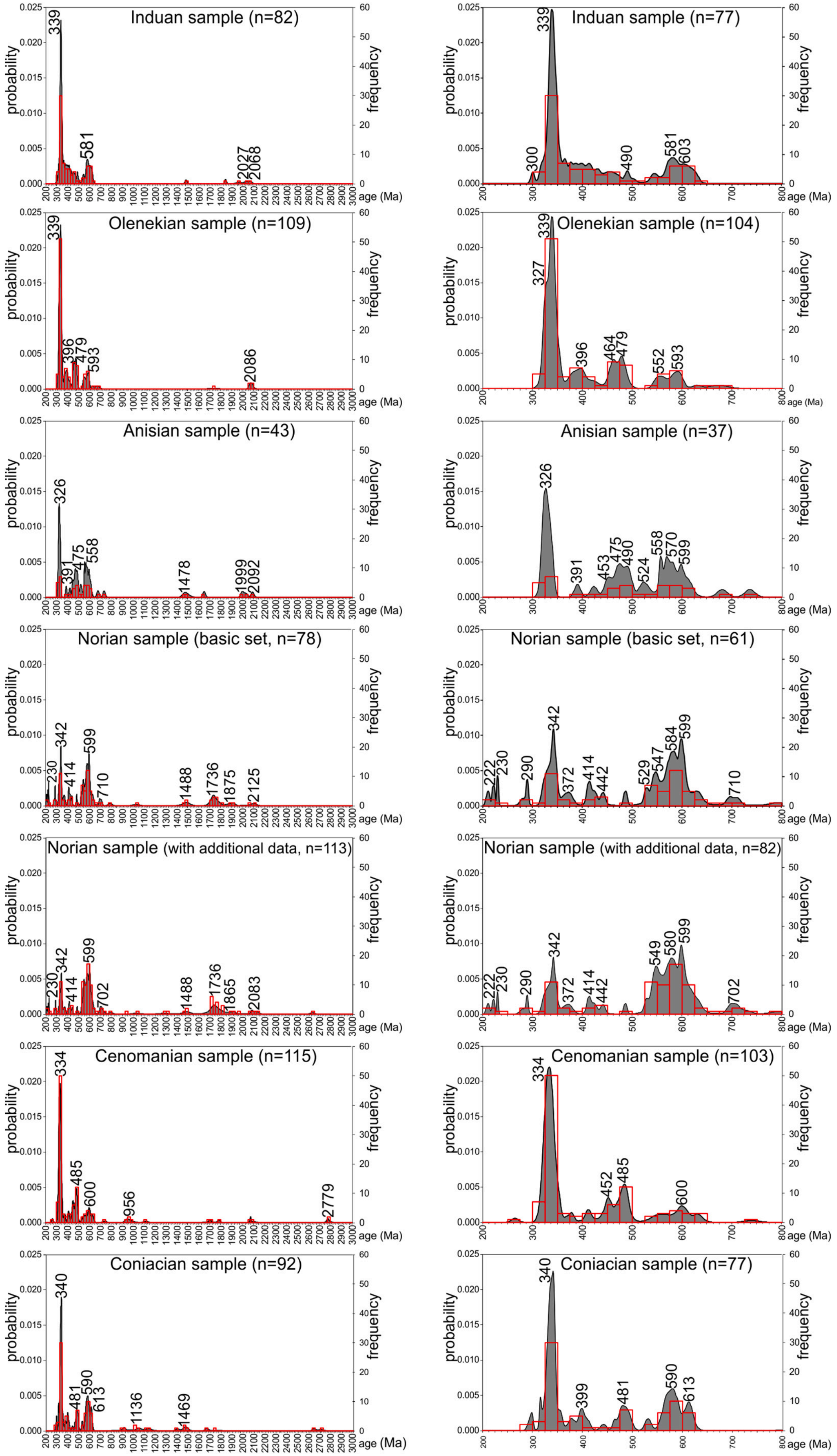


Fig. 5. Probability density plots and histograms for six samples under study. The age data were plotted (by AgeDisplay after Sircombe, 2004) as histograms with superimposed probability curves, in order to represent both the age measurement and the associated uncertainty. Two age scales were used for the X-axis: 200–3000 Ma for the diagrams in first column, and 200–800 Ma for those in the second column, to make differences in peak positions clearer. The values of the major peaks are indicated as ages in Ma (millions of years). Note the two plots for the Norian sample: the first plot shows the basic data obtained from analysis of random grains, while the second plot shows the basic data combined with additional data (see Section 3. *Samples and methods* for details).

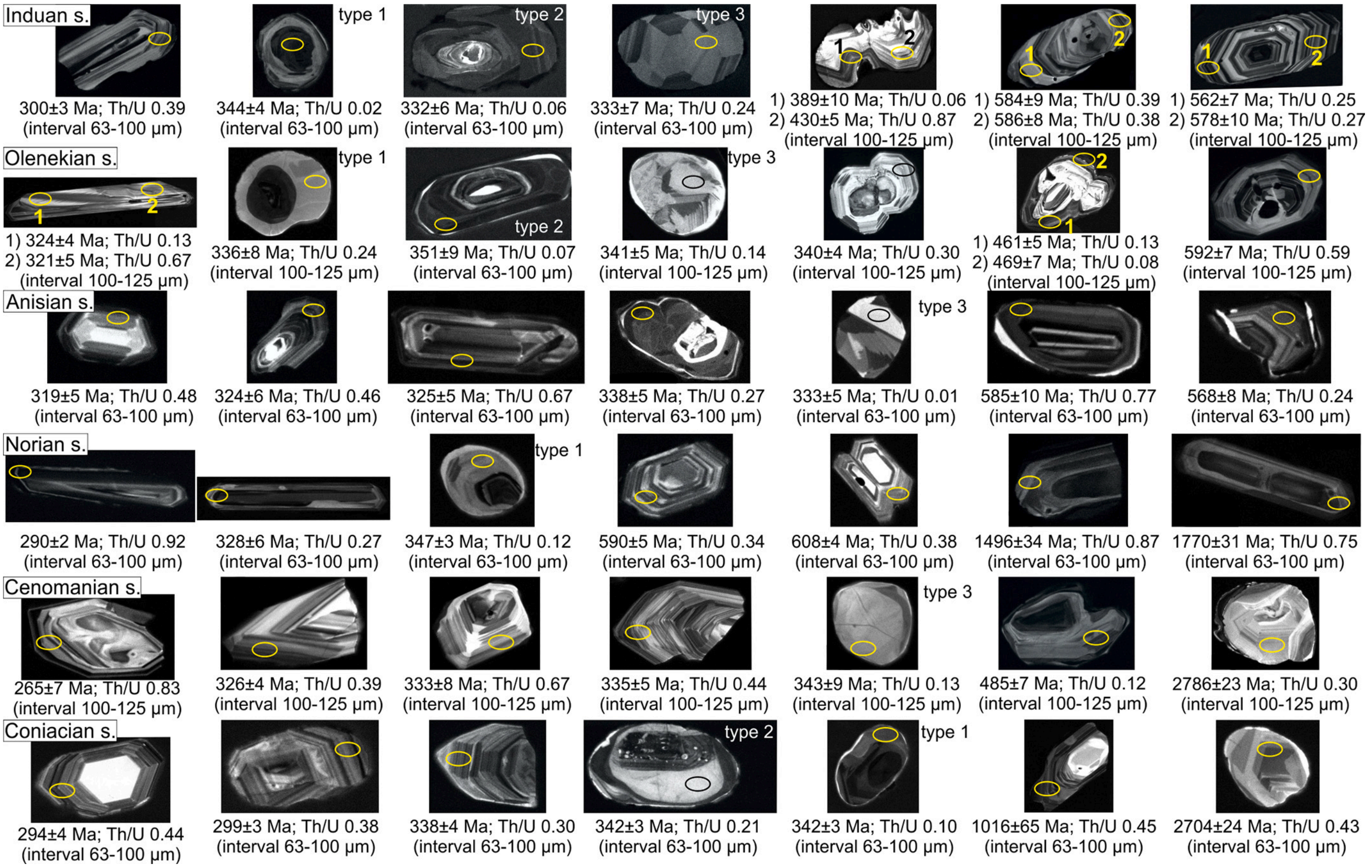


Fig. 6. Cathodoluminescence photomicrographs of representative grain types in terms of internal texture, age, and Th/U value in the individual samples. Yellow and black ellipses in the photos (selected depending on the background color) indicate where the measurements were made. For the Carboniferous zircons with the complex textures, the type of texture (1, 2, or 3) is indicated in the photo or next to it. The grain size intervals are also indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

internal textures, but the percentage of such grains (~84%) is noticeably lower than in all the older samples. The most numerous are zircons of the third and first types. The Serpukhovian and Bashkirian populations are dominated by oscillatory-zoned grains with Th/U values above 0.2 (subpop. 8 and 9; Figs. 3 and 6).

The pre-Ediacaran pop. I (11.3%) includes two the oldest grains of 2786 ± 23 Ma and 2779 ± 9 Ma. The small distinct subpop. 7, consisting of three complex-textured nonluminescent and almost homogenous grains of 958–996 Ma was isolated (Fig. 3). Such zircons are not present at all in the three oldest samples.

The zircons bearing late Cambrian–Early Ordovician ages (pop. III) form another abundant cluster (10.4%) with the maximum at 485 Ma (Fig. 5). The Cambrian-age zircons are exclusively oscillatory-zoned and form a coherent cluster (subpop. 10; Fig. 3). Most of the zircons display very narrow, brightly luminescent, more or less continuous external rims.

4.6. *Zircons from the Coniacian marlstone*

The grains are from well-rounded to angular (Fig. 4). Ninety-two analyses yielded a zircon age spectrum from 294 ± 4 Ma to 2704 ± 24 Ma. The Carboniferous zircons (pop. VIII; 39.1%) form the maximum at 340 Ma (Figs. 3 and 5). Approximately 69% of the Tournaisian and Visean zircons display complex textures, mostly of the second type (40%) and the third type (35%; Fig. 6). The Visean population contains as much as ~35% entirely oscillatory-zoned zircons with Th/U values commonly above 0.2 (78%), and sharp terminations (subpop. 11; Figs. 3 and 6), which is the highest percentage among all other samples. Approximately 60% of the Visean zircons show narrow brightly luminescent external rims or domains. The sample reveal only the tiny quantity of the Serpukhovian and Bashkirian zircons.

The Ediacaran–early Cambrian zircons (pop. II; 26.1%) show maxima at 590 Ma and 613 Ma (Fig. 5). Over 83% of these grains have complex textures. Among the pre-Ediacaran zircons (pop. I; 16.3%) subpop. 9 (1460–1480 Ma) should be highlighted (Fig. 3).

5. Results of the comparative analysis

The comparative analysis was performed for the separated age populations I-X (Fig. 3; Supplementary Material 3), with an emphasis on the subpopulations (Fig. 3; Supplementary Material 4) and the pre-Ediacaran clusters (Supplementary Material 3). Here we present only the most important information, while the detailed results are shown in Figs. 7–10 and Tables 2–3.

5.1. *Probable source rocks for the pre-Ediacaran zircons (population I)*

Pre-Ediacaran complex-textured zircons are common (but usually minor) components of Bohemian Massif metamorphic rocks present in various units (e.g., Linnemann et al., 2007; Jastrzębski et al., 2010; Mazur et al., 2012, 2015; Košler et al., 2014) (Table 2); thus zircons of these ages are not useful indicators of source rocks for grains classified as clusters I.2, I.5, and I.6. The exceptions are zircons with the ages of 1.43–1.53 Ga (cluster I.4) and 1.62–1.77 Ga (I.3), which are rare in the Bohemian Massif rocks and are characteristic of, among others, the Moravo–Silesian Zone metamorphic rocks, including the gneisses of the Strzelin Massif, and the Bittesch gneiss of the Thaya Dome (cf., Friedl et al., 2000; Klimas et al., 2009). Moreover, the zircons assigned to

Table 2

The results of the comparative analysis, showing the types of rocks and units containing zircons most similar to the grains under study. The comparative analysis was performed for the individual age populations containing at least five grains (populations V and X were thus excluded), and separately for complex-textured zircons and oscillatory-zoned zircons (references as in Fig. 8).

Age populations	Units and rocks containing zircons most similar to the studied zircons with complex textures	Units and rocks containing zircons most similar to the studied oscillatory-zoned zircons
latest Carboniferous -Permian (population IX)	(only one grain found in the samples under study)	*Lugicum*: volcanic and pyroclastic rocks of the North-Sudetic Basin; *the Moravo-Silesian Zone*: pyroclastics of the Boskovice Basin
Carboniferous (population VIII)	*the Saxothuringian Zone:* high-pressure felsic granulites of the Saxonian Granulite Massif; gneisses of the Erzgebirge; *Lugicum:* high-pressure felsic granulites, eclogites, some gneisses and migmatites (the Śnieżnik Formation) of the Orlica-Śnieżnik Dome; *the Moldanubian Zone*: high-pressure felsic granulites, gneisses and migmatitic gneisses of the Gföhl Unit including the Náměšt Granulite Massif, the Blanský les Massif, and the Lower Austrian massifs; *the Teplá-Barrandian Unit:* the Vír felsic granulite of the Polička Crystalline Complex; *the Kutná Hora Unit:* high-pressure felsic granulite of the Běstvina granulite body	*Lugicum*: various magmatic rocks of the Kłodzko–Złoty Stok Pluton; syenite of the Orlica-Śnieżnik Dome; magmatic rocks of the Stare Město-Belt; pyroclastics of the Bardo Unit; *the Moldanubian Zone*: magmatic rocks of the Jihlava Pluton and Třebíč Pluton; magmatic rocks of the Moldanubian Composite Batholith (especially its two large eastern group bodies: the Weinsberg Composite Pluton and Eisgarn Composite Pluton) including the intrusions; *the Teplá-Barrandian Unit*: syenite porphyry of the Central Bohemian Plutonic Complex; detrital zircons included into the Kasimovian sedimentary rocks of the Kladno Formation (Nýřany Member);
Devonian (ages not older than 410 Ma) (population VII)	*the Saxothuringian Zone:* high-pressure felsic granulites of the Saxonian Granulite Massif; gneisses of the Erzgebirge; *Lugicum:* high-pressure felsic to intermediate granulites of the Góry Sowie Massif, *the Moldanubian Zone*: high-pressure felsic granulites of the Gföhl Unit including the Náměšt Granulite Massif and the Lower Austrian massifs;	(no grains found in the samples under study)
“middle” Silurian –earliest Devonian (population VI)	*the Saxothuringian Zone:* high-pressure felsic granulites of the Saxonian Granulite Massif; *Lugicum*: granulites of the Góry Sowie Massif; granulites of the Orlica-Śnieżnik Dome; *the Moldanubian Zone*: granulites of the Gföhl Unit;	(only four grains found in the samples under study)
Ordovician (ages not older than ~470 Ma) (population IV)	*the Saxothuringian Zone:* high-pressure felsic granulites of the Saxonian Granulite Massif; gneisses of the Erzgebirge; *Lugicum*: the Kowary orthogneiss of the Karkonosze-Izera Massif; the Orla-Gołogłowy orthogneiss of the Kłodzko Metamorphic Massif;	*the Saxothuringian Zone:* granofels of the Eger Complex; *Lugicum*: the Orla-Gołogłowy orthogneiss of the Kłodzko Metamorphic Massif;
late Cambrian– Early Ordovician (population III)	*the Saxothuringian Zone:* high-pressure felsic granulites of the Saxonian Granulite Massif; *Lugicum*: the Kowary orthogneiss of the Karkonosze-Izera Massif; the Orla-Gołogłowy orthogneiss of the Kłodzko Metamorphic Massif; gneisses and migmatites (mainly the Śnieżnik Formation) and the metasediments (including the Stronie Formation quartzite and the Goszów quartzite) of the Orlica-Śnieżnik Dome; *the Moldanubian Zone:* felsic granulites and gneisses of the Gföhl Unit (the Lower Austrian massifs); the Dobra gneiss type B2 of the Drosendorf Unit (the Lower Austria); gneisses of the Varied Unit;	*Lugicum*: some magmatic rocks of the Karkonosze-Izera Massif;
Ediacaran–early Cambrian (population II)	*Lugicum*: metasediments of the Orlica-Śnieżnik Dome including the Goszów quartzite, the Młynowiec Formation paragneiss, the Stronie Formation quartzite, the Wyszki paragneiss; the Brousek metasandstone of the Stare Město Belt; the Orla-Gołogłowy gneiss of the Kłodzko Metamorphic Massif; *the Moravo-Silesian Zone*: gneisses of the Keprník Nappe and the Desna Dome; the Bittesch gneiss and the Eggenburg gneiss of the Thaya Batholith (Lower Austria); *the Moldanubian Zone:* the Spitz gneiss and the Dobra gneiss type B2 of the Drosendorf Unit (the Lower Austria); gneisses and migmatitic gneisses of the Monotonous Unit and Varied Unit;	*the Saxothuringian Zone*: (meta)sediments of the Schwarzburg Anticline; (meta)sediments of the Lausitz Block; magmatic rocks of the Lusatian Granodiorite Complex; *Lugicum*: the Gackowa Formation (meta) sandstones of the Kaczawa Metamorphic Unit; metasediments of the Orlica-Śnieżnik Dome including the Młynowiec Formation paragneiss, the Stronie Formation quartzite and mica schists, the Wyszki paragneiss; the Orla-Gołogłowy gneiss of the Kłodzko Metamorphic Massif; magmatic rocks of the Kłodzko-Złoty Stok Pluton; the Moldanubian Zone: gneisses of the Monotonous Unit; the Dobra gneiss type B2 of the Drosendorf Unit (the Lower Austria); *the Moravo-Silesian Zone*: the Nowolesie gneiss of the Strzelin Complex)Fore Sudetic Block); metapegmatite of the Desná Dome; the Bittesch gneiss and the Eggenburg gneiss of the Thaya Batholite (the Lower Austria;) *the Carpathians:* clast of granitoids uprooted from

(*continued on next page*)

Table 2 (*continued*)

Age populations	Units and rocks containing zircons most similar to the studied zircons with complex textures	Units and rocks containing zircons most similar to the studied oscillatory-zoned zircons
		the Brunovistulian basement included into the Carpathian rocks
Pre-Ediacaran (> 635 Ma) (population I)	I.1 (2.62–2.81 Ga) *Saxothuringian Zone:* the Lausitz Block; *Lugicum*: metasediments of the Orlica-Śnieżnik Dome; *the Moldanubian Zone*: gneisses of the Monotonous Unit; I.2 (1.79–2.13 Ga) *Saxothuringian Zone*: (meta) sediments of various units; *Lugicum*: (meta)sediments o the Kaczawa Metamorphic Unit and the Orlica–Śnieżnik Dome (including the Goszów quartzite, the Młynowiec Formation paragneiss, the Stronie Formation quartzite, the Wyszki paragneiss); *the Moravo-Silesian Zone*: the gneisses of the Strzelin Massif and the Thaya Batholith; *the Moldanubian Zone*: the Dobra gneiss type B2 of the Drosendorf Unit, and gneisses the Monotonous and Varied units; *Baltica:* gneisses and migmatites of Fennoscandian Shield; I.3 (1.62–1.77 Ga) and I.4 (1.43–1.53 Ga) quite rare in the Bohemian crystalline units: *the Moravo-Silesian Zone*: the gneisses of the Strzelin Massif the Bittesch gneisses of the Thaya Batholith; *the Moldanubian Zone*: the Dobra gneiss type B2 of the Drosendorf Unit, and gneisses the Monotonous and Varied units; *Baltica:* gneisses and migmatites of Fennoscandian Shield; I.5 0.88–1.16 Ga *Saxothuringian Zone:* (meta) sediments of various units; *the Moravo-Silesian Zone*: the gneisses of the Keprník Nappe and the Desná Dome; *the Moldanubian Zone*: the Dobra gneiss type B2 of the Drosendorf Unit, and gneisses the Monotonous and Varied Units; *Baltica:* gneisses and migmatites of Fennoscandian Shield; I.6 0.65–0.75 Ga *Saxothuringian Zone*: metasediments of the western part of the zone; *Lugicum*: metasediments the Kaczawa Metamorphic Unit and the Orlica–Śnieżnik Dome; *the Moldanubian Zone:* rare in some gneisses;	Clusters I.1–1.6: *the Saxothuringian Zone*: magmatic rocks of the Lusatian Granodiorite Complex; *Baltica*: its Fennoscandian part;

clusters I.2, I.3, and I.5 are typical of various gneisses and migmatites of the Fennoscandian Shield (Baltica; e.g., Bogdanova et al., 2015, Scherstén et al., 2000; Zariņš and Johansson, 2009; Bingen and Viola, 2018) (Fig. 10; Table 2).

5.2. *Probable source rocks for the Ediacaran–early Cambrian zircons (population II)*

Zircons of this age range are common in Bohemian Massif rocks, but complex-textured zircons merely accompany the more numerous oscillatory-zoned zircons (Figs. 7–9). The complex-textured grains we examined have a set of characteristics that makes them similar especially to zircons contained in low-grade metasediments and gneisses of the Orlica–Śnieżnik Dome (Figs. 7–8; Table 2) (cf., Mazur et al., 2012, 2015; Jastrzębski et al., 2010, 2015). Most zircons from these metasediments are oscillatory-zoned, but homogenous zircons are also present. In fact, CL microphotographs presented in the contributions mentioned above clearly show signs of resorption of cores, thin homogenous rims, or homogenous domains of different CL luminescence than the cores, which makes the metasediment-included zircons similar to the complex-textured grains under study. The ages and Th/U values of the zircons from the Orlica–Śnieżnik Dome metasediments are most closely comparable to the grains assigned to subpop. 5 of the Induan sample, 8 of the Olenekian sample, 5 and 6 of the Cenomanian sample, as well as 6 and 7 of the Coniacian sample (Figs. 7–8; Table 2). Besides, gneisses of the Moravo–Silesian Zone and the Moldanubian Zone contain similar zircons (cf., Friedl et al., 2000, 2004; Kröner et al., 2000b; Košler et al., 2014; Lindner et al., 2020) (Figs. 7–8). Importantly, the zircons contained in these gneisses usually have very low Th/U values, often >0.2, which is very rare considering the Bohemian-Massif-rock-bearing zircons of such ages, and make them comparable particularly to the grains assigned to subpop. 6 of the Induan sample, 8 of the Olenekian sample, and 6 of the Coniacian sample (Figs. 7–8; Table 2).

Oscillatory zoned zircons with comparable features occur in the Bohemian Massif igneous rocks, (meta)volcanics, metasediments, and gneisses, which had magmatic protoliths. Such zircons have been found in the rocks of the Saxothuringian Zone, including Lugicum (cf., Kröner et al., 1994; Mazur et al., 2004; Linnemann et al., 2004, 2007; Kryza et al., 2007; Jastrzębski et al., 2010; Mazur et al., 2012, 2015) and fit into the fields of various subpopulations (Figs. 8–9). It is worth emphasizing that the metasediments of the Orlica–Śnieżnik Dome contain zircons that are best suited to the early Cambrian grains included in subpop. 10 of the Norian sample (Figs. 8–9; Table 2). Similar zircons occur also as an inherited, subordinate component of magmatic rocks of the Kłodzko–Złoty Stok Pluton (cf., Mikulski et al., 2013; Jastrzębski et al., 2018) (Figs. 8–9). Moreover, gneisses and quartzites of the Moldanubian Zone (cf., Košler et al., 2014; Lindner et al., 2020), and the Moravo–Silesian Zone (cf., Friedl et al., 2004; Żelaźniewicz et al., 2005; Klimas et al., 2009) bear similar zircons (Figs. 8–9). It is also worth pointing out clasts of granitoids uprooted from the Brunovistulian basement during the Alpine orogeny and included into the Carpathians (cf., Budzyń et al., 2011; Burda et al., 2019). Their zircons fit best into subpop. 11 of the Norian sample and 7 of the Induan sample but in a lesser degree (Figs. 8–9).

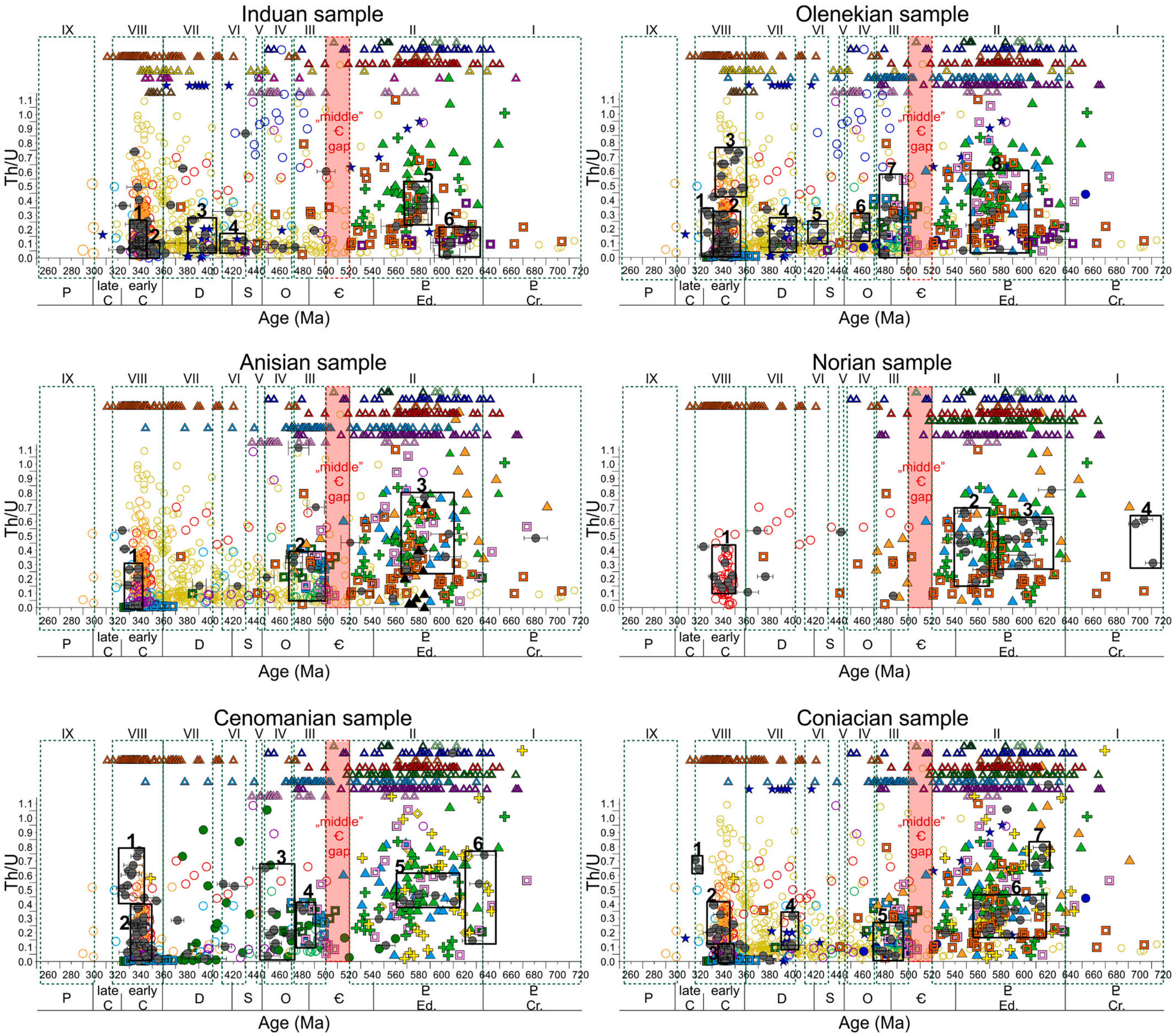


Fig. 7. Diagrams for the examined samples showing the results of comparative analysis for complex-textured zircons with ages ≤635 Ma. Only data from the most similar zircons in terms of their ages, Th/U values, and internal textures are presented. At the top of the diagram, above the X axis, are the age data points with no Th/U values. The Roman numerals visible above the diagrams refer to the selected populations I–X, while black rectangles and the Arabic numbers indicate the fields of the specific subpopulations (see also Table 2 and Table 3). The "middle" Cambrian gap of ~500–520 Ma is marked with a reddish rectangle. The legend for the diagrams is provided in Fig. 8. (For the colors in this figure, the reader is referred to the online version of this article.)

5.3. *Possible source rocks for the late Cambrian–Early Ordovician zircons (population III)*

In general, crystalline rocks containing zircons of this age range occur in the Saxothuringian Zone, including Lugicum, and the Moldanubian Zone, but are practically absent in the Moravo–Silesian Zone. In particular, the most comparable zircons occur in the metamorphic rocks of the Orlica–Śnieżnik Dome (cf., Żelaźniewicz et al., 2006; Jastrzębski et al., 2010; Mazur et al., 2012, 2015; Redlińska-Marczyńska et al., 2016) (Figs. 7–8). The zircons from the Orlica–Śnieżnik Dome gneisses most closely match the grains assigned to subpop. 2 of the Anisian sample (Figs. 3 and 7–8). Other possible counterparts are zircons contained in the granulites and gneisses of the Moldanubian Zone (cf., Friedl et al., 2004, 2011; Košler et al., 2014); they most closely match the grains classified as subpop. 7 of the Olenekian sample, 2 of the Anisian sample again, and 5 of the Coniacian sample (Figs. 7–8; Table 2).

The oscillatory zoned zircons of this age population are similar to the rare zircons found in various (meta)igneous and metasedimentary rocks of the Saxothuringian and Lugian domains (e.g., Jastrzębski et al., 2010; Mazur et al., 2012; Linnemann et al., 2014) (Figs. 8–9).

5.4. *Probable source rocks for the Ordovician zircons (population IV)*

The Ordovician detrital zircons with complex textures show features comparable to zircons contained mostly in the Saxothuringian Zone rocks, including the gneisses of the Erzgebirge (cf., Tichomirowa et al., 2005), which are most similar to zircons assigned to subpop. 3 of the Cenomanian sample (Figs. 7–8). Comparable zircons occur also in the Lugian rocks, the gneisses of the Karkonosze–Izera Massif (cf., Oberc-Dziedzic et al., 2010b) (see subpop. 6 in the Olenekian sample), but they constitute subordinate populations in these rocks (Figs. 3 and 7–8).

In the case of the Ordovician oscillatory-zoned zircons, comparable

Fig. 8. Legend for Figs. 7, 9, and 10. Data on zircons from rocks cropping out in: the Saxothuringian Zone, the Schwarzburg Anticline after Linnemann et al., 2004; the Granulitgebirge – Sagawe et al., 2016; the Erzgebirge – Tichomirowa et al., 2005; the Eger Crystalline Complex – Konopásek et al., 2014; the Lausitz Anticline – Linnemann et al., 2004, 2007; the Lausitz-Izera Massif – Kröner et al., 1994; the Karkonosze-Izera Massif – Oberc-Dziedzic et al., 2010a; Žák et al., 2013; the Kaczawa Complex – Kryza et al., 2007; the Góry Sowie – O'Brien et al., 1997; Kryza and Fanning, 2007; the Bardo Unit – Kryza et al., 2011; the Kłodzko Metamorphic Massif – Mazur et al., 2004; the Kłodzko-Złoty Stok Pluton – Mikulski et al., 2013; the Orlica-Śnieżnik Dome – Żelaźniewicz et al., 2006; Bröcker et al., 2010; Jastrzębski et al., 2010; Mazur et al., 2012, 2015; Walczak et al., 2017; Redlińska-Marczyńska et al., 2016; the Stare Město Belt – Jastrzębski et al., 2015, 2018; the Moravo-Silesian Zone, the Strzelin Massif – Klimas et al., 2009; the Desna Dome – Kröner et al., 2000b; Żelaźniewicz et al., 2005; the Keprník Nappe – Kröner et al., 2000b; the Bittesch gneiss – Friedl et al., 2000, 2004; the Thaya Batholith – Friedl et al., 2004; the Teplá-Barrandian Unit, the Polička Crystalline Complex – Tajčmanová et al., 2010; the western part of the Teplá-Barrandian Unit – Žák et al., 2018; the Kutná Hora Unit – Nahodilová et al., 2014; the Moldanubian Unit, the Náměšt Granulite Massif – Kusbach et al., 2015; the Blanský les – Wendt et al., 1994; Kröner et al., 2000a; the other metamorphic units of the Moldanubian Zone – Friedl et al., 2004, 2011; Košler et al., 2014; Lindner et al., 2020; the Třebíč and Jihlava plutons – Kotková et al., 2010; Kusiak et al., 2010; the Moldanubian Composite Batholith and intrusions – Klomínský et al., 2010; the other units, the Central Bohemian Plutonic Complex – Kubínová et al., 2017; the Boskovice Basin – Opluštil et al., 2017; the North Sudetic Basin – Awdankiewicz et al., 2013; the Western Outer Carpathians – Budzyń et al., 2011; Burda et al., 2019; Fennoscandia – Scherstén et al., 2000; Rämö et al., 2001; Andersen et al., 2000a, Andersen et al., 2000b; Andersson et al., 2001; Bingen et al., 2008; Zariņš and Johansson, 2009; Waight et al., 2012; Bogdanova et al., 2015; Lahtinen et al., 2017; Bingen and Viola, 2018. (For the colors in this figure, the reader is referred to the online version of this article.)

data are also very scarce. Only some granofels and gneisses of the Saxothuringian Zone and Lugicum bear similar zircons (Mazur et al., 2004; Konopásek et al., 2014), but the available data points are too poor to allow them to be confidently compared with subpop. 11 in the Olenekian sample (Figs. 8–9).

5.5. *Probable source rocks for the Devonian zircons (population VII)*

The grains of this age are similar to zircons, which are additional, often less numerous, components accompanying the Carboniferous zircons in the granulites and high-grade gneisses of the Bohemian Massif (e.g., Sagawe et al., 2016; Figs. 7–8; Table 2). Moreover, the Devonian granulites of the Góry Sowie Massif contain numerous zircons with similar features to those we studied (Figs. 7–8) (cf., O'Brien et al., 1997; Kryza and Fanning, 2007). The abundant data reported from the Bohemian granulites cover all the fields of the separated subpopulations in the studied samples (Figs. 7–8; Table 2). The grains assigned to subpop. 3 of the Induan sample and 4 of the Olenekian sample are particularly comparable to the zircons, which were reported from the felsic granulites of the Moldanubian Zone (Figs. 3 and 7–8) (cf., Friedl et al., 2004, 2011; Kusbach et al., 2015).

5.6. *Probable source rocks for the Carboniferous zircons (population VIII)*

Crystalline rocks that contain Carboniferous zircons or zircon domains are very common in the Bohemian Massif. In the case of the zircons with complex textures, the studied early Carboniferous grains have features characteristic predominantly of zircons contained in high-grade gneisses and the felsic granulites of the western part of the Saxothuringian Zone (cf., Tichomirowa et al., 2005; Sagawe et al., 2016), and granulites, eclogites, gneisses and migmatites of the Lugicum (mostly the Orlica–Śnieżnik Dome; cf., Bröcker et al., 2010; Redlińska-Marczyńska et al., 2016; Walczak et al., 2017), and granulites and gneisses of the Moldanubian Zone (the Gföhl Unit; e.g., Kröner et al., 2000a; Kusbach et al., 2015; Košler et al., 2014) (Figs. 7–8; Table 2). It is worth highlighting the similarity of zircons from the Lugian granulites reported by Walczak et al. (2017) to the Visean and late Tournaisian grains, in particular to: subpop. 1 in the Induan sample, 2 in the

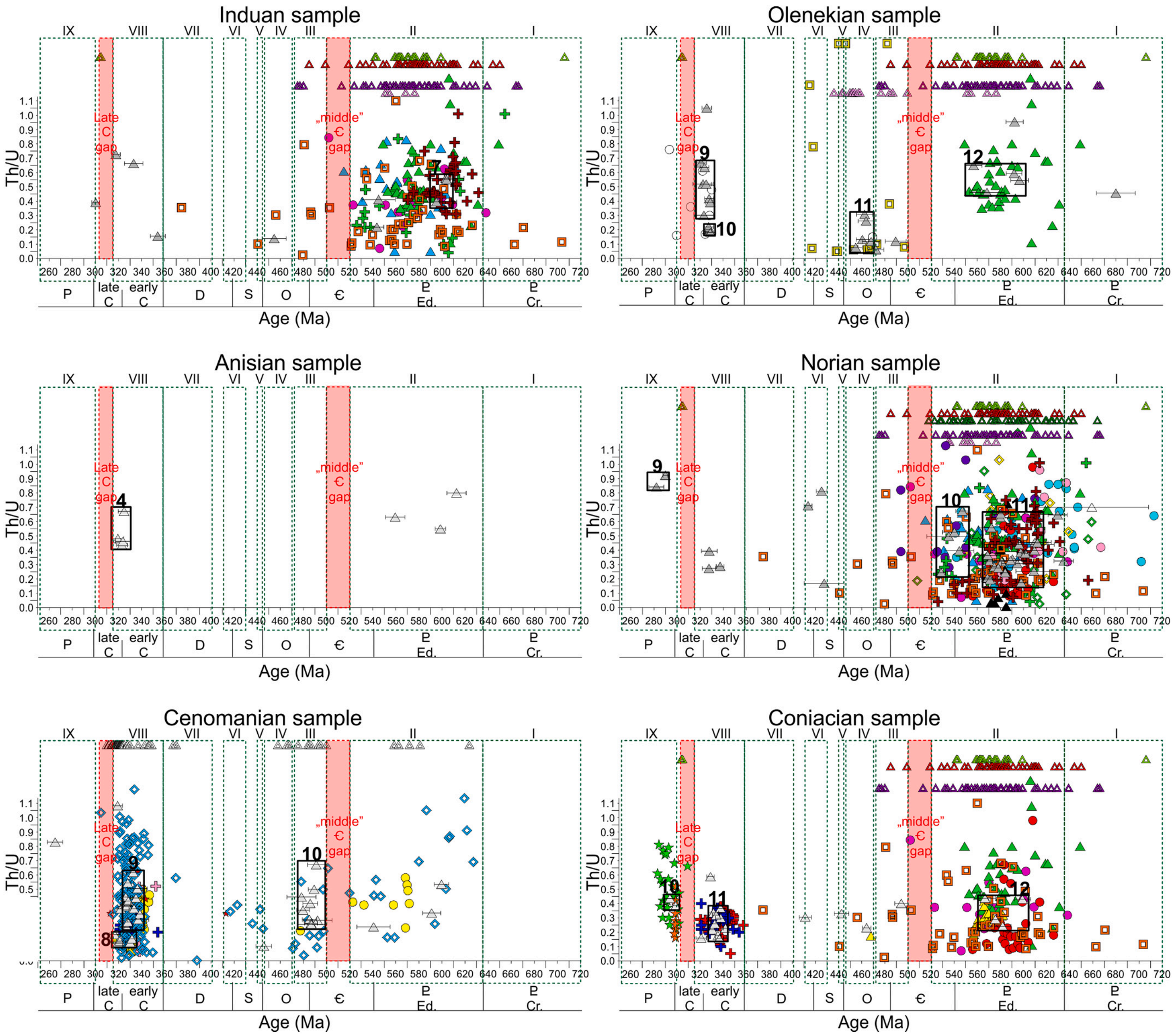


Fig. 9. Diagrams for the examined samples showing the results of comparative analysis for oscillatory-zoned zircons with ages ≤635 Ma. Only data from the most similar zircons in terms of their ages, Th/U values, and internal textures are presented. At the top of the diagram, above the X axis, are the age data points with no Th/U values. The Roman numerals visible above the diagrams refer to the selected populations I–X, while black rectangles and the Arabic numbers indicate the fields of the specific subpopulations (see also Table 2 and Table 3). The latest Carboniferous gap of ~303–315 Ma and the "middle" Cambrian gap of ~500–520 Ma are marked with reddish rectangles. The legend for the diagrams is provided in Fig. 8. (For the colors in this figure, the reader is referred to the online version of this article.)

Olenekian sample, 1 in the Norian sample, 2 in the Cenomanian sample, as well 2 and 3 in the Coniacian sample (Figs. 7–8; Table 2). The U-Pb ages and Th/U values coming from zircons of the Gföhl Unit rocks most closely match those obtained from the complex-zoned grains classified as subpop. 1 and 2 in the Induan sample, 2 in the Olenekian sample, 2 in the Cenomanian sample, and 3 in the Coniacian sample (Figs. 7–8). Interestingly, the data from these authors, in contrast to those from Walczak et al. (2017), do not really fit into subpop. 1 in the Norian sample due to very low Th/U values.

The oscillatory-zoned detrital zircons studied here, whose ages range mostly from Bashkirian to Visean, have a set of features characteristic of the zircons that are the constituents of the Bohemian Massif igneous rocks. Zircons contained in the magmatic rocks of Lugicum showed the greatest resemblance to these grains (Figs. 8–9) (cf., Kryza et al., 2011; Mikulski et al., 2013; Oberc-Dziedzic et al., 2015; Jastrzębski et al., 2018). The U-Pb and Th/U data obtained from zircons of the magmatic rocks of the Kłodzko–Złoty Stok Pluton most closely matches those of grains assigned to subpop. 8 and 9 of the Cenomanian sample, those from bentonite of the Bardo Unit best fit into field of subpop. 9 in the Cenomanian sample, and those from the Staré Město Belt granitoids fit into the field of subpop. 11 in the Coniacian sample (Figs. 8–9; Table 2). Considering the Moldanubian Zone, plutonic rocks of the Jihlava Pluton and Třebíč Pluton (cf., Kotková et al., 2010; Kusiak et al., 2010) contain zircons with features similar to the grains under study, particularly to those of the grains in subpop. 9 of the Cenomanian sample and 11 of the Coniacian sample (Figs. 8–9; Table 2). Furthermore, the Moldanubian Composite Batholith mainly contains Serpukhovian zircons, while its younger felsic intrusions contain the Bashkirian zircons, which makes all of them suitable as source rocks for such Carboniferous grains; unfortunately no Th/U values have been published (Gerdes et al., 2003;

Finger et al., 2003; Klomínský et al., 2010) (Figs. 8–9).

5.7. Significance of the age gaps

Four age gaps are identified in the examined zircon suite: ∼ 303–315 Ma, 500–520 Ma, 2.13–2.60 Ga and > 2.81 Ga. The lack of grains in these age ranges makes it necessary to exclude rocks and units containing such zircons as probable counterparts of source rocks (Table 3). This concerns predominantly magmatic and metamorphic rocks of various Saxothuringian units, e.g., (meta)sediments of the Schwarzburg Anticline, the Torgau–Doberlung Syncline and the Elbe Zone, as well as the quite distant Baltician units (the Ukrainian Shield, the Podolian Domain, and the Volyn–Orsha Aulacogen) (e.g., Bibikova et al., 2013; Shumlyanskyy et al., 2015; Abubaker et al., 2017). Various (meta)volcanic rocks from many Bohemian Massif units (e.g., Nowak et al., 2011) are also discarded (Table 3).

5.8. Probable secondary source rocks (sedimentary rocks) for the studied zircons

No studies of detrital zircon from syn-Variscan or post-Variscan sedimentary formations located in units adjacent to the study area have been published, which means that there are no materials suitable for comparative analysis and identification of potential secondary source rocks. The closest situated Carboniferous to Cretaceous siliciclastics with dated zircons occur within the Bohemian Massif, i.e., the Elbe Zone and the northern part of the Bohemian Cretaceous Basins (∼250–340 km west from the study sites; Hofmann et al., 2017; Nádaskay et al., 2019), the western part of the Bohemian Cretaceous Basin and the Teplá–Barrandian Unit area (∼260–410 km west from the study sites; Žák et al., 2018), and outside the Bohemian Massif, in the vicinity of Jena in Thuringia (∼450–500 km west from the study sites; Augustsson et al., 2018). Only the Kasimovian part of the Kladno Formation located in the Teplá–Barrandian Unit contains detrital zircons (cf., Žák et al., 2018) with features comparable to the Carboniferous oscillatory-zoned zircons we studied, and in particular to the zircons of subpop. 8 and 9 in the Cenomanian sample (Figs. 8–9; Table 2). Importantly, in contrast to the samples studied, all the above-mentioned grain suites are dominated by oscillatory-zoned zircons with relatively high Th/U values (the references as above).

6. Discussion

The diverse shapes, internal textures, chemical and isotopic compositions, and crystallization ages of the zircons studied here provide evidence that each of the six samples must be a mixture of the grains that were originally released from various crystalline source rocks and likely derived from different source areas. Although the comparative analysis has some restrictions and insufficiencies it nonetheless allowed for the selection of the most likely counterparts of the eroded crystalline source rocks and further interpretations.

6.1. Crystalline source rocks and their paleolocations

6.1.1. Felsic granulites as the source rocks for the complex-textured zircons

The comparative analysis reveal that the high-grade and medium-grade metamorphic rocks must have been the most important source rocks for the majority of the examined complex-textured zircons. Firstly, the Bohemian Massif high-pressure felsic granulites contain zircons similar to the studied grains, mainly of the Paleozoic ages. These granulites contain two characteristic types of complex-textured zircons: spherical or nearly spherical grains, and elongated, anhedral to subhedral zircons with rounded terminations (e.g., Bröcker et al., 2010; Friedl et al., 2011). Both types occur in the examined samples.

Importantly, the granulites contain zircons of various ages. The zircons with early Carboniferous ages (usually found in rims or external domains) clustering mostly at ∼340 Ma are the most numerous, while late Carboniferous and Devonian to Proterozoic zircons accompany them (Bröcker et al., 2010; Kusbach et al., 2015; Sagawe et al., 2016; Walczak et al., 2017), with the exception of the Góry Sowie Massif granulites (O'Brien et al., 1997; Kryza and Fanning, 2007; Tabaud et al., 2021). This range of ages clearly coincides with the ages and frequency

Table 3

Results of the comparative analysis showing the types of rocks and units containing complex-textured zircons and oscillatory-zoned zircons in the age ranges of the found age gaps. Data on zircons within the ∼303–315 Ma gap are after: Awdankiewicz et al., 2010; Oberc-Dziedzic et al., 2010a, 2013; Kryza et al., 2012, 2014; Žák et al., 2013; Mikulski and Williams, 2014; Turniak et al., 2014; Opluštil et al., 2016; Jastrzębski et al., 2018. Data on zircons within the 500–520 Ma gap are after: Turniak et al., 2000; Klimas et al., 2003, 2009; Kryza and Fanning, 2007; Tyszka et al., 2007; Oberc-Dziedzic et al., 2009, 2010a, 2013, 2015, 2018; Mazur et al., 2010, 2012, 2015; Nowak et al., 2011; Białek et al., 2014; Košler et al., 2014; Turniak et al., 2014; Jastrzębski et al., 2015; Redlińska-Marczyńska et al., 2016; Abubaker et al., 2017; Zieger et al., 2017; Szczepański et al., 2020. Data on zircons within the both Precambrian gaps are after: Linnemann et al., 2007, 2014; Żelaźniewicz et al., 2009; Žáčková et al., 2012; Bibikova et al., 2013; Shumlyanskyy et al., 2015; Lobach-Zhuchenko et al., 2016; Abubaker et al., 2017; Žák and Sláma, 2018; Žák et al., 2018; Paszkowski et al., 2019; Szczepański et al., 2020.

Age gap	Units and rocks containing complex-textured zircons with ages in ranges of the separated age gaps	Units and rocks containing oscillatory-zoned zircons with ages in ranges of the separated age gaps
the late Carboniferous gap of ∼303–315 Ma		*Lugicum:* some magmatic rocks of the Karkonosze–Izera Massif, the Strzegom–Sobótka Pluton, the Orlica–Śnieżnik Dome, rhyolites of the Kaczawa Metamorphic Unit; *the Moravo–Silesian Zone*: some plutonic rocks of the Strzelin Massif; *the Intra-Sudetic Basin:* the volcanics and pyroclastics;
the "middle" Cambrian gap of 500–520 Ma	*Lugicum*: metavolcanics of the Lausitz-Izera Massif, the Kłodzko Metamorphic Unit, the Orlica–Śnieżnik Dome, and the Staré Město Belt; some types of gneisses from the Karkonosze–Izera Massif, the Strzelin Massif, and the Doboszowice Massif, the migmatitic gneisses of the Orlica–Śnieżnik Dome; *the Moravo-Silesian Zone:* some mica schists; the Moldanubian Zone: some gneisses of the Varied Unit;	*Saxothuringian Zone:* some (meta)sediments of the Torgau–Doberlung Syncline; some (meta)sediments, plutonic and (meta)volcanic rocks of the Lausitz-Izera Massif, the Kaczawa Metamorphic Unit, the Strzegom–Sobótka Pluton; Lugicum: (meta)volcanics and metasediments of the Kłodzko Metamorphic Unit, the Orlica–Śnieżnik Dome, and the Strzelin Massif
2.13–2.60 Ma and > 2.81 Ma	*Saxothuringian Zone*: (meta) sediments of the Schwarzburg Anticline, the Torgau–Doberlung Syncline and the Elbe Zone; *Lugicum*: metasediments of the Bystrzyckie Mountains in the Orlica–Śnieżnik Dome and the Karkonosze–Izera Massif; *the Teplá–Barrandian Unit:* (meta)sedimentary rocks; Baltica: metamorphic, and sedimentary rocks of Sarmatia (the Ukrainian Shield and the Podolian Domain) and the Volyn–Orsha Aulacogen;	*Saxothuringian Zone*: (meta) sediments of the Schwarzburg Anticline, the Torgau–Doberlung Syncline and the Elbe Zone; *Lugicum*: metasediments of the Bystrzyckie Mountains in the Orlica–Śnieżnik Dome and the Karkonosze–Izera Massif; *the Teplá–Barrandian Unit:* (meta)sedimentary rocks; Baltica: magmatic, metamorphic, and sedimentary rocks of Sarmatia (the Ukrainian Shield and the Podolian Domain) and the Volyn–Orsha Aulacogen; the Małopolska Block: magmatic rocks;

of grains in the examined samples. Moreover, the granulite-contained zircons have Th/U values most often lower than or equal to 0.2 (cf., Sagawe et al., 2016), as is the case for most of the Carboniferous-to-Cambrian zircons under study.

Presently, the small-volume bodies of felsic granulites are scattered in various units of the Bohemian Massif, with the most numerous near its eastern margin (cf., Kotková, 2007; Pertoldová et al., 2010; Faryad et al., 2010). Strong similarity of zircons from different granulite bodies makes it difficult to identify specific bodies as probable counterparts of the source rocks. However, taking into account the eastern part of the Bohemian Massif, the most similar zircons to the early Carboniferous and Devonian grains (pop. VIII and VII), as well as to the Ordovician and Cambrian grains (pop. III and IV) are present in the granulites of the Orlica–Śnieżnik Dome, the Náměšt Granulite Massif, and the Lower Austrian massifs, though a relatively small number of data points were available for the comparison (Figs. 3 and 7) (Friedl et al., 2004; Bröcker et al., 2010; Kusbach et al., 2015; Walczak et al., 2017). It is also worth mentioning that some Carboniferous-to-Ordovician zircons contained in these bodies have CL-induced bright rims (Friedl et al., 2004; Bröcker et al., 2010; Sagawe et al., 2016; Walczak et al., 2017), as have some of the examined zircons with corresponding ages.

The proposed interpretation is consistent with the results of previous studies on detrital garnets contained in the Carboniferous to Middle Triassic sedimentary rocks, which crop out in the northeastern and eastern margins of the Bohemian Massif and its foreland. The felsic granulite-derived pyrope-almandines outnumber other types of garnets present in these deposits (Hartley and Otava, 2001; Čopjaková et al., 2005; Kowal-Linka and Stawikowski, 2013; Kowal-Linka and Walczak, 2018), which suggests that the Bohemian Massif granulite bodies had to be much larger and better exposed in the past and must have been a significant source of detritus (cf., Čopjaková et al., 2005). This clear concordance between our present results based on detrital zircons and the previous outcomes based on detrital garnets speaks in favor of the above interpretation.

6.1.2. *Gneisses, eclogites, and migmatites as the source rocks for the complex-textured zircons*

The Bohemian Massif high-grade to medium-grade gneisses, eclogites, and migmatites contain elongated anhedral to subhedral zircons with rounded terminations, which have a wide range of the Carboniferous to Precambrian ages, often low Th/U values, and predominantly complex textures (e.g., Bröcker et al., 2010), which make them (though not all) the probable counterparts of the eroded source rocks.

The "middle" Cambrian age gap found in the examined samples (Fig. 7) forced the exclusion of some of the Bohemian Massif metamorphic rocks as likely counterparts (Table 3). While this gap initially narrows the choice and facilitates the identification of potential counterparts of source rocks, it hinders in the next step the selection of the tectonostratigraphic units as potential source areas, since at the present erosional level, the metamorphic rocks containing zircons with the sought-for characteristics coexist in the same units with other metamorphic rocks containing relatively abundant 500–520 Ma-old zircons. For instance, the Orlica–Śnieżnik Dome gneisses and eclogites are especially worth attention as probable counterparts of the source rocks, as they contain Carboniferous zircons characterized by extremely low Th/U values (cf., Bröcker et al., 2010; Redlińska-Marczyńska et al., 2016), which are very rare in the other Bohemian Massif metamorphic rocks. These values, along with the other features being compared, makes these zircons similar to some of the Carboniferous grains we examined (see subpop. 1 in the Induan sample, 2 in the Olenekian sample, 3 in the Coniacian sample, and others) (Figs. 3 and 7–8) and clearly suggest their derivation from these rock types. However, some migmatitic gneisses of the Orlica–Śnieżnik Dome, which are now exposed in the immediate vicinity contain relatively abundant zircons bearing 500–520 Ma ages, which make them unlikely as equivalents. These results suggest that the metamorphic rocks containing zircons with the required characteristics, or some sedimentary rocks comprising their debris, previously formed larger and more exposed bodies that were more prone to erosion than those containing the numerous "middle" Cambrian zircons, which could form only tiny exposures or be buried.

Moreover, the presently exposed gneisses and eclogites contain zircons with diversified ages and textures, which make them the likely equivalents of the source rocks for various detrital zircons. For example, the Orlica–Śnieżnik Dome eclogites contain numerous Carboniferous-to-Devonian zircons displaying diffuse and blurred zoning patterns, patchy, sector and fir-tree zoning, but also the Ordovician and Cambrian zircons with variably preserved relics of the oscillatory zoning (cf., Bröcker et al., 2010). These characteristics are similar to those of the grains with corresponding ages we examined.

Besides, the thin, bright external rims on the Paleozoic zircons, commonly observed in the examined grains, were also reported for zircons contained in the gneisses and eclogites of the Orlica–Śnieżnik Dome (cf., Bröcker et al., 2010; Redlińska-Marczyńska et al., 2016) and the gneisses of the Monotonous and Varied units (Košler et al., 2014). Their presence additionally suggests the derivation of the Paleozoic zircons from such rocks and units.

6.1.3. *Metasediments as the source rocks for the complex-textured zircons*

The Bohemian Massif quartzites, mica schists, and paragneisses, which underwent (very) low-grade metamorphism or mid-amphibolite facies metamorphism and further retrogression to the greenschist facies, are likely other important counterparts for the source rocks. Admittedly complex-textured zircons usually accompany the more numerous oscillatory-zoning zircons in these metasediments, but they were often indicated for the pop. II–IV (Figs. 3 and 7–8).

The metasediments of the eastern margin of the Bohemian Massif, mostly of the Orlica–Śnieżnik Dome, are the most likely counterparts of the source rocks. Importantly, at the present erosional level, the metasedimentary rocks coexist in the Orlica–Śnieżnik Dome with the previously indicated granulites, gneisses and eclogites (e.g., Redlińska-Marczyńska et al., 2016).

Besides, the metamorphic rocks of Baltica may have supplied complex-textured zircons, particularly the Precambrian ones occurring in the Norian sample (Fig. 10).

6.1.4. *Magmatic and metamorphic rocks as the source rocks for the oscillatory-zoned zircons*

Considering the oscillatory-zoned zircons, which have Th/U values commonly above or close to 0.2, they must have been released from magmatic rocks, metamorphic rocks having magmatic protoliths, or (meta)sedimentary rocks containing the debris of such rocks (cf., Corfu et al., 2003). The Carboniferous zircons (pop. VIII) showed the greatest resemblance to those contained in the various Variscan and post-Variscan magmatic rocks and pyroclastics of the Saxothuringian and Moldanubian zones, while the Precambrian and early Paleozoic zircons (pop. I–IV) have features similar to those occurring in the metasediments of the above units, as well as of the Moravo–Silesian Zone and Baltica (Figs. 8–10).

The proportions of the grains bearing various Carboniferous ages are what limit and facilitate the selection of the most probable equivalents of the source rocks. The Induan, Olenekian, and Anisian samples mainly contain the Serpukhovian and Bashkirian grains and no Visean zircons at all. This suggests derivation of the zircons from Serpukhovian and/or Bashkirian magmatic bodies without 303–315-Ma-old component, due to the identified age gap. Only the Moldanubian Composite Batholith (Fig. 1C) meets these criteria, as about 80% of it was formed during Serpukhovian, and its main bodies are accompanied by younger intrusions (Gerdes et al., 2003; Finger et al., 2003; Klomínský et al., 2010). In the case of both Cretaceous samples, in which the Visean zircons outnumber the Serpukhovian and Bashkirian grains, or are similar in number, the zircons must have been derived from Visean igneous bodies

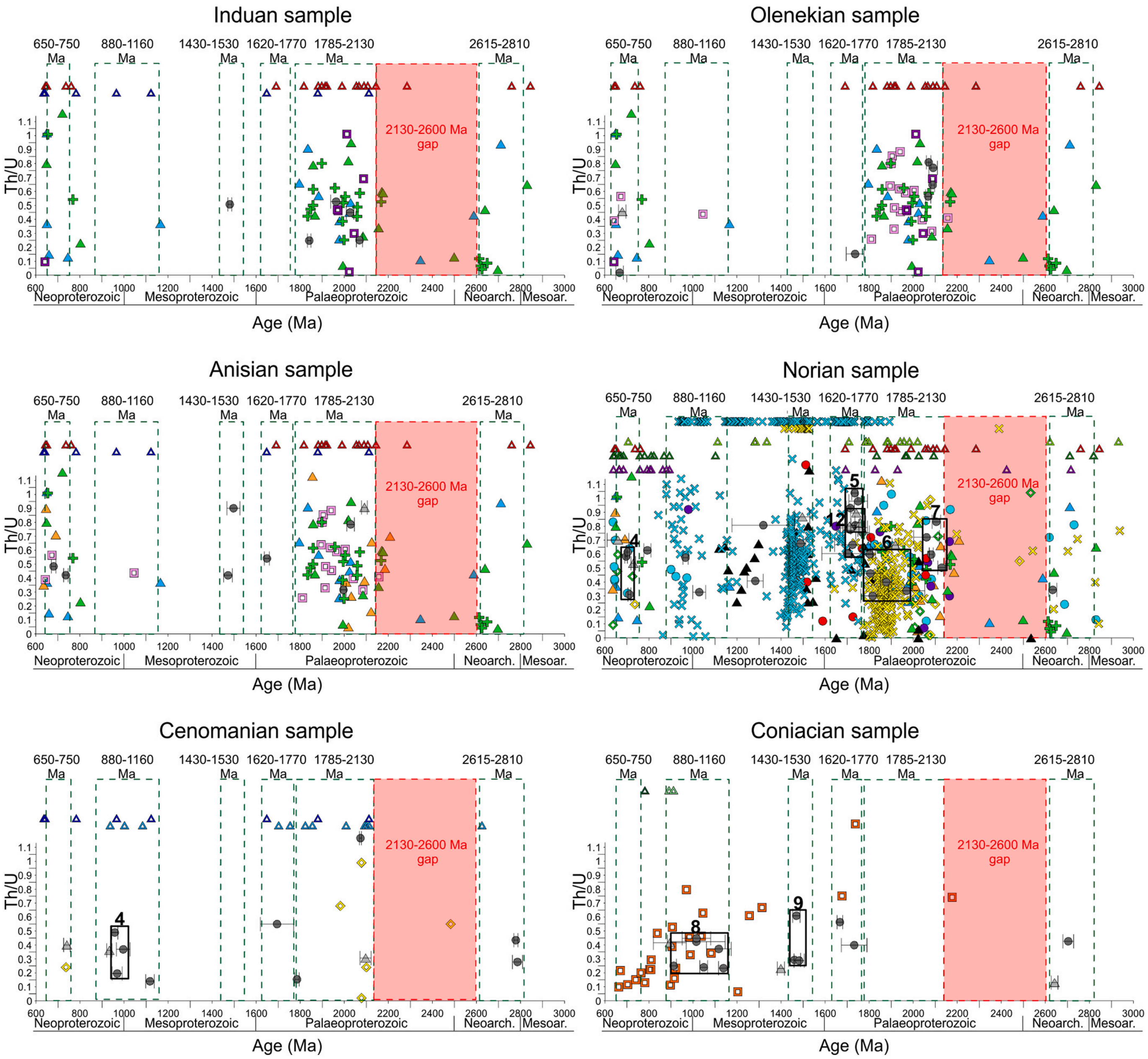


Fig. 10. Diagrams for the examined samples showing the results of comparative analysis for complex-textured zircons and oscillatory-zoned zircons of the Precambrian ages >635 Ma. Only data from the most similar zircons in terms of their ages, Th/U values, and internal textures are presented. At the top of the diagram, above the X axis, are the age data points with no Th/U values. The Roman numerals visible above the diagrams refer to the selected populations I–X, while black rectangles and the Arabic numbers indicate the fields of the specific subpopulations (see also Tables 2 and 3). The age gap of 2130–2600 Ma is marked with a reddish rectangle. The legend for the diagrams is provided in Fig. 8. (For the colors in this figure, the reader is referred to the online version of this article.)

containing also younger Carboniferous zircons (for example from the Kłodzko-Złoty Stok Pluton) (Fig. 1C).

Furthermore, the early Cambrian–Ediacaran oscillatory-zoned zircons, along with the other early Paleozoic and pre-Ediacaran zircons (pop. I–IV), showed greatest similarities to the zircons that occur mainly in the metasediments, as well as some of the (post)Variscan magmatic rocks, as their subordinate constituents (Figs. 8–10) (e.g., Mikulski et al., 2013; Jastrzębski et al., 2018); these are exposed again at present, in the eastern part of the Bohemian Massif, mainly in the Orlica–Śnieżnik Dome (cf., Jastrzębski et al., 2010; Mazur et al., 2012, 2015). The other possibility is that the early Paleozoic and pre-Ediacaran zircons are derived from medium-grade gneisses, in which the original textures of the inherited zircons were preserved—as is the case with some gneisses of the Thaya Dome and the Kłodzko Metamorphic Massif (e.g., Friedl et al., 2004; Mazur et al., 2004).

6.2. Changes in the erosional levels of the source areas and the transport directions

As presented above, the multiple indication of the same rocks and units in the eastern part of the Bohemian Massif clearly show that this region must have been the most important source area for the detrital zircons investigated here. This coherence also confirms that the choice of the parameters used in this study is sufficient, appropriate, and correct.

At present, felsic granulites, migmatites, gneisses, eclogites, metasediments, magmatic rocks, and pyroclastics often coexist in the same units, and can provide debris, being a mixture of zircons with different ages and characteristics. It is therefore highly probable that a similar situation could have occurred in the past, and that the studied populations could have been derived from more or less adjoining metamorphic and magmatic rocks. After the debris was generated, the grains must have been subjected to transport together. The varying degrees of grain abrasion in the individual samples suggest that they contain detrital zircons that have experienced different depositional histories, including recycling from sedimentary rocks.

Moreover, differences in the composition of samples may result from changes in the erosional levels of source areas, transport directions, and other reasons. However, any interpretation requires caution, as the composition may be affected by sedimentary processes, for example by sorting by grain size or weight (e.g., Morton and Hallsworth, 1999; Augustsson et al., 2018; Kołtonik et al., 2018). What information was recorded in the examined samples?

6.2.1. *Changes during the Induan and Olenekian*

The relatively high proportions of the Carboniferous zircons (pop. VIII) in two oldest Triassic samples, among which the complex-textured Visean and Tournaisian zircons definitely dominate (subpop. 1–2 in the Induan sample and subpop. 2–3 in the Olenekian sample), combined with the highest shares of the Devonian zircons (pop. VI and VII), which exclusively have complex textures (subpop. 3–4 in the Induan sample and subpop. 4–5 in the Olenekian sample; Fig. 3), clearly indicate that the vast majority of the zircons were released from the high-pressure felsic granulites, gneisses and eclogites (Figs. 7–8). Their likely derivation from equivalents of the metamorphic rocks of the eastern parts of Lugicum and the Moldanubian Zone, or some unidentified sedimentary rocks containing their debris, is additionally confirmed by the presence in both samples of Paleoproterozoic zircons (pop. I), which are typical of the rocks occurring in these areas (Fig. 10) (cf., Friedl et al., 2004; Košler et al., 2014). The eastern part of the Bohemian Massif was therefore the most important source area during the Early Triassic (Fig. 11A-B).

The presence in the Olenekian sample of the oscillatory-zoned Serpukhovian grains accompanied by the oscillatory-zoned Bashkirian grains (subpop. 9 and 10; Figs. 3 and 8–9) suggests some changes in the type of source rocks and source areas in the late Early Triassic. These zircons must have been supplied from the Carboniferous igneous rocks, which most probably were the equivalents of the Moldanubian Composite Batholith rocks or some unidentified sedimentary rocks containing their debris. Such derivation is supported by the fact that the Olenekian sample also contains the Ediacaran-to-Ordovician grains (subpop. 8 and 7), similar to the zircons contained in the gneisses of the Monotonous and Varied units (Figs. 3 and 8–9) (cf., Košler et al., 2014), which have presently been exposed west of the batholith. Therefore, these grains likely recorded the spatial extension of the source area to the west during the Olenekian. This example definitely justifies and confirms the need for a separate analysis of grains possessing different internal textures, which result from their formation in different crystalline rocks. If the grains had not been divided into those having complex textures versus those with oscillatory-zoned textures, this subtle change would probably not have been noticed.

Several other differences between the samples indicate changes in provenance in the late Early Triassic (Fig. 11A-B). The high degree of abrasion of the grains from the Induan sample suggests that they came mainly from (multiple) recycled sedimentary rocks (the sedimentary cover of the massif or its foreland), while the grains from the Olenekian sample—which show variable degrees of abrasion—must have been delivered from more diversified types of source rocks and source areas located at different distances. Compared to the Induan arenite, the Olenekian wacke comprises more younger Carboniferous zircons (subpop. 1, 9, and 10) likely of the above-mentioned provenance, late Cambrian–early Ordovician zircons (subpop. 7)—which may have been derived from the counterparts of the gneisses and metasediments of the Orlica–Śnieżnik Dome, and other sources (cf., Jastrzębski et al., 2010; Redlińska-Marczyńska et al., 2016)—and the Ediacaran–early Cambrian zircons (subpop. 8), which are characterized by a relatively wide range of ages and Th/U values and were likely supplied from more diversified equivalents of the metasediments of the latter unit (Figs. 3 and 7–9). Moreover, the Olenekian sample contains Paleozoic zircons (subpop. 2 and 4–7) and the Ediacaran–early Cambrian zircons (subpop. 8) that have features characteristic of those contained in the gneisses and granulites of the Lower Austrian part of the Gföhl Unit (Figs. 3 and 7–8), which suggests that the grains may have been transported from the far southwest, likely along the eastern coast of the massif (Fig. 11B). All these findings advocate for the exposure of a greater variety of the crystalline rocks, or sedimentary rocks containing their debris, in the eastern part of the Bohemian Massif, particularly in the Orlica–Śnieżnik Dome and the Moldanubian Zone units, during the late Early Triassic.

This change in erosional level may have been an effect of the successive removal of the sedimentary cover from the massif, combined with tectonic movements on the eastern edge of the Bohemian Massif. The Silesian–Moravian Gate, adjacent to the sedimentary basin studied here, superimposed on the Silesian–Moravian Fault, developed in the late Early Triassic due to tectonic motion caused by the spreading of the Tethys Ocean (Fig. 11B) (Nawrocki and Szulc, 2000; Szulc, 2000). This tectonic activity must have affected at least the eastern part of the massif.

6.2.2. *Stagnation during the Anisian*

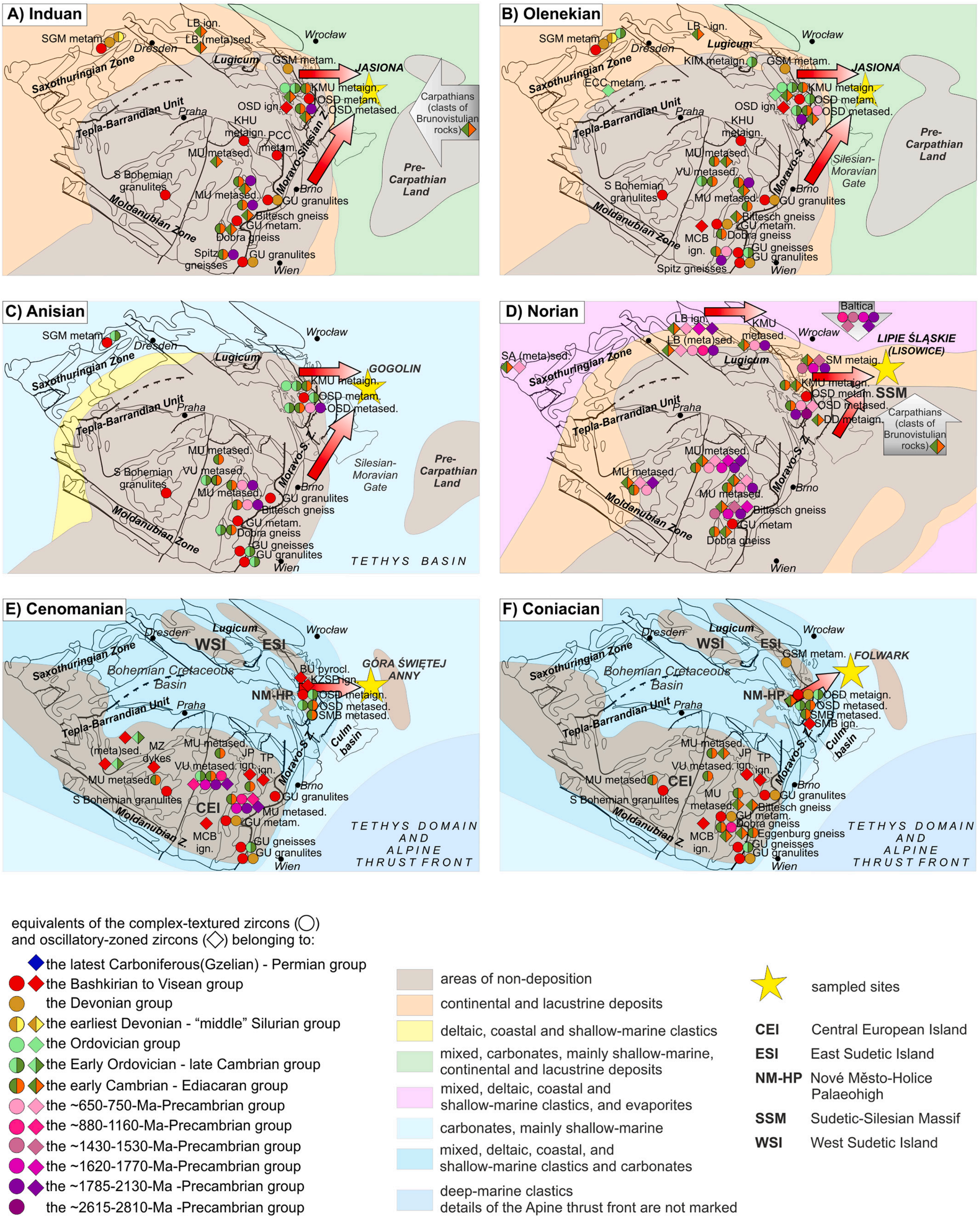
The Anisian sample contains only small and well-sorted zircons of variable roundness, which clearly demonstrates the distinct impact of the sedimentary process on its composition. It means that this sample cannot be considered as containing the full spectrum of zircons that have been supplied during the Anisian, but some hints suggest possible source areas at that time.

The sample showed relatively high proportions of early Paleozoic zircons (pop. III and IV; subpop. 2) and Precambrian zircons (pop. I and II; subpop. 3), at the expense of the Carboniferous grains, which makes it different from both older samples (Figs. 3 and 5), however, these Paleozoic zircons form the peaks of almost the same ages as in the Olenekian sample (Fig. 5), which in turn makes both samples relatively similar in this. It can thus only be concluded that the Anisian sample contains zircons likely derived from the equivalents of the source rocks and areas at least in part the same as to those identified for the Olenekian sample (Fig. 11B-C).

6.2.3. *Changes during the Norian*

The Norian sample displayed the most different frequency distribution pattern (Figs. 3 and 5), which suggests that detrital material was largely supplied from other source rocks and areas. First of all, the striking largest proportion of Ediacaran–early-Cambrian zircons (pop. II), among which as much as 60% are oscillatory-zoned grains (subpop. 10 and 11; Fig. 3), indicates a distinct change in source rocks. The great similarity of these zircons to those occurring in the igneous rocks of the Brunovistulian unit (currently partially buried under the Carpathians), suggests that the grains were transported from the southwest and south (Fig. 11D). The low degree of roundness of most grains strongly argues for short transport distances. The relatively numerous zircons with ages of ~1000 Ma, 1300 Ma, ~1500 Ma and ~ 1700–1750 Ma (very rare in all older samples) (pop. I; subpop. 5–7 and 12; Fig. 3) additionally supports the above interpretation, since the ages are characteristic of the Brunovistulian rocks (Fig. 10) (cf., Friedl et al., 2000; Żelaźniewicz et al., 2009). The Brunovistulian rocks were generally less affected by the Variscan tectonometamorphic events, which may explain the relatively small proportion of Devonian and Carboniferous zircons in the sample.

Moreover, the oscillatory-zoned Ediacaran–early Cambrian zircons from this sample (subpop. 10 and 11) are similar to those contained in the Lusatian Granodiorite Complex magmatic rocks and Lausitz Block (meta)sandstones (the northern part of the Saxothuringian Zone) (Figs. 8–9), which may also suggest more distant transport from the west (Fig. 11D), though this is rather true for grains with a higher degree of



equivalents of the complex-textured zircons (○) and oscillatory-zoned zircons (◇) belonging to:

- ◆ the latest Carboniferous(Gzelian) - Permian group
- ● ◆ the Bashkirian to Visean group
- ● the Devonian group
- ◐ ◆ the earliest Devonian - "middle" Silurian group
- ● ◆ the Ordovician group
- ◐ ◆ the Early Ordovician - late Cambrian group
- ◐ ◆ the early Cambrian - Ediacaran group
- ● ◆ the ~650-750-Ma-Precambrian group
- ● ◆ the ~880-1160-Ma-Precambrian group
- ● ◆ the ~1430-1530-Ma-Precambrian group
- ● ◆ the ~1620-1770-Ma-Precambrian group
- ● ◆ the ~1785-2130-Ma -Precambrian group
- ● the ~2615-2810-Ma -Precambrian group

- ▨ areas of non-deposition
- ▨ continental and lacustrine deposits
- ▨ deltaic, coastal and shallow-marine clastics
- ▨ mixed, carbonates, mainly shallow-marine, continental and lacustrine deposits
- ▨ mixed, deltaic, coastal and shallow-marine clastics, and evaporites
- ▨ carbonates, mainly shallow-marine
- ▨ mixed, deltaic, coastal, and shallow-marine clastics and carbonates
- ▨ deep-marine clastics details of the Apine thrust front are not marked

★ sampled sites

CEI	Central European Island
ESI	East Sudetic Island
NM-HP	Nové Město-Holice Palaeohigh
SSM	Sudetic-Silesian Massif
WSI	West Sudetic Island

(caption on next page)

Fig. 11. Paleogeographic maps showing the units that were most likely to have delivered detritus to the sedimentary basins for the examined samples. The arrows indicate the most probable and important transport directions during the individual periods. The base paleogeographic maps A–D are after Ziegler (1982), while E–F are a simplified compilation after Ziegler (1982), Marek and Pajchlowa (1997), Uličný et al. (2009b), and Čech (2011). Explanation of abbreviations: ign. – igneous rocks; metaign. – metaigneous rocks; metam. – metamorphic rocks; metased. – metasedimentary rocks; pyrocl. – pyroclastic rocks; BU – the Bardo Unit; DD – the Desná Dome; ECC – the Eger Crystalline Complex; GSM – the Góry Sowie Massif; GU – the Gföhl Unit; JP – the Jihlava Pluton; KHU – the Kutná Hora Unit; KIM – the Karkonosze–Izera Massif; KMU – the Kłodzko Metamorphic Unit; KZSP – the Kłodzko–Złoty Stok Pluton; LB – the Lausitz Block; MBC – the Moldanubian Composite Batholith; MU – the Monotonous Unit; MZ – the Moldanubian Zone; OSD – the Orlica–Śnieżnik Dome; PCC – the Polička Crystalline Complex; SA – the Schwarzburg Anticline; SGM – the Saxonian Granulite Massif; SM – the Strzelin Massif; SMB – the Stare Město Belt; TP – the Třebíč Pluton; VU – the Varied Unit. (For the colors in this figure, the reader is referred to the online version of this article.)

roundness. In addition, the various metasediments of the Orlica–Śnieżnik Dome are also possible equivalents of the source rocks for these zircons.

Furthermore, the Norian sample, unlike the older samples, does not contain grains (of any age) that would be similar to the zircons from the rocks presently exposed in the southern units of the Bohemian Massif (the Lower Austrian parts of the Moldanubian Zone), which excludes transport from this remote area. Moreover, the striking absence of Ordovician zircons also suggests a lack of material supply from the equivalents of the gneisses of the Orlica–Śnieżnik Dome.

All these results indicate diversified directions of transport during the Norian, usually over short distances. It was most likely caused by the closure of the Silesian–Moravian Gate since the Bohemian Massif and the Sudetic–Silesian Massif merged into one elevated land area in the Late Triassic (Fig. 11D). This obstacle allowed transport only from the more northern parts of the Brunovistulian unit, as well as from the northern and northeastern part of the Saxothuringian Zone and Lugicum.

Besides, the Precambrian zircons in this sample showed similarity to the zircons included in the magmatic and metamorphic rocks of Baltica (Fig. 10). Although this area was far away from the studied deposition site, it cannot be completely excluded as the source area (Fig. 11D), in particular for the zircons characterized by a high degree of roundness.

6.2.4. Changes during the Cenomanian

The similarity of the Cenomanian sample to the Olenekian sample suggests that most of the grains (especially the complex-textured zircons) were supplied from the analogous source rocks and areas—that is, mainly the equivalents of metamorphic rocks from the eastern parts of Lugicum and the Moldanubian Zone (Fig. 11E). However, several differences, including the relatively high proportion of oscillatory-zoned zircons of Visean, Serpukhovian, and Bashkirian ages (subpop. 8 and 9; Fig. 3) in particular, prove another change in provenance.

The Cenomanian sample is the first one in which the oscillatory-zoned Visean zircons are present. The comparative analysis indicated the igneous rocks of the Kłodzko–Złoty Stok Pluton, the Jihlava and Třebíč plutons, the Central Bohemian Plutonic Complex, the Bardo Unit pyroclastics, and the Kasimovian sedimentary rocks of the Teplá–Barrandian Unit as the most likely equivalents of their source rocks (Figs. 8-9 and 11E). These rocks and units were not indicated for zircons in the older samples. In addition, the magmatic rocks of the Moldanubian Composite Batholith could also be the source of the Carboniferous zircons. Two facts allow us to exclude some possibilities. First, the oscillatory-zoned Carboniferous zircons, although usually grain fragments, are angular or only slightly rounded, or even with pointed terminations, which strongly argues for short transport distances—especially considering that they were transported with a considerable amount of detritus, which most likely led to their fragmentation. Secondly, the paleolocations of lands and seas changed a lot due to the global Cenomanian transgression, which flooded most of the Bohemian Massif and its foreland, leaving only several elevated highs. As the result, the Bohemian Cretaceous Basin was formed, which was surrounded by a few emerged areas, including the Central European Island, the Western Sudetic Island, and the Eastern Sudetic Island (Fig. 11E). Moreover, smaller paleohighs resisted within the basin (e.g., the Nové Město–Holice Paleohigh; Fig. 11E) (e.g., Uličný et al., 2009b; Čech, 2011; Čech and Uličný, 2021). Besides, the Cenomanian eastern river paleodrainage systems located between the southwestern edge of the Eastern Sudetic Island and the northeastern edge of the Central European Island ran south to the Tethys Ocean (Uličný et al., 2009b), which excludes the possibility of detritus being transported from the Moldanubian Zone to the northeast. Taking all these facts into account, the most probable equivalents of the source rocks for the oscillatory-zoned Carboniferous zircons are the igneous rocks of the Kłodzko–Złoty Stok Pluton and the Bardo Unit pyroclastics, or unidentified sedimentary rocks containing their debris. Importantly, the rocks of the pluton contain zircons of various Carboniferous ages corresponding well with those from the sample. It is worth emphasizing that this is quite a rare type of igneous body in the Bohemian Massif, in which there are no ~303–315-Ma-age zircons that are not present at all in the examined samples. The first exposure of the rocks from these units, or the erosion of nearby sedimentary rocks containing their debris, therefore most probably occurred not earlier than after the Triassic.

There is controversy about the spatial extent of the Eastern Sudetic Island in the Late Cretaceous (in particular, the location of its southern margin), its paleotopography, and the issue of units were part of the island (e.g., Uličný et al., 2009b; Biernacka and Józefiak, 2009; Danišík et al., 2012; Kowalski, 2021). The detailed research on the island concerns only the Turonian, and the results suggest that it was a small area did not extend far south (Biernacka and Józefiak, 2009), and to the south of it there was probably a deep marine basin that covered much of the Sudetes (Danišík et al., 2012). However, the paleogeographic reconstruction presented by Uličný and coauthors (Uličný et al., 2009a; Uličný et al., 2009b) for the late Cenomanian points to the possibility that another land comprising the Orlica–Śnieżnik Dome could have been located south of this basin and east of the Nové Město–Holice Paleohigh. Our results suggest that the Kłodzko–Złoty Stok Pluton, along with the Bardo Unit, belonged to the Eastern Sudetic Island during the Cenomanian (Fig. 11E); they were not previously identified as parts of this island. Moreover, the probable derivation of the complex-textured Carboniferous-to-Ediacaran zircons from the equivalents of the metamorphic rocks of the Kłodzko Metamorphic Unit and the Orlica–Śnieżnik Dome (which are units adjacent to a varying degree to those mentioned above) suggests that the first unit could also be a part of the Eastern Sudetic Island, and that the other one might have existed as a separate land (cf., Uličný et al., 2009a, 2009b).

The oscillatory-zoned Cambrian zircons for which no suitable source rock equivalents could be found are very puzzling. However, their low degree of roundness suggests they had nearby source rocks and were transported only a short distance. Likewise, the provenance of the grains with ages of ~960–1000 Ma (subpop. 7) and > 2700 Ma, which are lacking in the older samples, has not been reliably explained. These grains might perhaps have come from the unnamed land east of the study site (Fig. 11E), or from rocks that had already been eroded or were buried. Their presence also recorded a significant change in the source rocks, source areas, and transport directions.

Therefore, the composition of the Cenomanian sample resulted from the supply of detritus mainly from the local sources, which was due to the distribution of the palaeohighs and seas at that time. It is worth emphasizing that the division of the studied zircons into two groups with different textures made it (again) possible to recognize important, though subtle, changes in the composition, to identify previously not indicated igneous rocks as potential equivalents of the source rocks, and to designate units not mentioned so far by other authors, which probably belonged to the Eastern Sudetic Island.

6.2.5. Changes during the Coniacian

The Coniacian sample showed several differences compared to the Cenomanian sample, which suggests another change in the provenance of the examined zircons. Firstly, the largest share of the oscillatory-zoned Visean zircons (among all samples), in combination with a very small amount of the Serpukhovian and the Bashkirian zircons speaks for their supply from the Visean intrusions, including counterparts of the Třebíč and Jihlava plutons (the Moldanubian Zone) and the Staré Město Belt granitoids (Figs. 8-9). Taking into account that during the Coniacian the distribution of lands and seas was similar to that in the late Cenomanian, and the Visean grains under study are angular, albeit fragmented, suggesting short transport distance, the Staré Město Belt is more likely the source area (Fig. 11F).

Secondly, the larger proportion of the mostly complex-textured Ediacaran–early Cambrian zircons combined with the smaller proportion of Ordovician zircons (for which comparative analysis indicated, inter alia, the metamorphic rocks of the Orlica–Śnieżnik Dome as the best equivalents) suggests that the metasediments of this unit (or sedimentary rocks containing their debris) may have been the main source rocks (Fig. 11F), while the high-grade gneisses were less important. This may have resulted from the extent of their exposure at that time.

Moreover, the Coniacian sample, in addition to a relatively high proportion of pre-Ediacaran zircon in general, includes grains of 1.0–1.80 Ga, some of which form a distinct peak at ~1470 Ma (Fig. 5). This is the only sample, apart from the Norian sample, to contain the relatively large number of the Mesoproterozoic zircons and latest Paleoproterozoic zircons. These ages are characteristic of zircons contained in the Brunovistulian rocks (cf., Linnemann et al., 2007; Mazur et al., 2010) and indicate this unit as the another source area at that time.

This clear shift of the source areas to the eastern edge of the Bohemian Massif (Fig. 11F) was most likely the result of changes in paleotopography. From the late Turonian to Paleocene, the Bohemian Massif and its foreland were affected by the stress due to the Alpine orogeny. This led to the reactivation of the Variscan basement faults, the exhumation and uplift of fragments of the massif, and the inversion of the intramassif basins (e.g., Ziegler, 1987; Coubal et al., 2015). The multiphase fault-block movements, which took place during the late Turonian and Coniacian, led to the formation of the Nysa Kłodzka Graben, inter alia, cutting the Orlica–Śnieżnik Dome towards the NNW–SSE and the uplift of its two limbs on the sides of the graben (Don and Gotowała, 2008; Badura and Rauch, 2014). The Orlica–Śnieżnik Dome was undoubtedly the land during the Coniacian, most likely together with the neighboring units. Therefore, the Coniacian sample zircon populations, supplied mainly from the local sources, recorded the Late Cretaceous uplift and erosion of the basement blocks of the eastern margin of the Bohemian Massif, due to the regional compression caused by the Alpine Orogeny.

7. Conclusions

1. We have applied and tested an approach based on the combination of four data types: crystallization ages, Th/U values, CL-induced internal textures, and general grain shapes. These proved to be useful parameters for investigating the provenance of detrital zircons, enabling the identification of even subtle differences between populations.
2. The samples of Mesozoic deposits of the Bohemian Massif foreland contain zircons with ages ranging from the Neoarchean (2786 ± 23 Ma) to the Late Triassic (211 ± 3 Ma), divided into ten age populations (I-X). The Carboniferous zircons (population VIII; 38.6%), the Ediacaran–early Cambrian zircons (population II; 23.6%), and the pre-Ediacaran zircons (population I; 15.5%) are most frequent.
3. The detrital zircons were divided into two groups according to the type of internal texture: those with complex textures (72%) and those with oscillatory zoning (28%). This approach allowed us to identify the crystalline source rocks more reliably and accurately, and indicate the times when they were exposed to erosion less diverse (the Induan and Norian) and more diverse source rocks (the Olenekian, Cenomanian, and Coniacian).
4. The comparative analysis showed that the Bohemian Massif felsic granulites, eclogites, migmatites, and gneisses must have been the most important source rocks for the majority of the complex-textured zircons. The oscillatory-zoned zircons were mostly released from the Bohemian Massif magmatic rocks and (meta) sediments.
5. Northeastern and eastern parts of the Bohemian Massif were the most important source areas, but the importance of the individual units changed over time. Only during the Norian, the northern part of the Saxothuringian Zone, the Brunovistulian unit, and Baltica also likely supplied debris, while during the Coniacian, detrital material was also derived from the Staré Město Belt and the Brunovistulian unit.
6. The four age gaps found in the samples (~ 303–315 Ma, 500–520 Ma, 2.13–2.60 Ga and > 2.81 Ga) made it necessary to exclude rocks and units containing such zircons as probable counterparts of source rocks, which narrowed the selection of potential source areas.
7. The variations in the age distributions of the samples indicate that the proportion of individual rocks in the Bohemian Massif exposed to erosion in Mesozoic changed over time and was unlike the present situation. In particular, bodies of the Variscan felsic granulites had to have been larger in volume and better exposed in the Mesozoic erosional incision, while bodies of the Cambrian gneisses must have been less exposed than they are today.
8. The differences in composition of the samples indicate distinct changes in the erosional levels of source areas during Mesozoic, caused by the removal of the sedimentary cover from the Bohemian Massif and by the erosion of its crystalline rocks, combined with tectonic movements, particularly in the Olenekian and Coniacian, which reactivated the Variscan faults.
9. The changes in transport directions from the generally observed northeastward and eastward during the Induan, Olenekian, Anisian, also to the northward and southward during Norian, from near and far areas, were largely controlled by paleogeography. The establishment of the Sudetic–Silesian Massif resulting from the closure of the Silesian–Moravian Gate, prevented the supply of material during the Norian from the distant southwestern areas. The global Cretaceous transgression and the flooding of a large area of the Bohemian Massif led to the delivery of debris during the Cenomanian and Coniacian mostly from units adjacent to the Opole Basin.
10. Distinct changes in the type of eroded source rocks, recognized by dividing the zircons into two internal-texture groups, were identified in the Induan versus Olenekian samples, and in the Cenomanian sample. In the latter case, the relatively high proportion of Visean oscillatory-zoned zircons provides a record of the change in the erosional level of the source area at an indefinite time after the Triassic, which resulted in the exposure of the igneous rocks and pyroclastics occurring in small units of the northeastern margin of the Bohemian Massif. These results emphasize the need for a separate analysis of zircons with different textures.
11. More units than previously indicated (including the Kłodzko Metamorphic Unit, the Bardo Unit, the Kłodzko–Złoty Stok Pluton, and larger parts of the Orlica–Śnieżnik Dome) may have

been included in the Eastern Sudetic Island during the Cenomanian and Coniacian.

12. We strongly recommend using a combination of several such parameters when investigating detrital zircon provenance. The use of a too-small number of parameters may make it impossible to identify discrete but important changes and age gaps, and is likely to have a negative effect on the interpretation of the data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2022.111035.

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