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THE EASTERN PART OF THE SAXOTHURINGIAN TERRANE CHARACTERIZED BY ZIRCON AND MONAZITE DATA FROM THE DOBOSZOWICE METAMORPHIC COMPLEX IN THE SUDETES (SW POLAND)

Mirosław JASTRZĘBSKI[1 *], **Andrzej ŻELAŹNIEWICZ**[1], **Wojciech STAWIKOWSKI**[2], **Bartosz BUDZYŃ**[3], **Ewa KRZEMIŃSKA**[4], **Katarzyna MACHOWIAK**[5], **Stanisław MADEJ**[6], **Dawid BIAŁEK**[6], **Jiří SLÁMA**[7], **Zbigniew CZUPYT**[4] & **Aleksandra JAŹWA**[1]

[1] *Institute of Geological Sciences, Polish Academy of Sciences,*
Podwale 75, 50-449 Wrocław, Poland;
e-mails: mjast@twarda.pan.pl, pansudet@pwr.edu.pl, aleksandra.jazwa@twarda.pan.pl
[2] *Adam Mickiewicz University, Faculty of Geographical and Geological Sciences, Institute of Geology,*
B. Krygowskiego 12, 61-680 Poznań, Poland; e-mail: wojst@amu.edu.pl
[3] *Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków,*
Senacka 1, 31-002 Kraków, Poland; e-mail: ndbudzyn@cyf-kr.edu.pl
[4] *Polish Geological Institute - National Research Institute,*
Rakowiecka 4, 00-975 Warszawa, Poland; e-mails: ekrz@pgi.gov.pl, zczu@pgi.gov.pl
[5] *Poznań University of Technology, Institute of Civil Engineering,*
Piotrowo 5, 60-965 Poznań, Poland; e-mail: katarzyna.machowiak@put.poznan.pl
[6] *University of Wrocław, Institute of Geological Sciences, Maksa Borna 9, 50-204 Wrocław, Poland;*
e-mails: stanislaw.madej@uwr.edu.pl, dawid.bialek@uwr.edu.pl
[7] *The Czech Academy of Sciences, Institute of Geology,*
Rozvojová 269, Prague 6, 16500, Czech Republic; e-mail: slama@gli.cas.cz
** Corresponding author*

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Abstract: In the Variscan Bohemian Massif, orthogneiss complexes of different sizes, derived from early Palaeozoic granitoids, are accompanied by metavolcano-sedimentary successions. They are common in the Sudetes, SW Poland, and belong mainly to the Saxothuringian Terrane. In order to better characterize the evolution of the latter, new U-Pb and O isotopic zircon analyses, combined with zircon typology and new U-Th-Pb isotopic monazite analyses, were performed. The present data show that the S-type granitic precursors of the Doboszowice orthogneisses (Fore-Sudetic Block) and the Śnieżnik gneisses (Sudetes) were formed at ca. 495 Ma from differently evolved magmas. Protoliths of the Doboszowice orthogneisses developed entirely in the crust, whereas the precursors to the Śnieżnik gneisses received some mantle input. Metasediments that accompany the Doboszowice orthogneisses reveal zircon spectra, which point to a late Cambrian-Early Ordovician sedimentary age. These spectra, in addition to predominant grains with Ediacaran ages, contain up to 10% of zircons dated at ca. 1.0 Ga. Therefore, it is suggested that the parent basin was supplied with detritus coming from areas, located in the Libyan-Nubian part of North Africa. Using also earlier published data, such a provenance is assigned to the units that now occur in the eastern part of the Fore-Sudetic Block. Late Cambrian-Early Ordovician granite intrusions and the concurrent accumulation of sediments originated in an extensional setting of the peri-Gondwana rifted continental margin or a back-arc setting. The Pb/U and Pb/Th monazite data constrain the ca. 346–341-Ma peak of the Variscan regional metamorphism in the eastern Saxothuringian Terrane and the prolonged juxtaposition of now adjacent tectonic units at least until 330 Ma.

Key words: Bohemian Massif; Doboszowice Metamorphic Complex; Saxothuringian Terrane; isotope geochronology; Cambro-Ordovician magmatism, Variscan collision.

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INTRODUCTION

Early Palaeozoic magmatism at the northern margin of the Gondwana continent is well represented in the Bohemian Massif, Central Europe, by orthogneiss complexes of various sizes (e.g., Pin *et al.*, 2007; Buriánek *et al.*, 2009) and bimodal volcanogenic rocks (e.g., Floyd *et al.*, 2000; Kröner *et al.*, 2000). The latter are part of metavolcano-sedimentary successions, the clastic material of which generally indicates source areas in the West African craton of northern Gondwana (e.g., Linneman *et al.*, 2004; Jastrzębski *et al.*, 2010; Drost *et al.*, 2011; Oberc-Dziedzic *et al.*, 2018; Žák and Sláma, 2018; Tabaud *et al.*, 2021).

In the Sudetes, NE Bohemian Massif, ubiquitous Cambrian-Ordovician orthogneisses, mantled by metasedimentary rocks of Gondwana provenance (see the review in Oberc-Dziedzic *et al.*, 2018), occur in different tectono-stratigraphic units, correlated with various Variscan terranes/microplates (e.g., Matte *et al.*, 1990; Cymerman *et al.*, 1997; Franke and Żelaźniewicz, 2000; Aleksandrowski and Mazur, 2002; Mazur *et al.*, 2006). The late Carboniferous through Cenozoic fault tectonics has further complicated a mosaic of the Sudetic units (Fig. 1A). The Sudetic Boundary Fault (e.g., Badura *et al.*, 2007) divides some of those units into two parts that represent significantly different structural levels, whereas others simply abut against the fault. The mountainous parts of the Sudetes are better exposed, in contrast to the Fore-Sudetic Block that presently is mostly concealed beneath Cenozoic sediments (Fig. 1A). For that reason, different aspects of the evolution and terrane affiliation of the Fore-Sudetic units are partly obscured.

One of the poorly exposed units is the Doboszowice Metamorphic Complex (DMC) of the Kamieniec Ząbkowicki Metamorphic Belt (KZMB) that is located in the Fore-Sudetic Block, north of the Sudetic Boundary Fault and the Orlica-Śnieżnik Dome (OSD), the latter being situated in the mountainous part of the Sudetes (Fig. 1A). The OSD, intensely investigated for nearly 60 years (e.g., Don, 1964; Smulikowski, 1979; Żelaźniewicz, 1988; Don *et al.*, 1990, 2003; Chopin *et al.*, 2012), commonly has been linked with the Saxothuringian Terrane (e.g., Franke and Żelaźniewicz, 2000; Chopin *et al.*, 2012; Aguilar *et al.*, 2020) and also with the West African part of Gondwana (e.g., Jastrzębski *et al.*, 2010; Mazur *et al.*, 2012). Both the DMC and OSD contain orthogneisses, accompanied by amphibolite facies metasediments, yet their correlations still are not supported by detailed data. The Śnieżnik orthogneisses in the OSD and the Doboszowice orthogneisses in the DMC comprise protoliths ca. 500 Ma old (e.g., Turniak *et al.*, 2000; Oberc-Dziedzic *et al.*, 2003, 2018; Klimas *et al.*, 2009; Mazur *et al.*, 2010; Redlińska-Marczyńska *et al.*, 2016). However, besides the timing of intrusion, other characteristics of the DMC metaigneous rocks are poorly known and thus need more attention. The age and provenance of the DMC two-mica migmatitic paragneisses (Achramowicz *et al.*, 1995; Puziewicz *et al.*, 1999) remain even less specified.

This study provides new data on the petrogenesis, protolith ages and provenance of the Doboszowice Metamorphic Complex at the time of formation of its protoliths. Additionally, it defines the terrane affiliation of this unit. New isotopic data from the DMC in the Fore-Sudetic Block are compared with both new and previous isotopic data from the thoroughly investigated OSD. The present study aims to specify: 1) the timing and duration of felsic magmatism in this part of the Saxothuringian Terrane in the early Palaeozoic, 2) possible sources of the parental magmas from determination of the proportions of mantle and crust components in felsic plutons of the DMC and OSD, 3) the provenance of the detritus in the metasedimentary rocks of the DMC, and 4) the age of metamorphism in the DMC. Assessing the validity of the supposed correlations between the DMC and the OSD is vital for a better understanding of the geological evolution of the Sudetes Mts. and the Bohemian Massif. The authors aim to achieve this through investigations of zircon typology, U-Pb zircon geochronology, the oxygen isotopic record in zircons, obtained for the DMC and OSD orthogneisses, and the U-Pb zircon and the U-Th-Pb monazite geochronology of the DMC metasedimentary rocks.

GEOLOGICAL SETTING

In the NE part of the Bohemian Massif, where the DMC and OSD units are located, four Variscan zones (terranes) are juxtaposed: 1) Saxothuringian, 2) Teplá-Barrandian, 3) Moldanubian, and 4) Moravo-Silesian (e.g., Matte *et al.*, 1990; Franke *et al.*, 2017; Fig. 1A – inset). The OSD usually is assigned to the Saxothuringian Terrane (e.g., Franke and Żelaźniewicz, 2000), though its Moldanubian affinity also has been proposed (Matte *et al.*, 1990; Cymerman *et al.*, 1997). In the Saxothuringian Terrane, Cambro–Ordovician to lower Carboniferous (meta)volcano-sedimentary successions, accompanied by orthogneisses with Cambro–Ordovician protolith ages, were laid down on or intruded into the Cadomian basement, all metamorphosed at 360–330 Ma (e.g., Franke and Żelaźniewicz, 2000).

In the Fore-Sudetic Block, the Saxothuringian affinity was confirmed for the Ediacaran metagranites in Wądroże Wielkie (Żelaźniewicz *et al.*, 2004), upper Cambrian metagranites in Stachów (Oberc-Dziedzic *et al.*, 2018) and mica schists of the Kamieniec Ząbkowicki Metamorphic Belt (Jastrzębski *et al.*, 2020). In the east, the Saxothuringian successions are in direct tectonic contact with the Cadomian basement of the easterly located terrane of Brunovistulia (Kröner *et al.*, 2000; Oberc-Dziedzic *et al.*, 2003, 2021; Mazur *et al.*, 2010; Jastrzębski *et al.*, 2021; Fig. 1A). To the west, the Niemcza Shear Zone separates the Saxothuringian domain from the Góry Sowie Massif, which is commonly considered the north-easternmost fragment of the Teplá-Barrandia Terrane (e.g., Matte *et al.*, 1990; Franke *et al.*, 2017).

The DMC is situated in the Fore-Sudetic Block, in the south-eastern part of the Kamieniec Ząbkowicki Metamorphic Belt (Fig. 1A). The DMC is mainly concealed under a Cenozoic cover, being exposed only in small, elongate outcrop belts (Fig. 1B). In the west, the Doboszowice

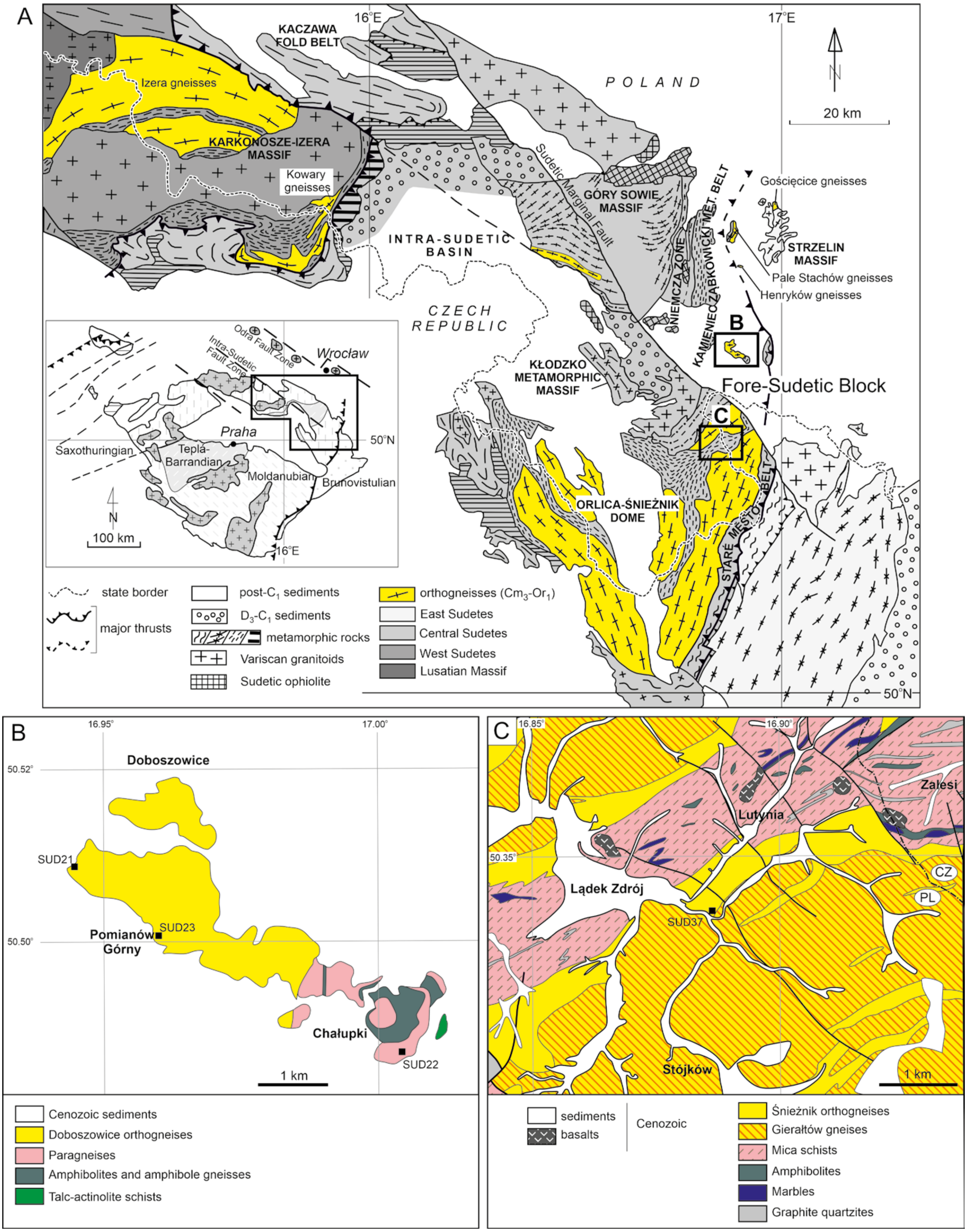

Fig. 1. Geology of the study area **A.** Distribution of the late Cambrian orthogneiss complexes in the Sudetes (after Mazur *et al.*, 2006, modified). Major thrust (the dashed line) in the area of the Fore-Sudetic Block after Oberc-Dziedzic *et al.* (2018). Names of tectonic zones in the inset after Franke *et al.* (2017). **B.** Location of the studied samples SUD22 and SUD23 in the Doboszowice Metamorphic Complex on the geological map after Baraniecki (1956), Sawicki (1956) and Rembocha (1960), with the boundary between Doboszowice orthogneisses and Chałupki paragneisses after Puziewicz and Rudolf (1998) and Awdankiewicz (2008). **C.** Location of the sample SUD37 in the Orlica-Śnieżnik Dome on the geological map after Don *et al.* (2003).

orthogneisses dominate, whereas in the east the Chałupki paragneisses with mica schists and amphibolites occur (Fig. 1B).

The Doboszowice orthogneisses consist of quartz, K-feldspar and plagioclase, accompanied by minor amounts of muscovite, biotite and occasional garnet, albite and chlorite. They show great textural diversity with a constant chemical composition, being calc-alkaline rocks with A/CNK ratios in the range of 1.05 to 1.35. Their magmatic precursor was due to the re-melting of sedimentary rocks and was intruded at 488 ± 6 Ma (Buriánková *et al.*, 1999; Mazur *et al.*, 2010). The orthogneisses contain xenoliths of metasediments (Mazur *et al.*, 1995).

The paragneisses at Chałupki consist of quartz, oligoclase, K-feldspar, muscovite, biotite and garnet. The paragneisses gradually pass into mica schists that are devoid of K-feldspar, with garnet, staurolite and kyanite abundant in places. Protoliths of rocks in the eastern part of the DMC, including also amphibolites and amphibole gneisses, correspond to a clay-greywacke series as well as basalts and their tuffs (Puziewicz *et al.*, 1999). The DMC paragneisses underwent metamorphism at maximum conditions of ca. 700–740 °C and 8–10 kbar (Puziewicz *et al.*, 1999) or 670 °C and 8 kbar (Szczepański and Marciniak, 2018). Marciniak and Szczepański (2019) reported relics of an episode at lower-temperature (610–640 °C) and higher-pressure (12–15 kbar), recorded by white mica grains.

The OSD is located in the mountainous part of the Sudetes (Fig. 1A). The OSD consists of two main rock groups: the metasedimentary Młynowiec-Stronie Group and gneisses that traditionally are subdivided into coarse-grained, augen Śnieżnik orthogneisses and finer-grained, often migmatitic Gierałtów gneisses (e.g., Don *et al.*, 1990; Fig. 1C). The Śnieżnik gneisses are derived from late Cambrian, S-type granites (e.g., Turniak *et al.*, 2000; Lange *et al.*, 2005; Buriánek *et al.*, 2009; Redlińska-Marczyńska *et al.*, 2016) with an anorogenic signature, consistent with the envisaged intracontinental rifting of Gondwana (Pin *et al.*, 2007), yet also with some calc-alkaline characteristics, believed to be inherited from the Cadomian granite precursor (Oliver *et al.*, 1993; Turniak *et al.*, 2000). On the basis of detrital zircons, the clastic protoliths of the Młynowiec-Stronie Group have an Ediacaran to Early Ordovician maximum sedimentary age (e.g., Jastrzębski *et al.*, 2010, 2015; Mazur *et al.*, 2012; Szczepański *et al.*, 2020). The felsic metarhyolites in the Młynowiec-Stronie Group (Don *et al.*, 2003) have the ca. 500 Ma protolith (e.g., Jastrzębski *et al.*, 2015; Mazur *et al.*, 2015) and a geochemical affinity to the Śnieżnik orthogneisses. Hence, both lithologies have been interpreted as the products of melting of the Cadomian continental crust (e.g., Wojciechowska *et al.*, 2001; Murtezi, 2006), or, alternatively, a Cambrian magmatic arc (Murtezi, 2006). In contrast, the basic metavolcanites of the Młynowiec-Stronie Group were the originally variably contaminated MOR tholeiites and alkali (meta)basalts with an enriched OIB-type signature (Floyd *et al.*, 1996; Ilnicki *et al.*, 2013). The OSD rocks were regionally metamorphosed under mid- to high-grade conditions with signs of (U)HP metamorphism (e.g., Bakun-Czubarow, 1992; Bröcker and Klemd, 1996; Skrzypek *et al.*, 2011, 2014; Štipská *et al.*, 2012, 2019; Jastrzębski *et al.*, 2014, 2019; Twyrdy and Żelaźniewicz, 2017; Walczak *et al.*, 2017; Majka *et al.,* 2019) between 360 Ma and 330 Ma (e.g., Lange *et al.*, 2005; Bröcker *et al.*, 2009; Skrzypek *et al.*, 2017; Jastrzębski *et al.*, 2019; Walczak *et al.*, 2017 and references therein).

ANALYTICAL METHODS

Zircon grains were separated from the ortho- and paragneisses using standard techniques, including crushing, magnetic and heavy liquid separation, and handpicking under a binocular microscope. The typological classification of Pupin (1980) was applied to the zircons from samples of the Doboszowice (SUD21, SUD23) and Śnieżnik orthogneisses (SUD37).

Zircon grains from four rock samples (SUD21, SUD23, SUD22, SUD37) were mounted in epoxy resin, polished and imaged with cathodoluminescence (CL) before the isotopic analyses. A Thermo Scientific Element 2 sector field ICP-MS, coupled to a 193 nm ArF excimer laser (Teledyne Cetac Analyte Excite laser), at the Institute of Geology of the Czech Academy of Sciences, Prague, Czech Republic, was used to measure the Pb/U and Pb isotopic ratios in zircons (analytical details are provided in Supplementary Tab. S1). The same instrument was used for U-Th-Pb measurements of monazite in thin sections from five samples of the two-mica paragneisses. The procedure follows that described in Budzyń *et al.* (2021). See Supplementary Table S2 for analytical details. The U-Th-Pb data are presented as concordia and mean plots, generated with ISOPLOT v. 4.16 (Ludwig, 2012).

The Secondary Ion Mass Spectrometer (SIMS) technique has been used to determine the oxygen isotope signatures of previously dated zircon grains. SIMS analysis of oxygen isotope ratios was performed at the Polish Geological Institute (PGI, Warsaw), using a SHRIMP IIe/MC ion microprobe, operating with a primary Cs^+ beam. The data presented in this study were acquired during two analytical sessions. The details of sample preparation, imaging, instrumental calibration standards can be found in Supplementary Table S3.

Backscattered electron (BSE) imaging of monazite grains was performed prior to LA-ICPMS U-Th-Pb measurements, using a JEOL SuperProbe JXA-8230 electron microprobe, equipped with five wavelength dispersive spectrometers, at the Laboratory of Critical Elements AGH-KGHM at the AGH University of Science and Technology (Kraków, Poland). Compositional analyses of monazite were conducted, using a Cameca SX 100 electron microprobe, equipped with four wavelength spectrometers at the Laboratory of Electron Microanalysis, Geological Institute of Dionýz Štúr (Bratislava, Slovak Republic). The measurements were performed, using an accelerating voltage of 15 kV, a probe current of 180 nA, and a beam size of 3 µm. See Supplementary Table S4 for counting times, standards, spectral lines and WDS crystals.

Major elements of whole-rock samples SUD21, SUD23 and SUD37 were analysed at the Actlabs in Ancaster, Ontario, Canada, with the use of ICP-MS following lithium metaborate/tetraborate fusion and the rapid digestion in weak nitric acid solution of each sample.

SAMPLE DESCRIPTIONS

Doboszowice orthogneisses

Sample SUD21 from an active quarry near the Village of Pomianów Górny (50°30´28.6″N 16°56´35.7″E; Fig. 1B) is a strongly mylonitized, two-mica gneiss. The gneiss is composed mainly of quartz, plagioclase, K-feldspar, muscovite and biotite (Fig. 2A). Zircon forms 50–150-µm-sized, mostly transparent, normally- and long-prismatic grains. Approximately 25–30% of the zircon population are rounded grains, which is indicative of the inherited sedimentary character of this part of the SUD21 zircons. Morphological study indicates the predominance of P1, G1 and S10 types, which are characteristic for mainly alkaline and subalkaline magmas, and, to some extent, for calc-alkaline magmas, according to the Pupin's (1980) classification (Fig. 3A). Most of the crystals show oscillatory zoning in CL imaging, which indicates an igneous origin (Fig. 4A). The vast majority of zircon grains have inherited older cores that generally are also oscillatory-zoned.

Fig. 2. Field photographs, showing rocks of the Doboszowice Metamorphic Complex. **A.** Doboszowice pencil orthogneiss, sample SUD21. **B.** Doboszowice orthogneiss, sample SUD23. **C.** Migmatitic paragneiss, locality SUD22. **D.** Strongly deformed Śnieżnik gneiss, sample SUD37. **E.** Strongly deformed Doboszowice metagranite with metasedimentary rocks. **F.** Sharp contact between the Doboszowice orthogneiss and metasedimentary rocks.

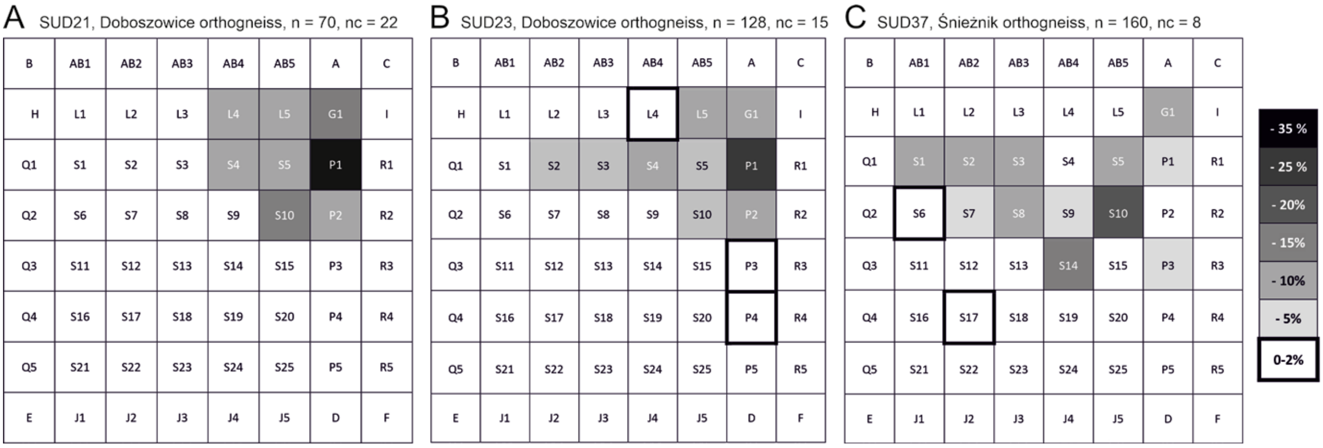

Fig. 3. Typological diagrams of zircon morphology (according to Pupin, 1980). **A, B.** Zircon populations from Doboszowice gneisses SUD21 and SUD23. **C.** Zircon population from Śnieżnik gneiss SUD37; n – number of studied crystals, nc – number of non-classified crystals.

Sample SUD23 from a small, abandoned quarry in Pomianów Górny (50°30´00.8″N 16°57´32.0″E; Fig. 1B) is a strongly foliated, medium-grained, two-mica orthogneiss, composed of quartz, plagioclase, K-feldspar, muscovite, biotite and accessory garnet (Fig. 2B). The zircons are transparent, and normally- to long-prismatic. They are mainly up to 120 µm long, but larger grains also occur (Fig. 4B). In contrast to sample SUD21, the SUD23 orthogneiss does not contain any rounded zircon grains. The sample includes an insignificant proportion of crystals, representing peraluminous magmas, whereas most of them have been attributed to types P1, P2, G1, L5 and S4, according to Pupin's (1980) classification (Fig. 3B). Most crystals are oscillatory-zoned. The presence of inherited, oscillatory-zoned cores is also a dominant feature of the SUD23 zircons. Part of the cores could be primarily rounded or resorbed.

Chałupki paragneisses

Sample SUD22 represents the migmatitic plagioclase paragneisses and was collected from an abandoned quarry, east of the Village of Chałupki (Figs 1, 2B; 50°29´12.9″N 17°00´18.0″E). The paragneisses are medium- to coarse-grained foliated rocks, composed of quartz, plagioclase, muscovite and biotite with variable amounts of garnet. Two main varieties of paragneiss, which differ in the modal proportions of garnet and plagioclase, were collected from the quarry. For U-Th-Pb monazite dating, five thin sections, cut from five samples of paragneisses from the abandoned Chałupki quarry, were studied. Samples SUD22/3 and SUD22/4 are porphyroblastic and contain large (3–5 mm) garnets, whereas samples SUD22/2, SUD22/5 and SUD22/6 are garnet-free, but rich in plagioclase.

Zircon sample SUD22 and monazite sample SUD22/6 are from the same paragneiss specimen. The zircons in SUD22 are generally smaller (<100 µm; Fig. 4C), but more rounded than the zircons from orthogneisses (SUD21 and SUD23). Less than 10% of zircon grains are subhedral to euhedral, therefore Pupin's classification was not applied. The zircons are oscillatory-zoned or, occasionally, homogenous. Inherited cores and variable luminescence of individual grains are also present.

Śnieżnik orthogneisses

Sample SUD37, from a small, abandoned quarry in Lądek Zdrój (50°20´34.8″N 16°53´07.1″E; Fig. 1B), is a moderately foliated, medium-grained, two-mica gneiss, composed of quartz, plagioclase, K-feldspar, muscovite and biotite, with polymineral quartz-feldspar augens (Fig. 2D). The zircons are automorphic, transparent, and normally- and long-prismatic, with rare, short-prismatic grains. The size of crystals ranges from ca. 70 to ca. 200 µm, but sporadically zircon grains bigger than 300 µm, including their crushed fragments, also occur (Fig. 4D). Rounded grains constitute <1% of the zircon population. The most frequent zircon types are related to calc-alkaline and crustal magmas, whereas zircon crystals representing alkaline magmas are less common. S10 and S14 morphotypes (according to Pupin, 1980) predominate, whereas G1, S1, S2, S3, S5 and S8 types are less frequent (Fig. 3C). Numerous zircon grains have inherited, zoned cores. The middle parts and rims of these grains usually display oscillatory zoning.

U-PB ZIRCON AGES

In general, the selection of individual zircon populations from an array of nearly concordant ages is very difficult. The rocks studied show U-Pb data dispersion along Concordia similar to high-grade rocks with metasedimentary component, which is a commonplace in the Variscan orogen. In such a case, the pooled age of the youngest age cluster is considered to be the best estimate of the age of a significant geological event (magmatism or metamorphism). The other, older ages often represent inherited components that are more or less affected by the youngest U-Pb event. In any case, the accuracy of U-Pb ages obtained from rocks with a metamorphic overprint cannot be compared to the accuracy of ages from zircons that primarily crystallized

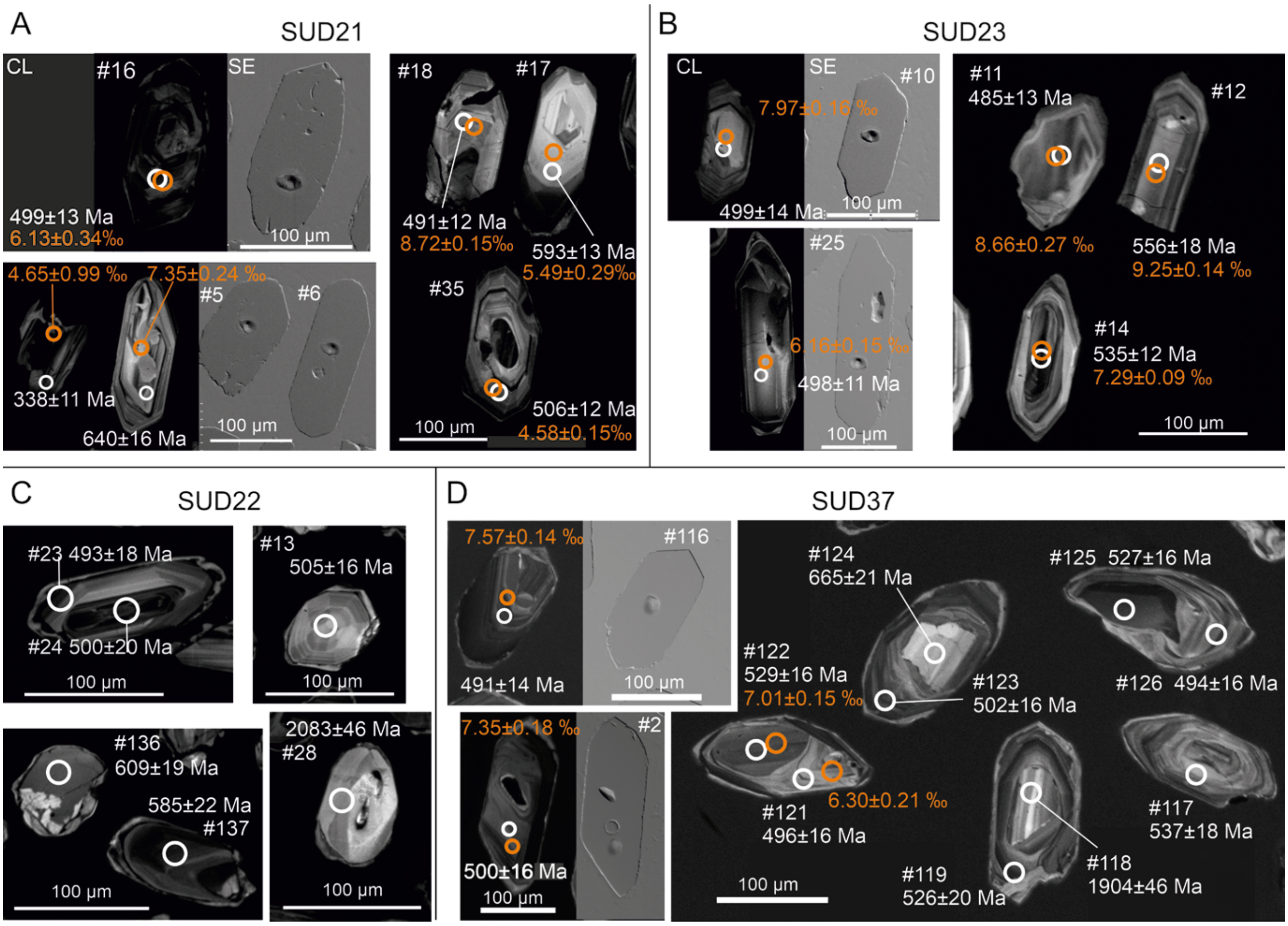

Fig. 4. Cathodoluminescence (CL) images of representative zircon grains from the Doboszowice orthogneisses (SUD21, SUD23), the Doboszowice paragneiss (SUD22) and the Śnieżnik orthogneiss (SUD37). Secondary electron (SE) topographic images of representative ca. 500 Ma crystals illustrate the sizes and positions of the measured SHRIMP spots for oxygen isotopic analysis. Spot labels of U-Pb dates (white) and O isotope data (orange) correspond to labels in Supplementary Tables S5 (U-Pb data) and S6 (O isotopes data).

in an igneous rock. In this paper, ^{207}Pb/^{206}Pb dates are used for zircons older than 1 Ga, whereas ^{206}Pb/^{238}U dates are used for zircons < 1 Ga.

Doboszowice Metamorphic Complex

In Doboszowice pencil orthogneiss SUD21, 53 out of 56 U-Pb analyses are <10% discordant (Supplementary Tab. S5). Two-thirds of these data represent both individual zircon grains and inherited cores, which are Ediacaran (635–552 Ma). The 605–585 Ma age cluster is the most prominent in this population (Figs 5A, 6). Twenty-four percent of zircon ages are middle to late Cambrian (525–488 Ma). Nine analyses (-1.0–3.6% discordance) plot along the linear regression with the upper intercept at 500 ± 16 Ma (2σ, MSWD = 0.15; Fig. 5B).

In orthogneiss sample SUD23, 47/53 U-Pb analyses are <10% discordant. Compared to sample SUD21, sample SUD23 shows a smaller number of Ediacaran U-Pb ages (660–543 Ma; 30% of the population) and a larger number of Cambrian ages (538–486 Ma; 68% of the population; Figs 5C, 6). One analysis yielded the Palaeoproterozoic, Orosirian age (1.9 Ga, Supplementary Tab. S5). Zircon ages of ca. 560–550 Ma and ca. 540 Ma predominate in the Ediacaran age population (Fig. 6). Nearly half of the analysed grains form the youngest concordant cluster of ages and probably represents late Cambrian crystallization (Fig. 6), with a Concordia age of 494.2 ± 4.6 Ma (2σ, MSWD = 2.0; Fig. 5D).

In paragneiss SUD22, 97 out of 140 U-Pb analyses are <10% discordant (Fig. 7A). The zircon U-Pb data demonstrate two predominant Neoproterozoic age clusters at 642–625 Ma and 596–583 Ma (Figs 6, 7B). Minor peaks are at ca. 2.13–2.08 Ga, 1.04–0.95 Ga, 859–817 Ma and 510–488 Ma (Fig. 7). The 510–488 Ma dates were obtained from subhedral to euhedral grains that are generally less rounded, compared to the older zircons in this sample.

Orlica-Śnieżnik Dome

In the Śnieżnik orthogneisses SUD37, 119 out of 136 analyses are <10% discordant. Two U-Pb dates represent the early Proterozoic – Orosirian period (1.9 Ga) and two U-Pb dates represent the Cryogenian Period (665–662 Ma; Supplementary Tab. S2). The zircon U-Pb age population includes 12% of Ediacaran dates (632–548 Ma) and 83% of Cambrian to Ordovician dates (539–486 Ma; Fig. 5E). The ca. 530–520 Ma age cluster predominates in the

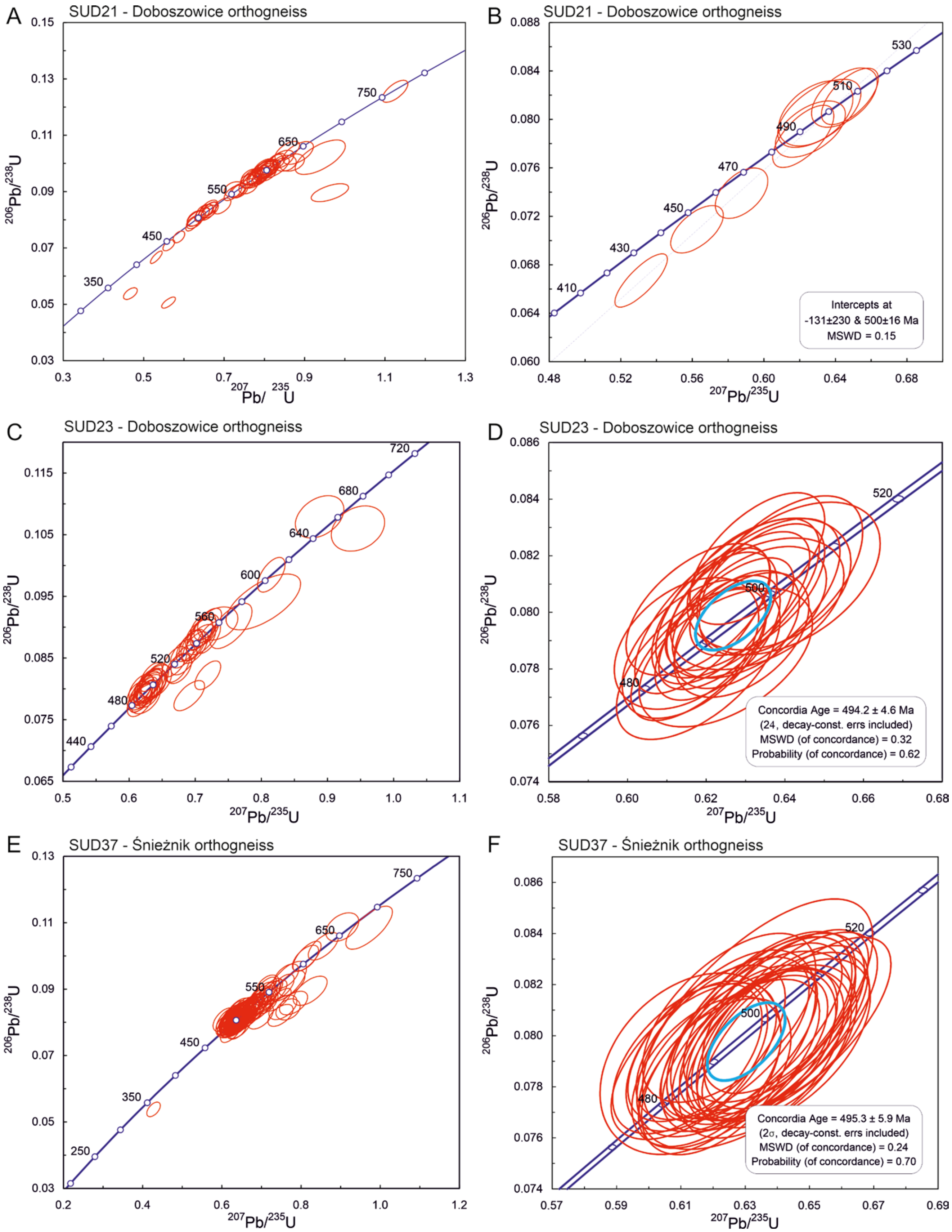

Fig. 5. Results of U-Pb LA-ICPMS zircon dating of the Doboszowice and Śnieżnik orthogneisses and the Doboszowice paragneisses. Data-point error ellipses are 2σ. **A.** Concordia U-Pb plot for the SUD21 sample. **B.** Concordia U-Pb plot in early Palaeozoic range for sample SUD21, **C.** Concordia U-Pb plot for the SUD23 sample. **D.** Concordia U-Pb plot in early Palaeozoic range for sample SUD23. **E.** Concordia U-Pb plot range for the SUD37 sample. **F.** Concordia U-Pb plot in early Palaeozoic range for sample SUD37.

inherited age component, which was obtained from individual zircon grains and the xenocrystic cores (Figs 4D, 6). As in sample SUD23, representing the Doboszowice gneiss, nearly half of the analysed grains are late Cambrian with a Concordia age of 495.3 ± 5.9 Ma (2σ, MSWD = 1.2; Fig. 5F), which indicates the age of the last magmatic crystallization and intrusion.

O ISOTOPES IN ZIRCON

In-situ oxygen analyses were conducted on zircons from orthogneisses SUD21, SUD23 (DMC) and SUD37 (OSD). On the basis of CL observations and U-Pb age results, the analysed zircon domains were divided into two groups as the first step:

1. inherited Neoproterozoic xenocrysts with dates >529 Ma, and
2. magmatic Cambrian zircons, with dates ranging from 485 to 519 Ma, accompanied by overgrowths, representing the last magmatic crystallization event, and by younger overgrowths, related to the post-magmatic stage (Fig. 8A; Supplementary Tab. S6).

All data from these groups revealed relatively similar ranges of values, although with slightly different proportions of inherited *versus* magmatic components within each group (Tab. 1).

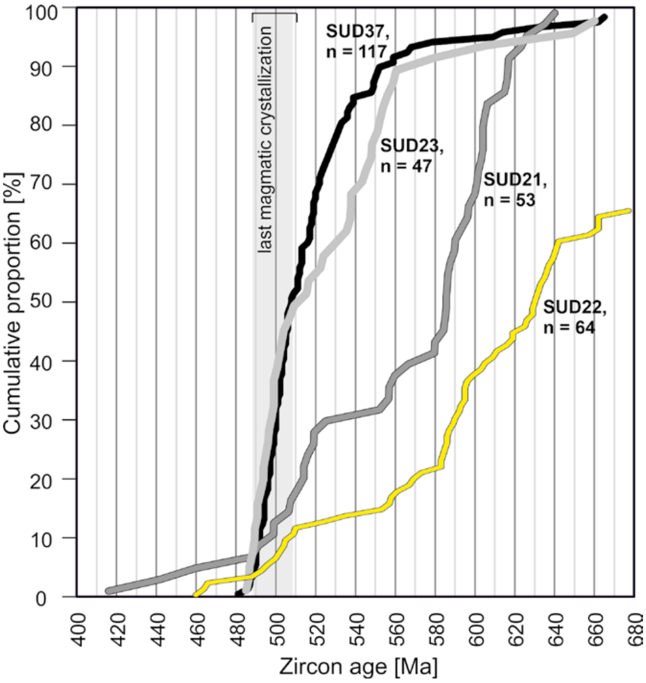

Fig. 6. Cumulative plots for zircon populations from SUD21 (DMC), SUD23 (DMC), SUD37 (OSD) orthogneisses and SUD22 (DMC) paragneiss. n: number of <10% discordant U-Pb data in the range of 680–400 Ma.

Table 1

The average zircon oxygen composition $\delta^{18}O$ calculated for orthogneiss samples.

Sample ID	Inherited [N] aver $\delta^{18}O$	Mantle-like	Magmatic [N] aver. $\delta^{18}O$	Mantle-like	post- magmatic [N] $\delta^{18}O$
SUD21	[28] 8.03 ± 0.53‰	6/28	[13] 7.62 ± 0.94‰	2/13	[3]
SUD23	[15] 7.85 ± 0.91‰	3/15	[19] 7.61 ± 0.56‰	2/19	[0]
SUD37	[1] not calculated		[18] 5.67 ± 0.50‰	8/18	[1]

Doboszowice Metamorphic Complex

Oxygen isotope $\delta^{18}O$ values, obtained from Neoproterozoic inherited zircons from Doboszowice orthogneisses SUD21 and SUD23, are in the range 5.15–11.95‰ and 5.13–9.65‰, respectively (Supplementary Tab. S5). Thus, they reflect values from mantle-like ($\delta^{18}O$ ca. 5‰) to elevated (ca. 10‰) indicating involvement of low-temperature altered material (e.g., Neoproterozoic supracrustal rocks) in the magma source. Ca. 500 Ma zircons from the two samples of Doboszowice gneisses SUD21 and SUD23 have comparable, consistent oxygen isotope distribution with values in the range of 4.58–9.37‰ and 5.07–9.20‰ (Fig. 8B), respectively, mostly higher than that of the primitive mantle and interpreted as reflecting the Si-rich composition (ca. 77 wt.% SiO_2 bulk content; Supplementary Tab. S7). The mantle-similar values are restricted to 2 grains in both samples.

Orlica-Śnieżnik Dome

Approximately 500 Ma zircon grains from Śnieżnik orthogneisses SUD37 revealed less heterogeneous and generally lower $\delta^{18}O$ values compared to those of the zircons of the Doboszowice orthogneisses. These features also concur with the slightly lower SiO_2 bulk content of ca. 73 wt% in sample SUD37 (Supplementary Tab. S7). The late Cambrian event produced zircons with $\delta^{18}O$ ranging from 4.38 to 7.57‰, notably containing a significant number (n = 8/18) of zircons that record a mantle-like $\delta^{18}O$ value of 5.3 ± 0.6‰ (2σ; Valley, 2003; Fig. 8B). A single analysis of oxygen isotopic composition from a Variscan (ca. 338 Ma) zircon grain yielded $\delta^{18}O$ of 5.29‰.

MONAZITE GEOCHRONOLOGY – MIGMATITIC PARAGNEISSES

Monazite in the paragneiss samples occurs as subhedral to anhedral grains (20 × 35 to 60 × 100 µm-sized) with irregular growth or sector zoning, while the smallest grains are commonly homogeneous (Fig. 9). Monazite is present in the matrix, forms inclusions in micas, and occasionally is intergrown with apatite or zircon. Rarely, monazite is overgrown by epidote or forms inclusions in garnet (sample SUD22/3). The compositional variations of the monazite (EPMA data

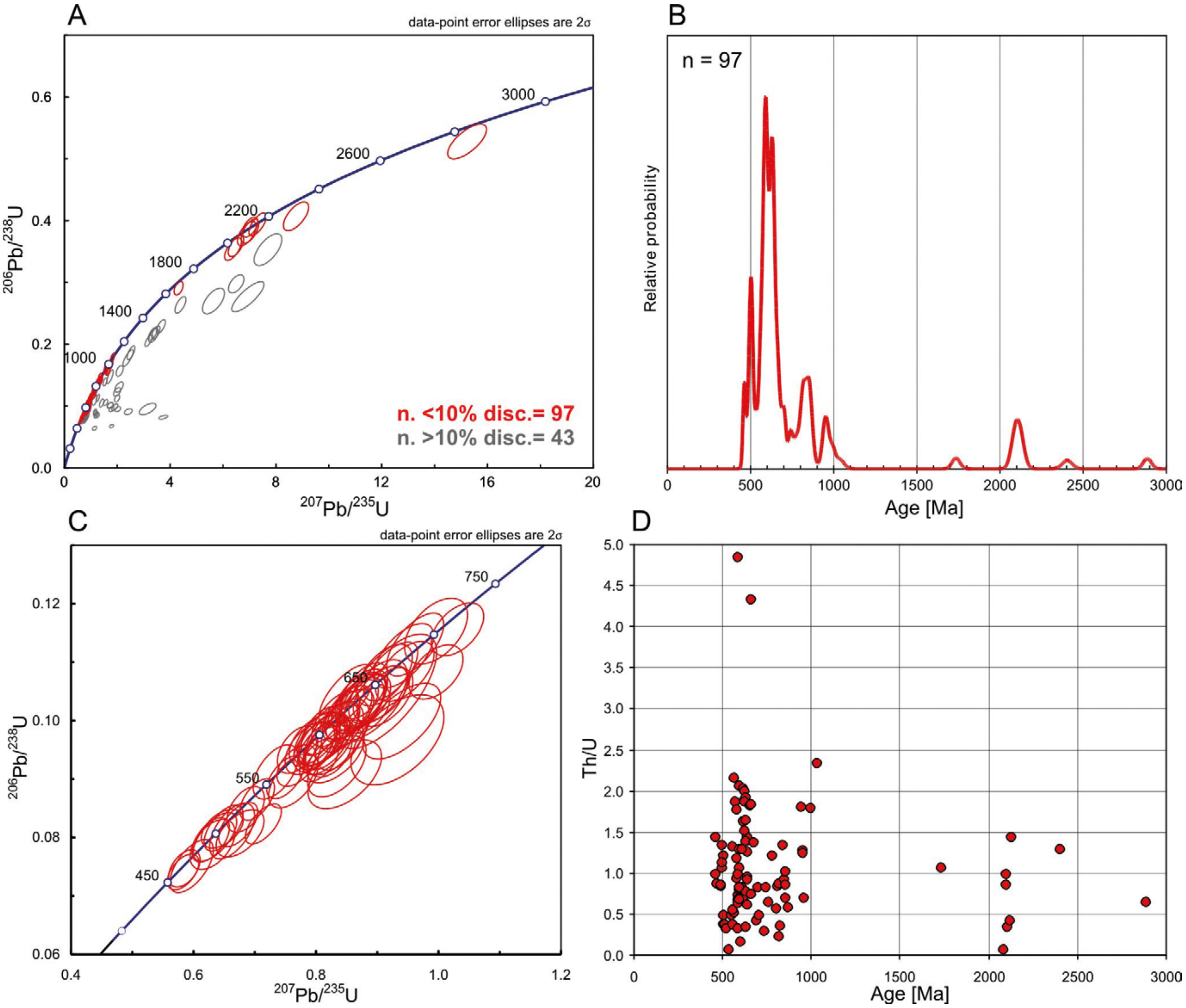

Fig. 7. Results of U-Pb LA-ICPMS zircon dating of paragneiss SUD22 (DMC). **A.** Concordia U-Pb plot showing concordant analyses (red ellipses) and analyses with discordance >10% (grey ellipses). **B.** Probability density plot for <10% discordant data. **C.** Concordia U-Pb plot in Neoproterozoic / early Palaeozoic range. **D.** Zircon age vs. Th/U ratio plot. (B, D) $^{206}Pb/^{238}U$ ages are given for dates <1 Ga, $^{207}Pb/^{206}Pb$ ages are given for dates >1 Ga.

in Supplementary Tab. S8) are a typical feature of this phase. The chondrite-normalized REE patterns are similar for monazite in the garnet-free samples SUD22/2, SUD22/5 and SUD22/6, indicating similar conditions and/or a similar geochemical environment of monazite growth (Fig. 10). In the garnet-bearing paragneisses SUD22/3 and SUD22/4, the chondrite-normalized compositional patterns of monazite are similar in the LREE region, but they show variable depletion in Y and HREE, which is related to preferential incorporation of Y and HREE by garnet over monazite.

Five to twenty-five LA-ICPMS U-Th-Pb measurements of monazite were performed in each sample, depending on the availability of the grains and their size being suitable for analysis (Fig. 9). Briefly considering the statistics, 19 analyses were conducted in 7 grains in paragneiss SUD22/2, 5 analyses in 3 grains in SUD22/3, 25 analyses in 9 grains in SUD22/4, 13 analyses in 7 grains in SUD22/5, and 5 analyses in 3 grains in SUD22/6 (Fig. 9; Supplementary Tab. S9). Monazite U-Pb dates mostly are moderately to highly discordant, with some dates showing up to 64.1% discordance (Fig. 11F). Only monazite from paragneiss SUD22/5 yielded U-Pb data mostly <2% discordance, i.e., 12 analyses out of 13 (1 analysis with 4.1% discordance), providing the concordia age of 345.9 ± 2.9 Ma (2σ, MSWD = 1.06; Fig. 11D). In the remaining samples, discordance and too scattered Pb/U dates prevent constraining the concordia ages, whereas the intercept ages may result in geologically meaningless data, even when standard filtering to <10% discordance is used. $^{207}Pb/^{235}U$ dates (<10% discordance) range from 331 to 377 Ma, whereas $^{208}Pb/^{232}Th$ and $^{206}Pb/^{238}U$ dates are ranging from 321 to 354 Ma and from 322 to 362 Ma, respectively. Therefore, more restricted data filtering to <5% discordance was applied to constrain the age of a metamorphic event. Calculated $^{208}Pb/^{232}Th$, $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ mean ages of 340.6 ± 3.6 Ma (95% conf., MSWD = 1.2, n = 36), 346.5 ± 6.4 Ma (95% conf., MSWD = 5.0, n = 36) and 341.8 ± 9.6 Ma (95% conf., MSWD = 1.03, n = 33), respectively, are within their uncertainties (Fig. 12).

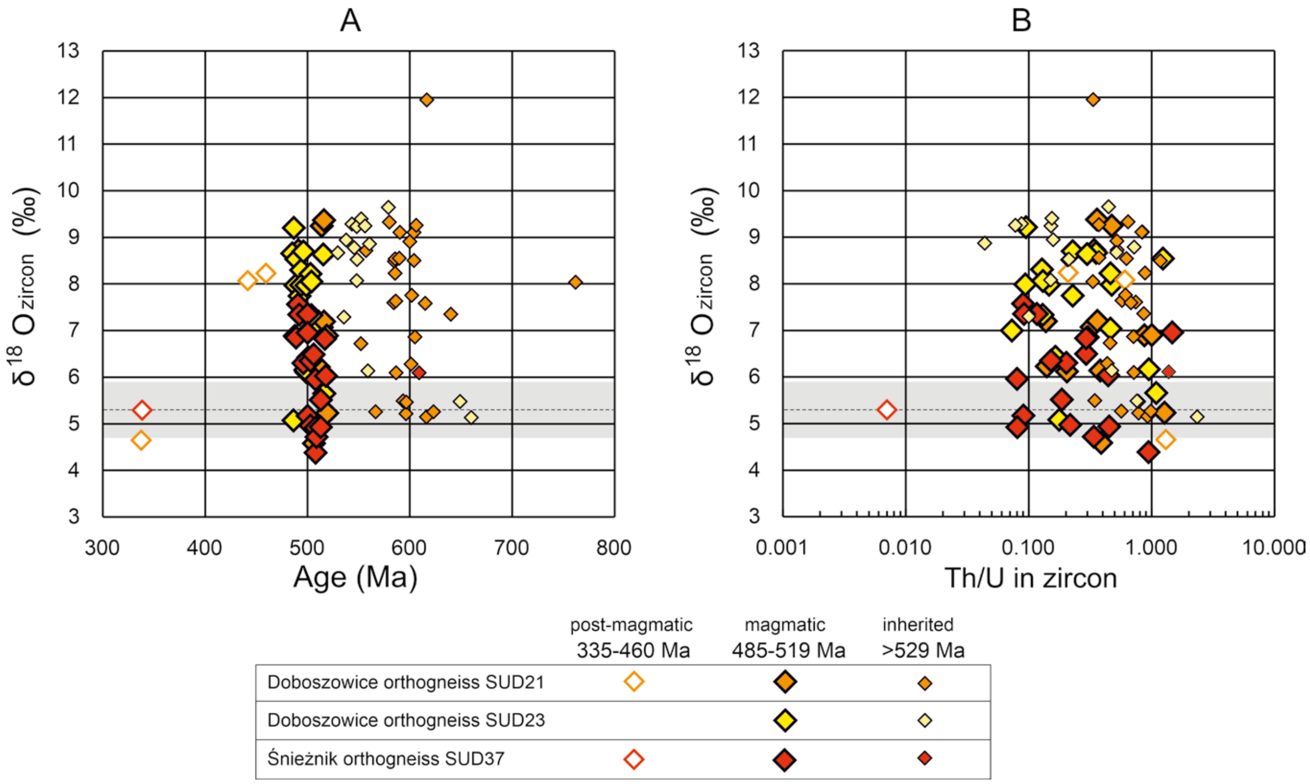

Fig. 8. Results of $\delta^{18}O$ isotopic analysis in zircon from the Doboszowice and Śnieżnik orthogneisses. **A.** Relationship between age (Ma) and oxygen isotopic compositions of zircon expressed as $\delta^{18}O$ (‰) in all studied orthogneisses. Three distinguished groups refer to i) inherited, Neoproterozoic–early Cambrian crystallization events, ii) crystallization of magmatic protolith(s) of orthogneisses, iii) post-magmatic events. **B.** Th/U ratio and $\delta^{18}O$ values for zircon in the Doboszowice and Śnieżnik orthogneisses. Mantle-equilibrated value for $\delta^{18}O$ in zircon (5.3 ± 0.6‰, 2σ, Valley, 2003) is indicated by grey colour.

DISCUSSION

Late Cambrian magmatism in the eastern Saxothuringian Terrane

The new zircon U-Pb data of the present study confirm that orthogneisses, abundant in the Sudetic part of the Saxothuringan Terrane, had magmatic precursors, which crystallized/intruded in the late Cambrian–Early Ordovician. The very similar 494 ± 5 and 495 ± 6 Ma concordia ages of zircon (Fig. 5D, F) were obtained in this study for gneisses of two different units subdivided by the Sudetic Boundary Fault: Doboszowice (SUD23) and Śnieżnik gneisses (SUD37), respectively. They concur with the previous ion microprobe zircon geochronology for the Śnieżnik gneisses that yielded, e.g., 500–488 Ma zircon ages (Redlińska-Marczyńska *et al.*, 2016, and references therein) and Doboszowice gneisses that yielded a concordia zircon age of 488 ± 6 Ma (Mazur *et al.*, 2010). Similar U-Pb concordia ages of zircon were obtained for other orthogneisses in the eastern part of the Fore-Sudetic Block (Fig. 1A), at Gościęcice (504 ± 3 Ma, U-Pb multigrain zircon age; Oliver *et al.*, 1993; 500 ± 12 Ma, ion microprobe U-Pb age; Mazur *et al.*, 2010) and Stachów (499 ± 4 Ma, ion microprobe U-Pb age, Oberc-Dziedzic *et al.*, 2018). This late Cambrian–Early Ordovician age constrains the timing of widespread granite magmatism in the region. The measured zircon ages of ca. 495 Ma are also in agreement with those obtained for the gneisses in the Izera-Karkonosze Block: the Kowary orthogneiss (492–481 Ma, U-Pb multigrain zircon age, Oliver *et al.*, 1993), 487 ± 8 Ma (SHRIMP U-Pb, Oberc-Dziedzic *et al.*, 2010) and the Izera orthogneiss (between ca. 512 to ca. 502 Ma, Pb-Pb zircon evaporation mean ages and U-Pb concordia ages; Kröner *et al.*, 2001) in the West Sudetic part of the Saxothuringian Terrane (Fig. 1; see Oberc-Dziedzic *et al.,* 2018 for review).

On the other hand, the new data of the present authors reveal that orthogneisses from the DMC and OSD differ in age of the inherited zircons, zircon morphology and oxygen isotopic systematics. Sample SUD21 from the DMC contains many more inherited zircons than samples SUD23 and SUD37, where the inheritance is negligible (Fig. 6). Interestingly, the zircon age spectrum in the Doboszowice orthogneiss (SUD23) is closely comparable to that of the Śnieżnik orthogneiss (SUD37), which might indicate that these two have the same or a similar precursor. However, the oxygen isotopic data of zircons from the Śnieżnik gneiss revealed that ⅓ of the studied population have the lowest $\delta^{18}O$ values, typical of the mantle, whereas the remaining ⅔ of grains have $\delta^{18}O$ values, indicative of a crustal origin (Fig. 8A; Tab. 1). The parental Śnieżnik magma possibly had a hybrid character, due to the important contribution of a mantle component, which is consistent with the lowest number of inherited zircons in sample SUD37. Furthermore, in this sample, some zircon grains display $\delta^{18}O$ values <5‰, thus below the mantle values, which can be explained by the high-temperature water-rock interaction. Generally, such an

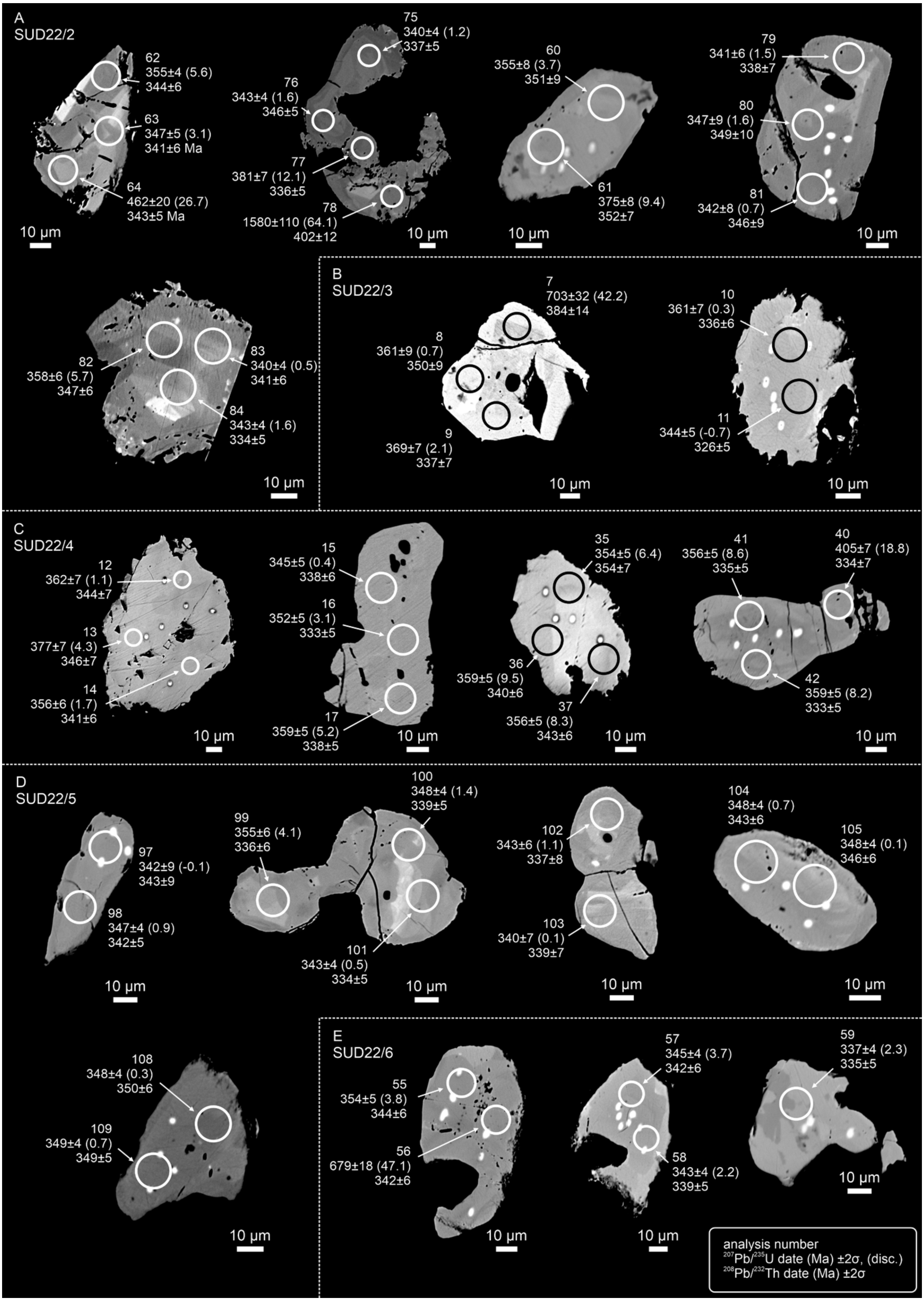

Fig. 9. High-contrast backscattered (BSE) images of representative monazite grains with marked laser ablation spots.

interaction can be expected in an extensional setting (such as a rift), where the low-$\delta^{18}O$ magmas can be readily generated (e.g., Eiler, 2001; Harris and Ashwal, 2002; Bindeman, 2008).

In Doboszowice gneisses SUD21 and SUD23, only a few analyses reflect the equilibration of the zircons with the mantle magma. In most zircon grains, the $\delta^{18}O$ values are distinctly higher than that of the primitive mantle (Tab. 1), which is interpreted as reflecting the evolved, Si-rich composition of the parent magma (ca. 77 wt% bulk rock SiO_2; Supplementary Tab. S7). The elevated $\delta^{18}O$ values plot away from the mantle field (Fig. 8). This observation, along with the abundance of the inherited zircons, provide evidence of melting of the Cadomian continental crust. In view of the data available, it cannot be firmly concluded whether the observed differences in late Cambrian–Early Ordovician magmas were due to different grades of differentiation or result from various protoliths, or possibly both reasons contributed in particular occurrences.

A relatively large amount of rounded zircons in sample SUD21 (25–30% of the population) indicates a significant proportion of sedimentary material in the formation of the parent magma. Zircon typology, studied by the present authors and by Puziewicz and Rudolf (1998), indicate alkaline and/or subalkaline igneous protoliths of the Doboszowice orthogneisses. Interestingly, the morphological features of the zircons differ from those, known from other occurrences of late Cambrian orthogneisses in the Fore-Sudetic Block (i.e., the Henryków, pale Stachów and Gościęcice orthogneisses; Fig. 1), the typology of which indicates a more diversified geochemistry than that of the Doboszowice zircons. The zircons in the former gneisses have higher aspect ratios and predominantly represent the "crustal" morphotypes S2 and S7 (cf. Klimas, 2008). Actually, the zircon morphotypes and relevant genetic trends in sample SUD37 from the OSD, compared to those observed in the Gierałtów and Śnieżnik gneisses by Turniak *et al.* (2000), indicate more varied typology and all indicate S-type granitic protoliths.

On the basis of the zircon populations from the studied orthogneisses, the present authors suggest that their protoliths differ considerably in U-Pb zircon ages of the inherited component, $\delta^{18}O$ signatures and zircon morphology. Such variations concur with the notion about complex and non-uniform, felsic/bimodal magmatism at the northern Gondwana margin in late Cambrian–Early Ordovician times.

Age and provenance of DMC metasedimentary rocks

The detrital age spectra of the Chałupki paragneisses demonstrate the predominance of Neoproterozoic zircons. There is little doubt that the relevant source area(s) were composed of Cryogenian to Ediacaran crystalline rocks, carrying some Palaeoproterozoic component (Fig. 7). Mesoproterozoic crystalline rocks or rocks containing Mesoproterozoic zircons were not exposed or were missing in those areas (Fig. 7). The zircon ages obtained for paragneiss sample SUD22 are comparable to those from other metasedimentary rocks, known from the Saxothuringian Terrane. In the West Sudetes, the presence of Palaeoproterozoic and Cryogenian-Ediacaran zircons with minor Cambro–Ordovician zircons is observed in metasediments of the Lusatian Massif (e.g., Linnemann *et al.*, 2014), the Izera-Karkonosze Massif (Żelaźniewicz *et al.*, 2009; Oberc-Dziedzic *et al.*, 2010; Žáčková *et al.*, 2012), the Kaczawa Fold Belt (Kryza *et al.*, 2007; Kryza

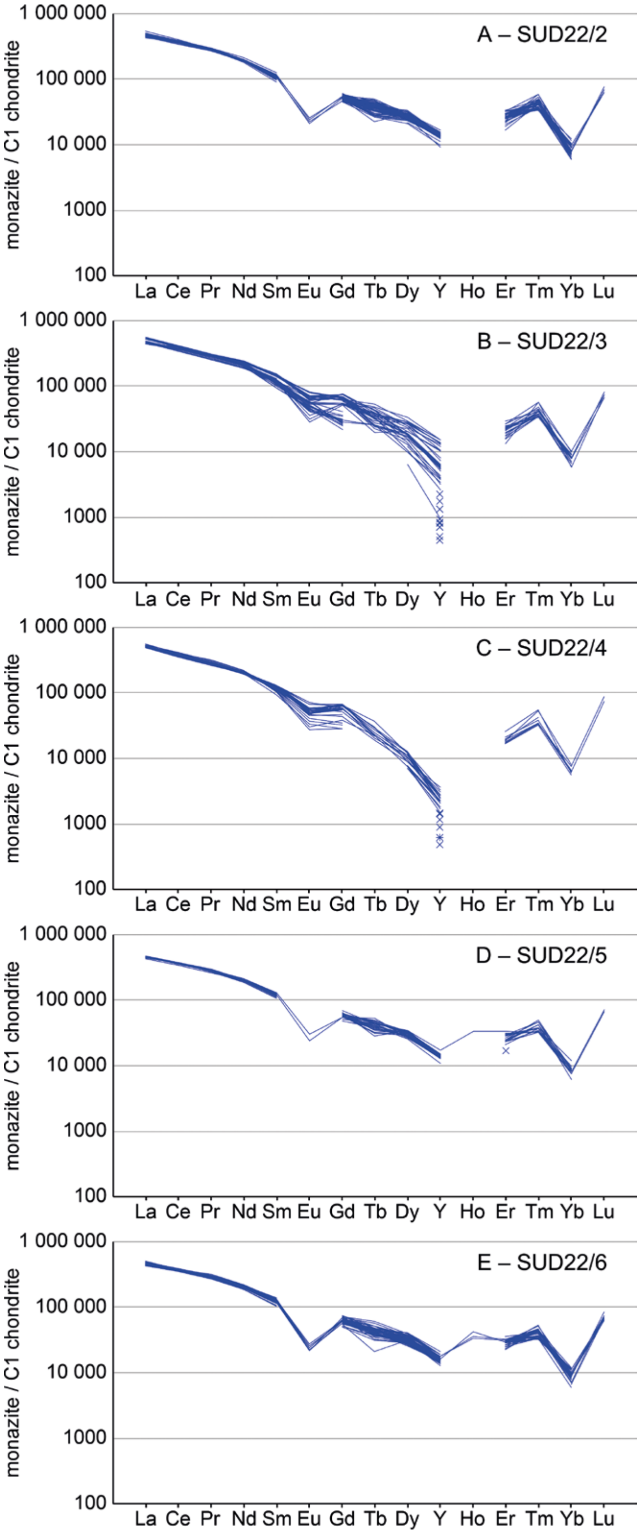

Fig. 10. Chondrite-normalized REE distribution patterns of monazite from migmatitic paragneisses SUD22/2–SUD22/6. C1 chondrite composition after McDonough and Sun (1995).

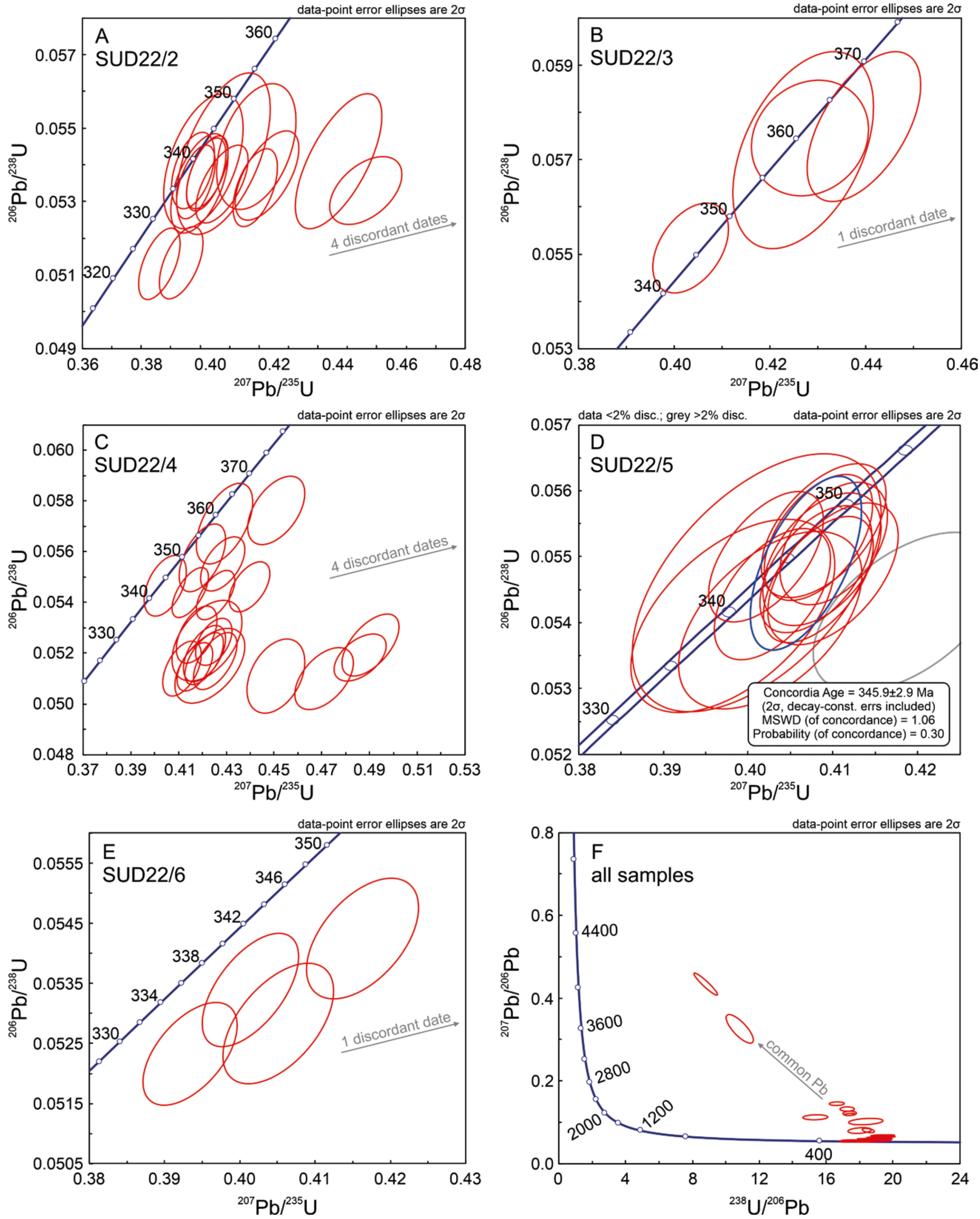

Fig. 11. Results of LA-ICPMS measurements of the migmatitic paragneisses SUD22/2–SUD22/6. **A–E.** Wetherill Concordia diagram for each sample; only monazite from paragneiss SUD22/5 yielded dates mostly <2% discordance (D). **F.** Terra-Wasserburg Concordia diagram plotted for all data and presenting discordant dates reflecting incorporation of common Pb.

and Zalasiewicz, 2008; Tyszka *et al.*, 2008), the Orlica-Śnieżnik Dome (Jastrzębski *et al.*, 2010, 2015; Mazur *et al.*, 2012, 2015; Szczepański *et al.*, 2020), the Staré Město Belt (Jastrzębski *et al.*, 2015; Śliwiński *et al.*, 2022) and the western part of the Strzelin Massif (Oberc-Dziedzic *et al.*, 2018). All those metasediments, like other Saxothuringian clastics, usually have been interpreted as being derived from the West African part of Gondwana (e.g., Linnemann *et al.*, 2004; Stephan *et al.*, 2019).

However, the Precambrian age spectrum, with a high proportion of Neoproterozoic and Palaeoproterozoic components and a certain proportion of ca. 1.04–0.95 Ga (Meso- and Neoproterozoic boundary) grains, obtained from sample SUD22, is comparable to that recently revealed for the mica schists from the south-western part of the KZMB (Jastrzębski *et al.*, 2020). The previous zircon U-Pb data also show the presence of ca. 1.1–0.9 Ga zircons in the OSD metasedimentary rocks studied as well as in the Staré Město Belt (Jastrzębski *et al.*, 2010; Mazur *et al.*, 2015; Szczepański *et al.*, 2020; Śliwiński *et al.*, 2022).

It is worth mentioning that Cambrian to Cambro–Ordovician sedimentary rocks that contain a significant 1.1–0.9 Ga zircon age cluster have been reported from various localities in northern Africa (e.g., Anti-Atlas, Morroco), Sardinia (Avigad *et al.*, 2012), Israel and Jordan (Morag *et al.*, 2011) and Saudi Arabia (Meinhold *et al.*, 2021). However, while such ca. 1.0 Ga zircons are scarce in Algeria and Morocco, they are abundant in Libya, Israel and Jordan (Meinhold *et al.*, 2013). Accordingly, the presence of 1.1–0.9 Ga zircons in the DCM points to source areas within the Cambro–Ordovician catchments, which were located in the central and/or eastern parts of northern Africa and not in West Africa. In view of this, alternative sources in the Grenvillian belt are less likely than those in north Africa and the Arabian-Nubian shield inclusive (e.g., Avigad *et al.*, 2012; Meinhold *et al.*, 2021; Fig. 13). Definitely, the zircon data indicate that the KZMB (with DMC) and OSD sedimentary basins were within the delivery reach of detrital material, derived from the areas partly composed of ca. 1.0 Ga rocks, probably in the framework of the Gondwana super-fan model (Meinhold *et al.*, 2013, 2021).

In the OSD and KZMB, the detrital age spectra of zircons from metagreywackes and metapelites, except for the Stronie quartzites (Jastrzębski *et al.*, 2010, 2020; Mazur *et al.*, 2012, 2015; Szczepański *et al.*, 2020), differ from those revealed in the DMC paragneisses (this study) by the presence of ca. 510–488 Ma zircons in the latter (Fig. 7C, D). Such an age cluster in these paragneisses is formed by the most euhehral zircons (Fig. 4C), which might indicate either short sedimentary transport or a volcanogenic/pyroclastic provenance. In view of the identical ages of the youngest zircons in the paragneisses and orthogneisses of the DMC, the latter option is favoured. Felsic effusives of bimodal late Cambrian–Early Ordovician volcanism are common in the adjacent OSD and Staré Město Belt (Kröner *et al.*, 2000; Wojciechowska *et al.*, 2001; Murtezi, 2006; Jastrzębski *et al.*, 2015; Fig. 1). In the DMC itself, metabasalts and basaltic tuffs occur, accompanying the metasediments (Puziewicz *et al.*, 1999; Awdankiewicz, 2008). At that very time, S-type granitic magma (moderate Th/U ratios, Fig. 7D) was emplaced at mid-crustal levels of the DMC and cooled at a depth of ca. 18–11 km (Puziewicz and Rudolf, 1998), which is indicative of extension. Accordingly, an extensional setting, whether rift or back-arc basin(s) at the margin of Gondwana, is confirmed for the DMC in the late Cambrian-Early Ordovician, which is similar to other Saxothuringian units (Fig. 1). Such a setting further evolved inevitably within a rift/drift scenario.

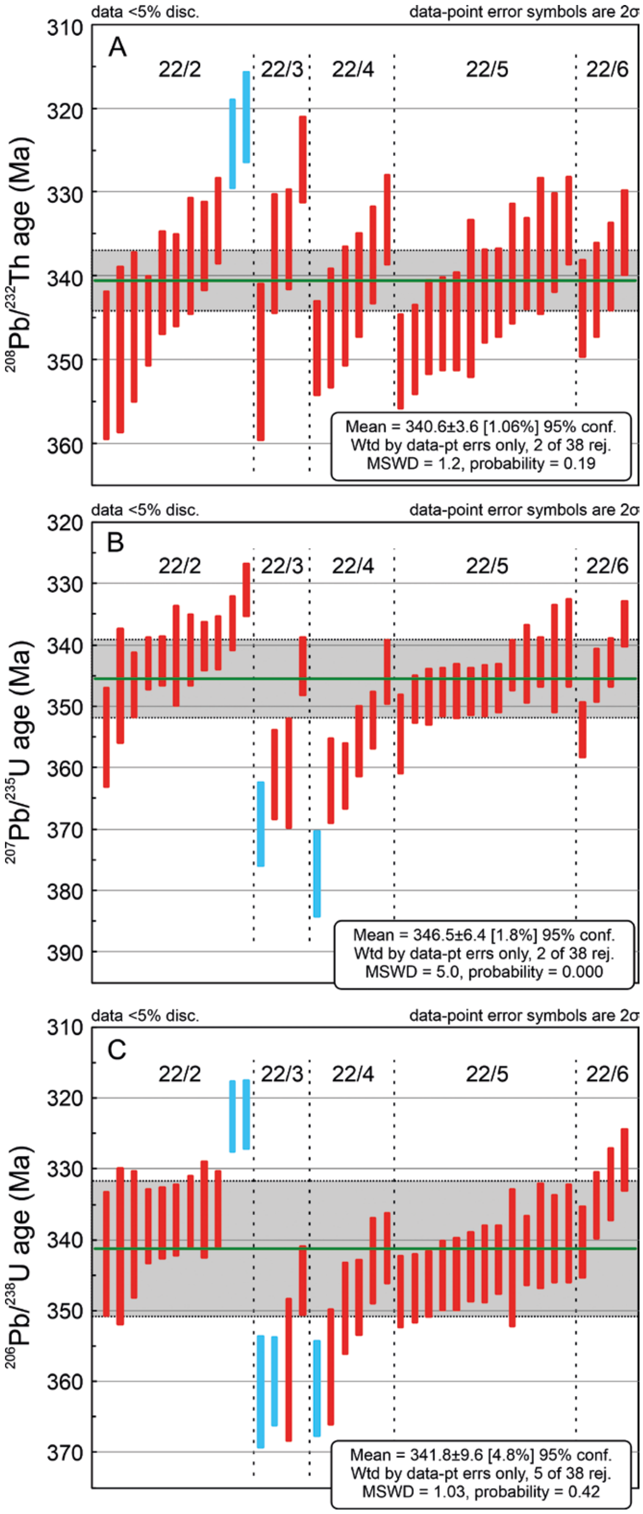

Fig. 12. Results of LA-ICPMS measurements of migmatitic paragneisses SUD22/2–SUD22/6 on the diagrams presenting ^{208}Pb/^{232}Th, ^{207}Pb/^{235}U and ^{206}Pb/^{238}U mean dates calculated using data filtered to <5% discordance.

Age of metamorphism and tectonic setting

The monazite grains in both the garnet-bearing and the garnet-free paragneisses at Chałupki provided relatively similar characteristics considering their textural position and features, composition and Pb/U and Pb/Th age data.

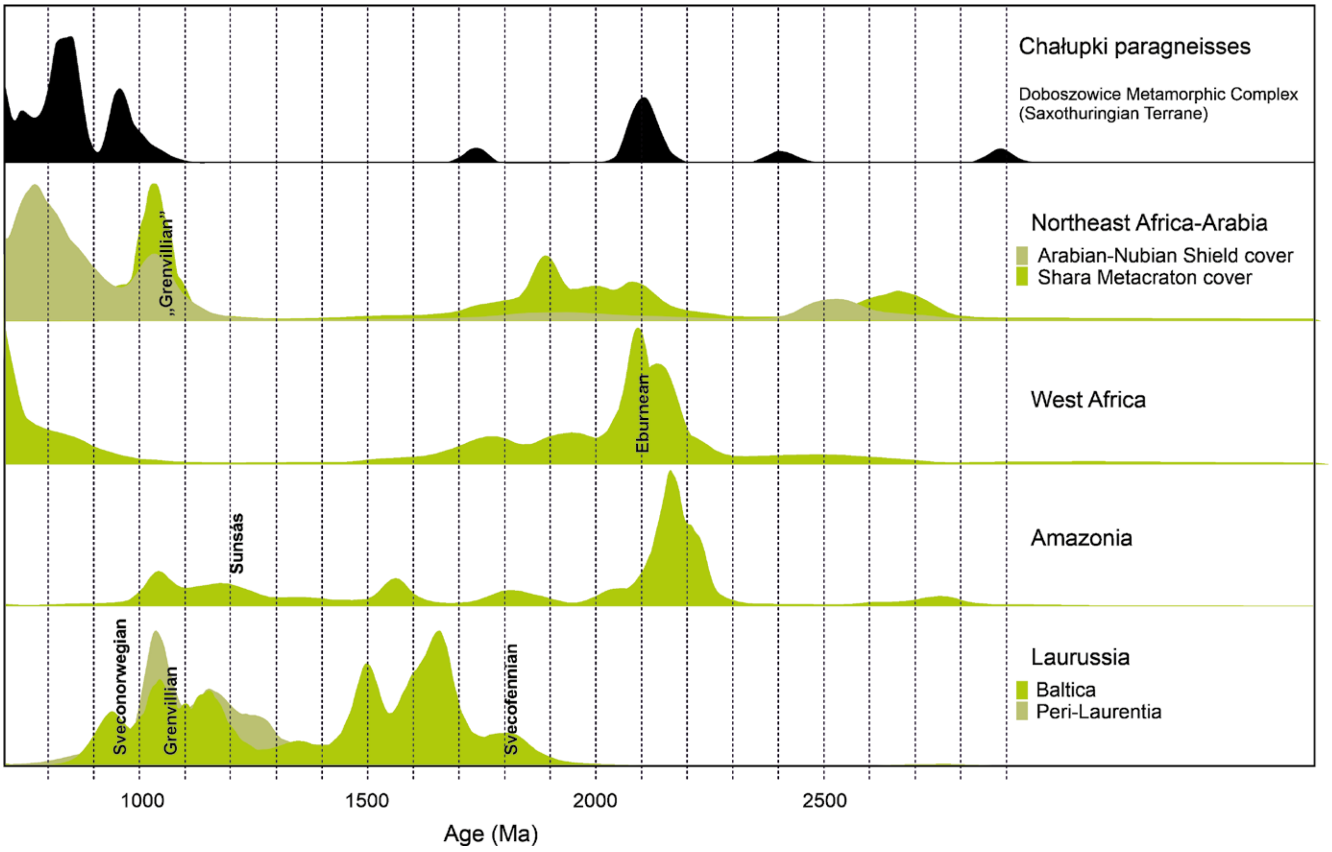

Fig. 13. Frequency plot (> 700 Ma) of the detrital age spectra in the Chałupki paragneisses (this study), compared to those compiled by Stephan *et al.* (2019) for Northeast Africa-Arabia, West Africa, Amazonia and Laurussia.

The U-Th-Pb data filtered to <5% discordance demonstrate $^{207}Pb/^{235}U$ monazite dates, ranging from 331 ± 4 to 377 ± 7 Ma, which are generally slightly older than $^{208}Pb/^{232}Th$ dates, ranging from 321 ± 5 to 351 ± 9 Ma and $^{206}Pb/^{238}U$ dates from 322 ± 5 to 362 ± 8 Ma (Fig. 12). The generally older trend of the $^{207}Pb/^{235}U$ dates is related to the low abundance of the ^{235}U isotope, and consequently the low concentrations of radiogenic ^{207}Pb, which cause that $^{207}Pb/^{235}U$ ratio, the most sensitive to the addition of common Pb, considering the Pb/U and Pb/Th isotope ratios used here. The internal textures of monazite grains do not show evidence of any significant compositional alterations (Fig. 9), such as the presence of microinclusions or patchy zoning in BSE imaging, which might result in disturbance of the age records. Recent study, involving transmission electron microscopy investigations of monazite from granulites, demonstrated lack of nanoscale evidence for alterations and linked the age discordance to addition of common Pb in the monazite lattice or microcracks (Budzyń *et al.*, 2022). These conclusions explain the dates with both low and high discordance in the same monazite grains that have been not affected by alteration (e.g., analyses 62 vs. 64 with $^{207}Pb/^{235}U$ dates of 355 ± 4 and 462 ± 20 Ma, and 5.6% and 26.7% discordance, respectively; Fig. 9). The $^{208}Pb/^{232}Th$ ratio is less sensitive to the addition of common Pb, owing to high contents of Th and high contents of daughter ^{208}Pb, and has been revealed as the most accurate isotopic system for constraining the age of monazite (Bosse *et al.*, 2009; Barnes *et al.*, 2021; Budzyń *et al.*, 2022). Therefore, a $^{208}Pb/^{232}Th$ mean age of 340.6 ± 3.6 Ma (MSWD 1.2, n = 26; Fig. 11A) obtained for all samples is interpreted as the age of metamorphic peak conditions, staying within the error of the concordia age 345.9 ± 2.9 Ma from SUD22/5. It cannot be excluded that the slightly younger mean $^{208}Pb/^{232}Th$ age is partially affected by late-metamorphic compositional alteration, but the accuracy of the LA-ICPMS U-Th-Pb method (1–2% at best for monazite) is not sufficient to distinguish between the concordia and $^{208}Pb/^{232}Th$ mean ages. Therefore, the ca. 346–340 Ma time frame is indicated as the age of the regional metamorphism, which peaked in a migmatisation episode that the DMC (south-eastern KZMB) paragneisses underwent (Fig. 2C).

There is no direct evidence that may allow us to link monazite age to growth during certain metamorphic stage(s). The dominating textural position in the matrix indicates monazite growth during progressive metamorphism, in general. Furthermore, because Y and HREE are preferentially incorporated in garnet, Y-depletion in monazite in the garnet-bearing paragneisses SUD22/3 and SUD22/4 indicates generally coeval growth of monazite and garnet during progressive metamorphism. Temperature conditions can be roughly estimated according to the previous study of the Chałupki paragneisses, which constrained the growth of garnet during thermal progression from ca. 650 to 750 °C in the presence of melt and pressure drop from 8–7 kbar to 5–4.5 kbar (Marciniak and Szczepański, 2017). These data imply that migmatization of the Doboszowice paragneisses at 346–341 Ma might be due to heating at ca. 5 kbar, feasibly from accompanying magmatic intrusion, seated in the middle crust. However, no Carboniferous syn- to post-tectonic igneous rocks are known from the KZMB. Thus, other options are decompression melting or thermal lag, following the pressure peak on the dextral P-T loop.

Interestingly, on the basis of the monazite data for mica schists, metamorphism of the south-western KZMB was younger by 15–10 m.y. and peaked at ca. 330 Ma (Jastrzębski *et al.*, 2020). In these rocks, regional metamorphism of the amphibolite facies (staurolite-grade) was preceded by an early (undated) HP event that occurred in eclogites under conditions of 500–600 °C/15 kbar (Achramowicz *et al.*, 1997; Bakun-Czubarow, 1998), though in mica schists at 490 °C/20 kbar (Szczepański and Goleń, 2021; Szczepański *et al.*, 2022). Though the HP episode still remains undated, a considerable time span must have elapsed before the mica schists, eclogites and paragneisses became elevated by ca. 55 to 25 km, respectively, and further metamorphosed at different temperatures. Such data, though requiring the study of more samples, point to remarkable differences in the timing and metamorphic evolution of metasediments in the two parts of the KZMB. The differences also have been matched by the detailed structural records, described so far in those rocks (e.g., Achramowicz, 1994; Nowak, 1998; Mazur and Józefiak, 1999; Gurgurewicz and Bartz, 2011; Szczepański and Goleń, 2021). In view of the above, the KZMB is most likely composed of rocks with different P-T-d histories that occurred mainly in the early Carboniferous. Moreover, the Saxothuringian metasediments that accompany the ca. 500 Ma pale Stachów orthogneisses farther north in the KZMB (Oberc-Dziedzic and Madej, 2002; Fig. 1A) also underwent a polyphase and complex tectonic evolution (Fig. 1). The present authors suggest that eventually the KZMB and the adjacent units were tectonically juxtaposed around 330 Ma. The ca. 15-m.y.-long time span revealed in the KZMB units of the Fore-Sudetic Block (346–330 Ma) coincides well with ca. 360–330-Ma metamorphic ages, obtained for metapelites of the Orlica-Śnieżnik Dome in the Sudetes (e.g., Skrzypek *et al.*, 2014, 2017 for review), all representing the Saxothuringian Terrane.

CONCLUSIONS

The new findings by the present authors, combined with the earlier data on complex tectonic evolution, variations in the P-T paths and timing of multiple metamorphism, are interpreted as follows.

1. The ca. 510–490 Ma granitoid massifs in the eastern part of the Saxothuringian Terrane were formed, owing to the same thermal event, ca. 20 m.y. in duration. Some differences in $\delta^{18}O_{Zrn}$ signatures, inherited age components and zircon morphology indicate, however, that the plutons were composed of magmas that evolved differently. In the case of the Śnieżnik orthogneisses, south of the Sudetic Boundary Fault, the $\delta^{18}O_{Zrn}$ values indicate some mantle input. On the other hand, in the Doboszowice orthogneisses, a predominant contribution from supracrustal rocks is recorded, which is consistent with the S-type affinity of their protolith.
2. Protoliths of the paragneisses from the DMC developed in a late Cambrian–Early Ordovician basin that was mainly supplied with detritus derived from eroded crystalline areas composed of rocks of Ediacaran to Cryogenian age. Those areas presumably occurred in the central and/or eastern parts of North Africa and provided clasts from the Libyan to Nubian-Arabian fragment of Gondwana. This also refers to other metasediments in the eastern Fore-Sudetic Block (KZMB) and in the OSD. In general, such a provenance seems characteristic of all the Saxothuringian units, located to the east of the Góry Sowie Massif (the NE Teplá-Barrandian Terrane).
3. The eastern Saxothuringian units originated in an extensional setting, as rift or back-arc basin(s) at the margin of northern Gondwana, not later than in the late Cambrian–Early Ordovician.
4. The U-Th-Pb monazite data show that the Variscan regional metamorphism of the DMC paragneisses occurred at ca. 346–340 Ma. The metamorphism was a result of the complex collision of the eastern Saxothuringian Terrane with Brunovistulia on one side and Teplá-Barrandia on the other. The most intense episodes of that process continued at least up to ca. 330 Ma, bringing units with different lithologies and tectonometamorphic histories into the tectonic contact observed today within the KZMB and the OSD farther south, where the latter unit became neighboured by the Moldanubian domain.

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Appendix A. Supplementary materials

Supplementary materials to this article with Tables S1–S9 can be found online at https://doi.org/10.14241/asgp.2023.11

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