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ORIGINAL PAPER

# Provenance of lower Palaeozoic metasediments of the East Odenwald (Mid-German-Crystalline Zone, Variscides)—a correlation with the East European Platform (Poland)

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## Abstract
U–Pb age spectra of detrital zircons related to the East European Platform could be traced in paragneiss through the whole Mid-German-Crystalline Zone (Variscides, Central Europe) from the Odenwald via the Spessart to the Ruhla crystalline forming an exotic unit between Armorica and Laurussia. The depositional ages of the paragneiss are defined by the youngest age of the detrital zircons and the oldest intrusion ages as Ordovician to Silurian. The Ediacaran dominated age spectrum of detrital zircons from the paragneiss of the East Odenwald suggests the latter to be derived from the shelf of the East European Platform (Baltica), which was influenced by the 1.5 Ga old detritus delivered from a giant intrusion (Mazury granitoid, Poland). The detrital zircon age spectrum of the lower Palaeozoic paragneiss of the East Odenwald and sandstone of the northern Holy Cross Mountains are identical. The pure Sveconorwegian spectrum of the lower Palaeozoic quartzite from the Spessart, (Kirchner and Albert Int J Earth Sci 2020) and the Ruhla (Zeh and Gerdes Gondwana Res 17:254–263, 2010) could be sourced from Bornholm and southern Sweden. A U–Pb age spectrum with 88% Palaeozoic detrital zircons from a volcano-sedimentary rock of the East Odenwald is interpreted to be derived from a Silurian magmatic arc (46%), which was probably generated during the drift of the Mid-German-Crystalline Zone micro-continent to the south. A tentative plate tectonic model of Mid-German-Crystalline Zone is presented taking into account (a) the East European Platform related age spectra of the detrital zircons (b) the Ordovician to Silurian depositional age of the metasediments (c) the Silurian and Early Devonian intrusion age of the plutonic and volcanic rocks and (d) the U–Pb ages of the Middle Devonian high-grade metamorphism. The East European Platform-related part of the Mid-German-Crystalline Zone is interpreted as a micro-continent, which drifted through the Rheic Ocean to the south and collided with the Saxothuringian (Armorican Terrane Assemblage) during the Early Devonian. Such large-scale tectonic transport from the northern continent to the southern continent is also known from the SW Iberia, where Laurussia-related metasediments of the Rheic suture zone are explained by a large scale tectonic escape (Braid et al. J Geol Soc Lond 168:383–392, 2011).

**Keywords** U–Pb ages · Detrital zircons · Baltic age spectra · Holy Cross Mountains · Odenwald · Mid-German Crystalline Zone · Variscides

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## Introduction

There is a consensus in the paleogeographic models of the configuration of the continents during the Palaeozoic in Central Europe (Cocks and Torsvik 2006; Torsvik and Cocks 2017 and references there in). Three continents, Laurentia and Baltica to the north and Gondwana to the south, were separated by large oceans (Stampfli and Borel 2002). From these large continents, micro-continents or terranes were rifted apart and drifted from the Cambrian (Małopolska, Bełka et al. 2002) until Permian (Minoean terrane, Dörr et al. 2014) colliding with Baltica or Laurentia. The pathways of some micro-continents like Avalonia are well established. The Avalonian terrane was a part of West Gondwana, which split off during the early Palaeozoic and collided after the closure of the TornquistOcean-with Baltica in the Late Ordovician (East Avalon) and with Laurentia (West Avalon) after the closure of the Iapetus Oceanin the Silurian. This subduction/collision, referred to as the Caledonian Orogeny, resulted in the formation of a large northern continent, Laurussia (Torsvik and Rehnström 2003; Winchester et al. 2002, 2006; Torsvik and Cocks 2013; Cocks and Torsvik 2006; Cocks and Fortey 2009; von Raumer et al. 2002, 2003; Murphy et al. 2004b; Nance et al. 2008; Domeier 2016).

The reconstruction of the positions of other micro-continents during the Palaeozoic is controversial, because evidence such as active/passive-margin configurations, and fossil record, paleomagnetism, are not well constrained. Armorica, the Moravo-Silesian- and the Małopolska terrane are interpreted in different ways. The Moravo-Silesian (Fig. 1) was correlated with Avalonia (Finger et al. 2000) or as part of the Teisseyre-Tornquist Terrane Asemblage (TTA, Żelaźniewicz et al. 2009; Nawrocki et al. 2004). In the Małopolska terrane (Fig. 1) early Palaeozoic faunal evidence point to the Baltic realm (Cocks 2002) whereas the age of detrital micas and zircons are interpreted as peri-Gondwana derived (Bełka et al. 2002). Armorica (including parts of the Mid-German Crystalline Zone = MGCZ; Dörr

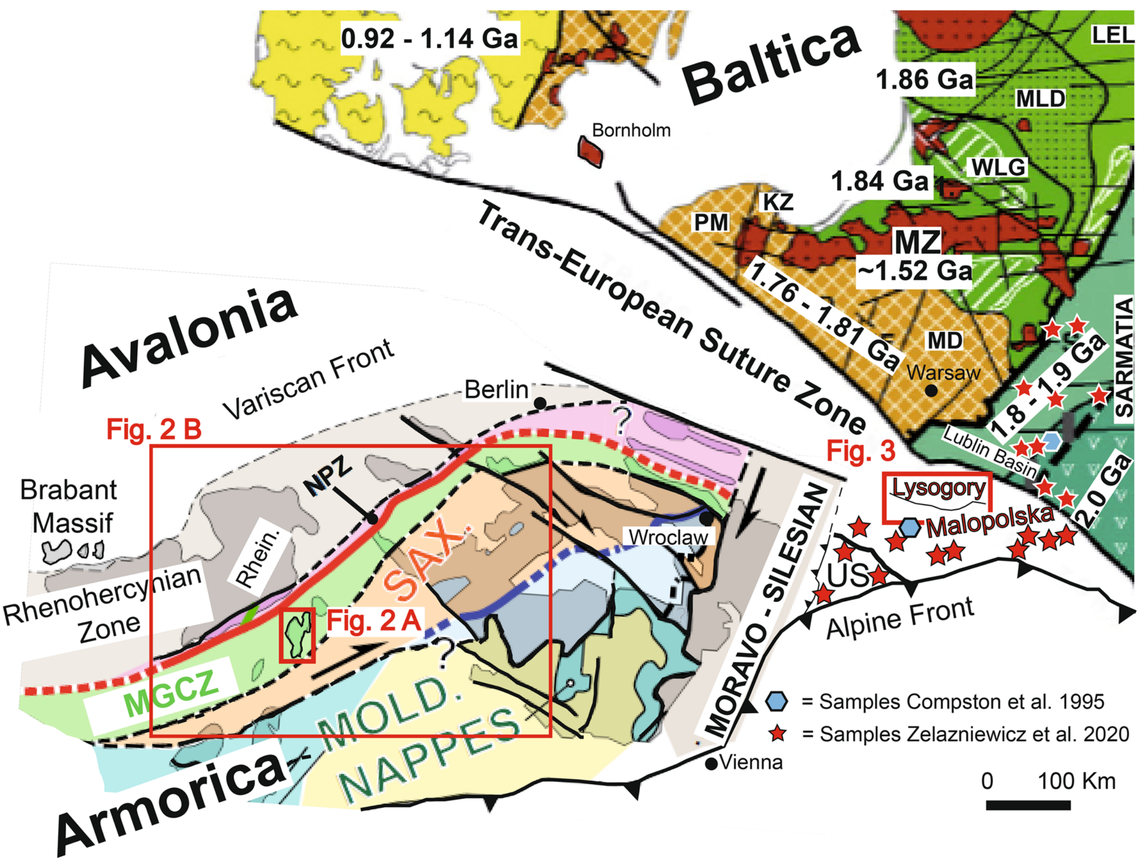


**Fig. 1** Map showing the distribution of main geotectonic units of Central Europe and the location of the Mid-German Crystalline Zone. Modified after Bogdanova et al. (2015) and Franke and Dulce (2016): *KZ* Kaszuby; *LEL* Latvian-East Lithuanian; *MD* Mazowsze; *MGCZ* Mid-German-Crystalline Zone in green; *MLD* Mid-Lithuanian domain; *MZ* Mazury granitoid; *NPZ* Northern Phyllite Zone; *PM* Pomorze; *Rhein.* Rheinisches Schiefergebirge in grey; *SAX* Saxo-thuringian Zone in brown; *US* Upper Silesian; *WLG* West Lithuanian granulite domain; *red line* supposed Rheic suture zone

and Stein 2019, West Odenwald) could be interpreted as one micro-continent or as terrane assemblage, because there are no striking differences concerning faunas or paleomagnetic data (Tait et al. 1997, 2000). For the pathways and positions of the MGCZ, two contrary models are presented. Zeh and Gerdes (2010) interpreted the MGCZ (Balonia) as a part of Rhenohercynian rifted off from it during Early Devonian whereas Torsvik and Cocks (2017) and Franke et al. (2017) correlate the MGCZ with the west part of Armorica (Franconia) colliding with the Rhenohercynian during the Early Devonian. Linnemann et al. (2004) argue at the basis of provenance analyses on detrital zircons and of Nd isotope data from late Neoproterozoic to early Carboniferous sedimentary rocks that Armorica (Saxothuringian Zone) never leaft Gondwana before the Carboniferous Variscan collision with Laurussia.

In the last two decades numerous studies on zircon forming events of the cratons and provenance analyses with the U–Pb age of detrital zircon were performed. U–Pb age spectra from stratigraphically defined sediments help to constrain a source of clastic rocks at a certain time and so possible palaeo-position of its deposition area. Intensive provenance research in Europe defines four different source regions with specific U–Pb zircon age spectra (Dörr et al. 2014). During the early Palaeozoic two detrital zircon age spectra could be correlated in Central Europe with (a) Avalonia, north of the MGCZ, being part of Laurussia from Silurian onwards (Fig. 2B purple colour) and (b) Armorica, in the south, representing a part of the peri-Gondwana in the Ediacaran and Cambrian, probably until the Silurian (Fig. 2B brown colour). Parts of the MGCZ (Cadomian basement of the West Odenwald, Dörr and Stein 2019; South Spessart, Kirchner and Albert 2020; South Ruhla, Zeh and Gerdes 2010, Fig. 2B brown colour) belong also to Armorica. The Avalonian detrital age spectrum is related to the Amazonian Craton with a high amount of Neoproterozoic zircons (max. 40–60% Ediacaran) and age peaks of 600–640 Ma. Typical is the 9–30% input of Mesoproterozoic zircons (Linnemann et al. 2012; Murphy et al. 2004a; Willner et al. 2013; Dörr and Stein 2019; Herbosch et al. 2020). The Armorican age spectrum of the detrital zircons is related to the West African Craton, which contains also mainly Neoproterozoic zircons but with Cadomian age peaks from 540 to 570 Ma. Typical is the Mesoproterozoic age gap and abundant Palaeoproterozoic zircons (Linnemann et al. 2004, 2007, 2008, 2013; Drost 2008; Drost et al. 2010; Gerdes and Zeh 2006; Hajna et al. 2013, 2016).

A contrasting U–Pb zircon age spectrum of metasediments with Mesoproterozoic and Late Palaeoproterozoic detrital zircons, but without Ediacaran input, was discovered by Zeh and Gerdes (2010) in the MGCZ (North Ruhla Crystalline Complex, Fig. 2B). This U–Pb age spectrum is characteristic of the West Baltic provenance (S Norway and S Sweden). Recent investigation of Kirchner and Albert (2020) discovered a Baltic U–Pb age spectrum in the Spessart (Fig. 2B: green colour = inferred occurrence). These Baltica-related metasediments were intruded by Silurian plutons (Fig. 2B: red stars). Zeh and Gerdes (2010) interpreted these sediments as deposited on the southern continental slope of the Rhenohercynian Zone (Fig. 1). A micro-continent rifted off during the formation of the Lizard-Giessen Ocean, which collided with the Saxothuringian plate during the Carboniferous (Zeh and Gerdes 2010). Kirchner and Albert (2020) explained the current position of the Baltic related sediments by tectonic displacement from parts of the Rhenohercynian Zone to the south against the MGCZ during the Variscan collision. A similar geological history of the South Portuguese Zone with contrasting detrital zircon age spectra (Baltica/Armorica) was interpreted by Braid et al. (2011) as a continental escape.

In this paper, we will present U–Pb zircon ages obtained from orthogneiss and detrital zircons of paragneiss exposed in the East Odenwald (= Böllstein, Fig. 2A). This will help to constrain the depositional age, identify the provenance of the paragneiss and define the age of the magmatic activity. New published U–Pb data of detrital zircons of the lower Palaeozoic sandstones from a surface outcrop (this work) and from drill cores (Żelaźniewicz et al. 2020, Fig. 1 red stars) of the Łysogóry (Fig. 3, Holy Cross Mountains) enable a correlation with the Odenwald (Fig. 2). The ages of the detrital zircons are particularly important for the paleogeographic reconstruction of the MGCZ to define its rift, drift and docking history during the lower Palaeozoic.

## Regional geology

The Central Europe basement is constituted by the Palaeozoic Variscides (Avalonia and Armorica) in the west and the Precambrian of the East European Craton (Baltica), which are separated by the Trans-European Suture Zone (Pharaoh 1999). Figure 1 was drawn after Bogdanova et al. (2015) and Franke and Dulce (2016). The Palaeozoic sediments of the East European Platform (EEP) cover the East European Craton. The Łysogóry Massif (Fig. 1), a part of the Holy Cross Mountains (Fig. 3), is located in the area of the Trans-European Suture Zone. The Odenwald (Red frame Fig. 2A in Fig. 1) is the largest massif in the Rheic suture zone (including MGCZ, Northern Phyllite Zone, northern part of the Saxothuringian Zone), which separates Armorica from Avalonia (since the Silurian Laurentia).

### East Odenwald (Böllstein)

The Odenwald is a part of the MGCZ which belongs to the Variscan Saxothuringian Zone (Kossmat 1927, Fig. 1:

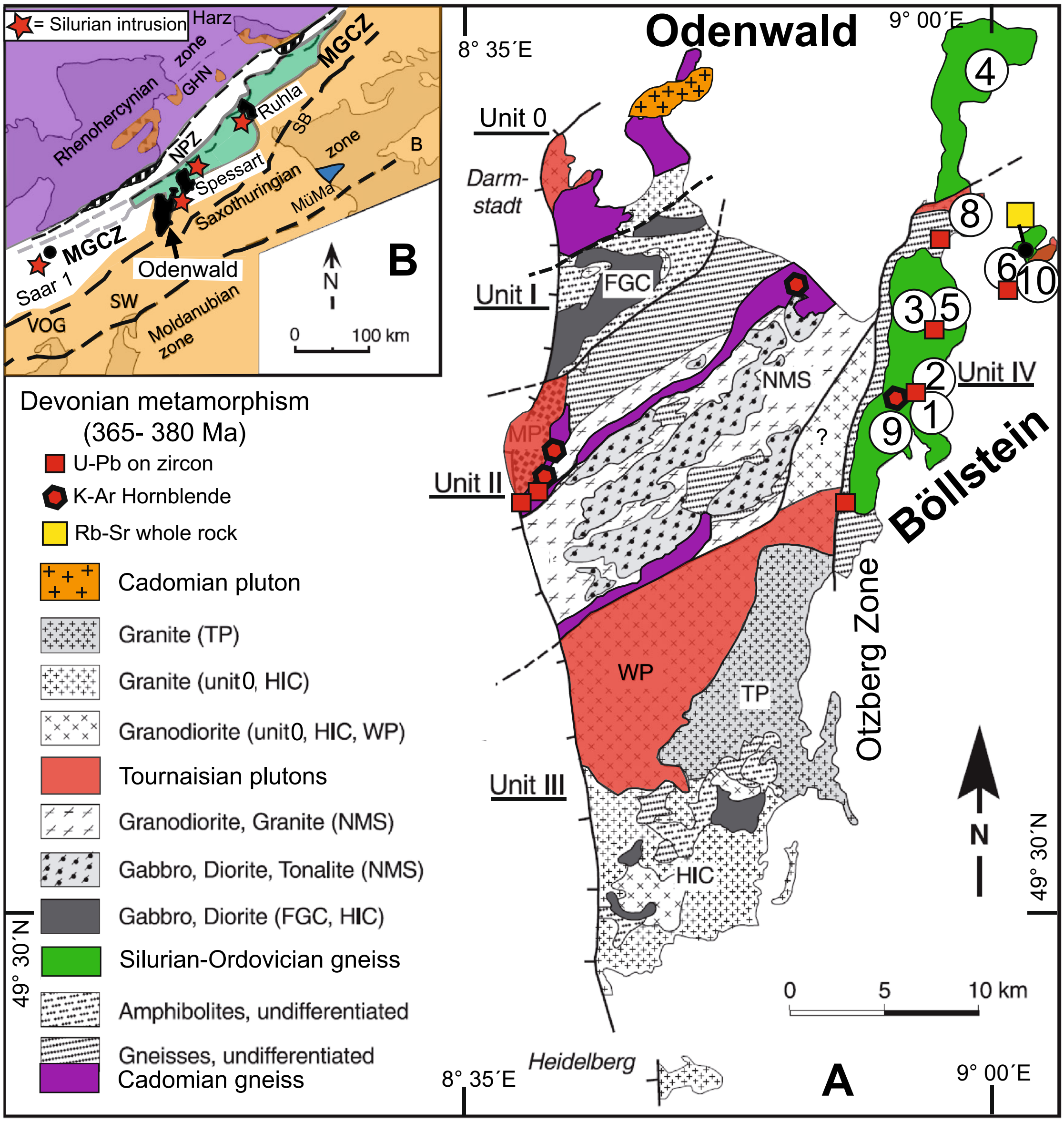


**Fig. 2** **A** Geological map of the Odenwald Crystalline Complex (after Altherr et al. 1999). showing the major tectonic units 0–IV. Large black number indicated the localities. *FGC* Frankenstein gabbro complex; *HIC* Heidelberg intrusive complex; *MP* Malchen pluton; *NMS* Neunkirchen magmatic suite; *TP* Tromm pluton; *WP* Weschnitz pluton. **B** *B* Barrandium; *GHN* Giessen-Harz Nappes; *MGCZ* Mid-German Crystalline Zone in green; *MüMa* Münchberger Massif; *NPZ* Northern Phyllite Zone; *SW* Schwarzwald; *VOG* Vosges; *Saar 1* borehole into a Silurian granite (Sommermann 1993)

SAX = Saxothuringian Zone). The MGCZ is not a coherent terrane and consists of different tectono-metamorphic units (Zeh 1996; Oncken 1997) with contrasting provenance (Zeh and Gerdes 2010) and tectonic settings (Zeh and Will 2010; Will et al. 2015, 2018).

The crystalline basement of the Odenwald can be subdivided into the larger West Odenwald and the smaller East Odenwald (Fig. 2A, Böllstein), which are separated by the N–S trending Otzberg Zone (Chatterjee 1960; Altenberger et al. 1990). A subdivision of the crystalline Odenwald into five subunits, based on their different ages, lithology and cooling history, is widely accepted. These five subunits consist of metamorphic complexes and intrusive bodies. Units 0 to III form the West Odenwald, whereas unit IV builds the East Odenwald. Significant differences in their tectonic structures (Krohe 1992; Altenberger and Besch 1993; Stein 1996, 2001) and metamorphic evolution (Kreuzer and Harre 1975; Lippolt 1986; Todt et al. 1995; Reischmann et al. 2001; Dörr and Stein 2019) suggest an

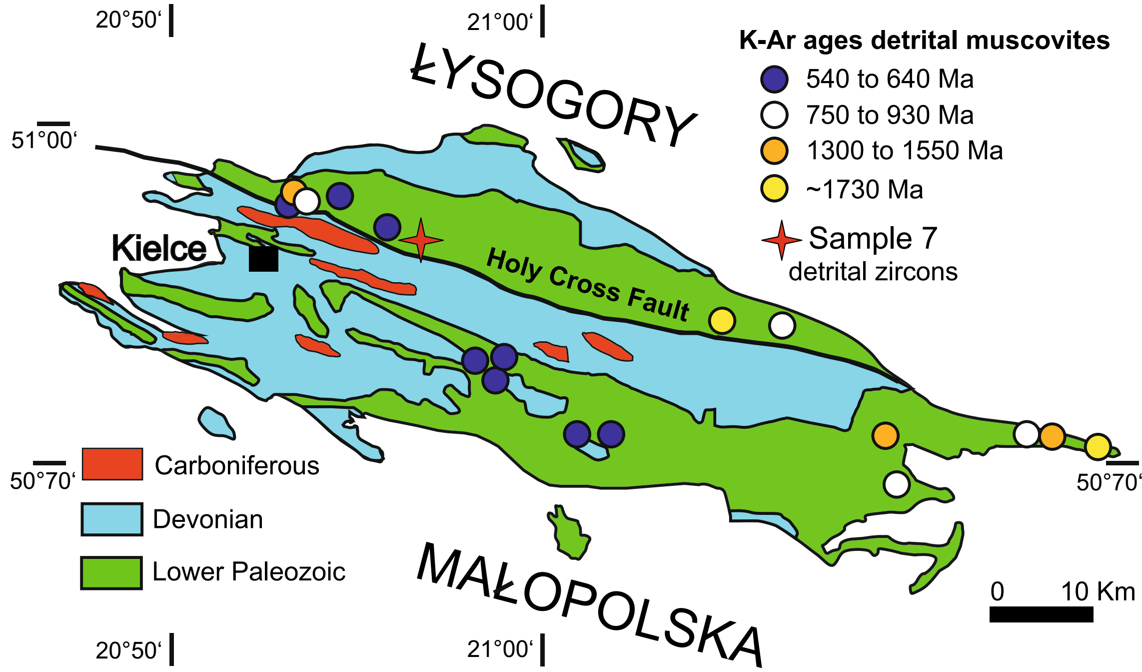


**Fig. 3** Geological map of the Holy Cross Mountains with K–Ar ages of detrital muscovite of Lower Palaeozoic sediments (after Bełka et al. 2000). Red star = sample 7

independent pre- to early Variscan development and later juxtaposition of the five units during the Carboniferous.

The Otzberg zone is dipping WNW and was active during the exhumation of the East Odenwald relative to the West Odenwald (Willner et al. 1991; Krohe 1992). Biotite of a cross-cutting lamprophyric dyke yield a $^{39}Ar$–$^{40}Ar$ age of 327 ± 3 Ma, which is interpreted as a minimum age for the normal sense of shearing along the Otzberg fault (Hess and Schmidt 1989). This biotite cooling age is similar to the K–Ar dating of hornblende from gabbro amphibolite (328 ± 15 Ma, locality Weichberg) and of muscovite from different pegmatites displaying ages from 325 ± 8 Ma (locality Steinkopf) and 325 ± 10 Ma (locality Wannberg; Lippolt 1986). Biotite of the host rocks yielded slightly younger K–Ar ages at 318 ± 8 Ma and 319 ± 9 Ma (Lippolt 1986). Kreuzer and Harre (1975) and Lippolt (1986) interpreted the contemporaneous K–Ar mineral ages of gneiss, gabbro amphibolite, lamprophyre and pegmatite between 320 to 330 Ma as the time of regional cooling of the East Odenwald below 500 °C (hornblende) or 300 °C (micas) after metamorphism, mylonitisation and exhumation.

The East Odenwald is a NNE striking anticline plunging slightly towards the NNE (Altenberger and Besch 1993; Stein 2001). The so-called schist envelope consists mainly of metasedimentary rocks developed as schist, migmatic mylonitic gneiss, quartzite with intercalated calc-silicate (Chatterjee 1960; Altenberger et al. 1990; Altenberger and Besch 1993) and with some small lenses of orthogneiss. Geochemical data of the metasediments from the schist envelope are interpreted as greywacke and subordinate arkose protolith. Arkosic sediments point to a continental magmatic arc as possible source for the detritus (Altenberger and Besch 1993). The metasedimentary schist envelope is the oldest unit of the Böllstein massif. The depositional age of the paragneiss protolith could be pre-Silurian (Lippolt 1986). The age of metamorphism has been dated with U–Pb analyses on zircons at 375 ± 2 Ma (Todt et al. 1995) and with K–Ar analyses on hornblende at 370 Ma (Kreuzer and Harre 1975, recalculated by Schubert et al. 2001). The youngest detrital zircons from a paragneiss of the East Odenwald are Devonian in age (Fig. 2A, 2 km south of sample 8). The Early- to Middle-Devonian zircons are detrital, whereas the Late-Devonian age at 371 ± 3 Ma could be the result of amphibolite facies metamorphism (Dörr et al. 2017).

The core of the East Odenwald dome is dominated by orthogneiss. There are coarse-grained granodiorite gneiss and a medium grained granite gneiss (Chatterjee 1960). Sometimes, both types of granitoids show evidence of migmatization (Chatterjee 1960; Altenberger and Besch 1993). Based on field relations the granitoids have a discordant contact to the metasediments (Altenberger and Besch 1993). Geochemical analyses of the orthogneiss could be interpreted that they were formed in a convergent setting, probably in a continent-island arc or collisional environment (Altenberger et al. 1990; Reischmann et al. 2001). Single zircon Pb–Pb evaporation dating yielded an age of 405 ± 3 Ma for a granitoid (Reischmann et al. 2001). Field evidence suggests that the protolith of the granodioritegneiss intruded into the schist envelope earlier than the granitegneiss (Chatterjee 1960).

In the orthogneiss core and in the schist envelope mafic rocks are present. Some of them show relic magmatic mineral assemblages and fabrics. Additionally, geochemical whole-rock analyses point to their igneous origin (Knauer et al. 1974). Gabbros are forming stock-like bodies whereas diabases occur as sills. The REE-distribution of amphibolites and metabasites displays a pattern with an affinity to subduction-type igneous rock (Altenberger et al. 1990). The ultramafic rocks are similar to the Ordovician counterparts of the Spessart crystalline complex (Will et al. 2018; Knauer et al. 1974).

Eclogite-facies metabasic rocks are exposed in the northernmost part of the orthogneiss core (between sample 5 and 8, Fig. 2A). They suffered a peak temperature of 700 ± 50 °C at a minimum pressure of 16–17 kbar (Will and Schmädicke 2001). Scherer et al. (2002) determined Lu–Hf Grt-WR minimum ages from two samples at 357 ± 7 Ma and at 353 ± 11 Ma with an initial ℇHf of + 11.3. The eclogite facies event must be older than early Carboniferous. The magmatic protolith age is probably late Ordovician or early Silurian at around 440 Ma, like the protolith age of a xenolith of eclogite rocks in a Carboniferous lamprophyre from the West Odenwald (Soder 2017, U–Pb method on zircon). Lenses of former eclogite are retrogressed into garnet amphibolite during the prograde Carboniferous amphibolite facies metamorphism (8 kbar/580 °C; Will and Schmädicke 2001; U–Pb method on zircon at 333.7 ± 4.1 Ma, Will et al. 2018).

Based on the metamorphic evolution, cooling history, petrographic and geochemical similarities, a close relation of the East Odenwald and the Spessart to the N has been supposed (Korn 1929; Chatterjee 1960; Okrusch and Richter 1986; Altenberger et al. 1990; Dombrowski et al. 1995; Will et al. 2015, 2018). The orthogneisses of the Spessart (Red gneiss, 418 ± 18 Ma; Haibacher Gneiss, 410 ± 18 Ma; Dombrowski et al. 1995) have been correlated with similar intrusions of the East Odenwald (Lippolt 1986; Reischmann et al. 2001). The paragneiss protoliths of the Spessart antiform are probably Cambrian to Silurian (Okrusch et al. 2011) containing detrital zircons with Baltic or Armorican provenance (Kirchner and Albert 2020).

## Holy Cross Mountains

The Holy Cross Mountains form a window of Palaeozoic rocks that is surrounded by Mesozoic-Tertiary cover and were divided into the Łysogóry Massif and Małopolska Massif. Żelaźniewicz et al. (2020) renamed them as Łysogóry fold belt and Kielce fold belt, which will be used in this work for a better comparison of the U–Pb analyses of detrital zircons. The Łysogóry fold belt and Kielce fold belt are bounded to the south by the Małopolska Block and to the north by Lublin basin of the continental slope of the EEP. The Holy Cross Mountains are located at the boundary of the EEP to the Trans-European Suture Zone (TESZ, Fig. 1). The TESZ is located between the Bohemian Massif in SW and the EEP in the NE and corresponds to the basement of the Permian-Mesozoic Polish Basin and the Małopolska Block. The TESZ is believed to represent the attenuated Baltica margin (Mazur et al. 2015; Mikołajczak et al. 2019) or a collage of proximal Baltica-derived terranes (Nawrocki et al. 2007; Narkiewicz et al. 2015). Provenance analyses (Bełka et al. 2000, 2002) and geochemical fingerprints (Walczak and Belka 2017) are interpreted that the Małopolska Block belongs to a peri-Gondwana terrane docked to Baltica in the middle Cambrian.

The Łysogóry fold belt and Kielce fold belt are recently interpreted as Baltica related terranes which form together with the Małopolska Block, the Upper Silesian Massif (US in Fig. 1), Moesia basement and Dobrogea terrane (Romania) the Teisseyre-Tornquist Terrane Assemblage in Neoproterozoic times (TTA, Żelaźniewicz et al. 2009, 2020). In this scenario, the TTA eventually overrode the TESZ passive margin of Baltica. Since the latest Cambrian and the Ordovician the Holy Cross Mountains belong to the shelf of the passive continental margin of the EEP. The Upper Silesian Massif (Fig. 1, US) probably constitutes the eastern part of a larger block, the Moravo-Silesian (Fig. 1), which was correlated with Avalonia (Finger et al. 2000; Friedl et al. 2000; Mazur et al. 2010).

### Kielce fold belt (southern part of the Holy Cross Mountains)

The Kielce fold belt is the best-exposed part of the Cambrian- and Ordovician rock in the Holy Cross Mountains. A crystalline basement of the Kielce fold belt is unknown. The presence of Baltic trilobites in the Cambrian of Kielce fold belt (Orlowski 1975) indicates a proximity to the Baltic realm during the Cambrian. This is not in agreement with the Ediacaran (?Cadomian) zircons in the same sediments, but could be explained by a close position of the Holy Cross Mountains to the Upper Silesian Avalonian/Cadomian terrane or that the Ediacaran zircons were delivered from the EEP similar to the Cambrian sediments of west Belarus and east Poland (Nawrocki and Poprawa 2006, Nawrocki et al. 2007; Żelaźniewicz et al. 2009, 2020; Paszkowski et al. 2019). The lower Palaeozoic of the Kielce succession represents sedimentary rocks of the EEP shelf, which contains coarse-grained sandstones overlain by few meters of Middle Ordovician detrital limestone. The Upper Ordovician rock are built up of marly shale, followed by the famous Silurian black graptolite shale, passing into the 500 m thick succession of sandstone and greywacke of the Upper Silurian.

### Małopolska block

In the Małopolska Block (former southern part of the Małopolska Massif) a crystalline basement is also unknown. Ediacaran (Vendian) shales and siltstones are intercalated by greywackes and volcanic rocks. Cambrian detrital zircons point to lower Palaeozoic sediments (Żelaźniewicz et al. 2020). The folded Ediacaran succession is unconformably overlain by flat-lying Ordovician to Silurian sediments of the EEP (Żelaźniewicz et al. 2009). Compston et al. (1995) have dated a volcanic tuff at 549 ± 3 Ma ($^{206}$Pb/$^{238}$U SHRIMP age, see blue hexagons Fig. 1) from the top of the Ediacaran (Vendian) sequence. Bełka et al. (2000) interpreted the Małopolska Block as a Late Precambrian fore arc to a trench system linked to the Avalonian/Cadomian active margin. Their reasons are the high amount of feldspar, pebbles of volcanic and plutonic rock, high thickness of the sequence and the "Cadomian" Ediacaran K–Ar ages of detrital muscovites. Ediacaran detrital zircons from drill holes (Fig. 1) of the Małopolska Block could be interpreted in the same way (Żelaźniewicz et al. 2009, 2020; Habryn et al. 2020). A late Cambrian deformation of the Małopolska Block (Gągała 2005) might be related to the docking of Małopolska Block against Baltica, which is since that time part of the continental slope of the EEP. This is supported by the palaeomagnetic data (apparent polar wander path), which indicate that the Małopolska Massif had accreted to southern Baltica before mid-Ordovician times (Schätz et al. 2006; Nawrocki and Poprawa 2006; Nawrocki et al. 2007).

### The Łysogóry fold belt (northern part of the Holy Cross Mountains)

The Łysogóry fold belt is separated from the Kielce fold belt (Małopolska Massif) by the Holy Cross Fault (Fig. 3), which was active until the early Carboniferous. The lower Palaeozoic succession of Łysogóry is estimated to be 4200–4800 m thick and includes very low-grade sediments of late Middle Cambrian to Devonian age, which were folded during Variscan deformation. The oldest rocks are Middle Cambrian sandstones forming an 1800 m thick clastic sequence, which extends into the Tremadoc. The clastic sequence was deposited in shallow-water environment (Jaworowski and Sikorska 2006; Żylińska et al. 2006). The mature sandstones yield a bimodal K–Ar age spectrum of detrital muscovite of ca. 600 Ma and ca. 1.7 Ga (Fig. 3; Bełka et al. 2000) and an U–Pb age spectrum of detrital zircons with Ediacaran and Mesoproterozoic ages (Żelaźniewicz et al. 2009, 2020). This could be interpreted as a mixture of two different sources (Żelaźniewicz et al. 2020: Fig. 7C therein) or as provenance from a single source similar to the Cambrian sediments of the EEP (Paszkowski et al. 2019). Walczak and Belka (2017) identified Svecofennian and Cadomian sources with Nd whole rock data.

The late Cambrian trilobite and brachiopod fauna of the Łysogóry is scarce, but the rocks are extremely rich in *Cruziana* (Orlowski et al. 1970). The Ordovician and Silurian are mainly represented by black graptolite shales intercalated by limestones (Trela 2009). The Upper Silurian part of the succession turns again into siliciclastic facies of 1500 m thick turbidity greywackes, interbedded by volcanoclastic rocks (Kozłowski 2008). As in the EEP, there are no angular unconformities in the pre-Carboniferous stratigraphy of the Łysogóry fold belt. This is different to the Małopolska Block with deformations in the Cambrian and Upper Silurian.

## Results

The LA-ICP-MS method of U–Pb analyses on zircons is described in the electronic supplement (ESM 1). Zircon standard GJ-1 (Jackson et al. 2004) and 91,500 (Wiedenbeck et al. 1995) were repeatedly analysed under the same conditions as the samples to monitor the reproducibility and accuracy. The in house standard Orlovice (Dörr et al. 2002a) was analysed for comparison of the Isotopic-dilution thermion-mass spectrometer (CA-ID-TIMS) method at 524 ± 1 Ma ($n$ = 8) and with the LA-ICP-MS method at 527 ± 3 Ma ($n$= 23, ESM 8 and 9). The U–Pb data of Tables 1 to 8 (2σ uncertainties) are stored in the electronic supplement. The U–Pb results obtained from the metasedimentary rocks are presented on frequency or density plots with a concordance ($^{238}$U–$^{206}$Pb age/$^{207}$Pb–$^{206}$Pb age × 100) from 90–110%. If not stated elsewhere, the age peaks are calculated as concordia age of a zircon population as defined by Ludwig (2001). In most cases the oscillatory zoned parts between the core and rim of the zircons are measured with the laser, because these parts reflect the undisturbed zircon growth and thus an undisturbed U–Pb system of the zircons with no or minor lead loss. The sample localities and lithology are stored in Table 9.

### Paragneiss from the East Odenwald

#### Biotite gneiss (Weichberg quarry)

A metavolcanosedimentary rock was sampled from the schist envelope of the East Odenwald. Sample 2 is from the same outcrop as sample 1 (Granodiorite gneiss) but shows a pronounced layering from 1 to 6 cm produced by the different amount and grain size of biotite, plagioclase and quartz. Amphibolite layers vary from 0.5 to 3 cm. In the lower part of the sequence one amphibolite reaches a thickness of 4 m. The biotite gneiss contains large (350 µm) short and long prismatic zircons with sometimes rounded edges (ESM 11). The grain size of the smaller zircons ranges from 80 to 140 µm. Most of them are long prismatic, euhedral and colourless. Only a few zircons are rounded and pink displaying pit marks. Most of the zircons have Th/U ratios between 0.3 and 1.3 (ESM 3). The four youngest analyses define an age of 372 ± 8 Ma (Fig. 4, sample 2), which is younger than the intrusion age of sample 1 (Fig. 6). The age spectrum of the detrital zircons is dominated by 47% Silurian ages with a high amount of Ordovician ages (29%). The Precambrian is represented only by an Ediacaran zircon population (11%) and a single Archean (2668 ± 43 Ma) zircon. The highest age peaks are in the Silurian population at 438 ± 2 Ma ($n = 27$) and at 421 ± 2 Ma ($n = 12$). The second group of age peaks in the Ordovician are at 466 ± 3 Ma ($n = 11$) and at 488 ± 5 Ma ($n = 6$).

### Biotite paragneiss ("Schmelz Mühle")

Sample 5 (Fig. 2) is located in the same outcrop like sample 3 (Orthogneiss). The paragneiss is of volcano-sedimentary origin and belongs to the schist envelope of the East Odenwald. The gneiss displays a pronounced layering marked by a variable amount of 10–40% biotite, 5–25% plagioclase, 20–50% quartz and a few K-feldspar with a strong foliation. The grain size of the zircons ranges from 40 to 230 µm. The large spherical zircons are rounded with pit marks. Most of them are colourless, only a few zircons are brown or red. The smaller zircons are elongated and rounded (ESM 12). Some are long prismatic to subhedral. Most of the zircons display Th/U ratios between 0.4 and 1.6. Seven zircons have low Th/U ratios between 0.01 and 0.08, which point to zircon growth under metamorphic conditions (ESM 6a). Three of them define poorly constrained a concordia age at around 381 ± 9 Ma. The youngest detrital zircon population yielded an age of 419 ± 4 Ma ($n = 3$; Fig. 5, sample 5), which is slightly older than the intrusion age of the orthogneiss sample 3. The age spectrum of the detrital zircons is dominated by 51% Neoproterozoic ages with a high amount of Palaeoproterozoic (19%) zircons and moderate number of Palaeozoic (12%) zircons. The Mesoproterozoic (12%) population is marked by an age peak at 1505 ± 8 Ma ($n = 7$, ESM 7a). There are only a few Archean (6%) zircons. The Cryogenian population (28%) is the main group of the Neoproterozoic detrital zircon age spectrum with an age peak at 697 ± 8 Ma ($n = 6$; Fig. 5). Ediacaran zircons (21%) form the second group with the highest age peak at 604 ± 4 Ma ($n = 8$). There are only 3 Tonian zircons. The Cambrian zircons define a mean age of 519 ± 7 Ma ($n = 7$). Compare to sample 2 (red histogram, Fig. 5A), which contains 88% Palaeozoic zircons, sample 5 displays only 12% Palaeozoic zircons (Fig. 5 blue histogram).

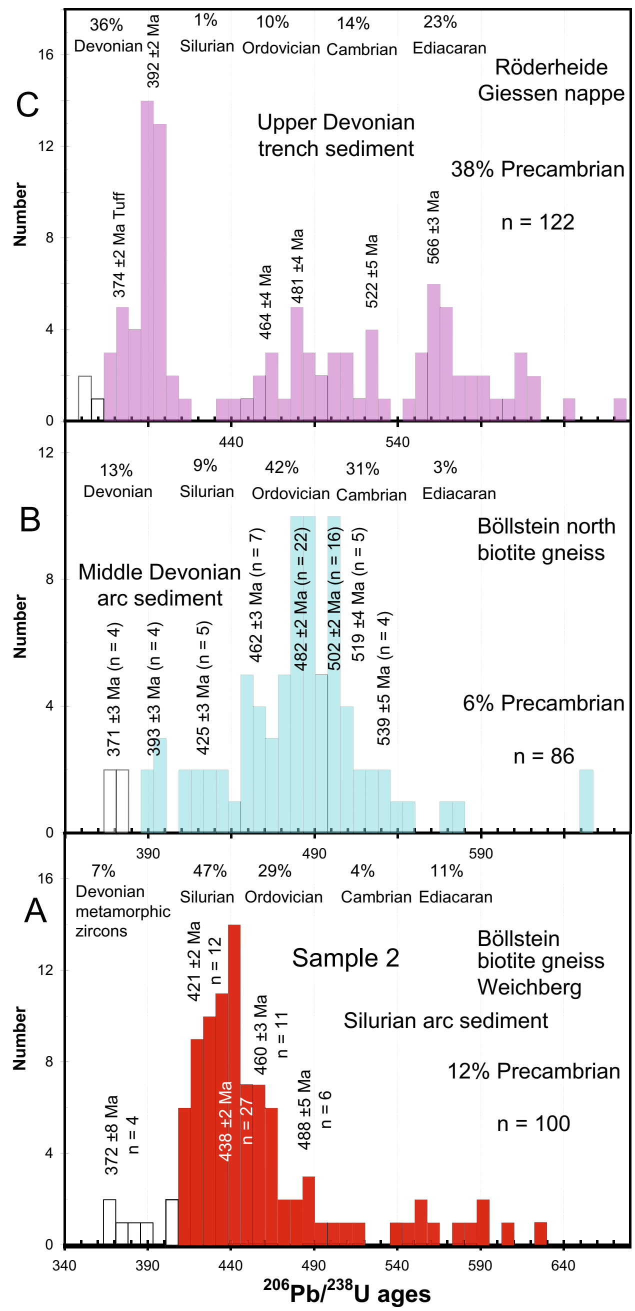


**Fig. 4** Comparative frequency plots of the $^{206}Pb/^{238}$ ages of detrital zircons of metasediments of the East Odenwald (MGCZ, **A** Silurian arc, **B** Middle Devonian arc) with trench sediment of the Giessen nappe (**C**). Concordance is 90–110%

### Paragneiss (East Böllstein)

Sample 6 (Fig. 2A) is exposed in a window of the Mesozoic cover. The paragneiss belongs probably to the schist envelope of the East Odenwald. The gneiss displays a layering marked by a variable amount of 5–15% biotite, 15–45% feldspar, 20–30% quartz and 10–20% amphibole. The grain size of the zircons of sample 6 ranges from 10 to 240 µm.

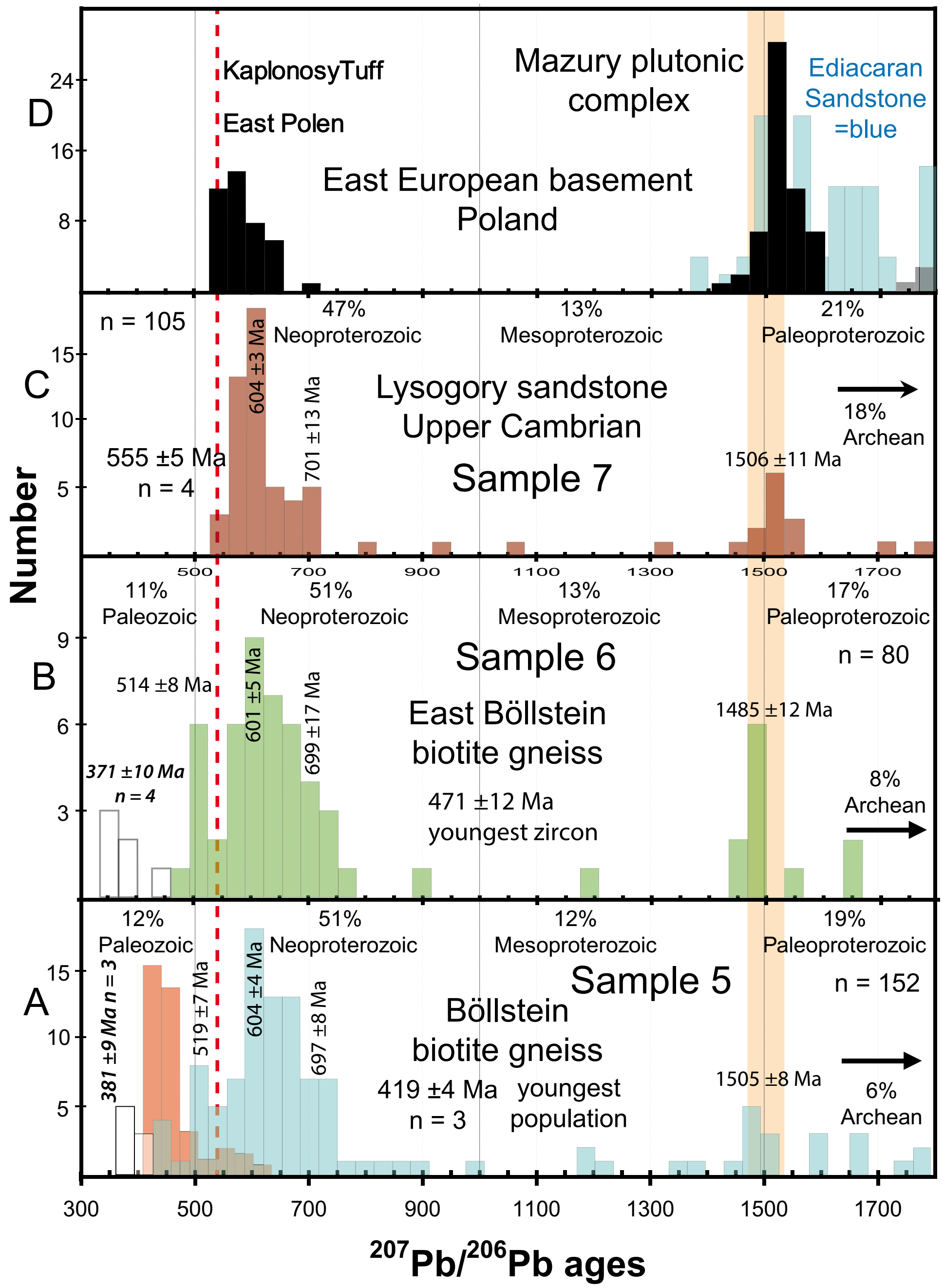


**Fig. 5** Relative frequency plots **A** and **B**: metasediments of the schist envelope (samples 5 and 6, East Odenwald, MGCZ), **C** Cambrian sandstone from the Holy Cross Mountains (sample 7), **D** East European basement of Poland (Compston et al. 1995; Dörr et al. 2002b; Wiszniewska et al. 2007)

Most of the colourless zircons are angular to subhedral. Only a few rounded, elongated zircons are pink. Some of them are euhedral. Most of the zircons display Th/U ratios between 0.5 and 0.9. Five zircons have low Th/U ratios between 0.01 and 0.08, which point to zircon growth under metamorphic conditions (ESM 6b). Four of them define a concordia age at around 371 ± 10 Ma, which is similar to sample 5. The youngest detrital zircon (concordance = 98%) yield an age of 471 ± 12 Ma (Fig. 5, sample 6). The age spectrum of the detrital zircons is like in sample 5 dominated by 51% Neoproterozoic ages with a high amount of Palaeoproterozoic (17%) zircons and moderate number of Palaeozoic (11%) zircons. The Mesoproterozoic (13%) population is again marked by an age peak at 1485 ± 12 Ma (*n* = 5, ESM 7b). There are only a few Archean (8%) zircons. The Cryogenian population (28%) is again the main group of the Neoproterozoic detrital zircon age spectrum with an age peak at 699 ± 17 Ma (*n* = 9, mean age). Ediacaran zircons (22%) form the second group with the highest age peak at 601 ± 5 Ma (*n* = 8), which is similar to sample 5. There is only 1 Tonian zircon. The Cambrian (8%) zircons define a peak at 514 ± 8 Ma (*n* = 6).

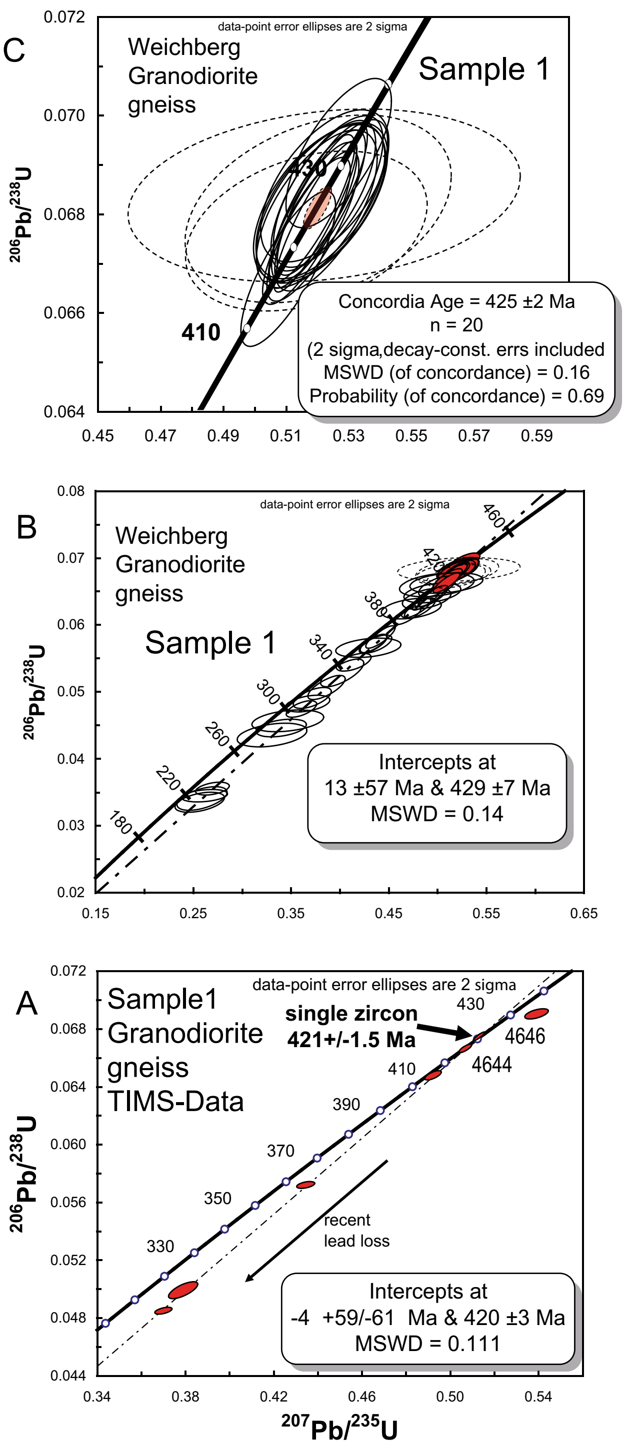


**Fig. 6** U–Pb concordia plots of zircon analyses from metagranodiorite sill (sample 1, East Odenwald, MGCZ)

## Sandstone Łysogóry (Holy Cross Mountains)

Sample 7 was collected from the upper Cambrian Wiśniówka Formation (Żylińska et al. 2006), 13 km east of Kielce (Fig. 3 red star). The well-sorted fine-grained quartz-arenite contains white mica and only a few rock fragments. The well-rounded zircons (100–130 µm) are purple and pink. Sometimes clear colourless zircons (80 µm) preserve crystallographic faces. Most of the zircons display Th/U ratios between 0.5 and 1.9. Palaeozoic zircons, which grew under metamorphic conditions, are missing (ESM 6c). The youngest zircon population yields an age of 555 ± 5 Ma ($n$ = 4, Fig. 5, sample 7). The age spectrum of the detrital zircons is dominated by 47% Neoproterozoic ages with a high amount of Palaeoproterozoic (21%) ages. The amount of Archean (18%) zircons is 10% higher than that of samples 5 and 6. The Mesoproterozoic (13%) population is again marked by an age peak at 1506 ± 11 Ma ($n$ = 6, ESM 7c). The Ediacaran population (32%) is the main group of the Neoproterozoic detrital zircon age spectrum with the highest age peak at 604 ± 3 Ma ($n$ = 8). Cryogenian zircons (12%) form the second group with an age peak at 701 ± 13 Ma ($n$ = 5, mean age). There is only 1 Tonian zircon.

## Orthogneiss from the East Odenwald

### Granodiorite gneiss (Weichberg quarry)

Sample 1 intruded as a sill into the sequence of mafic to acid metavolcanoclastic and metasedimentary rocks of the schist envelope of the East Odenwald (Fig. 2A), 20 m below sample 2. The sill displays a boudinage with a variable thickness of 10–60 cm and contains 40% plagioclase, 30% quartz, 15% K-feldspar and 10% biotite. The granodiorite gneiss contains a homogenous population of colourless, short prismatic zircons with a mean grain size of 180 µm. Their CL-images display oscillatory zoning. Euhedral cores are surrounded by fine oscillatory zoned shells. Most of the Th/U-ratios of sample 1 scatter from 0.2 to 1.9 (ESM 2), which are typical of magmatic zircons. Only a few reach ratios at around 3. The zircons contain moderate uranium with contents between 150 to 430 ppm. The uranium content of the highly discordant analysis is the highest with 1340 ppm. The zircons were first analysed with the chemical-abrasion isotopic-dilution thermion-mass spectrometer method (ESM 1). Only one of seven U–Pb analyses is concordant at 421 ± 1.5 Ma (number 4646). Analyse 4644 is slightly discordant (99% concordance) at 418 ± 2 Ma. Together with four discordant analyses they define a discordia line (MSWD = 0.111) with an upper intercept age at 420 ± 3 Ma and a lower intercept at −4 + 59/−61 Ma (Fig. 6A). Because of the high lead loss of the zircons and the low number of concordant analyses, the sample was analysed with the laser-ablation ICP-MS method. The small volume of the zircons analysed and the spatial resolution monitored with cathodoluminescence (CL) images during the laser-ablation help to avoid regions of the zircons with high lead loss. All 53 analyses define a discordia line (MSWD = 0.14) with an upper intercept age at 429 ± 7 Ma and a lower intercept age at 13 ± 57 Ma (Fig. 6B), which fit with the data of the chemical-abrasion isotopic-dilution thermion-mass spectrometer method. Twenty concordant zircons define a concordia age at 425 ± 2 Ma (MSWD = 0.16 and probability = 0.69 of concordance; Fig. 6C). Two zircons with Precambrian ages point to minor inheritance.

### Orthogneiss ("Schmelz Mühle")

Sample 3 (Fig. 2A) is in a similar lithostratigraphic position like sample 1. The orthogneiss has a variable thickness of 0.5 to 1.2 m and occurs together with paragneisses of volcano-sedimentary origin of the schist envelope of the East Odenwald (sample 5). The orthogneiss displays a strong foliation marked by large plagioclase, quartz, K-feldspar and biotite. The mean grain size of the zircons of the orthogneiss is 200 µm. Most of the zircons are colourless, prismatic displaying oscillatory zoning (ESM14). Irregular to subhedral zircons with a smooth surface are covered by rims of variable width, which appear as a highly luminescent phase. The Th/U-ratios of sample 3 define a homogenous population of zircons (0.6–1.1; ESM 4), which is typical of magmatic zircons. 75% of the zircons contain moderate uranium with contents between 52 to 396 ppm. The highest uranium content is 888 ppm. 23 discordant analyses fall on a line (MSWD = 0.14) with an upper intercept age at 406 ± 20 Ma and a lower intercept age at 122 ± 97 Ma (Fig. 7, sample 3). Most of the zircons have an age between 400 to 420 Ma. A population of 30 concordant zircons define a concordia age at 415 ± 1 Ma (yellow ellipsis, MSWD = 0.067 and probability = 0.73 of concordance). A second population of 22 concordant analyses is slightly younger and plots around 405 Ma (red ellipsis). Because the high discordant zircons prove lead loss, the U–Pb ages of the younger population (red ellipsis) could be explained by shifting along the discordia to 405 Ma. The age of 415 ± 1 Ma is close to the intrusion age of the granitoid. The oldest zircons define a concordia age at 425 ± 4 Ma (*n* = 4, MSWD = 0.0029, probability = 0.96), which is similar to the granodiorite gneiss of the first sample.

### Orthogneiss (North Böllstein)

The northern part of the East Odenwald is poorly exposed and its rocks are deeply weathered. Only in an abandoned quarry (Fig. 2A, sample 4) different solid orthogneisses and paragneisses occur. One of these orthogneisses displays a strong foliation, which is marked by plagioclase and quartz. The orthogneiss contains a homogenous population of long prismatic zircons with a mean grain size of ca 230 µm. Their CL-images display oscillatory zoning typical of magmatic

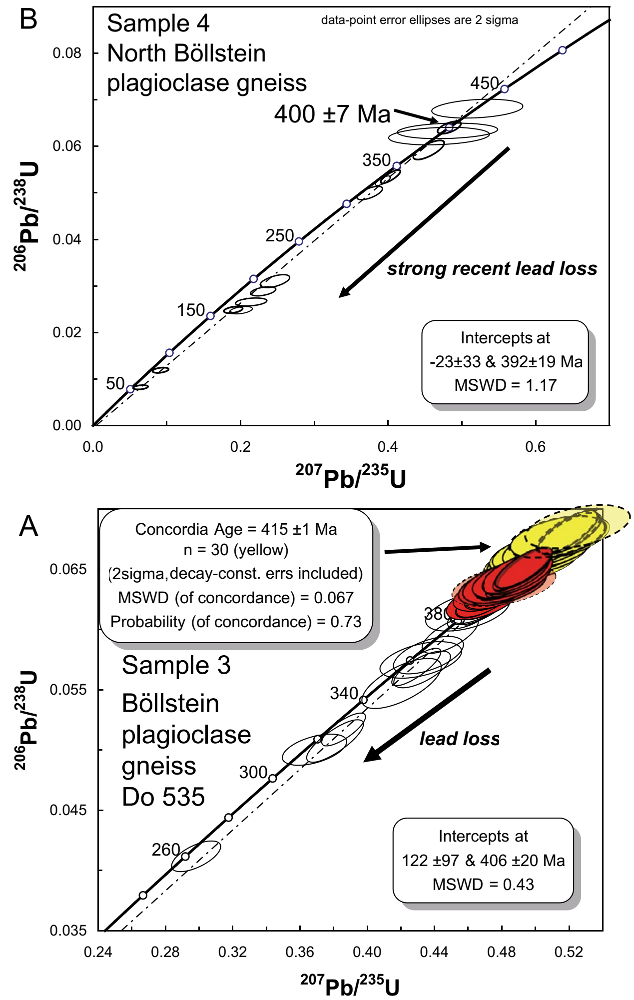


**Fig. 7** U–Pb concordia plots of zircon analyses from orthogneisses (sample 3 and 4) of the East Odenwald (MGCZ)

zircons (ESM 13). The oldest zircons have a low uranium (345–565 ppm) and low thorium (120–374 ppm) content with Th/U-ratios between 0.24 to 0.66 (ESM 5). The zircon with the lowest concordance (13%) contains 2900 ppm uranium and 5000 ppm thorium. The other discordant zircons have Th/U-ratios between 1 and 2. The concordant zircons of sample 4 contain a highly common lead content of 0.8–8.1%. The common lead content of the high discordant zircons is much higher, up to 34.1%. All analysed zircons fall on a line (MSWD = 1.2) with an upper intercept age at 392 ± 19 Ma and a lower intercept age at -23 ± 33 Ma (Fig. 7, sample 4), which is similar to sample 3. The errors (9–12%) of the U–Pb analyses of three concordant zircons are high due to their common lead corrections. One concordant zircon with a lower common lead content (0.8%) yields an age of 400 ± 7 Ma. The sample could be younger than samples 1 and 3.

### Orthogneiss (borehole Heubach)

Sample 8 was extracted from the orthogneiss core of the borehole Heubach from depths of 613.3 to 617.8 m (Fig. 2A). Some of the layers are richer in quartz (up to 40 vol%), while others mainly consist of feldspar (40 – 80 vol.%, Loeckle et al. 2016). The feldspar rich sample contains numerous apatite and few zircons. There are only 20 zircons with a grain size from 60 to 130 µm. Most of them are colourless, elongated and angular. The Th/U ratios of the zircons range from 0.46 and 0.83, which are typical of magmatic zircons. Three of the 20 zircons display a concordance below 70% (not shown in Table 8) with $^{207}Pb/^{206}Pb$ ages around 500 Ma. The youngest analysis A848 is concordant at 322 ± 7 Ma. The sample contains only a small homogenous population of zircons with an early Carboniferous age (351 ± 3 Ma, $n$ = 5, Fig. 8). Only two Devonian-, one Ordovician- and one Neoproterozoic zircons are present.

## Discussion

### Depositional age and lithostratigraphic model

The depositional age of metasediments can be defined by the age of volcanic layers. An estimation of the range of a depositional age can be established with the youngest detrital zircon population (maximal depositional age = MDA) and the oldest intrusion in a basement. The range of the depositional age is bracketed between the MDA (lower, older limit) and the age of the intrusion (upper, younger limit).

In the East Odenwald the U–Pb zircon ages of granodiorite gneiss (sample 1, sample 3) are younger than 430 Ma, whereas the U–Pb ages of metavolcano-sedimentary rocks are older than 430 Ma (sample 2, sample 5). The paragneiss sample 5 contains the oldest zircon from the Odenwald with an age at 3.45 Ga (concordance = 102%). The intrusion age of the granodiorite gneiss at 425 ± 2 Ma (sample 1) and the MDA of the metavolcano-sedimentary rock (sample 2) at 421 ± 2 Ma are within their errors the same age. The protolith age of the granodiorite gneiss and the sedimentation age of the metavolcano-sedimentary rock are nearly coeval. The granodiorite sills intruded shortly after deposition of the volcanoclastic sequence. The depositional age of sample 5 is bracketed between the intrusion age of sample 3 at 415 ± 1 Ma and the MDA of the paragneiss at 419 ± 4 Ma. The orthogneiss (sample 3) and the paragneiss (sample 5) also display nearly coeval sedimentation and intrusion ages. The depositional age of the metavolcano-sedimentary rocks of the East Odenwald ranges from the late Silurian to Early Devonian (Lochkovian).

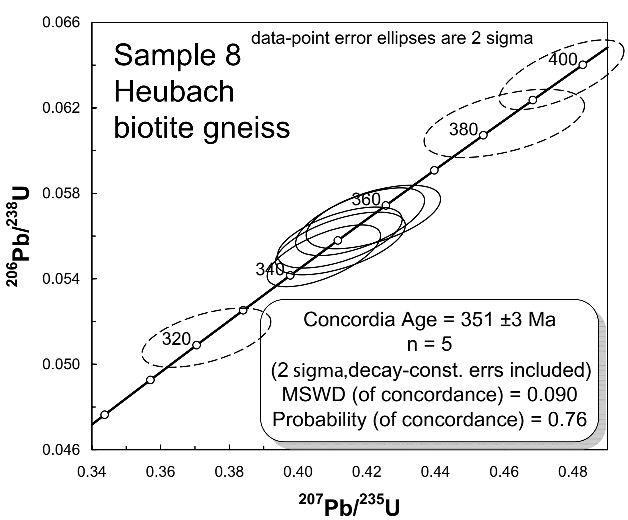


**Fig. 8** U–Pb concordia plot of zircon analyses from the orthogneiss drill core close to Heubach (sample 8, East Odenwald, MGCZ)

The youngest detrital zircons of the paragneiss of sample 6 with an age at 471 ± 12 Ma is interpreted as MDA. The sedimentation age of the paragneiss protolith is limited by the MDA and the metamorphic overprint. Rb–Sr analyses conducted by Lippolt (1986) point to a Devonian metamorphism (369 ± 14 Ma, Sr isotope initial at 0.7066 ± 0.002). The low Th/U ratios of the youngest zircons of the paragneiss (sample 6, ESM 6c) could be interpreted that these zircon grew also during the Devonian (371 ± 10 Ma) under metamorphic conditions. The depositional age is bracketed between the Devonian metamorphism and the MDA (471 ± 12 Ma) of the paragneiss. The sedimentation age of the paragneiss protolith could be Ordovician to Early Devonian. An Ordovician depositional age is most likely, because of the lack of Silurian zircons which are a significant feature of the other samples. The youngest concordant zircon analysis (a105, Table 7) with an age at 533 ± 11 Ma (concordance 97%) of the Łysogóry sandstone (sample 7) is inline with the late Cambrian to Ordovician depositional age (Żylińska et al. 2006; Trela 2009).

Figure 9 displays a combined lithostratigraphic model of the Spessart (Okrusch et al. 2011) and the East Odenwald. The oldest metasediment of the Spessart is Palaeozoic, probably Ordovician in age, because its MDA is 598 ± 19 Ma (Alzenau Formation, Kirchner and Albert 2020) and the extrusion age of a intercalated mafic metavolcanic rock is 460 ± 5 Ma (Fig. 9, green colour, U–Pb on zircon, Will et al. 2018). The MDA of the metagreywackes of the central Spessart (Mömbris Formation, Okrusch et al. 2011) varies from 477 ± 16 Ma to 539 ± 20 Ma (Kirchner and Albert 2020). An age limit is given by the U–Pb zircon age of a mafic metavolcanic rock at 445 ± 6 Ma (Fig. 9, green colour, Hörstein-Huckelheim-Formation, Will et al. 2018). An Ordovician age of the metagreywackes is plausible. The MDA of the metaquartzites of the N Spessart (Geiselbach Formation) at

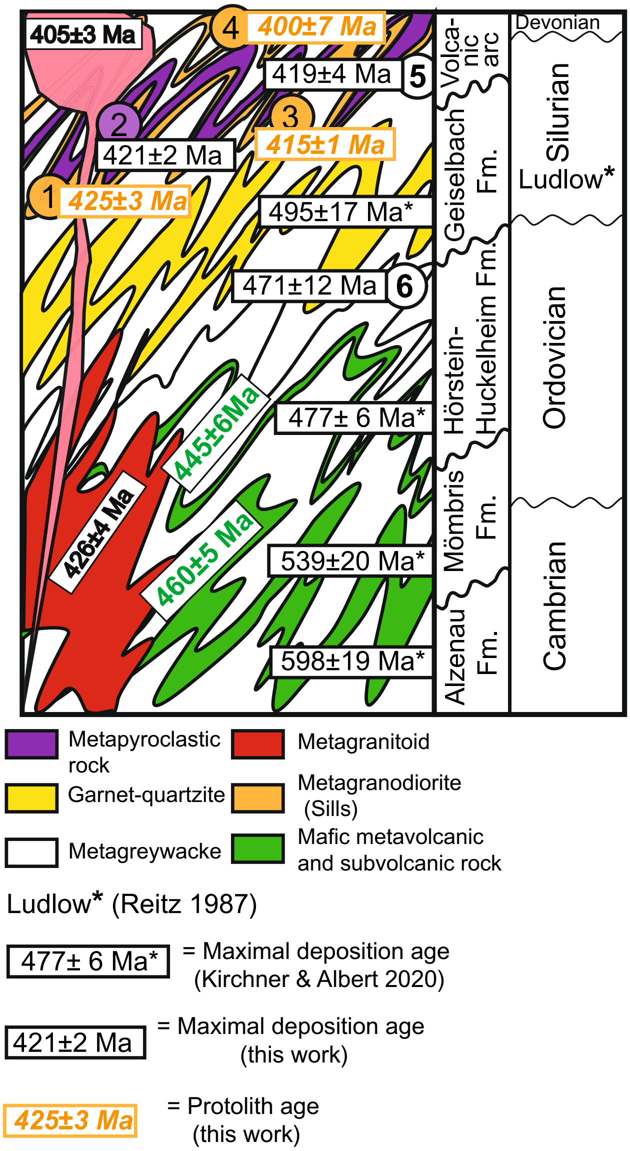


**Fig. 9** Combined lithostratigraphic model of the Spessart (Okrusch et al. 2011) and the East Odenwald. Devonian: 405 ± 3 Ma Reischmann et al. 2001; Silurian: 426 ± 4 Ma Brätz (2000); Ordovician: 460 ± 5 Ma, 445 ± 6 Ma, Spessart, Will et al. (2018); numbers 1 to 6 = samples in Fig. 2A

495 ± 17 Ma is much older than the Silurian deposition age (Reitz 1987, Ludlowian (425–423 Ma spores).

The oldest metasediment (sample 6, maximum depositional age 471 ± 12 Ma) of the East Odenwald has probably the same depositional age like that from the Spessart. The U–Pb ages of the zircons of the igneous (Fig. 9, orange colour sample 1, 3 and 4) and sedimentary rocks (samples 2 and 5) of the East Odenwald prove a Silurian to early Lochkovian (Devonian) depositional age, which is the youngest of the whole succession.

## Provenance

The U–Pb age spectra of detrital zircons from clastic metasediments of the East Odenwald display two contrasting compositions. One spectrum shows a strong cratonic influence (ca. 89% Precambrian zircons, Fig. 5 A and B), whereas the other is related to an active margin (ca. 90% Palaeozoic zircons, Fig. 4). The age spectrum of detrital zircons from the Silurian arc sediment (sample 2) of the schist envelope of the East Odenwald could not be correlated with any coeval age spectrum of clastic sediments to the north (Laurussia) or south (Armorica) of the MGCZ (Murphy et al. 2004a; Geisler et al. 2005; Linnemann et al. 2004, 2008, 2012; Drost 2008; Hajna et al. 2016 and references therein), because it is dominated by 47% Silurian zircons without Mesoproterozoic and Palaeoproterozoic detritus. The metagranodiorite (sample 1) with an intrusion age of 425 ± 2 Ma represents the Silurian magmatic arc in the Odenwald, which could be traced along strike of the MGCZ via the borehole Saar 1 (444 ± 22 Ma, Sommermann 1993), the Spessart (418 ± 18 Ma, Dombrowski et al. 1995) to the Ruhla crystalline complex (426 ± 4 Ma, Brätz 2000, red stars in Fig. 2B) to the NE. The detrital zircons with late Ordovician and early Silurian ages of sample 2 could be recycled from an older part of the magmatic arc. Few Ediacaran zircons could be delivered from a more distal source, probably recycled from lower Palaeozoic sediments of the MGCZ. Detrital zircon age spectra with a high input of Palaeozoic zircons are only known from the Devonian sediments of the active margin of the MGCZ and related nappes (North Odenwald, Fig. 4B; Fig. 2B: GHN = Giessen-Harz nappe, Fig. 4C; Dörr et al. 2017).

A second type of U–Pb age spectra of detrital zircons occurs in the East Odenwald, which is strongly influenced by old cratons. The age spectrum of the Ordovician to Silurian metagreywackes (Fig. 5, samples 5 and 6) is dominated by Neoproterozoic zircons (51%). Characteristic is an age gap from 0.8 to 1.4 Ga with a pronounced age peak at ca 1.5 Ga. A comparison between the zircon age spectrum of lower Palaeozoic metasediments of the East Odenwald (Fig. 10D, E) with that of the contemporaneous sandstones of the Saxothuringian Zone (Fig. 10B, MüMa = Münchberger Massif) and Rhenohercynian Zone (Fig. 10A, Brabant Massif) shows no correlation. The Ordovician sandstones of the Saxothuringian Zone are characterized by an Armorican detrital zircon age spectrum with a Mesoproterozoic age gap (Fig. 10B, Bahlburg et al 2010). The Silurian sandstone from the Brabant Massif (Linnemann et al. 2012; Rhenohercynian Zone, Fig. 1) displays an Ediacaran dominated Avalonian spectrum with Mesoproterozoic zircons (18%). A prominent age peak at 1.5 Ga (Fig. 10A, B) is not obvious. The Ordovician to Silurian metasediments of the Spessart are dominated by Mesoproterozoic zircons (Fig. 10F) with

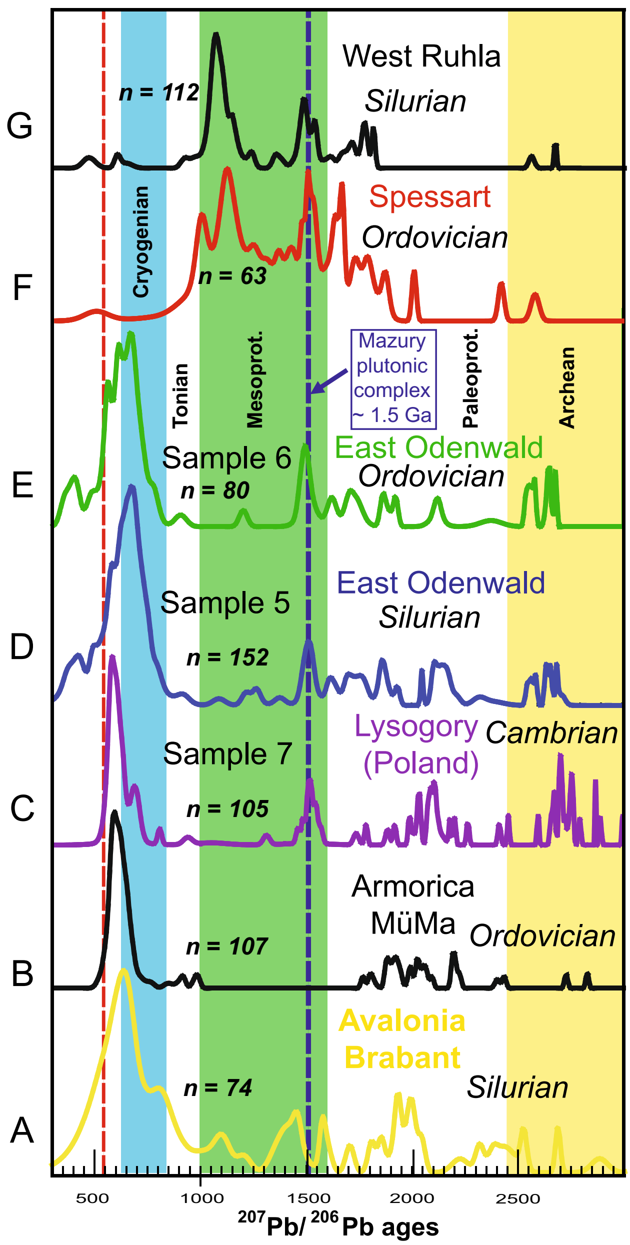


**Fig. 10** Density plots **A** Brabant Massif, Linnemann et al. (2012), **B** Münchberg Massif, Bahlburg et al. (2010), **C** Holy Cross Mountains this work, **D** East Odenwald this work, **E** East Odenwald this work, **F** Spessart Massif, Kirchner and Albert (2020), **G** Ruhla Massif, Zeh and Gerdes (2010)

sometimes Ediacaran input (Kirchner and Albert 2020). The Silurian quartzite of West Ruhla contains only Meso- and Palaeoproterozoic zircons (Fig. 10G) and could be correlated with the age spectrum of the Spessart.

The unique U–Pb age spectrum of the East Odenwald with the 1.5 Ga peak (sample 5 and 6) correlates with that of the Ediacaran and lower Palaeozoic sandstones of the continental slope of Baltica (Poland, sample 7, Fig. 10C, Żelaźniewicz et al. 2020) and with the U–Pb age spectrum of detrital zircons from the Ediacaran sediments of the EEP from Republic of Moldova (Francovschia et al. 2021). The Ediacaran zircons of the sandstone from Łysogóry (sample 7) fit with the U–Pb ages of zircons from the Kaplonosy Tuff of the Lublin Basin (EEP) and from the volcanoclastic rocks of the Małopolska Block (TTA) in Poland (Fig. 5D, Compston et al.1995). The Volyn volcanoclastic rocks of Belarus (Fig. 11 green colour, Paszkowski et al. 2019) are also a potential source area. The pronounced zircon age peaks at ca 1.5 Ga of the Łysogóry sandstone (sample 7) and of the metasediments from the East Odenwald (samples 5 and 6) are the same as the intrusion ages at ca 1.5 Ga of the Mazury plutonic complex (blue stippled line in Fig. 10, Dörr et al. 2002b) from the East European crystalline basement (Fig. 1, MZ red colour). The 1.5 Ga zircon detritus could be traced across the shelf of EEP (Żelaźniewicz et al. 2020) from the Mazury High via the Lublin Basin to Łysogóry (white arrow East of Warsaw, Fig. 11). The spectra with the 1.5 Ga peak (up to 80%) contains sometimes Ediacaran (ca 30%, Fig. 11: red filled circles) or sometimes only Palaeoproterozoic zircons (20%, Fig. 11: half blue and half red filled circles). These spectra occur together with a spectrum containing zircons of the whole Proterozoic time range, with Ediacaran (30%), Mesoproterozoic (40%), Palaeoproterozoic (25%) and few Cambrian zircons (purple filled circles, Żelaźniewicz et al. 2020). This full Proterozoic spectrum (0.54 to 2.2 Ga) is the most abundant of the EEP (Paszkowski et al. 2019, Porębski et al. 2019: sample Syczyn QU 1, Żelaźniewicz et al. 2020). The 1.0–1.4 Ga old zircons (40%) of this spectrum could not be derived from the local crystalline basement of Poland (Fig. 1, Bogdanova et al. 2015), which is mainly constituted of Palaeoproterozoic magmatic arcs and the 1.5 Ga granites of the Mazury High (Valverde-Vaquero et al. 2000; Dörr et al. 2002b; Wiszniewska et al. 2007). The Mesoproterozoic detritus can be explained by sediment transport parallel to the coast from the Sveconorwegian belt of southern Sweden to the shelf of the EEP in Poland mixing there with the local Ediacaran zircons of the Volyn volcanic rocks (Fig. 11, green colour), which cover a large area of the EEP of Belarus and Russia (south of Moscow).

As described above, the crystalline of the Mazury High together with its Ediacaran to early Cambrian shelf sandstones of the EEP are the possible sources of the detrital zircons of the upper Cambrian sandstones of the Łysogóry. Mesoproterozoic and Late Palaeoproterozoic (ca. 1.3–1.73 Ga) K–Ar cooling ages of large detrital white mica of the Łysogóry point also to the EEP as source (Bełka et al. 2000). The high amount of Ediacaran zircons (30–47%) of the Łysogóry sandstones were explained by Żelaźniewicz et al. (2020) with a derivation from the Małopolska Block in the south (tuffite, Compston et al.1995). The K–Ar cooling ages of small detrital white mica from 0.54 to 0.65 Ga

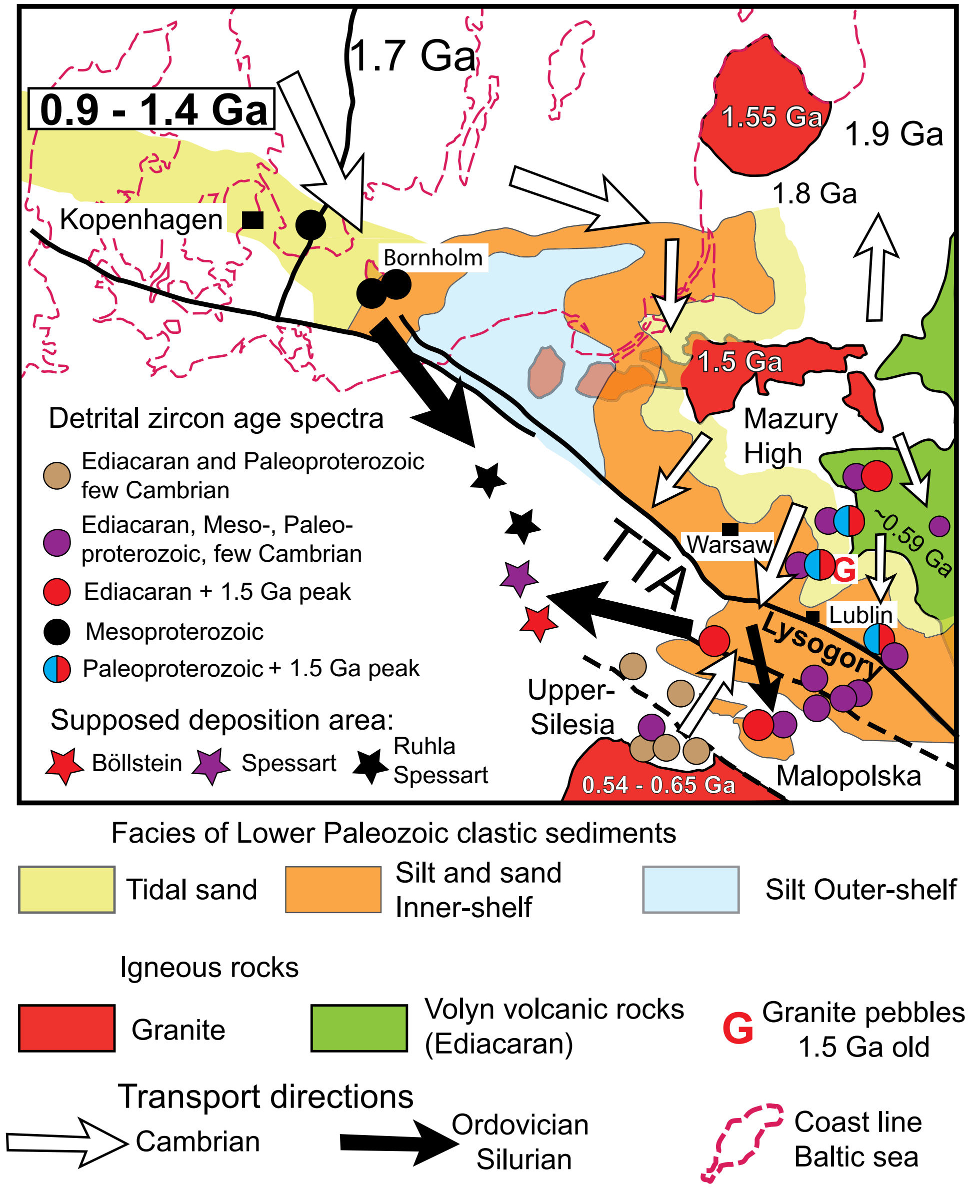


**Fig. 11** Facies of the lower Palaeozoic sandstone (late Cambrian to Ordovician) of the East European Craton (modified after Jaworowski 1997) and their detrital zircon age spectra (Lorentzen et al. 2018; Żelaźniewicz et al. 2009, 2020, this study). *TTA* Teisseyre-Tornquist Terrane Asemblage

of the Łysogóry (Fig. 3) are interpreted that they were also delivered from Cadomian magmatic arc in the south (Bełka et al. 2000). The K–Ar data of white mica and the U–Pb data of zircon could be explained by mixing of the two sources in the Łysogóry. Sedimentological field work revealed bidirectional transport marks. One direction points to the EEP and the other to an oppositely located source (Jaworowski and Sikorska 2006), which is unknown or probably the Ediacaran volcanoclastic rocks from the Małopolska Block (Compston et al. 1995). The mixing of Gondwana and Baltica-related fauna in the Holy Cross Mountains and Upper Silesia point to a close relation of both terranes during the Cambrian (Nawrocki and Poprawa 2006; Nawrocki et al. 2007).

The U–Pb analyses of the detrital zircons of the western Małopolska Block (Żelaźniewicz et al. 2009, Fig. 11, brown filled circles) are similar to the Upper Silesian detrital zircon age spectrum, which is dominated by Ediacaran zircons (60–90%, Żelaźniewicz et al. 2020; Fig. 11, brown filled circles). From a total of 172 zircons only 5 of the Upper Silesian detrital zircons are Mesoproterozoic in age. This reminds the Cadomian Arc of Gondwana with West African signature (Mesoproterozoic age gap) and does not correlate with the samples of Łysogóry or EEP (red and purple filled circles).

The Ordovician sandstones of the eastern Małopolska Block display the same detrital zircon age spectra as the Łysogóry (Żelaźniewicz et al. 2020). Again, there is the spectrum with a 1.5 Ga age peak (Red filled circle) and the full Proterozoic spectrum of the EEP (purple-filled circle). This could be interpreted as recycling of the zircons from the Cambrian sandstones of the EEP into the Ordovician sandstones of the eastern Małopolska Block (black filled arrow, Fig. 11). The age spectra of the detrital zircons from the lower Palaeozoic metasandstones of the East Odenwald and Spessart correlate with the age spectra of the EEP including eastern Małopolska Block and Łysogóry and could be also explained by the recycling of zircons from Cambrian to Ordovician sandstones from the Palaeozoic slope of Baltica in Poland (black filled arrow, Fig. 11). The red star marked the supposed depositional region from the lower Palaeozoic metasandstones of the East Odenwald with the 1.5 Ga age peak. The metasandstones of the Spessart (Kirchner and Albert 2020) contain the full Proterozoic spectrum (0.54–2.2 Ga) of the EEP from Poland (purple filled circle, Żelaźniewicz et al. 2020, Porębski et al. 2019: sample Syczyn QU 1) and from Belarus (Paszkowski et al. 2019). Their supposed position is marked by a purple star (Fig. 11). The detrital zircon age spectrum with pure Mesoproterozoic input of the Ordovician to Silurian metaquartzite from the Spessart (Kirchner and Albert 2020) and West Ruhla (Zeh and Gerdes 2010) could be recycled from the Cambrian Hardeberga quartzite of Bornholm and southern Sweden (Lorentzen et al. 2018, black filled circles and black arrow, Fig. 11). The two black stars mark the supposed depositional region of the lower Palaeozoic metaquartzite from the Spessart and West Ruhla.

The Ordovician spectrum of detrital zircons of the Rhenohercynian Zone contains only a few Mesoproterozoic input (1–4%) and is dominated by Ediacaran zircons (45%, Linnemann et al. 2012), which were correlated with Avalonia. Baltica-derived pure Mesoproterozoic age spectrum (without Ediacaran zircons) occurs in the Rhenohercynian Zone since the Devonian (late Emsian), 30 myr later than in the MGCZ, and in Carboniferous quartzite (Haverkamp 1991; Geisler et al. 2005; Eckelmann et al. 2013). The Devonian sandstones of the SE Rhenohercynian Zone cannot be interpreted as protolith of the Spessart metaquartzites, which are intruded by Silurian plutons.

## Devonian metamorphism

The first U–Pb analyses of zircons with an age of 375 ± 2 Ma, which grew under metamorphic condition in the schist envelope of the East Odenwald, were performed by Todt et al. (1995, Otzberg Zone, red squares in Fig. 2A). Twelve zircons from metasediments (this study) of the East Odenwald contain low amount of thorium and thus display Th/U ratios between 0.01 and 0.08 (ESM 6 a, b), which point to zircon growth under metamorphic conditions. Their U–Pb ages are similar to the paragneiss of the Otzberg Zone defined by concordant zircons at 371 ± 10 Ma and at 381 ± 9 Ma (Fig. 2A, red square, samples 5 and 6). The Devonian U–Pb ages of the zircons from a metavolcanoclastic rock of the East Odenwald (Fig. 2A, sample 2, red square) could not be explained by new zircons growth during a metamorphism, because the zircons display Th/U ratios around 1; typical for magmatic rocks. A detrital origin has to be excluded, because a granodiorite sill intruded at 425 ± 2 Ma ($n = 20$) into the metavolcanoclastic rock defining a Silurian minimum age. The four youngest analyses define an age of 372 ± 8 Ma (Fig. 4A), which could be explained by a lead loss of the Silurian and Ordovician detrital zircons. The youngest zircons of Devonian arc sediments (Fig. 4B, paragneiss) from the East Odenwald are around 371 ± 3 Ma (Fig. 2A, red square south to the sample 8). The Early- to Middle Devonian zircons from the paragneiss are detrital (Dörr et al. 2017), whereas the Upper Devonian age at 371 ± 3 Ma could be the result of the amphibolite facies overprint of the East Odenwald at 375 ± 2 Ma (Todt et al. 1995, U–Pb on zircon, schist envelope) cooling down to 550 °C at 367 Ma (Kreuzer and Harre 1975, K–Ar hornblende age, orthogneiss).

Devonian zircon ages are also common in the West Odenwald (Fig. 2A, Unit II). In the Cadomian basement zircons grew under solid-state conditions in metagranitoids at 386 ± 7 Ma and at 384 ± 4 Ma. U–Pb ID-TIMS analyses of single titanite grains of the variegated series of the Cadomian basement also prove the Devonian metamorphism at 369 ± 1 Ma (Dörr and Stein 2019). Similar Devonian K–Ar ages of amphibole at 370 Ma (Fig. 2A, red hexagons, Kreuzer and Harre, 1975) from the Cadomian basement and the Silurian gneisses of the East Odenwald also point to a Devonian metamorphism and no later heating of these parts of the basements above a temperature of 550 °C. Such a Devonian event is widespread in the allochthon units of the Saxothuringian Zone and the Tepla Barrandian Unit. In the Münchberger nappe Ar–Ar and K–Ar ages on muscovite and hornblende of 372,390 Ma (Kreuzer and Seidel 1989; Söllner et al. 1981) are common. In paragneiss of the Münchberger nappe Koglin et al. (2018) recently discovered metamorphic zircons with an age at 390 ± 3 Ma (Fig. 2B, MüMa in blue), which fits with the metamorphic zircons of the Cadomian basement of the West Odenwald (Unit II).

## Devonian to Carboniferous rocks of the East Odenwald

Based on the different sedimentation ages Dörr et al. (2017) divided the East Odenwald into to a southern Silurian part and a younger northern Devonian part. The paragneisses from the southern part were intruded by Silurian to early Devonian plutons (Reischmann et al. 2001, this work) whereas the paragneisses of the northern part are intruded by a Carboniferous pluton at 351 ± 3 Ma (sample 8). This Tournaisian age is wide spread in all tectonic units from the Odenwald (Fig. 2: red colour, Stein et al. 2021, under

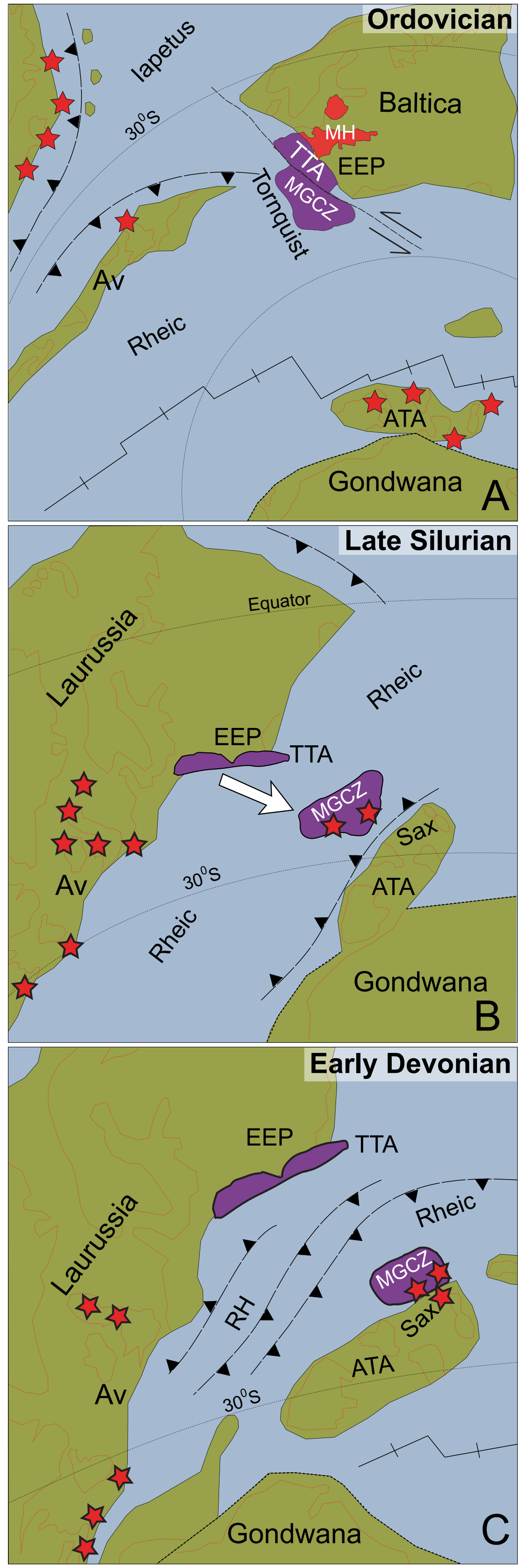


**Fig. 12** Paleogeography modified after Cocks and Torsvik (2006). ▸ *ATA* Armorican Terrane Assemblage; *Av* Avalonia; *EEP* East European Platform; *MGCZ* Mid-German Crystalline Zone microcontinent; *MH* Mazury High; *Sax* Saxothuringian Zone; *TTA* Teisseyre-Tornquist Terrane Asemblage; *red star* plutons, *white arrow* movement of the MGCZ

review), the Spessart (Kirchner and Albert 2020: Fig. 7) and the Ruhla (Zeh and Will 2010). All Tournaisian plutons probably belong to the same active continental margin of the MGCZ, which could be traced through the European Variscides from Poland (Dörr et al. 2006) via Odenwald to the Armorican Massif (Léon block, see compilation in Faure et al. 2010). A Carboniferous amphibolite facies metamorphism was dated in the orthogneiss core (Fig. 2A, green colour) 2 km to the southwest of locality 8 at 333.7 ± 4.1 Ma (U–Pb on zircon) and 328.6 ± 4.7 Ma (U–Pb on rutile, Will et al. 2018), which is similar to the age of the peak metamorphism of the West Odenwald (Todt et al. 1995) and Spessart (Will et al. 2018). This high-grade Carboniferous metamorphism points together with the Middle Devonian metamorphism to a polyphase evolution of the MGCZ.

## Tentative model

Compiling geochronological data from the literature for lower Palaeozoic sediments of Central Europe (Murphy et al. 2004b; Linnemann et al. 2007, 2008, 2012, 2013; Drost 2008; Drost et al. 2010; Bahlburg et al. 2010; Hajna et al. 2013, 2016; Bogdanova et al. 2015; Żelaźniewicz et al. 2007, 2020; Paszkowski et al. 2019; Porębski et al. 2019) with the U–Pb age spectra of the detrital zircons from the wall rock of the MGCZ (Zeh and Gerdes 2010; Dörr et al. 2017; Dörr and Stein 2019; Kirchner and Albert 2020, this work), the following paleogeographic sketch could be created.

In the paleogeographic reconstructions of the Ordovician from Nawrocki and Poprawa (2006), Cocks and Torsvik (2006) and Torsvik and Cocks (2017: Fig. 6.2b) the MGCZ is interpreted as a part of the ATA of peri-Gondwana origin, which was separated by the Rheic Ocean from Baltica with its EEP shelf (Fig. 12C). This does not fit with the provenance analysis of detrital zircons. During the Ordovician the sedimentation area of the greywacke and quartzite of the East Odenwald and the Spessart could be located close to the slope of the EEP of Baltica (Poland), because the different U–Pb age spectra of the detrital zircons of the MGCZ could neither be correlated with Avalonia (Av, Fig. 12) nor with Armorica (ATA, Fig. 12). The source area was the Cambrian to Ordovician shelf sediments of the EEP on top of the former Teisseyre-Tornquist Terrane Assemblage (Fig. 12, TTA, purple colour), which received their detritus from the Proterozoic basement of the Baltic craton (Fig. 1) and from the

1.5 Ga old a giant intrusion of the Mazury High of Poland (Fig. 12A, MH = Mazury High).

The tectonostratigraphic units of the TTA were probably separated from each other by the NW-trending faults, parallel to the EEP margin, that coincide with the Teisseyre–Tornquist Line (Znosko 1977; Żelaźniewicz et al. 2020). Probably, at a similar NW trending fault starts further to the south the separation from the EEP. The southern most part (later MGCZ) was split off from Baltica during the Late Ordovician (Fig. 12A). The other possibility is a similar NW-trending fault like the Odra Fault to the west where the attenuated Baltica margin is today close to the Variscan Saxothuringian Zone (Mazur et al. 2015).

In the early Silurian, the MGCZ micro-continent drifted from Baltica in the direction of Gondwana forming a magmatic arc at its southern margin. Zircons of the arc sediments with an age of 438 ± 2 Ma were pointing to this early magmatic activity. During the drifting minor parts of Ordovician oceanic crust, probably from the Rheic Ocean (460 ± 5 Ma, 445 ± 6 Ma, Spessart, Will et al. 2018), were accreted against the micro-continent. In the Silurian, the phase of drifting continued (white arrow, Fig. 12B) producing a volcanoclastic sequence, which was intruded by Silurian granodiorite sills (425 ± 2 Ma sample 1, 415 ± 1 Ma sample 3) and plutons (Brätz 2000). Altenberger and Besch (1993) interpreted the volcanoclastic sequence with the metabasalts intercalated as an accretionary prism of a convergent margin. The Silurian age of the granodiorites matches within its errors with the age of granite gneisses of the northern Ruhla Crystalline Complex (423 ± 6 Ma and 426 ± 4 Ma, Brätz 2000), with the metagranodiorites of the central part of the Spessart (Fig. 12B, red stars MGCZ; Dombrowski et al. 1995) and with the granite of borehole Saar 1 (444 ± 22 Ma, Sommermann 1993). During the Silurian, the Saxothuringian Zone (Fig. 12B, Sax) was still a part of the Armorican Terrain Assemblage (ATA) close to Gondwana (Linnemann et al. 2007).

The Baltic part of the MGCZ, the above-mentioned micro-continent, collided not later than Early Devonian with the Saxothuringian part of the MGCZ producing magmatism in both micro-continents (Fig. 12C Early Devonian, red stars MGCZ and Sax). (Meta)granitoids were emplaced at 411 ± 5 Ma into the metasediments of the Saxothuringian part of the MGCZ (West Odenwald, Dörr and Stein 2019) with Armorican affinity (ATA) and into the (meta)volcanoclastic sequence with Baltica (EEP) affinity of the East Odenwald at 405 ± 3 Ma (Reischmann et al. 2001; Fig. 2A, number 4 this study). Altenberger and Besch 1993 interpreted these plutons as a remnant of an Early Devonian magmatic arc in a continent arc collisional setting (Altenberger et al. 1990; Reischmann et al. 2001). Similar Devonian ages of metaigneous rocks are known from the Spessart Crystalline (410 ± 18 Ma, U–Pb on zircon, Dombrowski et al. 1995) and the Central Gneiss Unit of Ruhla from 398 ± 3 Ma to 413 ± 5 Ma (Brätz, 2000, Fig. 2B) of the MGCZ.

The collision continues during the Middle Devonian (not displayed in Fig. 12). The Saxothuringian part of the MGCZ (West Odenwald) was thrust to the NW over the Baltic part of the MGCZ (East Odenwald). This crustal stacking culminated in a high-grade metamorphism of the wall rock of the Odenwald and Otzberg Zone dated with the U–Pb method on zircon at around 380 Ma (Fig. 2A, red squares, see description Devonian metamorphism above). The Ar–Ar and K–Ar cooling ages from 365 to 370 Ma (Fig. 2A, red hexagons; Kreuzer and Harre 1975; Schubert et al. 2001) could be interpreted as a Late Devonian exhumation. At the same time the ocean between the Saxothuringian Zone and the Moldanubian Zone was closed (Schäfer et al. 1997) and crustal stacking occurred in the northern part of the Tepla-Barrandian (Zulauf et al. 1997), which was thrust over the Saxothuringian Zone forming the Münchberg nappe pile (Fig. 2B, MüMa in blue). From the Middle Devonian, the Armorican Terrane Assemblage was unified and acting as one continent, which drifted to the NW with subduction direction of the ocean crust to the SE. The East and West Odenwald was now the active continental margin of Armorica, which was intruded by subduction-related plutons in the early Tournaisian (Fig. 2A, 346–354 Ma, Kirchner and Albert 2020; Stein et al. 2021 submitted). The East Odenwald (Baltic part of the MGCZ) belongs also to this arc and was intruded by plutons at 351 ± 3 Ma (Fig. 2A, samples 8). Plutons with similar intrusion ages cloud be traced from the Spessart (Kirchner and Albert 2020) via Ruhla in strike of the MGCZ to the NE (Zeh and Will 2010) and to the West Armorican Massif (Leon Block, Faure et al. 2010). All this implies that the Baltica-related part of the MGCZ was a micro-continent that docked to the Armorican Terrane Assemblage during the Middle Devonian.

In an alternative model, Zeh and Will (2010) interpreted the metabasalts of the Spessart as Emsian (ca 405 Ma) rift related volcanism during the opening of the Lizard-Giessen Ocean, which split the west part of the MGCZ off from the Rhenohercynian Zone (Old Red Continent) and named it South Avalonia. This is not compatible with the Ordovician ages and with the MORB trace element patterns of this metabasalts of the Spessart (460 ± 5 Ma and 445 ± 6 Ma U–Pb method on zircon), interpreted as divergent margin of the Rheic Ocean (Will et al. 2018).

Torsvik and Cocks (2017) published two different paleogeographic models from the Ordovician to Silurian time. One based on paleomagnetic and palaeontological data which favours a wide Rheic Ocean and placed the ATA close to Gondwana (Torsvik and Cocks 2017: figs. 6.2, 6.9 and 7.1). The other model based on regional geological observations and splits the ATA by a wide Saxothuringian Ocean into a Bohemian and Saxothuringian part (Thuringia and

Franconia), which are interpreted as separate terranes (Torsvik and Cocks 2017: Fig. 8.9). In this model the Saxothuringian terrane moved to the north, closing the Rheic Ocean, and collided with the Old Red Continent during the Early Devonian. The MGCZ is named Franconian, which forms an integral part of Armorica (see also Franke et al. 2017). This does not fit with the observation that the provenance area during the Ordovician to Silurian of parts from the MGCZ is the EEP and not the West African Craton. The supposed collision in the Early Devonian left no signs of a tectonic event at the southern most part of Laurussia (Rhenish Massif, Northern Phyllite Zone = NPZ in Figs. 1, 2). The Devonian sediments (Lochkovian to Frasnian) display only two Carboniferous deformations (Klügel 1997). The andesitic to rhyolitic rocks of the NPZ (Old Red Continent) are not the volcanic equivalents of the plutons from the MGCZ, because they are Ordovician to Silurian in age (Sommermann et al. 1992, 1994) whereas most of the granodiorite plutons of the MGCZ are Early Devonian (Brätz 2000; Dombrowski et al. 1995; Reischmann et al. 2001, this work). The continuous Silurian to Devonian (Eifelian) age (Grösser and Dörr 1986) of the Lizard-Giessen ophiolite and their equivalent to the east (403 ± 0.5 Ma to 420 ± 3 Ma, Sudetes, Poland, Oliver et al. 1993; Awdankiewicz et al. 2020; 428 ± 6 Ma, Austria, Raabs unit, Finger and von Quadt 1995) contradict also the supposed collision in the Early Devonian. The MGCZ and the Rhenohercynian Zone are separated by Lizard-Giessen Ocean (West part of the Rheic Ocean).

Franke et al. (2019) interpreted in their model of frontal accretion the Baltoscandia-derived quartzites from the MGCZ (Spessart and Ruhla) as Devonian in age deposited onto an Early Devonian magmatic arc. This is not in accordance with the Ordovician to Silurian depositional age of the Baltoscandia-derived quartzites (Reitz 1987; Zeh and Gerdes 2010; Kirchner and Albert 2020).

The occurrence of exotic Mesoproterozoic detrital zircon age spectra is not restricted to the suture zone between the Saxothuringian- and Rhenohercynian Zone, the MGCZ. Braid et al. (2011) described Mesoproterozoic detrital zircon age spectra in the suture zone (Pulo do Lobo Zone) between the Ossa Morena Zone and the south Portuguese Zone. They interpreted an equivalent of the southern Uplands terrane of the British Caledonides as the source area, which was transported during the Early Devonian by a large-scale continental escape as a crustal fragment southward to Gondwana.

## Conclusions

A part of the Mid-German-Crystalline Zone belongs during the lower Palaeozoic to the shelf of the East European Platform (Baltica). The provenance analysis of metasediments of the Mid-German-Crystalline Zone displays two different Baltica related source areas. The age spectrum with Ediacaran zircons together (a) with Mesoproterozoic input (1.0–1.6 Ga, Spessart, Kirchner and Albert 2020) and (b) with an age peak at 1.5 Ga (East Odenwald) could be located at the EEP and the Trans-European-Suture-Zone (Poland, Pharaoh 1999; Żelaźniewicz et al. 2020), where zircons of a giant intrusive complex (Mazury High, 1.5 Ga) were mixed with Ediacaran (probably from the Volyn volcanoclastic rocks) and Sveconorwegian related zircons.

The other source area is dominated by pure Sveconorwegian ages from western Baltica, which could be correlated with sandstones of southern Sweden and Bornholm. Both locations acted as sources for the quartzites from the Ruhla and Spessart massifs of the MGCZ (Zeh and Gerdes 2010; Kirchner and Albert 2020). The combination of Baltica provenance of the metasandstones with Ordovician and Silurian depositional ages from the East Odenwald, Spessart and Ruhla are not in accordance with the coeval detrital age spectra of Armorica and Avalonia. The Baltica-related detrital age spectra define a small area between the Saxothurigian- and Rhenohercynian Zone, which correlates with the main part of the Mid-German-Crystalline Zone (MGCZ, Fig. 2B, green colour). An exception is the West Odenwald, which is a nappe of Armorican origin.

The Baltica-related clastic sediments of the MGCZ are all intruded by Silurian granitoids (Fig. 2B) forming together a micro-continent or a sliver of it, now named as the MGCZ micro-continent. The rifting from Baltica starts probably in the Ordovician (detrital zircon ages of sample 2, 460 ± 3 Ma) far away from the present slope of the EEP in the south. The drift phase is documented by Silurian arc sediments from 438 ± 2 Ma to 421 ± 2 Ma intruded by plutons at 426 ± 4 Ma (Brätz 2000) coeval with subvolcanic sills at 425 ± 2 Ma. The docking phase generates collisional related granitoids in the MGCZ micro-continent with Baltica affinity (East Odenwald, Reischmann et al. 2001 and sample 4 this study: 405 ± 3 Ma, 400 ± 7 Ma; Ruhla Massif, Brätz 2000: 398 ± 3 Ma, 413 ± 5 Ma) and in the MGCZ with Armorican affinity (West Odenwald, Dörr and Stein 2019: 411 ± 5 Ma) culminating in a Middle Devonian crustal stacking and exhumation during the Late Devonian. Since that time trench sediments in front of an accretionary wedge were deposited and thrust during the Carboniferous together with the upper part of the ophiolite of the Giessen Nappe onto the foreland fold- and-thrust belt in the NW.

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