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ORIGINAL PAPER

New detrital zircon age data reveal the location of the Rheic suture in the Mid-German Crystalline Zone (Spessart and Odenwald Crystalline Complexes)

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Abstract
New detrital zircon age data of metasedimentary rocks from the Spessart and Odenwald basement (Mid-German Crystalline Zone, Variscides) revealed results, which are not compatible with current tectonic models. The previously proposed existence of a tectonic window, which includes lower plate Rhenohercynian rocks within the upper plate (Saxothuringian Zone) in the Spessart and Odenwald basement, does not agree with the results of this study. This leads to a new course of the Rheic suture and, therefore, a non-coherence of the two major fault zones in these complexes. The southern Spessart Crystalline Complex accommodates the Rheic suture, which is most likely explained by a southward displacement of a whole segment of the Mid-German Crystalline Zone. This displacement might extend over the Ruhla Crystalline Complex. A hitherto unknown age spectrum of a unit in the Böllsteiner Odenwald was found, which might indicate a sliver of unidentified material in the Variscan collision zone. An unknown magmatic age of 350 Ma is reported for igneous intrusions in the Saxothuringian Zone and can be used as an additional indicator to distinguish between Laurussia- and Gondwana-related rocks.

Keywords U–Pb ages · Detrital zircon · Spessart Mts. · Böllsteiner Odenwald · Mid-German Crystalline Zone · Variscides · Age spectra

Introduction

The reconstruction of lithospheric plate movements is well constrained from the formation of the Pangaea Supercontinent until present. The evidences left of these plate motions are scarcer with increasing age, due to erosional processes and orogenies, which overprint the remnants of previous events.

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Dating detrital zircon grains with LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) enables the reconstruction of provenance areas, provides information about the source rock types and the magnitude of sedimentary transport (Zeh and Gerdes 2009; Linnemann et al. 2012; Zulauf et al. 2014; Dörr et al. 2017). Continents and terranes can be distinguished with this method from each other, as they have a traceable age fingerprint in their eroded material. This age fingerprint is linked to the magmatic and metamorphic events, which are responsible for zircon growth and can be visualized in an age spectrum, showing abundance peaks and age hiatus in the sedimentary rock characteristic age distribution. These age spectra help to reconstruct former plate movements and to understand complex collision zones consisting of different terranes or continents, like the Mid-German Crystalline Zone (MGCZ).

During the Caledonian Orogeny, in the Paleozoic era, the continents of Laurentia, Baltica and the microcontinent of Avalonia were amalgamated to Laurussia, the Old Red Continent (Winchester et al. 2002, 2006; von Raumer et al. 2002, 2003; Torsvik and Rehnström 2003; Murphy et al. 2004; Cocks and Torsvik 2006; Kroner et al. 2007; Linnemann et al. 2008; Nance et al. 2008, 2010; Cocks and Fortey 2009; Torsvik and Cocks 2013). First, the Avalonian terrane was separated from peri-Gondwana in the Early Ordovician and drifted northwards, opening the Rheic Ocean, closing the Tornquist Sea and collided with Baltica in the Late Ordovician. These two continents started to converge to Laurentia, closing the Iapetus Ocean and ended up forming Laurussia, around 420 Ma. The source of the Avalonian sediments is the Amazonian Craton, and, therefore, their age spectra are similar. A major input of Ediacaran and a distinct amount of Cryogenian ages characterizes an Avalonian age spectrum. Clastic material derived from the Baltic part of Laurentia must be distinguished into SW-Baltica-derived material (todays Norway), which is characterized by a high abundance of Mesoproterozoic and Paleoproterozoic ages with local Ediacaran and minor Silurian ages (Haverkamp 1991; Geisler et al. 2005; Zeh and Gerdes 2009; Linnemann et al. 2012; Eckelmann et al. 2013; Dörr et al. 2017) and East European Platform (EEP) derived material, which yields a similar age distribution than material of the Avalonian terrane. Furthermore, metasedimentary rocks of the Armorican terrane (derived from the West African Craton) show a characteristic Mesoproterozoic age gap, between 1 and 1.6 Ga, and a major input of Ediacaran and Paleoproterozoic detrital zircon ages (Linnemann et al. 2004, 2008; Gerdes and Zeh 2006; Drost 2008; Zeh and Gerdes 2009; Hajna et al. 2013, 2016; Dörr et al. 2014). The tectonic history of the Armorican terrane is controversial and its possible separation from Gondwana is under debate. Tait et al. (1997, 2000) assume a separation of Armorica, as a single continent or multiple microcontinents (in this case the Armorican Terrane Assemblage), from peri-Gondwana, with a northward drift in the Late Ordovician and finally colliding with Laurussia. This idea contrasts with other publications, e.g. Linnemann et al. (2004), who assume that a separation of the Armorican terrane from the Gondwanan mainland never happened. Kroner and Romer (2010) propose the existence of an "Armorican spur", attached to North Gondwana, which collided with Laurussia first, followed by the Gondwana mainland. Nevertheless, the Rheic Ocean polarity of subduction changed during the Devonian from north- to southward dipping, underneath Armorica, forming the Saxothuringian magmatic arc (Oncken 1997; Stampfli et al. 2013; Franke et al. 2017). The final collision of Laurussia and Gondwana happened during the Carboniferous, forming the Variscan orogeny (Tait et al. 1997, 2000; Winchester et al. 2002). The Rheic suture runs through Central Europe separating rocks from different continents with characteristic magmatic and metamorphic histories.

Kossmat (1927) divided the European Variscides in four main zones, which are distinguished by their lithology, age, and grade of metamorphism: Moravo-Silesian, Moldanubian/Teplá-Barrandian, Saxothuringian and Rhenohercynian (Fig. 1). The Rhenohercynian sediments are understood to be Laurussia derived, in contrast to the Saxothuringian sediments, which show an affinity to Gondwana. Brinkmann (1948) added the MGCZ, as a structural high, between the Rhenohercynian and the Saxothuringian Zones into this model (Fig. 1). The MGCZ is described as the collision zone between the Laurussian and the Armorican continent hosting the Rheic suture (Tait et al. 1997). Remnants of the MGCZ were not only found in Germany, but also in South Portugal, as Braid et al. (2011) discovered Baltica- and Gondwana-related zircon age spectra in the Ossa Morena Zone, Pulo do Lobo Zone and the South Portuguese Zone. They assumed a southward continental escape of a block, which includes Laurussia and Gondwana derived sediments, to its today's location in South Portugal. Furthermore, a continuation of the MGCZ over Cornwall in the Normannian High (Dörr et al. 1999), underneath the Paris Basin parallel to the Bristol Channel-Bray fault through Germany is assumed, pursuing in the Middle Odra Zone (Poland) and the Stáre Mesto area (Czech Republic; Kopp and Bankwitz 2003). The Rheic suture separates rocks of the Rhenohercynian and the Northern Phyllite Zone (NPZ) in the North, from the low to medium grade metamorphic rocks of the Saxothuringian Zone in the South (Zeh and Will 2010). The NPZ consists of low-grade metasedimentary and metavolcanic rocks (Massone 1995) which are exposed in the S-Hunsrück, the S-Taunus, and the S-Harz Mts. In the S-Hunsrück, metamorphic equivalents of the Rhenohercynian shelf sequence and MOR-basalts are exposed (Meisl 1995). The outcrops south of the Taunus show metavolcanic rocks of a Late Silurian volcanic arc (Sommermann et al. 1992), which record the closure of the Rheic Ocean. Franke (2000) interprets the NPZ to bear parts of the Rheic suture due to metamorphic equivalents of the Harzgerode Allochthon including Silurian and Devonian exotic rocks in the S-Harz Mts. (Rhenohercynian related) and further SE Ordovician clastic metasedimentary rocks with intra-plate metavolcanic rocks (Saxothuringian related).

According to Oncken (1997), the MGCZ is composed of a Saxothuringian Lower Carboniferous low pressure–high temperature (LP–HT) magmatic arc, which was thrusted over a stack of Rhenohercynian medium pressure–medium temperature (MP–MT) rocks. In this model, the contact between the plates is permeable and material transferred from the lower to the upper plate by basal accretion. It describes a tectonic window of lower plate rocks inside the upper plate reaching from north of the Ruhla Crystalline Complex over the central Spessart Crystalline Complex to the Böllsteiner Odenwald. With the application of LA-ICP-MS on two metasedimentary rocks of the Ruhla Crystalline Complex, Zeh and Gerdes (2009) found a part of the Rheic suture inside the complex. The analyses yielded a characteristic Armorican age spectrum in the southern part of

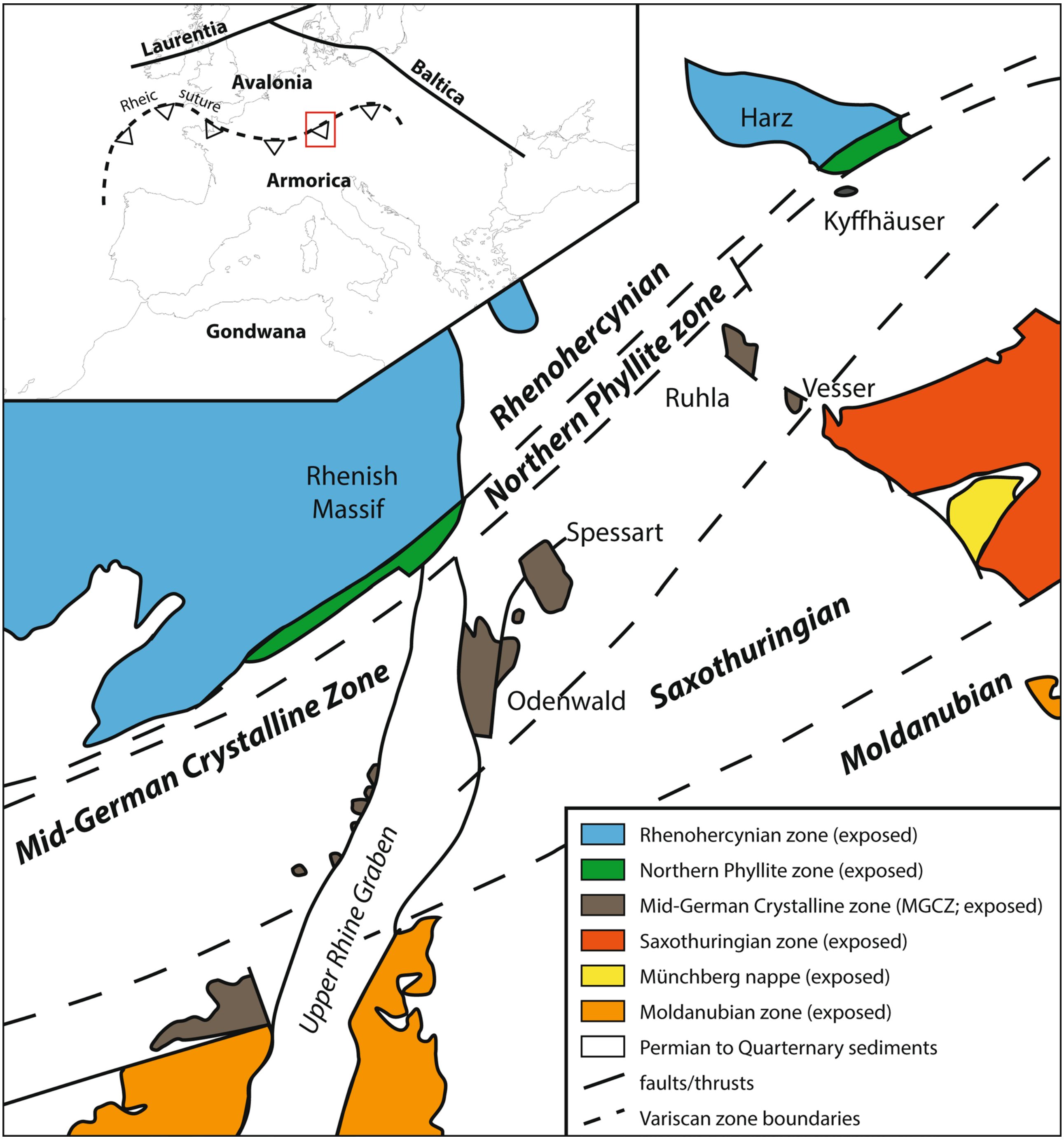

Fig. 1 Situation of the MGCZ in Central Europe; modified after Zeh and Will (2010)

the complex (Brotterode Group) and a distinct SW-Baltica derived age spectrum (Rögis quartzite) in the northern part. Will et al. (2015) based on geochemical analyses, refined Oncken's (1997) tectonic window model, involving only the Böllsteiner Odenwald and the central Spessart Crystalline Complex (Fig. 2). Geochemical analyses of amphibolites show similarities between the northern Spessart Crystalline Complex and the western Odenwald, as well as between the central Spessart Crystalline Complex and the eastern Böllsteiner Odenwald. This suggests that the Otzberg and the Michelbach faults are the same one, which represent the Rheic suture. Franke and Dulce (2016) proposed the MGCZ as "source regions of Baltica derived metamorphosed Devonian clastic sediments". Dörr et al. (2017), found a unique U–Pb zircon age spectrum in metasedimentary rocks of the Böllsteiner Odenwald. They described the samples as

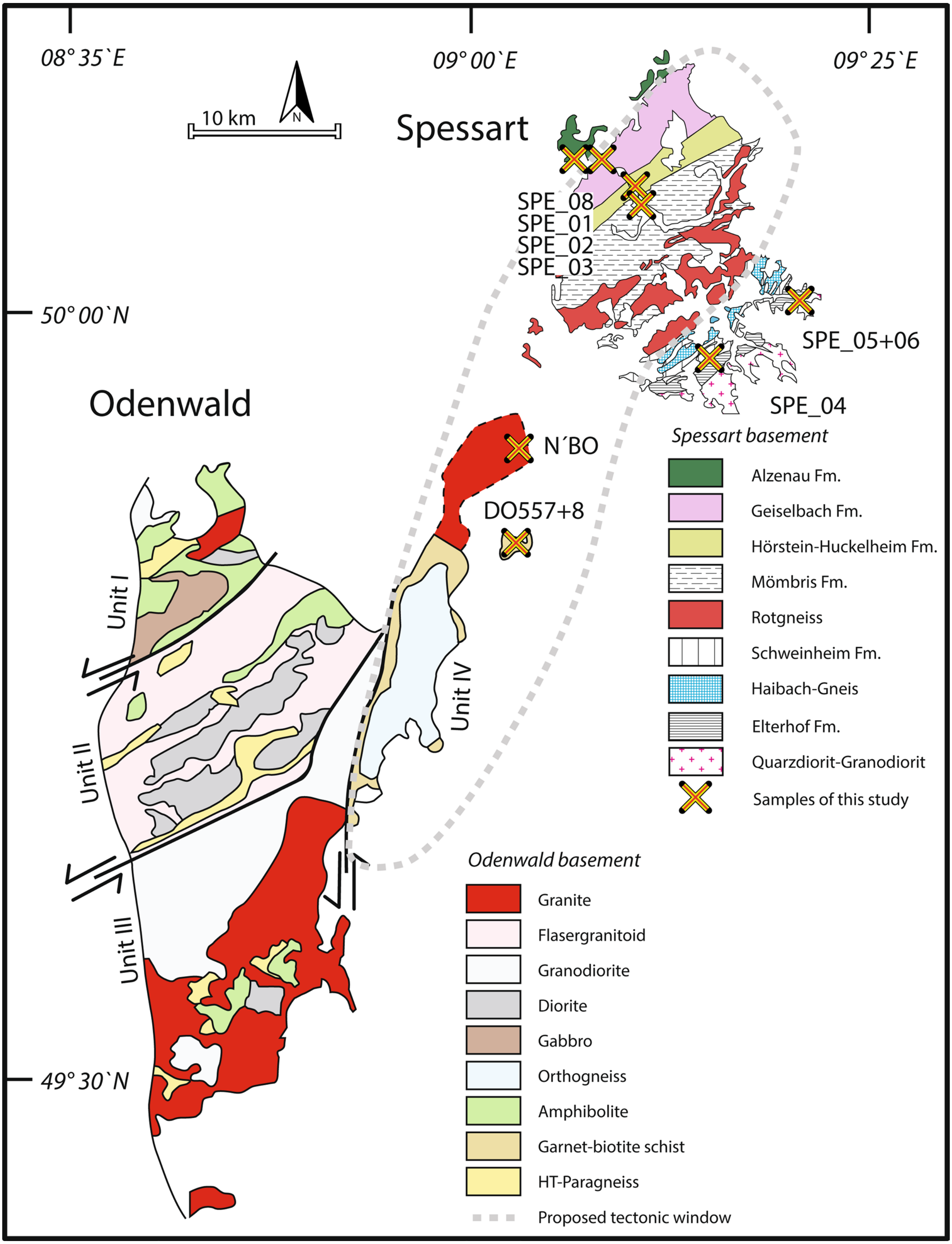

Fig. 2 Geological map of the Odenwald–Spessart basement with the proposed tectonic window. Modified after Will et al. (2018)

Late Devonian trench sediments, with Saxothuringian magmatic arc provenance, inside the proposed tectonic window zone, which is in contrast to the model of Will et al. (2015). Kołtonik et al. (2018) investigated Late Devonian clastic sediments of the northern Rhenish Massif (Rhenohercynian basin), which indicate a northern provenance region such as Baltica and the Scandinavian Caledonides, with minor input of the German–Polish (Rügen–Pomeranian) Caledonides. Therefore, a source from the South can be excluded, which was proposed due to prior sedimentological, paleogeographic and petrological evidence (e.g. Paproth 1986; Bless et al. 1993).

This work presents new U–Pb detrital zircon age data of paragneisses exposed in the Spessart Mts. and eastern Odenwald and compares them to existing detrital zircon age spectra to test the aforementioned models. Also, deposition ages of the protoliths of metasedimentary rocks in the study area are limited by dating igneous intrusive rocks, allowing, altogether, to determine whether they are of Laurussian or Gondwanan provenance. Doing so, the tectonic window model will be tested and hence unveil information about the position of the Rheic suture.

Regional geology

Spessart–Odenwald basement

The Spessart Crystalline Complex is a 300 km^2 basement outcrop in the northwestern part of the Spessart Mts., making up the second largest basement outcrop of the MGCZ. The crystalline rocks are covered in the North, East, and South by Permian to Early Triassic sediments, and to the West by the Wetterau basin, which is filled with Cenozoic sediments. Bücking (1892) and Thürach (1893) published the first investigations of the Spessart Crystalline Complex, which were refined by Bederke (1957), Matthes and Okrusch (1977), Okrusch (1983), Hirschmann and Okrusch (1988, 2001) and Zeh and Will (2010). The Spessart Crystalline Complex is a NE-trending asymmetric antiform, with a vertically dipping limb in the SE and a less steep one in the NW (Weber 1995) with lineations and fold axes plunge to ENE and WSW. The Michelbach fault, which is part of a larger mylonitic thrust zone, separates the Spessart Crystalline Complex into an upper and a lower tectonic unit. The upper tectonic unit consists of the Alzenau, Schweinheim, Elterhof formations, and the Haibach Orthogneiss (Fig. 2). The Alzenau Fm. in the North and the Elterhof Fm. in the South were thought to form a coherent unit, thrusted over the Spessart core (Thürach 1893; Braitsch 1957; Hirschmann and Okrusch 1988; Weber 1995), but the geochemical signature of amphibolites from these units point to the assumption of non-coherence (Will et al. 2015). The lower tectonic unit (central Spessart Crystalline Complex) consists of an Early Paleozoic continuous sedimentary succession (e.g. Matthes 1954; Bederke 1957; Hirschmann and Okrusch 1988, 2001), with younger rocks to the North (Geiselbach Fm.) and older rocks to the South (Hörstein–Huckelheim and Mömbris formations). The Rotgneiss Complex intrusion is intercalated with the Mömbris Fm.; therefore, it is also counted to the lower tectonic unit.

The description of the formations, from North to South, is as follows: the Alzenau Fm. consists of garnet-bearing biotite gneiss and additionally, in the lower part, amphibolite, hornblende gneiss, granitic gneiss, graphite quartzite, marble and calc–silicate rocks. The metabasites mainly provide a MORB signature and a few show an IAB signature (Okrusch et al. 1985).

The Michelbach fault borders the Alzenau Fm. to the South and marks the transition to the Geiselbach Fm. The updoming process of the Spessart Crystalline Complex, during the Variscan orogeny, folded the Michelbach fault (Weber and Juckenack 1990; Hirschmann and Okrusch 2001).

The Geiselbach Fm. (Fig. 2), south of the fault, consists of garnet-bearing mica schists, quartzites and quartz–mica schists. Reitz (1987) detected Ludlowian spores in a garnet-bearing mica schist in the central part of the Geiselbach Fm., indicating a Silurian deposition age.

The Hörstein–Huckelheim Fm. (Fig. 2) is situated SE of the Geiselbach Fm. and is composed of mica schists in the upper part and (staurolite) garnet-bearing gneisses in the lower part. Quartzites, quartzitic schists, and amphibolites make up a minor part. Amphibolite protoliths are subalkaline and tholeiitic basalts, similar to modern MOR basalts (Nasir et al. 1991).

The Mömbris Fm. (Fig. 2) follows the Hörstein–Huckelheim Fm. in the South and consists mainly of staurolite–garnet-bearing paragneisses (metagreywackes), intercalated with calc–silicate and ultrabasic rocks, quartz–plagioclase rocks, and metabasalts.

The Rotgneiss Complex (Fig. 2) is a granitic orthogneiss, which intruded the Mömbris Fm. at 418 ± 18 Ma (Pb–Pb zircon age, Dombrowski et al. 1995).

The Schweinheim Fm. (Fig. 2) is composed of garnet-bearing muscovite–biotite schists and minor amounts of quartzite.

The Haibach Gneiss (Fig. 2) is intercalated into the Schweinheim Fm., yielding a similar age as the Rotgneiss Complex. The changeover to the southern Elterhof Fm. is continuous (Hirschmann and Okrusch 2001).

The Elterhof Fm. (Fig. 2) consists of garnet-bearing biotite gneisses, amphibolites, hornblende gneisses, marbles, calc–silicate rocks, quartzites, graphite–quartzites, and a metarhyolite (Plattengneis). The formation was intruded in its southern part by the Quartzdiorite–Granodiorite

Complex, which was dated to 330 ± 1 Ma by Anthes and Reischmann (2001) and to 334 ± 2 Ma (concordant zircon U–Pb analysis; Siebel et al. 2012).

The Odenwald Crystalline Complex is the largest basement outcrop of the MGCZ (Brickmann 1948) and can be subdivided into two larger units, which experienced strongly different *P–T–t* conditions. The Bergsträsser Odenwald in the West makes up the largest part of the Odenwald Crystalline Complex and is divided by the N–S striking Otzberg Shear Zone from the Böllsteiner Odenwald in the East (Chatterjee 1960; Altenberger et al. 1990; Krohe 1992; Stein 1996, 2001). Undeformed lamprophyric dikes yielded an age of 327 ± 3 Ma, limiting the end of the ductile deformation of the Otzberg Zone (Hess and Schmidt 1989), which was created by the faster uplift of the Böllsteiner Odenwald compared to the Bergsträsser Odenwald (Willner et al. 1991; Krohe 1992). Further, four subunits define the crystalline rocks depending on their metamorphic grade and age; Units I–III are located in the Bergsträsser Odenwald and Unit IV makes up the Böllsteiner Odenwald (Fig. 2). It is suggested, that a Pre- to Early Variscan development and later juxtaposition of the four subunits formed the present Odenwald Crystalline Complex (Kreuzer and Harre 1975; Lippolt 1986; Todt et al. 1995; Reischmann et al. 2001). The magmatic rocks of the Bergsträsser Odenwald intruded during the Variscan orogeny, involving the evolution from a subduction stage around 360 Ma to a late collision stage at 330 Ma (Altherr et al. 1999). The intrusion of the northern Bergsträsser Odenwald (Frankenstein) took place at 362 ± 7 Ma (Pb–Pb zircon; Kirsch et al. 1988) making up the older magmatic part of the Bergsträsser Odenwald. The magmatic rocks of Unit II and III are progressively younger southwards: amphibole and biotite K–Ar ages of Unit II rocks yielded 345–338 Ma and 339–327 Ma, Unit III yielded ages of 336–332 Ma and 329–326 Ma (Kreuzer and Harre 1975; Hellmann et al. 1982; Hess and Lippolt 1996; Schubert et al. 2001). Pelites and pelitic greywackes are the protoliths of the major part of the metamorphic rocks converted into biotite–plagioclase gneiss, followed by minor abundances of quartzites, which developed from former sandstone beds (Bossdorf 1961; Eigenfeld 1963).

Metamorphic history of the Spessart–Odenwald basement

The Variscan orogeny led to an overprint of the pre-Variscan rocks, which began with subduction related melts taking place (~ 360 Ma) and ended with the late continent–continent collision related melts (~ 330 Ma). The central Spessart and the eastern Odenwald basement underwent a Barrovian-type metamorphism with peak metamorphic conditions of ~ 600–670 °C at 8–10 kbar (Will 1998). Todt et al. (1995) dated a zircon crystal from a biotite–plagioclase gneiss of the Bergsträsser Odenwald at 334 ± 2 Ma. Will et al. (2018) dated the metamorphism of a paragneiss of the Bergsträsser Odenwald with zircon to 334 ± 2 Ma and monazite to 330 ± 3 Ma. In addition, they investigated a retrogressed eclogite from the Böllsteiner Odenwald, which yielded a zircon age of 334 ± 4 Ma and a rutile age of 329 ± 5 Ma. Furthermore, amphibolites from the Spessart Crystalline Complex yielded a zircon age of 329 ± 2 Ma in the Elterhof Fm., a zircon age of 328 ± 9 Ma in the Alzenau Fm. and a rutile age of 321 ± 7 Ma. According to Will et al. (2017), the amphibolite facies metamorphism took place around 317 and 324 Ma (in situ monazite dating), which agrees with previously published K–Ar and Rb–Sr ages (Lippolt 1986; Nasir et al. 1991). Will et al. (2017) assumed a basement cooling from 500 to 300 °C between 328 and 311 Ma and a quick exhumation of the basement rocks within a few million years after the peak metamorphic conditions based on mica cooling ages. Will et al. (2018) interpreted the proposed eclogite and granulite facies rocks as a paired metamorphic belt, of which some parts experienced high temperature and coevally other parts high pressure at ca. 330 Ma ending up in amphibolite facies conditions shortly afterwards.

Analytical techniques and sampling

Laser-ablation LA-ICP-MS method

The preparation and measurements of all samples were performed in the Institut für Geowissenschaften of the Goethe University of Frankfurt. 3 kg of preferably unweathered material were collected in the field for further investigation. For petrological description, see ESM 2. The conventional mineral separation techniques were applied with every sample to extract the zircon crystals. Zonation structures are visualized using backscatter electron (BSE) and cathodoluminescence (CL) imaging. The zircon U–Pb isotope analysis was performed with a Thermo-Finnigan Element II sector field ICP-MS attached to a RESOLution S-155 (Resonetics) 193 nm ArF Excimer laser (CompexPro 102, Coherent) equipped with a two-volume ablation cell (Laurin Technic, Australia). The analytical methods are described in Electronic Supplementary Material (ESM) 1.

Sampling

See Table 1.

Results

LA-ICP-MS analysis

The LA-ICP-MS U–Pb data with 2σ uncertainties are shown in ESM 6. Preferably oscillatory zoned parts of the core

Table 1 Samples of this study

Sample	Petrology	Location	Unit	Relation
SPE08	Biotite–garnet gneiss	R 3,506,464, H 5,550,802	Alzenau Fm.	
SPE01	Quartzite	R 3,508,863, H 5,551,463	Geiselbach Fm.	
SPE02	Biotite–plagioclase gneiss	R 3,511,436, H 5,549,278	Hörstein–Huckelheim Fm.	
SPE03	Garnet–biotite–plagioclase gneiss	R 3,511,496, H 5,548,783	Mömbris Fm.	
SPE04	Granitic dike	R 3,516,579, H 5,537,050	Elterhof Fm.	
SPE05	Biotite–plagiclase gneiss (Pearl gneiss)	R 3,523,151, H 5,541,366	Elterhof Fm.	~100 m from SPE06
SPE06	Granodiorite	R 3,523,446, H 5,541,438	Quartzdiorite–granodiorite unit	~100 m from SPE05
DO557	Metaquartzdiorite	R 3,501,743, H 5,519,893	Unit IV—Böllsteiner Odenwald	Intrusion contact-DO558
DO558	Hornblende gneiss	R 3,501,743, H 5,519,893	Unit IV—Böllsteiner Odenwald	Intrusion contact-DO557
North Böllst	Granitoid	R 3,500,425, H 5,530,063	Unit IV—Böllsteiner Odenwald	

They are presented from North to South according to Fig. 2; SPE samples were taken in the Spessart Mts., the others in the Odenwald

and the rim of the zircon are measured, to prevent measuring regions which suffered lead loss and analyzing zones of undisturbed growth. Magmatic rocks and paragneisses are presented from North to South.

Magmatic rocks

SPE06 granodiorite intrusion into the Elterhof Fm.

Fifty-eight idiomorphic grains were analyzed. Eighty analyses were performed, of which 14 had a concordance between 96 and 105%. A main abundance peak of five analyses yields an age of 349 ± 4 Ma (Concordia age; Fig. 3b), a second peak (four analyses) yields 382 ± 7 Ma (Concordia age; ESM 3, Fig. m). Single zircon analyses deviate from the ages due to lead loss.

SPE04 granitic dike in amphibolite, Elterhof Fm.

During preparation, sample SPE04 turned out to contain a low number of zircon crystals. Seventeen zircon grains were analyzed applying the U–Pb method with 32 analyses, of which 5 had a concordance of 91–106%. These ages scatter on the Concordia between 320 and 380 Ma (all ages are $^{206}Pb/^{238}U$ ages, if not indicated differently; Fig. 3d).

North Böllstein granitoid

The extracted zircon grains ($n \sim 80$) of the granitoid sample yielded very bad analyses with high common lead content. Three analyses were used for the Concordia age of 351 ± 4 Ma (Fig. 3c).

DO557 metaquartzdiorite of the Neustädter Fenster

Eighty-eight zircon grains were analyzed with 128 ablation spots of which 59 yielded ages with a concordance of 95–108%. The zircon crystals are mainly idiomorphic (Fig. 4). Thirty-seven analyses form the main age peak at 351 ± 2 Ma (Concordia age; Fig. 3a), which is followed by a smaller age peak of 13 analyses at 360 ± 2 Ma (Concordia age; ESM 3, Fig. q). All analyses show magmatic Th/U ratios above 0.1 (ESM 4).

Paragneisses

SPE08 biotite-garnet gneiss of the Alzenau Fm.

One hundred sixty zircon grains were analyzed with 167 ablation spots, of which 64 yielded concordant ages (90–110%). The grain size of the zircon crystals varies between 70 and 250 µm. The youngest analysis (age 532 ± 21 Ma; conc. 108%; U369) yielded a metamorphic Th/U ratio of 0.01 and represents the rim of an older zircon core (1095 ± 37 Ma; conc. 95%, U370). The next concordant (98%) zircon has an age of 593 ± 21 Ma (U389). Age peaks occur at 551 ± 20 Ma, 618 ± 10 Ma and 735 ± 14 Ma (Concordia ages; ESM 5b, Fig. i; ESM 3, Fig. n–p). The wide Ediacaran and Cryogenian peak of sample SPE03 exhibits the same extension, but with significantly lower occurrence of ages at 635 Ma and 730 Ma (Fig. 5a). The age distribution has a continuous Mesoproterozoic (11%) input with no abundance peaks (ESM 5b, Fig. j). The sample contains 33% Paleoproterozoic zircon ages and 38% Neoproterozoic ages of which 11% are Ediacaran and 24% are Cryogenian. A strong Archean input of 18% is concentrated to the Late Archean.

SPE01 quartzite of the Geiselbach Fm.

Ninety-three zircon grains were analyzed with 101 laser spots, of which 63 yielded concordant (90–110%) ages. Grain size is ranging from 80 to 210 µm and the crystal shape is mainly rounded to spherical, very few ($n < 5$) show angular

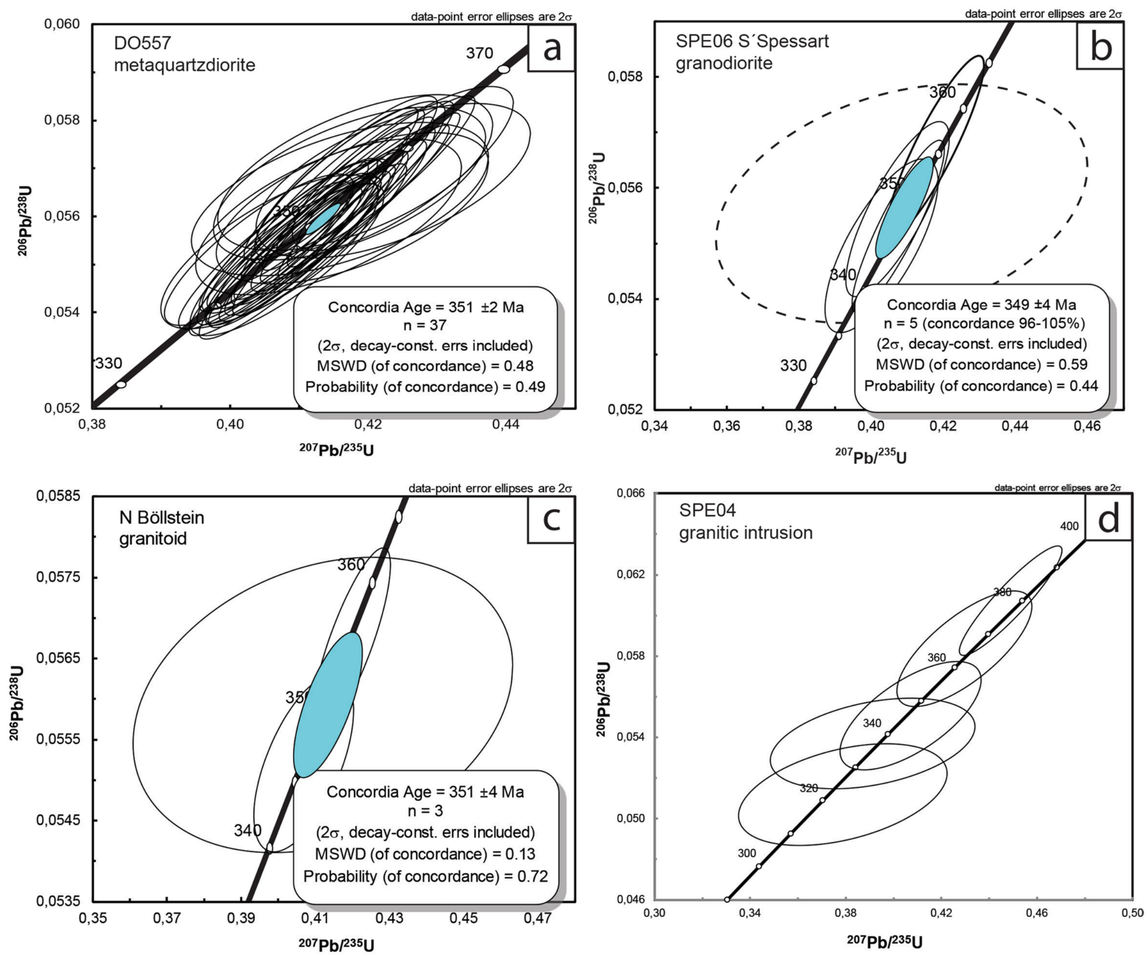

Fig. 3 Concordia ages of samples DO557 (Böllsteiner Odenwald), SPE06 (Spessart), the north Böllsteiner Odenwald granitoid and SPE04 (Spessart)

appearance (Fig. 4). Forty percent of the concordant analyses hold a typical magmatic Th/U ratio between 0.1 and 0.5, 20% are higher than 1. No zircon grains show typical metamorphic Th/U ratios below 0.1. The youngest analysis A478 yields an age of 495 ± 17 Ma with a concordance of 100%. Besides the single youngest zircon, all measured ages are of Precambrian age. The metasedimentary rock consists of 60% Mesoproterozoic, which form the main group with abundance age peaks at 1148 ± 12 Ma and 1489 ± 18 Ma. There are no Ediacaran and Cryogenian zircon Agnes. Tonian zircons are with 11% and an age peak at 965 ± 16 Ma present. Early Paleoproterozoic ages (25%) with an age peak at 1646 ± 12 Ma form the second important group (ESM 5a, Fig. a, b; Concordia ages, ESM 3, Fig. a–d). Two analyses yielded a late Paleoproterozoic and an Early Archean age.

SPE02 biotite-plagioclase gneiss of the Hörstein-Huckelheim Fm.

Sixty-one zircon grains with a size between 70 and 150 µm were separated and measured with 77 analyses, of which 35 yielded concordant (90–110%) ages. Four zircon grains have an idiomorphic shape, the rest is subhedral, but not spherical (Fig. 4). Only one zircon grain shows a spherical shape. Eight analyses have a Th/U ratio lower than 0.1. Two analyses show low Th/U ratios (< 0.1), yielding a Concordia age of 337 ± 8 Ma (Fig. 6c), followed by an analysis at 363 ± 17 Ma with a magmatic Th/U ratio (A153; conc. 108%). The next youngest magmatic zircon yielded an age of 477 ± 16 Ma (A134; conc. 95%), followed by the youngest population at 604 ± 7 Ma (Concordia age; $n = 7$, ESM

Fig. 4 SEM images (backscatter electron and cathodoluminescence imaging) of zircon grains to visualize growth structures

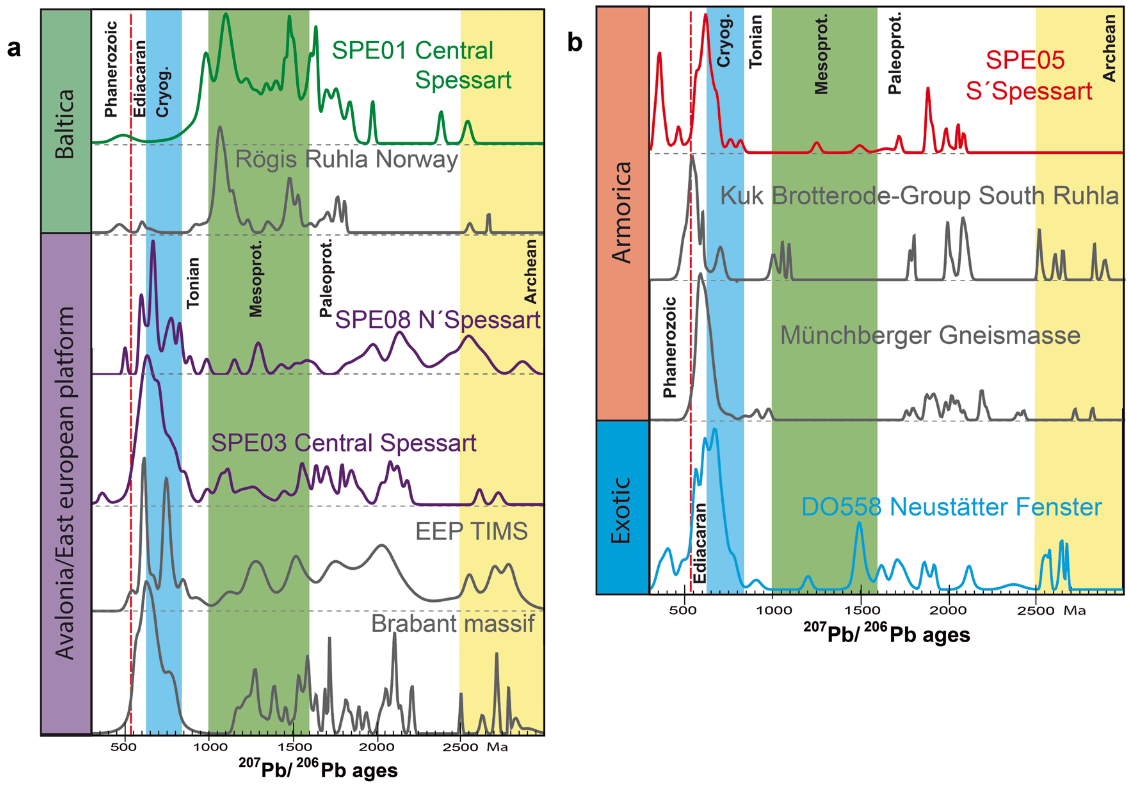

Fig. 5 **a** Probability plot of samples SPE01, SPE03, and SPE08. Grey spectra are displayed for comparison: Rögis Ruhla Norway (Zeh and Gerdes 2009); EEP TIMS (Valverde-Vaquero et al. 2000); Brabant Massif (Linnemann et al., 2012). **b** Probability plot of samples SPE05 and DO558. Grey spectra are displayed for comparison: KuK Brotterode (Gerdes and Zeh 2006); Münchberger Gneissmasse (Bahlburg et al. 2010)

3, Fig. e). The amount of Ediacaran ages is 31% and Cryogenian ages is 14% (ESM 5a, Fig. c). Only one zircon crystal yielded a Mesoproterozoic age. The main content of the sample yielded Neoproterozoic ages (51%; ESM 5a, Fig. d). Age abundance peaks are at 2079 ± 27 Ma (Concordia age; $n=3$; ESM 3, Fig. g), 685 ± 11 Ma (Concordia age; $n=3$; ESM 3, Fig. f). Sample SPE03 is further used to reflect the Hörstein–Huckelheim Fm. due to the similarity of the age distribution and the age peaks (ESM 5a, Fig. c, e).

SPE03 garnet–biotite–plagioclase gneiss of the Mömbris Fm.

One hundred forty-two analyses were performed on 140 zircon grains of sample SPE03. Eighty-two concordant (87–109%) ages were used for the age spectrum. The crystal sizes are 80–200 µm and they are mainly of rounded shape (Fig. 4). Analysis A407 yielded an age of 352 ± 16 Ma, which is in line with the metamorphic zircon ages of SPE02, although it has a very high Th/U ratio of 1.43. The youngest zircon has an age 540 ± 24 Ma with a concordance of 91% (A420). The next analysis is A366, which yielded an age of 598 ± 19 Ma (conc. 103%). 55% Neoproterozoic zircons form a peak at 633 ± 5 Ma (Concordia age; $n=14$; ESM 5a, Fig. e, f; ESM 3, Fig. h), 725 ± 8 Ma (Concordia age; $n=7$; ESM 3, Fig. i), 17% show Mesoproterozoic ages and 24% Paleoproterozoic zircons form the second peak at 2080 ± 36 Ma (Concordia age; $n=3$; ESM 3, Fig. k). The share of Ediacaran ages is 18% and of Cryogenian 33%. Four analyses form a peak at 1091 ± 14 Ma (Concordia age; ESM 3, Fig. j). Tonian ages are represented by 2% and two analyses yielded Archean ages.

SPE05 pearl gneiss of the Elterhof Fm.

Ninety-four zircon grains were analyzed with 104 ablation spots, providing 63 concordant ages (89–109%). The crystals have a size of 60–400 µm and exhibit a shape from angular to spherical. Eight analyses yield ages at 345 ± 3 Ma (Concordia age; $n=8$; Fig. 6b) with very low Th/U ratios. One of the largest zircons (300 µm; Fig. 4) of the sample was analyzed with two ablation spots, yielding similar concordant ages with a metamorphic Th/U ratio (A185, A186).

A maximal sedimentation age of 487 ± 11 Ma is given by the youngest zircon, though with a concordance of 109% (A193). The youngest zircon population is Cambrian ($n=3$;

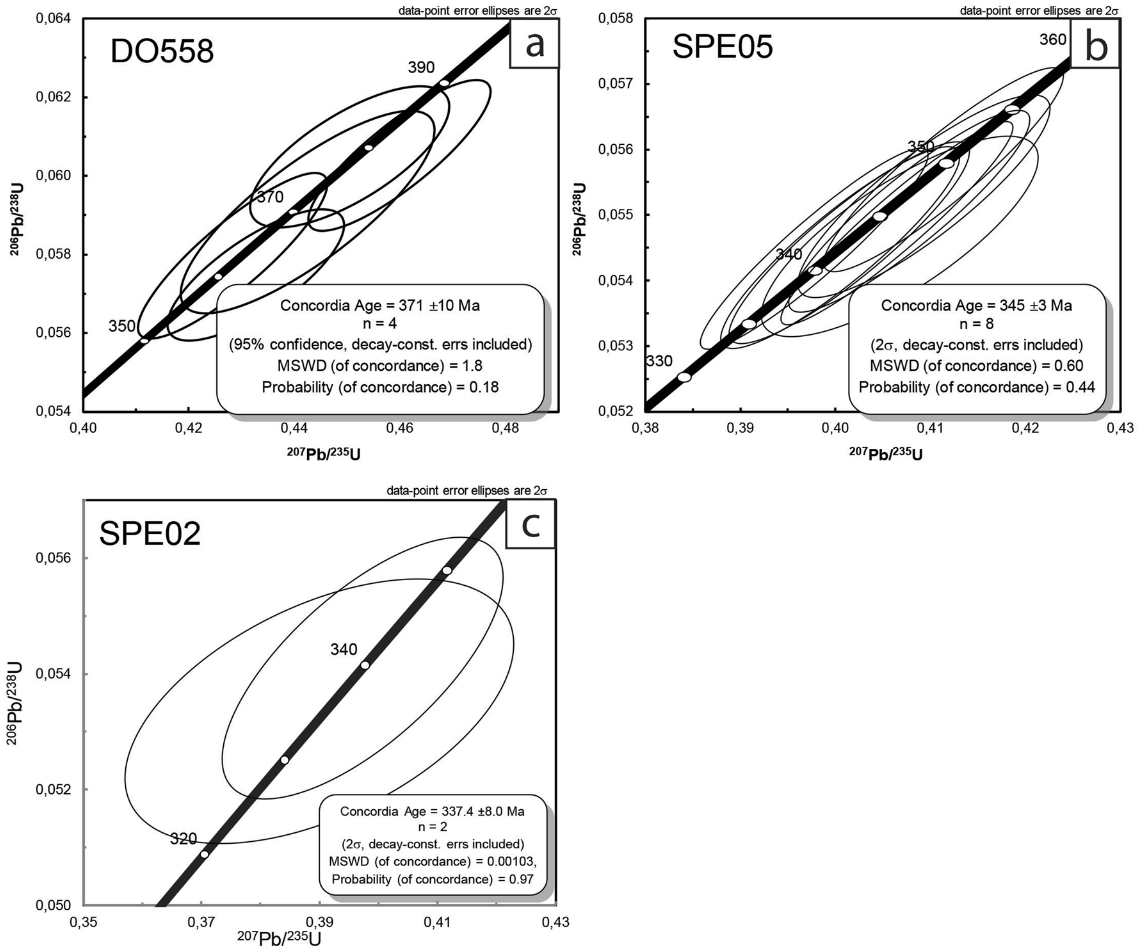

Fig. 6 Zircon populations of sample Do558, SPE05, and SPE02 indicating the metamorphic overprint

conc. 95–103%). The analyses yielded 17% Carboniferous ages, 6% Cambrian, 32% Ediacaran, and 19% Cryogenian (ESM 5b, Fig. g). 52% Neoproterozoic ages form a peak at 569 ± 4 Ma (mean age). A second peak at 1916 ± 32 Ma (Concordia age; $n = 2$; ESM 3, Fig. l) is the main share of the 17% Paleoproterozoic ages (ESM 5b, Fig. h). Two Mesoproterozoic ages are present (3%), but the analyses are > 9% discordant. Two Archean analyses represent the oldest ages.

DO558 hornblende gneiss of the Neustädter Fenster

One hundred nineteen zircon grains were analyzed in 119 analyses, of which 81 yielded an age with a concordance of 90–108%. The grain size varies between 90 and 530 µm; some of the crystals are slightly rounded, but most of the crystals show an idiomorphic shape (Fig. 4). The youngest zircon was dated to 301 ± 7 Ma but has a Th/U ratio of > 6 and only a concordance of 90% (A342). A population of four zircon grains with low Th/U ratios (ESM 5b, Fig. k; ESM 4) was dated to 371 ± 10 Ma (Concordia age; $n = 4$; Fig. 6a). The next older significant zircon with a good concordance yielded an age of 471 ± 12 Ma (A278). The main content of the age spectrum consists of Ediacaran (21%) and Cryogenian (25%) ages (ESM 5b, Fig. k). 9% Cambrian ages occur. Furthermore, the age spectrum consists of 53% Neoproterozoic ages, 10% Mesoproterozoic, 15% Paleoproterozoic and 10% Archean ($^{207}Pb/^{206}Pb$) ages (ESM 5b, Fig. l). One zircon yields a Tonian age. Five zircon analyses make up the second strongest peak at 1485 ± 12 Ma (Concordia age; ESM 3, Fig. s) of the Mesoproterozoic ages. All Mesoproterozoic ages (12%; $^{206}Pb/^{238}U$ ages) except 2% are concentrated at the peak. Further age peaks are at 514 ± 10 Ma (mean age), 598 ± 5 Ma (Concordia age; $n = 7$; ESM 3, Fig. r) and 649 ± 10 Ma (mean age; ESM 5b, Fig. k). The Paleoproterozoic era is represented by 19% share and is distributed in the late half of the era. 13% Archean zircon ages are concentrated in the Late Archean.

Discussion

Deposition age of the metasedimentary rocks protoliths

To compare different age spectra of detrital zircon analyses, it is important to know the stratigraphic ages of the samples, whereupon the lead loss should be kept in mind, as it can turn ages younger. The maximal deposition age is limited by the youngest non-metamorphic zircon age. The minimal deposition age is limited by crosscutting dikes or intrusions in contact to the formation. Closest deposition ages are given by dating lava flows or sills close to the surface. The youngest zircon grain of the biotite–garnet gneiss (SPE08) with magmatic Th/U ratio yielded an age of 539 ± 20 Ma (U358), but has a concordance of only 92%. The next zircon with a good concordance of 98% yielded 593 ± 21 Ma (U389), which is interpreted to be the maximal sedimentation age. But the younger and less concordant zircon grains should still be considered, which results in an assumed sedimentation age during Cambrian times or younger. No significant metamorphic ages or intrusions stablish the minimal sedimentation for this sample. The maximal deposition age of the Geiselbach Fm. (SPE01) is defined by the youngest zircon to 495 ± 17 Ma (A478) with a concordance of 100%; no dikes or intrusions were dated in this formation. The youngest zircon population appears after an age gap at 965 ± 16 Ma ($n = 4$; ESM 3, Fig. a). Reitz (1987) found Ludlowian (425–423 Ma) spores indicating a Silurian deposition age. The deposition age of the Rögis quartzite (Zeh and Gerdes 2009), which is thought to be an equivalent rock, is constrained between 423 ± 5 Ma (intrusion; Brätz 2000) and 466 Ma (youngest zircon age). The sedimentation age of the biotite–plagioclase gneiss (SPE02) is limited by the youngest zircon at 477 ± 16 Ma (A134) and the age of the amphibolite at 445 ± 6 Ma (U–Pb on zircon, SIMS; Will et al. 2018). The Devonian or Silurian Rotgneiss Complex (Dombrowski et al. 1995) intruded into the contact between the Hörstein–Huckelheim Fm. and the Mömbris Fm. The youngest zircon age of the garnet–biotite–plagioclase gneiss (SPE03) yielded a maximal deposition age of 598 ± 19 Ma (A366) and, as the Hörstein–Huckelheim Fm., a minimal deposition age of 445 ± 6 Ma given by the amphibolite contact. Therefore, the Ordovician or Cambrian are possible periods of deposition, but Ordovician is more likely due to the assumed continuous sedimentary deposition of the lower tectonic unit of the Spessart Crystalline Complex. The protolith of the pearl gneiss (SPE05) has a maximum deposition age of 487 ± 11 Ma given by the youngest zircon (A193, conc. = 109%). In contact to the metasedimentary rock is a granodiorite (SPE06), limiting the minimal deposition age to 349 ± 4 Ma (Fig. 3b), resulting in a sedimentation of the protolith between Ordovician and Early Carboniferous. The hornblende gneiss (DO558) has a maximal deposition age of 471 ± 12 Ma (A278) and a minimal deposition age of 371 ± 10 Ma, limited by metamorphic zircon growth (Fig. 6a). Therefore, the age of deposition is between Devonian and Ordovician.

Provenance

Previous detrital zircon age data of Central Europe were summarized by Dörr et al. (2014). They distinguished five distinct regions of the peri-Gondwanan terrane accretion. It is important to differentiate between accreted peri-Gondwanan terranes (Avalonia and Armorica) and Gondwana itself, as very different age spectra can occur.

The zircon age spectrum obtained from the Geiselbach Fm. (SPE01, Fig. 5a) features a main input of Mesoproterozoic zircons (60%), 25% of Early Paleoproterozoic ages and few Archean ages. The age spectrum for this formation fits very well to the one of the Rögis quartzite published by Zeh and Gerdes (2009) with minor differences (Fig. 5a). A peak at 950–1000 Ma displays the Early Tonian input ($n = 6$) from the Grenville Orogeny. Dörr et al. (2014) characterized SW-Baltica derived material to have almost no Neoproterozoic input; SPE01 includes 11% Tonian ages (ESM 5a, Fig. a; Fig. 5a). Also, Dörr et al. (2014) described a Paleoproterozoic input of 33–55%, which SPE01 underruns slightly with 25%. The described peaks at 1250 and 2200 Ma do not occur, 1420 and 1500 Ma are present. The dominance of 0.9–1.8 Ga old zircon ages is related to the granites, which intruded during the Sveconorwegian and Transscandinavian orogenies into SW-Baltica. Zircon ages older than 2.0 Ga might be derived from the Svecofennian and Karelian part of Baltica (Zeh and Gerdes 2009). Lorentzen et al. (2018) published zircon age spectra from Norway showing similar main age peaks as yielded by the Geiselbach Fm. Therefore, the provenance for this sample (Geiselbach Fm.) is proposed to be SW-Baltica.

The age spectrum of the biotite–plagioclase gneiss (SPE02; Hörstein–Huckelheim Fm.) is not very representative, due to the low amount of analysis with a suitable concordance. Although a presence of only a 6% of Mesoproterozoic zircon ages ($n = 2$) in SPE02 might lead to a Gondwanan provenance, the two main age peaks at 600 Ma and 2200 Ma display a strong resemblance to sample SPE03 (Fig. 5a; Mömbris Fm.) and, therefore, it is assumed to have an EEP or Avalonian affinity.

The garnet–biotite–plagioclase gneiss (SPE03) from the Mömbris Fm. is strongly dominated by zircon ages from Early Cryogenian to Late Ediacaran (ESM 5a, Fig. e). The presence of Neoproterozoic and Mesoproterozoic ages usually shows an Amazonian Craton (Avalonia; Linnemann et al. 2012) or EEP (Valverde-Vaquero et al. 2000) provenance. Dörr et al. (2014) describe the Avalonian age spectra with a strong Ediacaran (40–60%) and less Cryogenian input (20–35%) and this sample (SPE03) exhibits only 18% Ediacaran and 33% Cryogenian ages (ESM 5a, Fig. e). Described age abundance peaks (1250 and 1500 Ma) are present, but 1250 Ma is very weakly developed. A new age peak at 1091 ± 14 Ma shows up, which can be detected weakly in the EEP TIMS plot (Dörr, pers. comm.) in Fig. 5a. This is the main age peak (Grenvillian orogeny) of SW-Baltica-derived sediments. Dörr et al. (2014) also described 2% Tonian ages, which fit to sample SPE03, which yielded also 2% Tonian ages (mainly Late Tonian). The EEP TIMS plot displays a similar abundance of Tonian ages. A similarity between the EEP TIMS plot, the Brabant Massif plot (Linnemann et al. 2012) and sample SPE03 is the presence of the youngest peak at 635 Ma. The EEP TIMS data provide a second strong peak at 760 Ma, which has nearly the same intensity than the 635 Ma peak. The Brabant massif plot and sample SPE03 also show this peak, but with less than half of its intensity. Avalonian and EEP age spectra are hard to distinguish from each other but given into account that sample SPE03 has a Tonian input, its source area is proposed to be the EEP rather than the Amazonian Craton (Avalonia).

The three abovementioned formations (Geiselbach, Hörstein–Huckelheim and Mömbris formations), that form the central Spessart Crystalline Complex, are assumed to define a continuous sedimentary succession (e.g. Matthes 1954; Bederke 1957; Hirschmann and Okrusch 1988, 2001). The Geiselbach Fm. is proposed, in this study (see above), to have a SW Baltica provenance, the Hörstein–Huckelheim Fm. an EEP (which is also Baltica derived) or Amazonian Craton provenance and the Mömbris Fm. an EEP rather than an Amazonian provenance. Even so an Amazonian provenance for Hörstein–Huckelheim and Mömbris formations cannot be excluded with the data presented in this article, for the abovementioned reasons, it is concluded that the entire central Spessart Crystalline Complex has a Baltica provenance (SW-Baltica and EEP).

The spectrum of the biotite–garnet gneiss (SPE08; Alzenau Fm.; Fig. 5a) shows similarities to SPE03. The main age peak of both spectra is Ediacaran–Tonian, but the age abundance of SPE03 at the Ediacaran–Cryogenian boundary is much higher than sample SPE08. The second highest abundance peak of SPE03 is similar to the highest peak of SPE08. Both have very few Tonian ages. SPE03 has a relatively high abundance of Early and Late Mesoproterozoic ages, whereas SPE02 has not. The EEP and the Brabant Massif spectrum also show relative high abundances in the Mesoproterozoic. SPE08 has almost no Late Paleoproterozoic ages, which do appear in SPE03, EEP, and Brabant Massif spectra. Therefore, an Amazonian Craton or EEP provenance is proposed for SPE08.

The composition of the pearl gneiss in the south Spessart Crystalline Complex (SPE05; Elterhof Fm.; Fig. 5b) points to a West African Craton provenance which is in agreement with previously published age spectra of the Armorican terrane. Bahlburg et al. (2010) published several Armorican age spectra of the Saxothuringian Zone of which some contain few Tonian ages. The probability plot of sample DO558 (Fig. 5b) shows these Tonian ages, which are not present in sample SPE05. Gerdes and Zeh (2006) published an age spectrum of the Brotterode Group in Ruhla (Fig. 5b) that has strong similarities with sample SPE05. Due to the significant Mesoproterozoic age gap and strong similarities to other Armorican age spectra (Brotterode Group, Gerdes and Zeh 2006; Münchberger Gneismasse, Bahlburg et al. 2010), it is proposed that the pearl gneiss (Elterhof Fm.) has a Gondwanan provenance and belongs to the Armorican terrane.

The hornblende gneiss (DO558; Fig. 5b) contains an exotic distribution of zircon ages. The big Ediacaran and Cryogenian peaks are slightly shifted to older ages (compared to the Armorican age spectra), showing a higher amount of Cryogenian ages with respect to Ediacaran. Only one zircon (conc. = 98%) yielded a Tonian age. A Baltic provenance can be excluded as it presents a strong Ediacaran and Cryogenian input. Furthermore, the characteristic peak of the Grenville Orogeny does not show up at all in this sample (DO558), which is very distinct in SW-Baltica (Norway)-derived samples and sometimes weakly appears in Avalonian/EEP samples. The age spectrum is similar to Armorican-derived materials, but this sample has a 12% of Mesoproterozoic ages with a prominent peak at 1485 ± 5 Ma; therefore, it is not West African Craton (Gondwana) derived. DO558 sample has also similarities with the typical Avalonian/EEP detritus, but it contains less Mesoproterozoic ages (especially Early to Middle Mesoproterozoic ages). Therefore, an Amazonian Craton/EEP provenance is also implausible for this sample. Ages around 1500 Ma have been only found in the Mazury Complex (NE Poland) and at the East European Margin (Dörr et al. 2002; Zelazniewicz et al. 2009). Therefore, this sample is assumed to be an exotic sliver of hitherto unknown material, which was worked into its present day position, during the Variscan orogeny.

Intrusions

The metaquartzdiorite (DO557) mainly contains zircons with an age of 351 ± 2 Ma (Fig. 3a), which represents the intrusion age. The older occurring zircon ages are inherited material with an age of 360 ± 2 Ma (ESM 3, Fig. q). The granodiorite (SPE06, Quartzdiorite–Granodiorite Complex) has an intrusion age of 349 ± 4 Ma (Fig. 3b) and contains inherited zircons with an age of 382 ± 7 Ma (ESM

3, Fig. m). This intrusion took place at ~ 350 Ma, in a pre-collisional stage when the Rheic Ocean was still assumed to exist between Laurussia and Armorica. The intrusion age might be related to a granitic intrusion located in the northern Böllsteiner Odenwald, which yielded an age of 351 ± 4 Ma (Fig. 3c). The same origin for the intrusion of the northern Böllsteiner Odenwald, SPE06 and DO557 is conceivable, but only further geochemical investigations would give clear evidence about their affinity. All ~ 350 Ma intrusions in the study area, such as the northern Böllsteiner Odenwald granitoid, which is in contact to a Saxothuringian metasedimentary rock (Dörr et al. 2017) and the granodiorite (SPE06), which intruded into the Armorica related pearl gneiss (SPE05), are only found in Saxothuringian host rocks. In the Brotterode Group (Saxothuringian realm) of the Ruhla Crystalline Complex, granitic dikes yielded an age of 355 ± 6 Ma and 348 ± 5 Ma (Zeh et al. 2003). If we consider the 350 Ma old intusions to be an indicator for Saxothuringian host rock, a Gondwanan provenance for DO558 (Exotic age spectrum) is most likely, as it is in contact to DO557.

Siebel et al. (2012) dated a granodiorite of the Quartzdiorite–Granodiorite Complex in the southern Spessart Crystalline Complex, which yielded an age of 334 ± 2 Ma (U–Pb of one zircon with a conc. of 101%). Sample SPE06 of the same magmatic unit yielded an age of 349 ± 4 Ma. It might be possible, that sample SPE06 is a precursor of the magmatic event around 330 (late Variscan collision stage) or, which is more likely, the sample is in relation to the other ~ 350 Ma old intusions (DO557, northern Böllsteiner Odenwald intrusion) and they might be gathered to a new magmatic unit. According to Altherr et al. (1999), the subduction stage at 360 Ma turned into a late collision stage at 330 Ma, which leads to the conclusion, that the 350 Ma old intrusions (DO557, northern Böllsteiner Odenwald intrusion, SPE06) are subduction or early collision stage related, which supports the theory of host rocks in contact to ~ 350 Ma old intrusions are of Saxothuringian origin.

Metamorphic history

The biotite–plagioclase gneiss (SPE02) yielded two zircon grains, which show metamorphic-related Th/U ratios. If we consider that the metamorphic zircon growth at 337 ± 8 Ma under amphibolite facies conditions and the rutile growth at 321 ± 7 Ma (Will et al. 2018), then the cooling rate for the central Spessart will be unusually low (< 5 °C/myr). Taking the zircon age of an amphibolite in the Alzenau Fm. (328 ± 9 Ma; Will et al. 2018) into account, then the cooling rate of 53 °C/myr agrees with the tectonic setting. Therefore, the zircon ages of 337 ± 8 Ma and the rutile growth at 321 ± 7 Ma are most probably not linked to the same metamorphic event, and it could be indicative of an older, not yet defined, metamorphism in the central Spessart Mts.

The Granodiorite (SPE06) intruded into a host rock with an Armorican age spectrum (pearl gneiss; SPE05) and contains a population of four inherited zircons (magmatic Th/U ratios), which might have been assimilated from the country rock during the melt ascend. The Concordia age of this population is 382 ± 7 Ma, which fits to the dated metamorphic overprint of the Böllsteiner Odenwald at 375 ± 5 Ma (Todt et al. 1995). The hornblende gneiss (DO558) yielded zircon ages with metamorphic Th/U ratios at 371 ± 10 Ma of < 0.1 ($n = 4$), which fit to the Rb–Sr cooling age at 369 ± 14 Ma of two Neustädter gneisses (Lippolt 1986). According to Torsvik and Cocks (2017), the Armorican terrane was still in a subduction stage during that time, which might imply a subduction related metamorphism for these ages.

The pearl gneiss (SPE05) yielded a hitherto unknown metamorphic age of 345 ± 3 Ma ($n = 8$) with zircon analyses showing very low Th/U ratios. One zircon reaches a size of 300 µm and yielded metamorphic ages (Th/U) in the core (344 ± 8 Ma; A185) and in the rim (346 ± 8 Ma; A186; Fig. 4), which indicates a strong growth during metamorphism. The granodiorite (SPE06; 349 ± 4 Ma) located close to the pearl gneiss, might have been a precursor of other melts, which are responsible for the metamorphic overprint of the pearl gneiss. The timing of the metamorphism in the southern Spessart is significantly older than the previously dated metamorphic overprints of the northern and central Spessart (328 Ma; Will et al. 2018), which could be explained by different origins of the southern Spessart and the northern and central Spessart basement. The juxtaposition of these units seems to have occurred after the metamorphic overprint. In case of a contact metamorphism through intrusions, a local metamorphic zircon growth in the southern Spessart basement could also be possible. The high temperature fabric of the thin section leads to the assumption, that the pearl gneiss suffered migmatitic conditions, which led to a partial melting of the Elterhof Fm. crust due to intrusions.

Model

Previous studies argued that the central Spessart and east Odenwald formed a tectonic window (Will et al. 2015), which was delimited to the north and west by the Michelbach and Otzberg faults. This model proposed that both faults represented the Rheic suture. The biotite–garnet gneiss (SPE08, Alzenau Fm.) is a key sample, because its proposed Laurussian or Amazonian (Avalonian terrane) provenance implies an affinity between the northern and central Spessart Crystalline Complex, which is inconsistent with the mentioned tectonic window model. This also implies that the Rheic suture is located between south (Elterhof Fm.) and central Spessart and not between north (Alzenau Fm.) and central Spessart, i.e. the Rheic suture is not represented by the Michelbach and Otzberg faults. The provenance of the biotite–garnet gneiss (SPE08) supports the non-coherence of the Alzenau Fm. and the Elterhof Fm., as supposed by geochemical investigation (Will et al. 2015). This implies a revision of the upper and lower tectonic unit classification.

A new course of the Rheic suture must be assumed, as the Laurussian provenance of the Alzenau Fm. excludes the Michelbach fault to represent the Rheic suture. The provenance analysis of this study assigns the trend of the Rheic suture to run between the Mömbris Fm. and the Elterhof Fm. Between these two formations, there is still another metasedimentary unit, the Schweinheim Fm. from which no provenance studies have been performed so far. A possible southward displacement of a segment of the Central German Variscides, which might also include the Ruhla Crystalline Complex, could explain the proposed course of the Rheic suture. Possible N–S to NE–SW trending shear zones might be extensions of the Otzberg Shear Zone and the Franconian line (Fig. 7), which could separate the MGCZ into at least three segments. To the East, the suture runs through the Ruhla Crystalline Complex (Zeh and Gerdes 2009) before being displaced to the North close to the southern Harz Mts. As shown in Fig. 7, the Rheic suture transects the Spessart Crystalline Complex before it is displaced dextrally north of the Böllsteiner Odenwald, continuing in the NPZ south of the Rhenish Massif. The provenance of sediments from the Vesser Complex (Fig. 7) would give more evidence about a possible course of the suture. These fault trends also occur in the "Mid German Main Escarpments" (Mitteldeutsche Hauptabbrüche; Knape 1963a, b) or the Elbe Fault System (Late Carboniferous; Scheck et al. 2002). If the Otzberg Shear Zone is part of the displacement, the

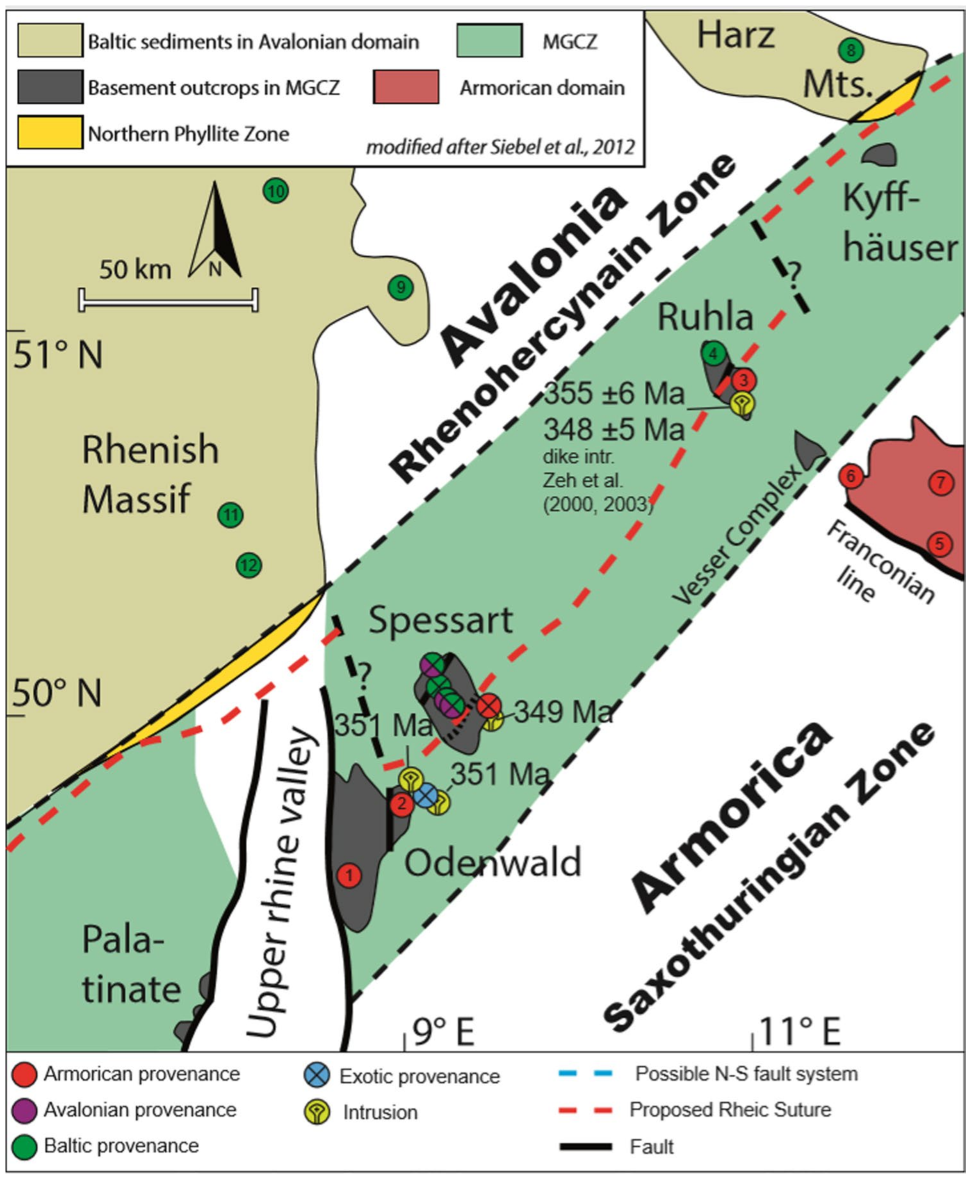

Fig. 7 Map of the Central European Variscides displaying the hitherto published provenance analyses and the ones of this study. The analyses of this study are marked with a cross. 1: Dörr and Stein (2019); 2: Dörr et al. (2017); 3: Gerdes and Zeh (2006); 4: Zeh and Gerdes (2009); 5: Bahlburg et al. (2010); 6, 7: Linnemann et al. (2004); 8: Geisler et al. (2005); 9, 11, 12: Eckelmann et al. (2013); 10: Kołtonik et al. (2018). The dashed red line is the proposed trend of the Rheic suture. The dashed blue line indicates the possible shear trend for southward displacement

movement must have occurred before 327 Ma, due to the deformation age limit of the Otzberg Shear Zone (Hess and Schmidt 1989). Lower Permian sediments cover the Spessart Crystalline Complex in the north indicating an end for the Variscan orogeny. The Saar-Nahe basin, which is underlain by MGCZ rocks, is filled with Westphalian coal indicating a changeover into an extensional environment at approximately sea level from 318 Ma onwards. This is not in line with the amphibolite facies metamorphism dating of Will et al. (2017) at 317 and 324 Ma (monazite). The model of this study still supports the tectonic underplating model by Oncken (1997).

The MGCZ can also turn out to be a large tectonic mélange zone, as the overlying younger sediments north of the Spessart Crystalline Complex prevent an insight into the underlying basement rocks. Overriding nappes could also have been displaced by faults, which juxtaposed lower plate material next to upper plate material leading to an exposure at today's surface.

Conclusions

- Four different age spectra are found in the Spessart Crystalline Complex and Böllsteiner Odenwald, of which the SW-Baltica (Norwegian) age spectrum and the Avalonian/EEP age spectrum indicate Laurussia derived detritus and the Armorican age spectrum indicates a source in the West African Craton and therefore a Gondwanan provenance.
- The central Spessart Crystalline Complex has different source regions; a change from Amazonian Craton or rather EEP derived material (Mömbris Fm., Hörstein–Huckelheim Fm.) to SW-Baltica derived material (Geiselbach Fm.) is assumed through U–Pb detrital zircon age dating. A continuous sedimentary succession is still assumed for the central Spessart Crystalline Complex.
- The tectonic window model including the central Spessart Crystalline Complex and the Böllsteiner Odenwald (Oncken 1997; Siebel et al. 2012; Will et al. 2015) is disproven by the Avalonian/EEP zircon age spectrum of the Alzenau Fm. The tectonic underplating model is still assumed (Oncken 1997). A former connection of the Alzenau Fm. and the Elterhof Fm. can be excluded with detrital zircon provenance analysis and supports the geochemical results of Will et al. (2015). Everything north of the Rheic suture is assumed to be Laurussia related.
- NNW–SSE trending shear zones might have displaced the central part of the MGCZ southwards, including the Rheic suture, which is assumed to run through the margin of central and southern Spessart Crystalline Complex. The Ruhla Crystalline Complex might also be included in the displacement.
- New data of intrusions revealed a melt ascent and crystallization around 350 Ma, which might be defined as a new magmatic unit extending from the eastern Spessart Crystalline Complex over the Neustädter Fenster to the northern Böllsteiner Odenwald and intruded into Saxothuringian host rock. This is in line with dikes from the Ruhla Crystalline Complex. No intrusions with an age of 350 Ma were found north of the proposed Rheic suture.
- The age spectrum of the Neustädter Fenster (Böllsteiner Odenwald) shows an exotic age distribution and was not found in the central MGCZ before. It is most likely of Saxothuringian origin and forms a sliver of hitherto unknown material inside the MGCZ. The youngest zircon analysis and the age of an intrusion reveal an Ordovician or Silurian deposition of the protolithic sediments.

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