International Journal of Earth Sciences (2019) 108:1937–1957
https://doi.org/10.1007/s00531-019-01741-7

ORIGINAL PAPER

Precambrian basement in the Rheic suture zone of the Central European Variscides (Odenwald)

Wolfgang Dörr[1] · **Eckhardt Stein**[2]

Received: 21 December 2018 / Accepted: 31 May 2019 / Published online: 28 June 2019
© Geologische Vereinigung e.V. (GV) 2019

Abstract

Detrital zircon age spectra of Ediacaran paragneiss from the Rheic suture between the Rhenohercynian Zone and Saxothuringian Zone suggest that they originated from different parts of peri-Gondwana. The paragneiss from the Northern Phyllite Belt displays an age spectrum of detrital zircons with a high amount of Neoproterozoic (82%) and Mesoproterozoic zircons (11%) typical for Amazonian provenance, whereas the spectrum from the metagreywacke of the Odenwald (Mid-German Crystalline Zone) shows a Mesoproterozoic age gap which is correlated with the West African Craton. The metagreywacke of the Odenwald contains 20% Paleoproterozoic and 32% Archean zircons, whereas the paragneiss of the Northern Phyllite Belt (Wartenstein Crystalline) contains only 6% Paleoproterozoic and no Archean zircons. The paleoposition of the basement of Northern Phyllite Belt was proximal to the Avalonian magmatic arc of the London–Brabant high. The Armorican metagreywacke of the Odenwald occupied a distal position to a Neoproterozoic magmatic arc, probably in a back-arc basin related to the West African Craton. Such a U–Pb age spectrum of detrital zircons together with a Mesoproterozoic age gap is typical for sediments of Armorica in Europe during the Ediacaran to Carboniferous. Neoproterozoic igneous rocks extruded at 566 ± 2 Ma forming a volcano-clastic sequence of the Cadomian magmatic arc which is the wall rock of the Silurian to Carboniferous plutons of the entire West Odenwald. This is the first occurrence of an extensive Cadomian crystalline basement in the Mid-German Crystalline Zone. Metagranite dykes crosscut the foliation of the Cadomian para- and orthogneiss at 542 ± 3 Ma. The deformation and migmatization of the Cadomian basement are bracketed between 566 and 542 Ma. A similar late Cadomian event is known from the Bohemian Massif and the Armorican Massif. Large Cadomian plutons with an age around 540 Ma, like that of the northern Odenwald, are common for Armorica. Silurian to Devonian granitoids (434 ± 4 Ma, 411 ± 5 Ma) are witness to an active margin along the northern boundary of Armorica. The Cadomian basement of the Odenwald together with the Palaeozoic granitoids is overprinted by a high-grade metamorphism at 384 ± 4 Ma (U–Pb on zircon) and cooled down below ca. 500 °C at 370 Ma (K–Ar ages of amphibole; U–Pb on titanite). Such a combination of late Cadomian and early Variscan ages could be correlated with the Münchberger Nappe, the Tepla–Barrandian Unit, Central Armorican Domain and the Massif Central.

Keywords Cadomian basement · Devonian metamorphism · U–Pb ages · Provenance · Saxothuringian Zone

Introduction

The Variscan belt in Central Europe was developed during the Palaeozoic collision between three continents: Laurentia, Baltica, and Gondwana. It can be traced from the Bohemian Massif in the east (Poland, Czech Republic, Germany), through western Europe (France, SW England, Spain) over northern Africa all the way to North America (Appalachian Mountains, Franke 1989; Murphy et al. 2004a, b; Linnemann et al. 2007). Microcontinents (Avalonia, Malopolska) were split off from Gondwana or Baltica and collided with the northern continent during Cambrian to Silurian time

---

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00531-019-01741-7) contains supplementary material, which is available to authorized users.

✉ Wolfgang Dörr
w.doerr@em.uni-frankfurt.de

[1] Institute of Geosciences, Goethe University, Altenhöferallee 1, Frankfurt am Main 60438, Germany

[2] Institut für Mineralogie, TU Darmstadt, Darmstadt, Germany

(Bachtadse et al. 1995; Belka et al. 2000, 2002; Valverde-Vaquero et al. 2000). During the Late Paleozoic, Armorica (sensu Tait et al. 1997) collided with Laurussia after the closure of the Rheic ocean (Tait et al. 2000; Cocks and Fortey 2009). The suture between them is marked by the Northern Phyllite Belt and the Mid-German Crystalline Zone (MGCZ, Fig. 1). The MGCZ is not a coherent terrane and consists of different tectono-metamorphic units (Zeh 1996; Oncken 1997) with contrasting provenance (Zeh and Gerdes 2009) and tectonic settings (Zeh and Will 2010; Will et al. 2015, 2018).

Weber and Behr (1983) interpreted the complex tectonostratigraphic units of the Mid-European Variscides as an intracontinental subduction of lithospheric mantel, but ophiolites of the Rhenish Massif (387–407 Ma, Germany, Dörr 1986) and the Lizard complex (> 397 ± 2 Ma, SW England, Clark et al. 1998), which rest discordant onto the thick shelf sediments of the Rhenohercynian Zone, point to an ocean between Laurussia and Armorica. A prolongation of this Silurian/Devonian ocean to the east is marked by the ophiolites in the Sudetes (400–420 Ma, Poland, Oliver et al. 1993; Dubińska et al. 2004) and Austria (428 ± 6 Ma, Raabs unit, Finger and von Quadt 1995) which are all situated along a dislocated suture (see inlet Fig. 1, green hexagon). The coeval island arc (Altenberger and Besch 1993) and the HP metamorphism of the eclogites (Will et al. 2015, 2017) of the Odenwald imply subduction of Silurian to Devonian oceanic crust below the MGCZ. A general plate tectonic scenario with a lower Rhenohercynian plate (foreland thrust and fold belt) and an upper Saxothuringian plate (magmatic arc) separated by an ocean seems to be plausible for the Late Devonian time (Franke 1989; Altherr et al. 1999), but there are different interpretations concerning the age and number of oceans that existed and their coinciding direction of subduction.

Different models have been proposed for this scenario. Massonne and Schreyer 1983 related the HP metamorphism of the Northern Phyllite Belt to a Variscan subduction zone at the southern margin of the Rhenohercynian Zone. Franke 1989 interpreted the Variscan Zones of Kossmat (1927) in

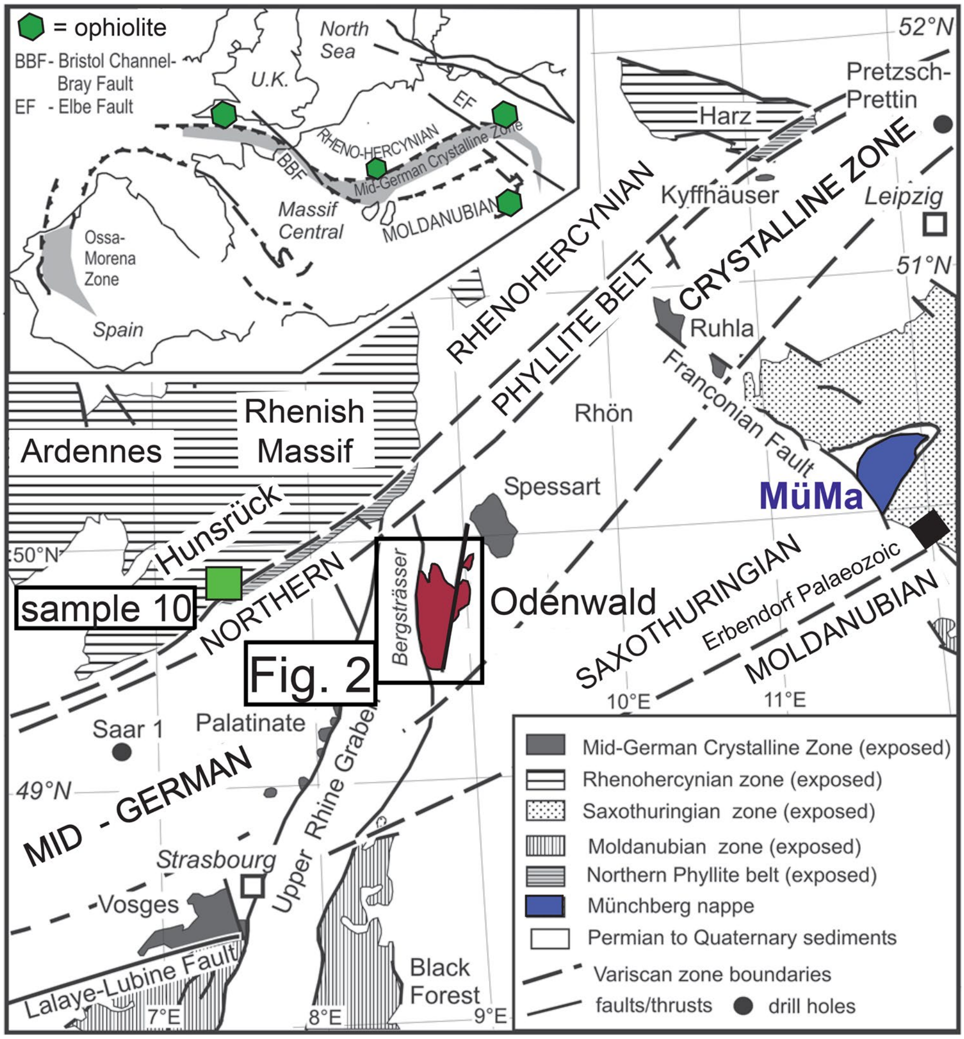


Fig. 1 Map showing distribution of main geotectonic units of Central Europe and the location of the Mid-German Crystalline Zone (mape modified after Zeh and Will 2010). Green square = location sample 10. Insert in the upper left corner: Lower Devonian ophiolites = green hexagon

term of tectono-metamorphic units in a plate tectonic context. Altenberger and Besch (1993) introduced a "two-ocean scenario" with an old Rheic ocean and a young Rhenohercynian one. Anthes and Reischman (2001) correlated the Carboniferous magmatism with a north-dipping subduction zone at the southern margin of the MGCZ. Zeh (1996) split the MGCZ from the Saxothuringian Zone by a second south-dipping subduction zone. Oncken (1997) was the first who attributed MP rocks of the Böllstein Odenwald and central Spessart (MGCZ) to the Rhenohercynian downgoing slab. In a model of tectonic underplating, the Rhenohercynian crust was accreted to the base of the overriding plate (Saxothuringian crust) and transferred from the lower to the upper plate by crustal extension, which induced the uplift and exhumation of Rhenohercynian crust. Zeh and Will (2010) give an extensive correlation of the tectonic units of the MGCZ presenting a model with a subduction of the Rheic ocean beneath Laurussia.

Despite this complex crustal architecture after the Variscan continent/continent collision of Gondwana with the Laurussia, some authors correlate different tectono-metamorphic units of the MGCZ with specific continents such as Baltica, Armorica and Avalonia (Oncken 1997; Okrusch et al. 2011; Will et al. 2015, 2017, 2018). These correlations are highly speculative, since there is little unambiguous evidence. U–Pb age clusters of the detrital zircon populations provide constraints on the provenance areas of the clastic rocks (Geisler et al. 2005; Zeh and Gerdes 2009; Linnemann et al. 2012, 2013; Eckelmann et al. 2013; Willner et al. 2013) and thus correlation of the tectono-metamorphic units of MGCZ with Laurussia or Armorica.

In the last decade, the laser ablation method combined with inductively coupled plasma mass spectrometry (LA-ICP-MS) has proven to be a robust and fast tool to determine U–Pb age clusters of detrital zircon populations (Frei and Gerdes 2008). Such detrital zircon ages are particularly important for the paleogeographic reconstruction (Fedo et al. 2003) of the Variscan Zones. The Rhenohercynian is characterized by a Baltic Mesoproterozoic dominated detrital zircon age spectra with minor input from Avalonia (Haverkamp 1991; Geisler et al. 2005; Linnemann et al. 2012; Eckelmann et al. 2013), whereas the age spectra of the detrital zircons of the Armorica (Saxothuringian) display a Mesoproterozoic age gap (Linnemann et al. 2008; Drost 2008). Zeh and Gerdes (2009) investigated the detrital zircons of the Ruhla Crystalline Complex, which is also part of the MGCZ (Fig. 1). They found two contrasting U–Pb age spectra, one with a Peri-Gondwanan and the other with a Laurussian (Baltica) provenance. The striking differences in the provenance prove the existence of the Rheic suture inside the MGCZ (Zeh and Gerdes 2009).

In the present paper, we focus on the wall rocks of the Lower Carboniferous plutonic rocks of the MGCZ (Odenwald). The U–Pb zircon ages of the orthogneiss will be used for the correlation with other Variscan crystalline basements. The U–Pb zircon ages obtained from detrital zircons of paragneiss of the Odenwald and Northern Phyllite Belt will provide information for the deposition age of the metasediments and the palaeogeography of the Rhenohercynian and Saxothuringian realm.

Regional geology

Kossmat (1927) subdivided the mid-European Variscides into four main NE–SW-trending geotectonic units: from N to S, these are the Subvariscan foredeep, the Rhenohercynian Zone, the Saxothuringian Zone, and the Moldanubian Zone (Fig. 1). The Odenwald Crystalline Complex is commonly assumed to represent the northern extremity of the Saxothuringian Zone, the so-called Mid-German Crystalline Zone (MGCZ). The medium-to-high-grade gneiss and granitic rocks of the MGCZ separate the low greenschist facies sediments and volcanic rocks of the Northern Phyllite Belt in northwest from greenschist facies rocks of the Saxothuringian Zone in southeast. This paper will focus on the Odenwald Crystalline Complex (Saxothuringian Zone, Fig. 2) and the Wartenstein Crystalline of the Hunsrück (Northern Phyllite Belt, Fig. 1) directly to the northwest.

Odenwald Crystalline Complex (Mid-German Crystalline Zone)

The crystalline Odenwald is the largest outcrop of the MGCZ (Brinkmann 1948). Based on different metamorphic histories and ages of the plutonic rocks, the Odenwald can be subdivided into the smaller Böllstein Odenwald to the East and the larger Bergsträsser Odenwald together with the Frankenstein Massif in the West (Fig. 2; Stein 2001). Krohe (1994) defines four main tectonic units (units I–IV, Fig. 2) of Odenwald Crystalline Complex, which were interpreted as mid-crustal rocks of different origins. The East Odenwald (unit IV) and the West Odenwald (units I–III) are separated by the N–S-trending Otzberg Zone (Altenberger et al. 1990). Significant differences in lithology, tectonic structures (Krohe and Willner 1995; Stein 1996, 2001), and the ages of magmatic and metamorphic evolution (Kreuzer and Harre 1975; Lippolt 1986; Todt et al. 1995; Reischmann et al. 2001) suggest an independent pre-to-early Variscan development.

West Odenwald (Bergsträsser)

The Carboniferous magmatic rocks (90% of the area) of the West Odenwald are separated by six narrow NE–SW-trending zones of metamorphic rocks (10%). Geochemical data

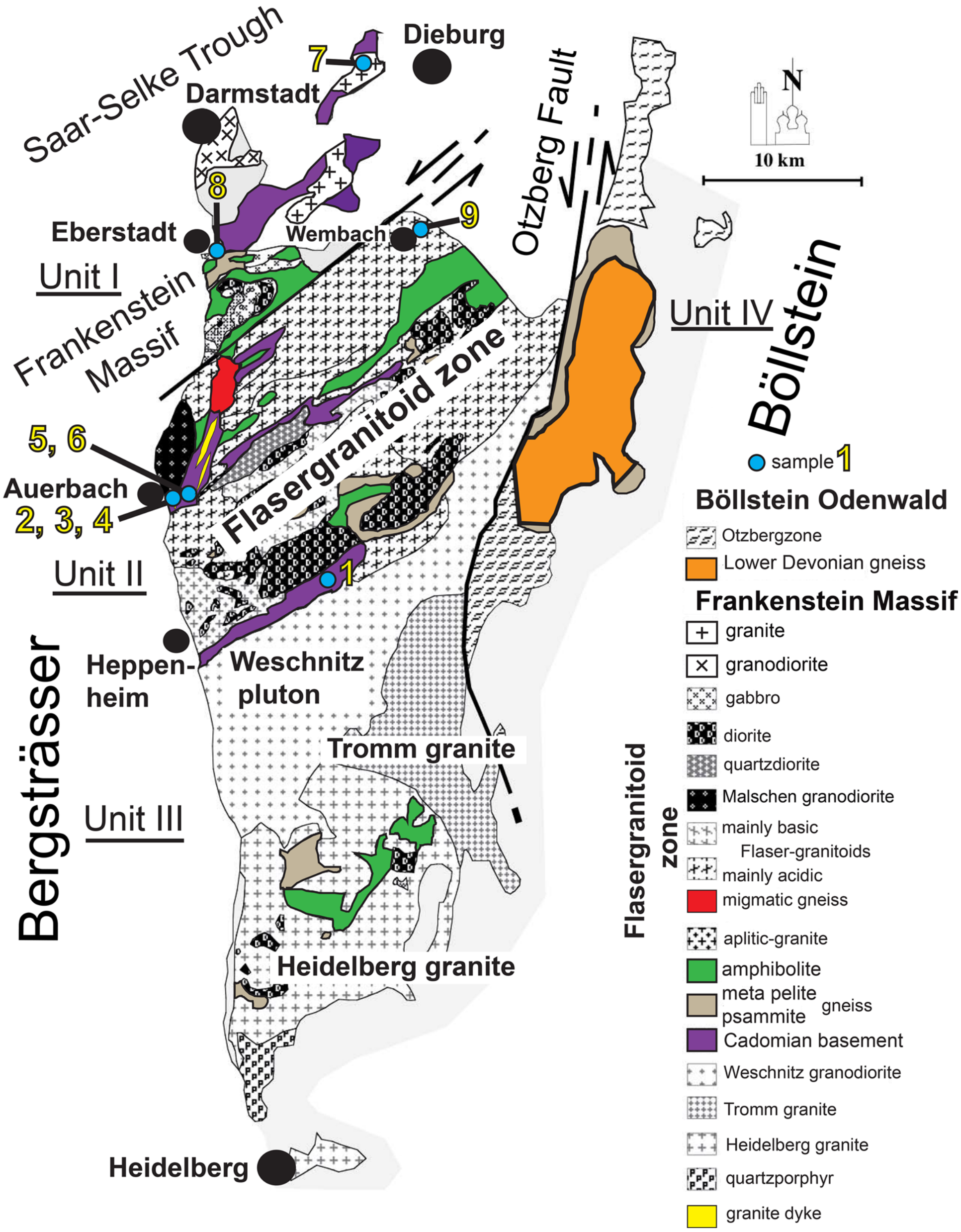


Fig. 2 Geological map of the Odenwald Crystalline Complex (mape modified after Stein 2001). Sample locality are indicated in yellow numbers

of the gabbros, gabbrodiorites, diorites, granodiorites, and granites characterize them as calc-alkaline rocks (Henes-Klaiber 1992; Kreher 1994), with I-type signature and a typical subduction-related geochemistry. There are large plutons (Fig. 2), such as the Frankenstein intrusive complex, Malchen pluton (Auerbach), the Weschnitz pluton, the Tromm pluton and Heidelberg pluton; or small intrusions mainly in the Flasergranitoid Zone closely association with metasedimentary rocks (Stein 2000).

Frankenstein intrusive complex (unit I)

The pyroxene–hornblende gabbros and olivine gabbros of the northern part of the West Odenwald consist of plagioclase (An_{80}), and clinopyroxene and olivine (Fo_{76}; Kreher 1994). Willner et al. (1991) determined PT conditions of 1.5 kbar and 880–930 °C for the intrusion of the gabbro. Two-pyroxene thermometry gave similar crystallization temperatures of about 900 ± 80 °C (Kreher 1994). Paragneiss, granodiorite, and granite are restricted in the northern part between the towns Eberstadt and Dieburg (Fig. 2).

Flasergranitoid zone (unit II)

The lithological association of the Flasergranitoid zone (Fig. 2) is more complex than in other parts of the West Odenwald. Gabbros and hornblende diorites form the so-called “Basischen Hauptgesteinszug” at its southern edge.

Northwards, the lithologies continuously change to more felsic biotite diorites, granodiorites, and granites. Small plutons of different composition are typical for the Flasergranitoid zone. Larger, discrete plutons such as the Malchen pluton at the western termination are scarce. Klemm (1918) described a pronounced planar flaser fabric in most of the magmatic rocks, from which he derived the name Flasergranitoid zone.

South Odenwald (unit III)

Three large plutonic complexes dominated the southern part of the Odenwald (Fig. 2). The Weschnitz pluton in the north consists of medium-grained hornblende-bearing granodiorites and tonalites. To the east and southeast, biotite-bearing granites and quartzmonzonites of the Tromm pluton are exposed, which are often porphyritic with K-feldspar phenocrysts several centimetres in size. The Heidelberg pluton in the southernmost part of the Odenwald consists of medium to coarse-grained, porphyritic biotite granites.

Wall rock

Six narrow zones of metamorphic rocks separate the magmatic plutonic complexes. They are several hundred metres-to-several kilometres wide and are composed of varied metasediment, metavolcanic rock, and orthogneiss. The four most important wall rock inliers (Fig. 2, purple and brown colors), are at the villages Eberstadt, Auerbach, Heppenheim and in the Heidelberg granite (Stein 2001) in the south. The wall rock of the plutonic complexes is built of biotite–plagioclase gneiss, muscovite gneiss, and schists. Biotite–muscovite gneiss is alternating with hornblende gneiss and quartzite, sometimes with metachert and metaphosphorite. Their chemical composition could be attributed to greywacke, clay, or sandstone protoliths. (Heppenheim wall rock, Hindel 1975; Matthes et al. 1972). Marble and calc-silicate rocks are rarely intercalated into the clastic metasediments. Very heterogeneous, banded as well as massive amphibolites alternate with these metasediments. The amphibolites are characterized by the mineral assemblage green amphibole, plagioclase, ± diopside, ± epidote, ± biotite, ± quartz, and ± titanite (Schubert 1968; Okrusch 1995). The ophitic or porphyritic textures of magmatic relics and the high An contents in plagioclase cores, as well as geochemical investigations (Schubert 1968; Klemm and Weber-Diefenbach 1975; Weber-Diefenbach 1974) attest, that basalts of tholeiitic composition were the protoliths. The gneiss of the central wall rock of the Flasergranitoid zone (Auerbach) are mainly constituted of grey, porphyroblastic biotite–plagioclase gneiss [32–50 vol% plagioclase, 9–39 vol% biotite, 17–35 vol% quartz, and 0–19 vol% hornblende; Kupfahl et al. (1972)] and hornblende gneiss, sometimes migmatic overprinted. East of the village Auerbach, dykes of granitic composition (31–46 vol% plagioclase, 26–31 vol% K-feldspar, 27–36 vol% quartz, 1 vol% muscovite, and 1 vol% biotite) crosscut the biotite–plagioclase gneiss and hornblende gneiss. The thickness of the granitoids dykes varies from 0.2 m up to 10 m (Kupfahl et al. 1972).

The mineral assemblage of Cordierite, andalusite, or wollastonite indicates a low-pressure high-temperature metamorphism of amphibolite facies conditions (Matthes et al. 1972; Raumer 1973). A polyphase history of the metasediments is documented by a low-pressure high-temperature event (2.5 kbar at 600 °C; Okrusch et al. 1975; Adusumalli and Schubert 2001) and a medium-pressure metamorphism in the garnet cores (8–9 kbar, 575–585 °C, Willner et al. 1991) of the Heppenheim wall rock inlier.

Previous dating

Rocks older than Devonian are until now not dated in the Odenwald. Two different magmatic cycles have been identified using different geochronological methods and minerals. Late Devonian mafic intrusions of the Frankenstein pluton have been dated with the Ar–Ar method on plagioclase at 359 ± 3 Ma, hornblende at 363 ± 7 Ma and with Pb–Pb evaporation method on zircon at 362 ± 9 Ma (Kirsch et al. 1988). The ages are undistinguishable within their errors. This cannot be explained by slow cooling due to widespread uplift, as in the southern part of the West Odenwald. The Frankenstein pluton must have intruded at shallow crustal levels (4 km, Kirsch et al. 1988) and cooled very fast, as indicated by the overlap of the ages despite different blocking temperatures of the minerals ($\gg$ 700 °C zircon, ca. 550 °C hornblende, ca. 200 °C plagioclase). Ar–Ar data of hornblende from two amphibolites of the wall rock at 355 ± 2 Ma (Schubert et al. 2001) could be interpreted as contact metamorphism. Lower Carboniferous granodiorites (Fig. 2, Darmstadt) yield K–Ar hornblende cooling ages at 340 ± 4 Ma and biotite cooling ages at 333 ± 4 Ma (Kreuzer and Harre 1975, recalculated) which point to a second magmatic cycle.

The oldest dated rocks of the West Odenwald are gneiss from the W Flasergranitoid zone (Fig. 2, 1 km east of the village Auerbach) dated with two K–Ar ages of amphibole at 371 Ma (Kreuzer and Harre 1975, recalculated). Ar–Ar data from amphibolitic hornblendes of the Flasergranitoid zone (Schubert et al. 2001) confirm the two different metamorphic events at around 360 ± 2 Ma and at 329 ± 2 Ma (average of 4 argon ages). Zircon dating from a diorite at 332.4 ± 1.4 Ma (Pb–Pb method, Siebel et al. 2012) and Ar–Ar analyses of hornblendes from two hornblende gabbros at 329 ± 2 Ma and at 335 ± 3 Ma (Schubert et al. 2001) are inline with the second magmatic event. Monazite ages from paragneiss scatter from 337 to 363 Ma (Will et al. 2017).

The pervasive low-pressure high-temperature metamorphism in West Odenwald was dated by Todt et al.

(1995) with the ID-TIMS U–Pb method. Small zircons (< 25 µ grain size) of the wall rock yield concordant U–Pb ages of about 332–342 Ma (in Todt et al. 1995: 336 Ma 2 km northeast of the village Auerbach; two overlapping analysis at 337 Ma northeast of sample 1; 342 Ma and 332 Ma in the Heidelberg granite) which fit well with the K–Ar hornblende and biotite cooling ages of the granitoid intrusions (Kreuzer and Harre 1975). Will et al. (2018) reproduced the two concordant ID-TIMS U–Pb ages of 337 Ma (Todt et al. 1995) with the SIMS-U–Pb method on zircons at 334 ± 2 Ma.

Northern Phyllite Belt

Scholtz (1934) described the narrow metamorphic belt at the boundary between the Saxothuringian Zone in the southeast and the Rhenohercynian Zone in the northwest as the Northern Phyllite Belt, which is interpreted by several authors to represent the suture zone of the Rheic ocean (Matte 1986; Ziegler 1986; Franke 1989; Franke and Oncken 1990, Fig. 1). Together with the Taunuskamm-Soonwald unit (Rhenish Massif), Wippra unit (Kyffhäuser) and the Harzgerode unit (Harz), the Northern Phyllite Belt was thrust over the Rhenohercynian Zone. The units form thrust bodies evolving from the sedimentary prism of the Rhenohercynian shelf (Anderle et al. 1995) or from quartzporphyr or MOR basalt (Meisl 1990). The felsic metavolcanic rocks are overlain by early Devonian clastic sediments of the Rhenish facies (Sommermann et al. 1994). This confirms the interpretation that the Silurian volcanic arc of the Northern Phyllite Belt is located at the southern edge of the Rhenohercynian and vanished in the Devonian.

The Northern Phyllite Belt is mainly composed of black to greenish metapelite, quartzite, sandstone, and metabasalt (Anderle et al. 1995), which were overprinted by a high-*P*/low-*T* metamorphism (5.8–6.5 kb and 300 °C, Massonne 1995) dated from 323 to 328 Ma (K–Ar, Ahrendt et al. 1983). In the Hunsrück, the Northern Phyllite Belt is divided by a thrust fault (Schafft 1985; Wiesbachtal mylonite) into a northern part with sedimentary rocks and a southern part with mainly metavolcanic rocks, metacherts and phyllites. At the boundary to the Rhenohercynian, small tectonic lenses of gneiss occur at the Wartenstein castle (sample 10, Fig. 1). The Wartenstein gneiss has been dated with Pb–Pb zircon evaporation method at 574 ± 3 Ma (Molzahn et al. 1998). The Wartenstein gneiss represents the basement of the Devonian shelf sequence of the Taunuskamm-Soonwald Unit (Oncken et al. 1999; Dittmar and Oncken 1992). A Gedinnian conglomerate rests unconformable on the basement (Bierther 1941).

Results

The methods of the ID-TIMS and LA-ICP-MS U–Pb analyses on zircon and titanite together with the TIMS $^{87}Sr/^{86}Sr$ analyses on apatite are described in the electronic supplement. The U–Pb and Sr data of ESM Tables 1–11 (2σ uncertainties) are stored in the electronic supplement. The U–Pb results obtained from the metasedimentary rocks are presented on density/probability plots with a concordance from 90 to 110%. The analyses of the metaigneous rocks are plotted with a concordance from 96 to 104% into concordia diagrams. 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, because these parts reflect the undisturbed zircon growth and thus an undisturbed U–Pb system of the zircons with no or minor lead loss.

Metasedimentary rocks

Metagreywacke (Odenwald)

Sample 1 is located in the wall rock between the Weschnitz pluton and the Flasergranitoid zone (Fig. 2). A high-temperature overprinted sequence of greywacke, marl, shale, and black chert is intruded by 1–2 m-thick Carboniferous granodiorite dykes. Sample 1 is a biotite–garnet paragneiss which consists of ca. 35% quartz, 25% feldspar, 25% biotite, and 5% garnet. The grain size of the zircons ranges from 40 to 320 µm. Most of them are colorless, only few rounded zircons are brown or pink. 40% of the zircons are angular to subhedral. 46% of the zircons are spherical with a lot of pit marks, whereas only 4% are elongated and rounded. 7% are subhedral to euhedral. Most of the zircons display Th/U ratios ratios between 0.5 and 1.1 (Fig. 3b). The five youngest analyses (ESM Table 2) define a $^{206}Pb/^{238}U$ mean age of 562 ± 5 Ma. The age spectrum of the detrital zircons is dominated by 47% Neoproterozoic ages with a high amount of Archean (32%) and Paleoproterozoic (20%) zircons (Fig. 4, red line). Only 1 Mesoproterozoic zircon (1230 ± 28 Ma) is present. Ediacaran zircons (29%) are the main population of the Neoproterozoic detrital zircon age spectrum (Fig. 5b) with the highest age peak at 577 ± 3 Ma ($n = 20$) and at 598 ± 3 Ma ($n = 11$, electronic supplement 2 A, B). Cryogenian zircons (17%) form the second largest group with a main peak at 621 ± 3 Ma ($n = 12$) and a second age peak at 670 ± 5 Ma ($n = 7$; electronic supplement 2 C, D). There is only 1 Tonian zircon.

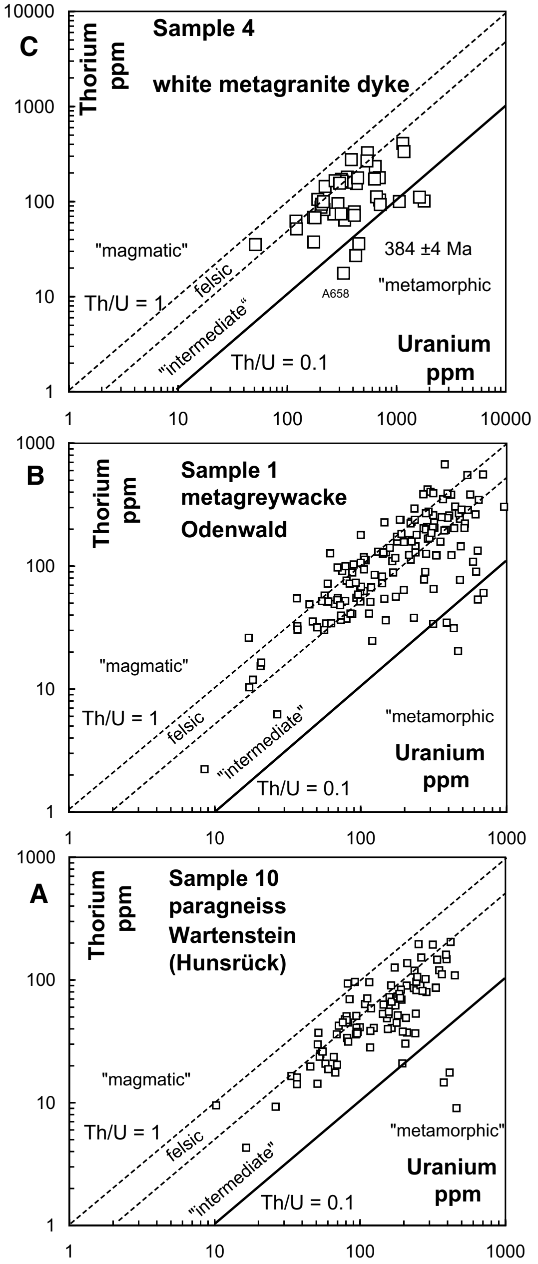


Fig. 3 Uranium/thorium plots: **a** Wartenstein gneiss (Rhenohercynian Zone); **b** metagreywacke Odenwald (Mid-German Crystalline Zone); **c** white metagranite dyke (Cadomian basement of the Mid-German Crystalline Zone)

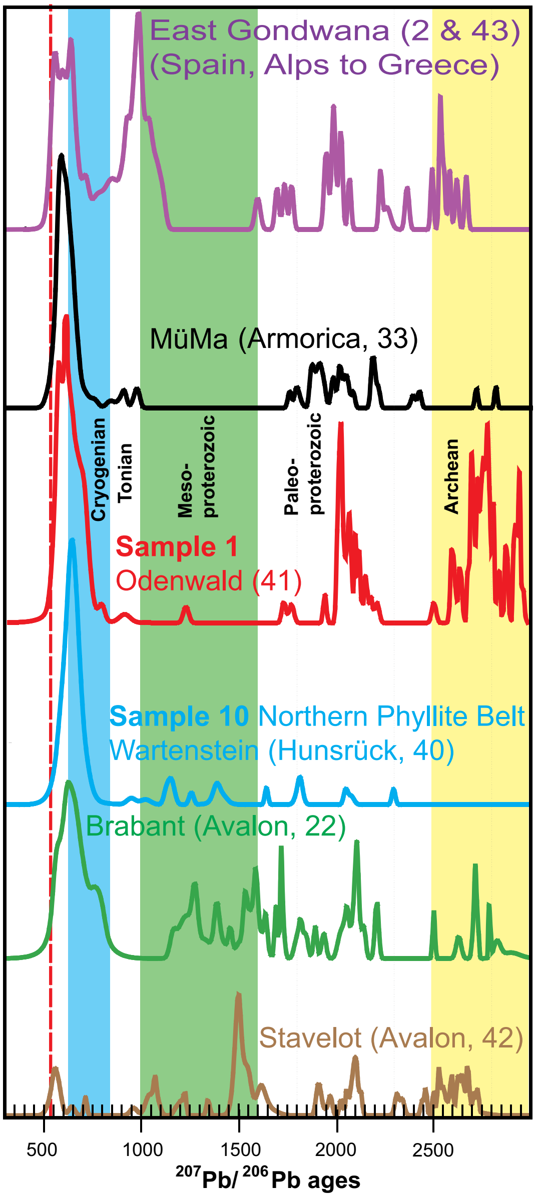


Fig. 4 Comparative relative probability plot of Ediacaran-to-Cambrian metasediments of Europe: magenta curve = Minoan terrane, Heinrichs et al. (2012) and Dörr et al. (2015); black curve = Armorica, Bahlburg et al. (2010); red curve = Mid-German Crystalline Zone, sample 1 this study; blue curve = Northern Phyllite Zone, sample 10 this study; green and brown curve = East Avalon, Linnemann et al. (2012) and Willner et al. (2013). Numbers in parenthesis in Fig. 4, see locality in Fig. 13

Paragneiss sample 10 (Northern Phyllite Belt)

For the comparison with U–Pb ages of detrital zircons of the Odenwald metagreywacke (sample 1), a paragneiss from the basement of the Northern Phyllite Belt (Hunsrück), the Wartenstein gneiss, was sampled (Fig. 1, sample 10). The outcrop at the Wartenstein castle is composed of mainly paragneiss containing phacoids of garnet amphibolite, marble, pegmatite, and quartzite (Bierther 1941). Sample 10 is a grey biotite–chlorit paragneiss sometimes bearing muscovite and small garnet. The grain size of the zircons ranges from 80 to 240 µm. A majority of zircons are colorless, only few rounded zircons are brown to yellow. Most of the zircons (56%) are angular. 30% are rounded with a lot of pit marks. Only 2% are elongated and rounded. 9% are subhedral to euhedral. The Th/U ratios between 0.1 and 0.5 of the sample (Fig. 3a) are

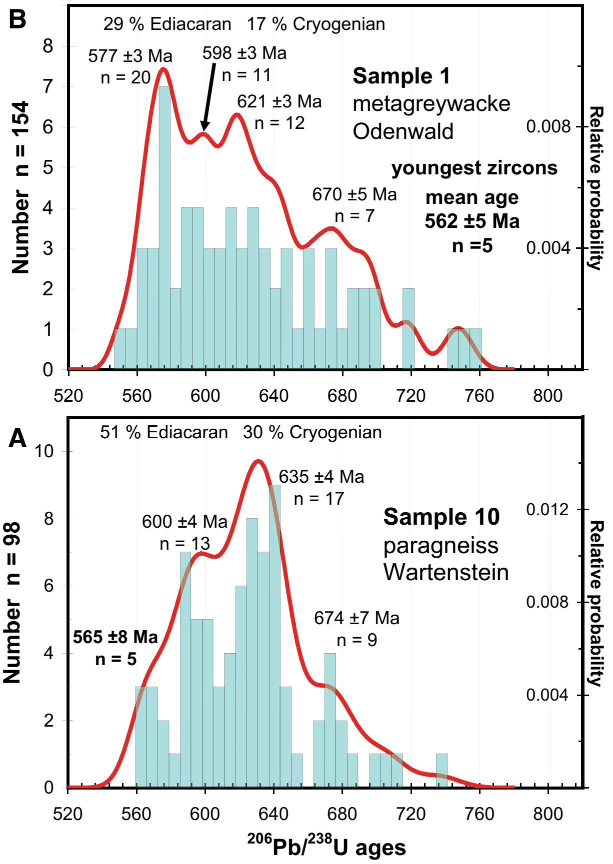


Fig. 5 Frequency/density together with relative probability plot of U–Pb ages (< 820 Ma) of detrital zircons (90–110% concordance of the ^{206}Pb/^{238} ages for detrital zircons). **a** Wartenstein gneiss (Northern Phyllite Zone); **b** metagreywacke Odenwald (Mid-German Crystalline Zone)

typical for magmatic zircons. The youngest zircon population defines a concordia age of 565 ± 8 Ma (*n* = 5, Fig. 5a). The age spectrum of the detrital zircons is dominated by 82% Neoproterozoic ages with 11% Mesoproterozoic, and only 6% Paleoproterozoic zircons. Archean zircons are not present (Fig. 4, blue line). Ediacaran zircons (51%) represent the main population of the Neoproterozoic detrital zircon age spectrum (Fig. 5a) with a peak at 600 ± 4 Ma (*n* = 13, electronic supplement 3B). The Cryogenian zircons (30%) form the second largest group with the highest age peak at 635 ± 4 Ma (*n* = 17, Fig. 5a) of the Neoproterozoic detrital zircons. A second age peak is at 674 ± 7 Ma (*n* = 9) similar to the peak in sample 1 (Fig. 5b). There is only 1 Tonian zircon at 949 ± 46 Ma.

Metaigneous rocks (Odenwald)

Biotite–plagioclase gneiss (Auerbach)

Sample 2 (Fig. 2) is a coarse-grained gneiss and displays a layering dominated by feldspar or quartz or biotite with a 10–30 cm spacing. The grain size of the zircons ranges from 60 to 220 µm. Most of them are irregular to subhedral, colorless, only few are pink and show a smooth surface without pit marks. Cathodoluminescence (CL) images display mostly typical oscillatory zoning, which reflects igneous crystallization. Homogeneous rims of variable width appear as highly luminescent phases around the zircons which are typical for resorption and precipitation of new zircon (e.g., van Breemen et al. 1987). Euhedral and bipyramidal cores are surrounded by both sector- and oscillatory-zoned rims too small for Laser-ICP-MS analyses. Most of the zircons (97%) plot into a small field with a Th/U ratio between 0.2 and 0.53, which is typical for intermediate magmatic zircons (Fig. 6c). Sample 2 contains only one zircon population. Most of the analyses (66) plot in a range of 570 Ma ± 1.8% (Fig. 7a) defining a concordia age at 566 ± 2 Ma with a probability of 0.7 (Fig. 7b). The small error is the result of the number of analyses. Realistic for Laser-ICP-MS analyses is an error around 2% (± 11 Ma). 100 zircons define a ^{206}Pb/^{238}U mean age at 567 ± 2 Ma. The two younger U–Pb ages could result from a lead loss during high-grade metamorphic overprint. Zircons with an age around 600 Ma are inherited probably from older igneous rocks.

Biotite gneiss (Auerbach)

Sample 3 is similar to sample 2, but show sometimes a strong mylonitic foliation with grain size reduction. The grain size of the zircons ranges from 80 to 270 µm. Most of them are irregular to subhedral, colorless without pit marks. CL images display again typical oscillatory zoning. Homogeneous rims of variable width appear as a highly luminescent phase around the zircons. The Th/U ratios of sample 3 scatters more than of sample 2. Most of the zircons (71%) plot between 0.12 and 0.50 (Fig. 6b). Metamorphic zircons have Th/U ratios from 0.004 to 0.09. Together, they define a ^{206}Pb/^{238}U mean age at 386 ± 5 Ma (*n* = 7, Fig. 6a). Sample 3 contains two concordant zircon populations. One at 568 ± 4 Ma (*n* = 10, Fig. 8c) and the other at 386 ± 7 Ma (*n* = 4, Fig. 8b). All analyses define a discordia line subparallel to the concordia curve with an upper intercept age around 539 ± 11 Ma and a lower intercept age around 373 ± 64 Ma (Fig. 8a). U–Pb ages younger than 545 Ma could not could not represent the protolith age, because a dyke (sample 4) with a concordia age of 542 Ma (see text below) crosscut the foliation of biotite–plagioclase gneiss (samples 2 and 3). Zircons with a concordia age at 600 Ma, 1088 Ma, 1578 Ma, 1984 Ma, and 2621 Ma are inherited (not shown).

White metagranite dyke (Auerbach)

Sample 4 intruded perpendicular to the foliation (160°/60°) of the gneiss (samples 2 and 3) as a ± vertical N–S

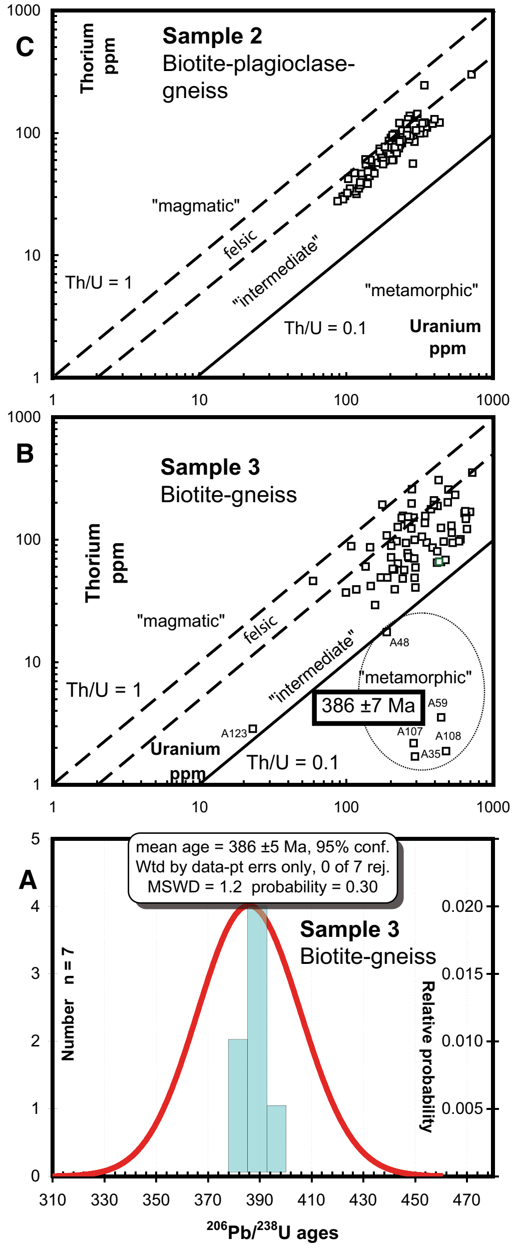


Fig. 6 Frequency/density together with relative probability plot of U–Pb ages of metamorphic zircons sample 3 and Uranium/Thorium plot of metaigneous rocks east of the village Auerbach (Mid-German Crystalline Zone). **a**, **b** Biotite gneiss (sample 3); **c** biotite–plagioclase gneiss (sample 2) Cadomian basement of Mid-German Crystalline Zone

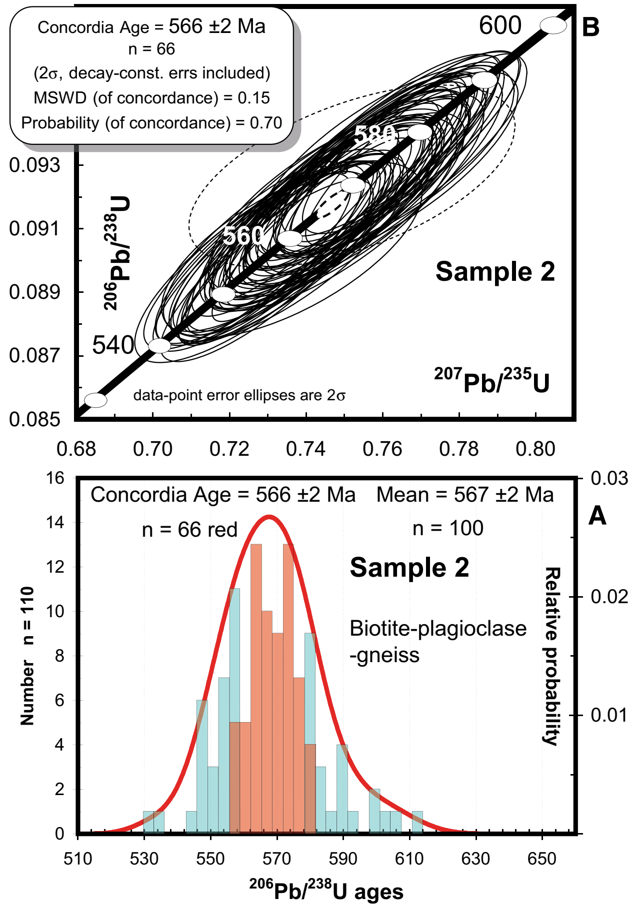


Fig. 7 Frequency/density together with relative probability plot of U–Pb ages of zircons and U–Pb concordia plot of metaigneous rock east of the village Auerbach (Mid-German Crystalline Zone). **a**, **b** Biotite–plagioclase gneiss (sample 2, Cadomian basement)

trending, 15 cm-thick dyke which contains 50% quartz, 38% K-feldspar, 8% plagioclase, and minor biotite. The grain size of the zircons ranges from 70 to 230 µm. Most of them are colorless euhedral (55%) and long prismatic. Their CL images display again typical oscillatory zoning. Irregular-to-subhedral zircons with a smooth surface are again covered by rims of variable width, which appear as a highly luminescent phase. Euhedral cores are surrounded by fine oscillatory-zoned shells. The Th/U ratios of sample 4 scatter more than of the sample 2. Most of the zircons plot between 0.2 and 0.70 (Fig. 3c). Discordant zircons below 320 Ma display the lowest Th/U ratios from 0.06 to 0.09 pointing to a lead loss triggered by fluids. Sample 4 contains two concordant zircon populations. A small population defines a concordia age of 384 ± 4 Ma (*n* = 4, Fig. 9b) with Th/U ratios scattering from 0.08 to 0.47 (Fig. 3c). An older population of zircons defines a concordia age of 542 ± 3 Ma (*n* = 16, Fig. 9c). U–Pb analyses between the concordia ages display different degree of lead loss during the high-grade metamorphic overprint (Fig. 9a). Four Neoproterozoic zircons (588 Ma, 593 Ma, 629 Ma, and 796 Ma) point to inheritance. The $^{87}Sr/^{86}Sr$ value of two apatite analyses of the white granite dyke is similar at 0.70557 ± 0.0055% and at 0.70564 ± 0.0047% (ESM Table 11).

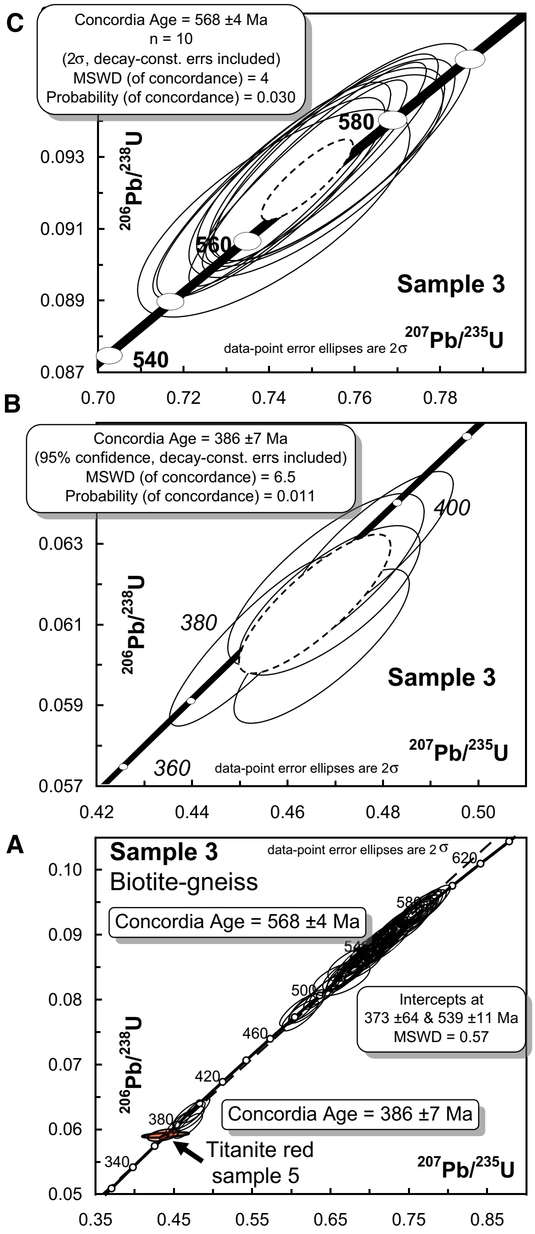


Fig. 8 U–Pb concordia plots of zircons of metaigneous rocks east of the village Auerbach (Mid-German Crystalline Zone). **a**–**c** Biotite gneiss (sample 3, Cadomian basement)

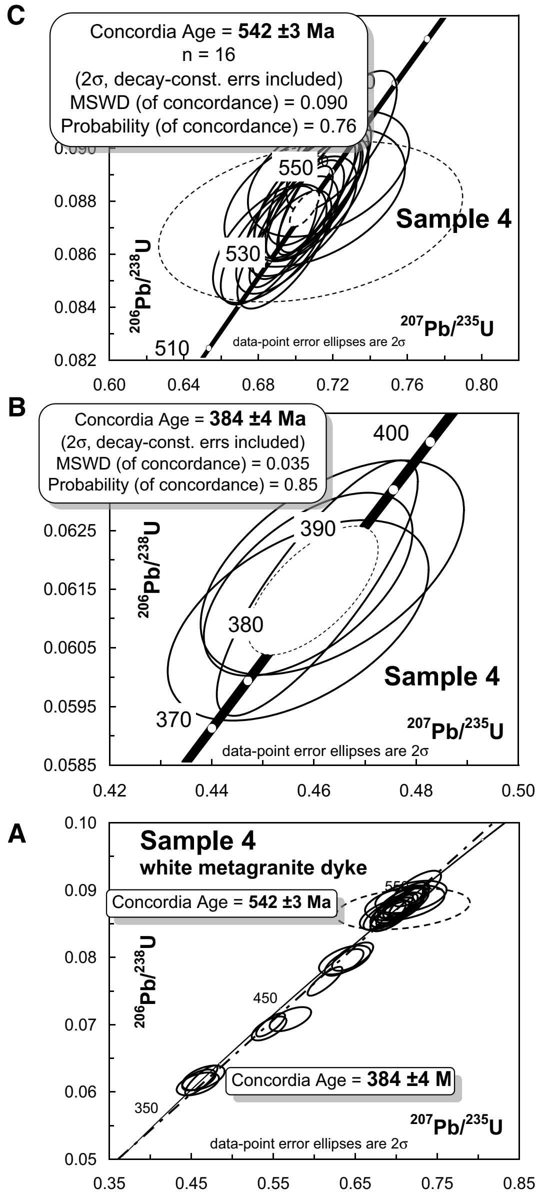


Fig. 9 U–Pb concordia plots of zircons of the white metagranite dyke east of the village Auerbach (Mid-German Crystalline Zone). **a**–**c** (Sample 4, Cadomian basement)

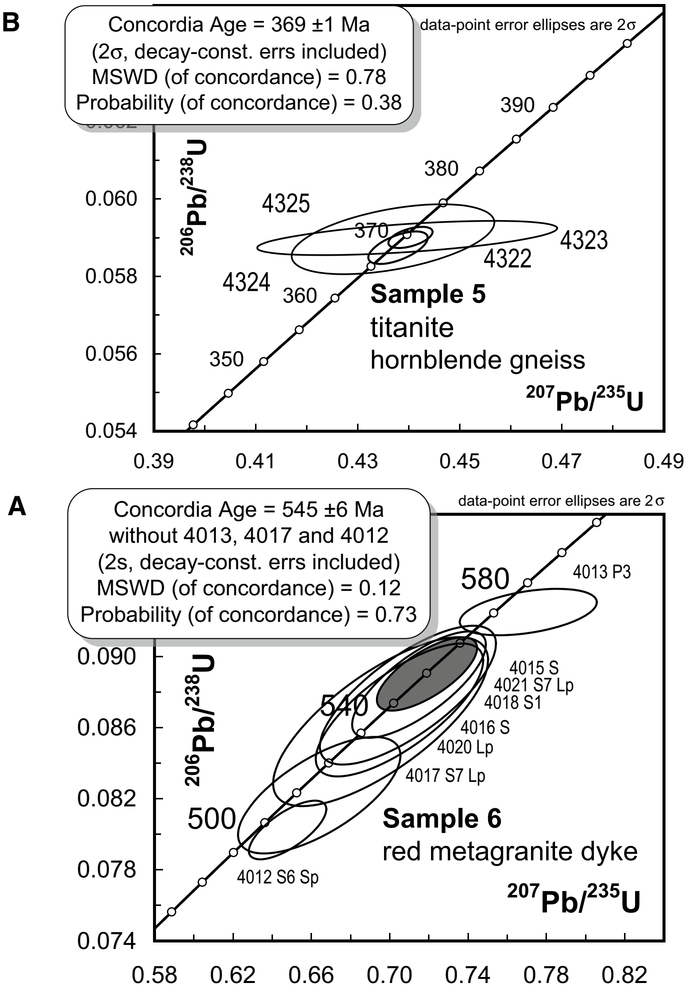
Hornblende gneiss (road from Auerbach to Hochstädten)

Sample 5 is a small band of hornblende gneiss which is intercalated into uniform, monotonous, and mylonitic plagioclase gneiss. It contains no zircons. The grain size of the titanite ranges from 100 to 870 µm. They are brown euhedral and have uranium contents from 138 ppm to 343 ppm (ESM Table 6). The high common lead content from 12% to 60% influences strong the errors of the $^{207}Pb/^{235}U$ ratios, up to 5.5%. The single titanite grain analysis number 4323 has the highest $^{206}Pb/^{204}Pb$ ratios of 242 with a concordant U–Pb age at 370 Ma. Together with two other single titanite grains and the titanite fraction with a grain size of 125µ, they define a concordia age of 369 ± 1 Ma (*n* = 4, Fig. 10b). The $^{87}Sr/^{86}Sr$ value of apatite is the highest of the Cadomian basement at 0.709493 ± 0.0025%.

Red metagranite dyke (road cut to Auerbach castle)

1.7 km east of the village Auerbach a variegated series of plagioclase gneiss, mica schist with boudins of amphibolite, quartz rich metapsamite, and hornblende gneiss is exposed along a road cut. Several granitoid dykes with a

Fig. 10 U–Pb concordia plots: **a** red metagranite dyke (zircon, sample 6, do141), **b** hornblende gneiss (titanite, sample 5, do140) Cadomian basement east of the village Auerbach (Mid-German Crystalline Zone)



thickness up to 2 m intruded into the gneiss. Sample 6 is a 0.4 m thick, red metagranite dyke (Fig. 2) intruding into porphyroblastic biotite–plagioclase gneiss, whose foliation dips in the direction 140°/70°. The red granite dyke crosscut the gneiss foliation in a pointed angle dipping to 120°/60°. A fine-grained chilled margin is visible. In the centre of the dyke, the biotite shows a preferred horizontal orientation parallel to the margin of the dyke. The grain size of zircons from the granite dyke ranges from 100 to 240 µm. They are long prismatic, colorless euhedral and belong mainly to S_7-type zircon after Pupin (1980). Few of them are S_6-type or P_3-type zircons or are short prismatic. They have low uranium contents from 52 ppm to 120 ppm (ESM Table 7). Because of the low amount of lead from 32 to 114 pg (total lead) and high common lead content of around 5%, the errors of the U–Pb ratios are high. The ^{206}Pb/^{204}Pb ratios of the analyses, which were used for calculating the concordia age of 545 ± 6 Ma ($n = 5$, Fig. 10a), are between 315 and 619. The ^{87}Sr/^{86}Sr value of two apatites of the granite is similar at 0.70531 ± 0.0043% and 0.70533 ± 0.0041% (ESM Table 11).

Dieburg metagranite

A greenschist facies metagranite is exposed (Fig. 2, sample 7) in a large quarry 4 km west of the village Dieburg, in the northern most Frankenstein Massif. The grain size of zircons ranges from 60 to 200 µm. They are colorless, euhedral short prismatic with uranium contents from 133 to 274 ppm (ESM Table 8). Their CL images display oscillatory zoning from the centre (broad zones) to their surface (fine zones) typical for magmatic zircons. Sometimes, sector zoning or small cores are visible. The Th/U ratios of the Dieburg metagranite plot into a small field between 0.18 and 0.29 (Fig. 11c). All zircons plot on a discordia line from 0 to 560 Ma (Fig. 11a). No older zircons could be detected. The zircons with the highest concordance (95–99%) define a concordia age of 540 ± 8 Ma ($n = 4$, Fig. 11b) which is similar to the two granite dykes of the Flasergranitoid Zone. The ^{87}Sr/^{86}Sr value of apatite varies from 0.70449 ± 0.0029% to 0.70472 ± 0.0036% (Table 10). Three analyses yield a mean value of 0.7045 which is lower than from the two granite dykes of the Flasergranitoid Zone.

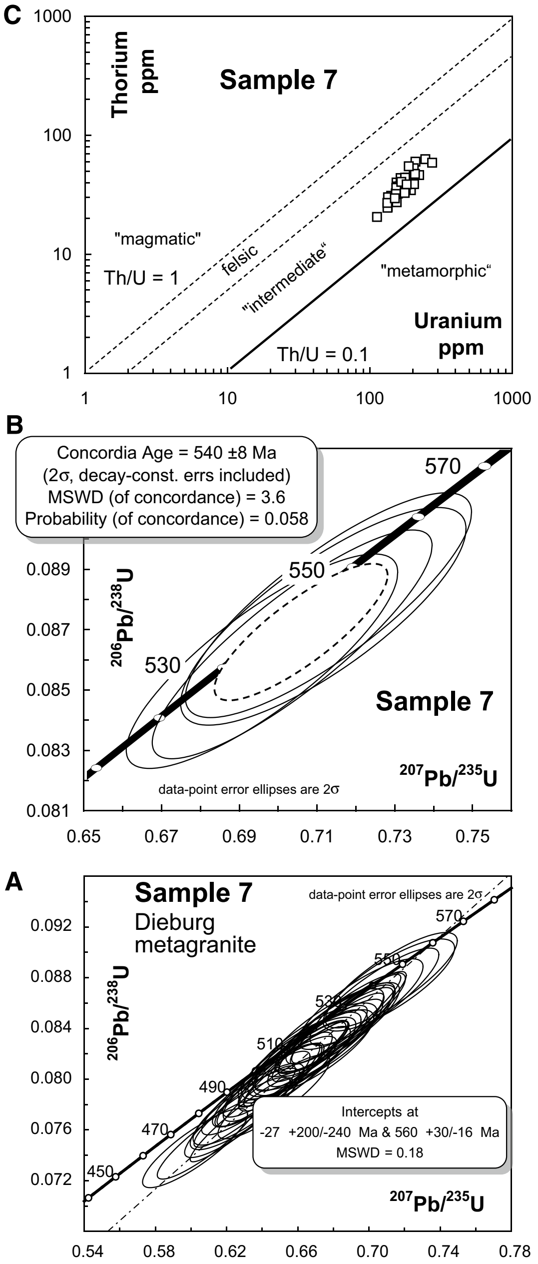


Fig. 11 U–Pb concordia plots (**a**, **b**) and Uranium/Thorium plot (**c**) of zircon of the Cadomian Dieburg metagranite (sample 7) of the northern Frankenstein Massif (Mid-German Crystalline Zone)

Eberstadt metagranite

Sample 8 is located east of the town Eberstadt, in the valley of the river Modau (Fig. 2). Several granite dykes intruded into gneiss, hornfels facies metasediments (graphite quartzite and pelites with andalusite), and diabase. Sample 8 is medium-grained metagranite which is composed of mainly quartz and K-feldspar with minor plagioclase and biotite. No foliation is visible, but the boundary of quartz grains is strongly lobate with pronounced undulose extinction. The grain size of the colorless, short prismatic zircons ranges from 60 to 180 µm. They have uranium contents from 134 to 583 ppm and Th/U ratios of zircons of the Eberstadt metagranite scatter from 0.14 to 1.48 (ESM Table 9). ^{206}Pb/^{238}U ages of zircons with a concordance of their U–Pb ages from 90 to 110% are calculated with TuffZir age extractor (Ludwig and Mundil 2002). They define a TuffZir age at 440 + 4/− 6 Ma (*n* = 27). The analyses of zircons with a concordance from 95 to 105% scatter from 399 to 528 Ma. The three youngest analyses around 400 Ma could be influenced by lead loss during metamorphic overprint. The main zircon population defines a concordia age at 434 ± 4 Ma (*n* = 14, Fig. 12, upper part) which is similar to the TuffZir age. Zircons with an age at 470 Ma and 520 Ma are inherited, probably from older igneous rocks.

Wembach orthogneiss

Sample 9 is located in an abandoned quarry east of the village Wembach. The orthogneiss is surrounded by Carboniferous granodiorite to diorite of the Flasergranitoid zone (Stein 2000). It contains 52% quartz, 35% K-feldspar (up to 16 mm), 6% plagioclase, and 8% small biotite. Feldspar and quartz mark a foliation. Quartz displays undulose extinction lobate grain boundaries. The grain size of the zircons ranges from 120 to 250 µm. They are mainly colorless, long prismatic grains. Their CL images display fine oscillatory zoning from the centre to their external part, typical for magmatic zircons. Sometimes, cores are visible. The zircons have uranium contents from 266 to 770 ppm (ESM Table 10). The Th/U ratios of the zircons from the Wembach orthogneiss scatter from 0.16 to 0.51. The analyses of zircons with a concordance from 95 to 105% scatter from 400 to 700 Ma (Table 10). The main population is Lower Devonian to Upper Silurian in age. Seven zircons define a concordia age at 411 ± 5 Ma (Fig. 12, lower part). Older, inherited zircon populations yield concordia U–Pb ages at 437 ± 6 Ma (*n* = 7) and at 468 ± 9 Ma (*n* = 4) pointing probably to Silurian and Ordovician igneous rocks as provenance. Three concordant analyses plot around 500 Ma. There are few inherited Neoproterozoic zircons and one zircon at around 2 Ga.

Discussion

Deposition age of the paragneiss protolith

The youngest concordant zircon analyses (A59, ESM Table 1) of the paragneiss of the Wartenstein Crystalline yielded an age of 561 ± 19 Ma. This is inline with the concordia age at 565 ± 6 Ma of 5 zircons which define the youngest detrital zircon population. This age could be

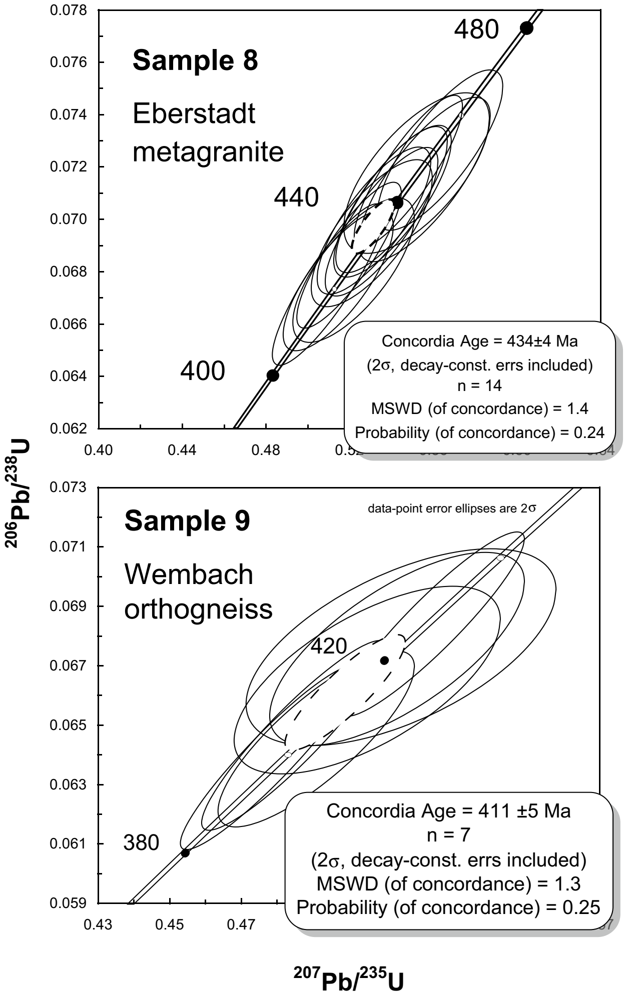


Fig. 12 U–Pb concordia plots of zircon of the Silurian Eberstadt metagranite (sample 8) of the northern Frankenstein Massif and the Devonian Wembach orthogneiss (sample 9) Mid-German Crystalline Zone

interpreted as the maximum deposition age (Dickinson and Gehrels 2009). The gneiss underwent cooling below 300 °C at 550 ± 20 Ma (K–Ar data on hornblende, Meisl et al. 1989) defining the youngest possible deposition age at ca. 530 Ma. The deposition age of the paragneiss from the Wartenstein Crystalline is bracketed by the age of the youngest detrital zircon population and the cooling age of the gneiss between 530 and 571 Ma. The paragneiss protolith was deposited during the Late Ediacaran to Lower Cambrian. The youngest concordant zircon (analysis number 315) of the metagreywacke from the West Odenwald yielded a U–Pb age of 550 ± 12 Ma. The five youngest analyses define a detrital zircon population with a ^{206}Pb/^{238}U mean age of 562 ± 5 Ma. Taking the U–Pb ages of the granite dyke 545 ± 6 Ma (sample 6, Fig. 2) of the Cadomian basement of central wall rock of Flasergranitoid into account than the youngest possible deposition age could be Latest Ediacaran. The deposition age of the metagreywacke is bracketed between 539 and 562 Ma. A several meter thick black metachert layer is intercalated into the metagreywacke sequence (sample 1, Fig. 2). This also points to an Ediacaran age, because such massive black chert layers together with greywackes (maximum deposition age ca. 560 Ma) occur in the volcano-sedimentary units of the Saxothuringian Zone (Torgau–Doberlug Syncline and the Schwarzburg Antiform; Buschmann 1995; Linnemann et al. 2000).

Provenance

Different source areas from clastic sediments can be distinguished by U–Pb age spectra of their detrital zircons. They reflect zircon-forming process in the source area, such as the genesis of igneous rocks or high-grade metamorphism. Processes define the geological evolution of different continents and terranes. In the MGCZ, the U–Pb age spectra of detrital zircons of two samples from of the Ruhla Crystalline Complex (Zeh and Gerdes 2009) and one from the Böllstein Odenwald (Dörr et al. 2017) were analyzed. The metasedimentary rocks of the northern Böllstein Odenwald were deposited during the Devonian. Their U–Pb age spectrum of detrital zircons is characterized by Palaeozoic zircons, which could be detected in the entire Saxothuringen Zone (Dörr et al. 2017). The Ordovician Rögis quartzite of North Ruhla (Zeh and Gerdes 2009) contains only two Ediacaran zircons, but 78% Mesoproterozoic zircons which are typical for Baltica-derived detritus of the Rhenohercynian Zone (Zeh and Gerdes 2009; Haverkamp 1991; Geisler et al. 2005; Eckelmann et al. 2013). The metapelite of South Ruhla (Brotterode group, Zeh and Gerdes 2009) also contains also a high amount of Precambrian zircons (68%) comparable to the Rögis quartzite (North Ruhla) but with a Mesoproterozoic age gap indicative for West Africa derived detritus typical for Armorica. This U–Pb age spectrum of detrital zircons from the MGCZ (metapelite, south Ruhla) compares with that of the metagrewacke of the West Odenwald (Mesoproterozoic age gap), but the metapelite contains 6 zircons which define a younger maximum deposition age at 507 ± 5 Ma (concordia age, Zeh and Gerdes 2009). An Ordovician sedimentation age of the metapelite from South Ruhla is plausible. Ediacaran and Ordovician sedimentary rocks of the Saxothuringian Zone (Linnemann et al. 2007, 2008, 2013) also display an Armorican-type detrital zircon age cluster typical for the West African Craton and fit well with the detrital zircon age cluster of south Ruhla and of the West Odenwald.

The published samples used for the correlation of their U–Pb age spectra of detrital zircons (Figs. 4, 13) with that of the samples from the Rheic suture zone are all deposited during the Lower Cambrian or Latest Ediacaran close to the Cadomian arc at different parts of peri-Gondwana. The age spectra of samples from the Alps and Greece (Uppermost magenta colored curve in Fig. 4, number 2 and 43 in Fig. 13, Heinrichs et al. 2012; Dörr et al. 2015) fit with none of the other age spectra, as they display a prominent Grenvillian age peak, typical for sediments with East Gondwana provenance of the Minoan continent (Fig. 13, Zulauf et al. 2007, 2014, Dörr et al. 2015). The boundary between the Armorican and the Minoan continent in Central Europe is probably in the East Alps between the recently discovered Armorican U–Pb age spectra of detrital zircons of the paragneiss from the Seckau nappe (sample 44, Fig. 13, Mandl et al. 2018) and the Minoean age spectra of the crystalline basement south of the Tauern window (number 43, Fig. 13, Heinrichs et al. 2012). The age spectra of the Cambrian sandstone from the Münchberg nappe pile (Bahlburg et al. 2010; black probability curve, Fig. 4) display a high amount of Ediacaran detrital zircons and a Mesoproterozoic age gap like the greywacke from the Odenwald (red curve, Fig. 4). The Odenwald sample (number 41, Fig. 13) correlates well with all the samples of the Saxothuringian Zone. Sample 26 (Fig. 13) is displayed as example for more than 20 analyzed samples of the Ediacaran and Cambrian of the Saxothuringian Zone (Linnemann et al. 2004, 2007, 2008, 2013, 2018) which all show the Mesoproterozoic age gap. The Ediacaran-to-Lower Cambrian sediments of the Tepla–Barrandian Unit sample 23 (Fig. 13) also show this age gap (Drost 2008; Sláma et al. 2008; Hajná et al. 2017). All these samples fit well with detrital zircon age spectra of the Northern Armorican Massif (sample 21, Fig. 13) further to the west and contain a high amount of Paleoproterozoic and Archean zircons (sample 18, Fig. 13) which together with the Mesoproterozoic age gap points to the West African Craton as their provenance area.

Sample 10 from the Northern Phyllite Belt (Wartenstein Crystalline, blue curve in Fig. 4) contains in contrast to the Odenwald greywacke 11% Mesoproterozoic zircons which

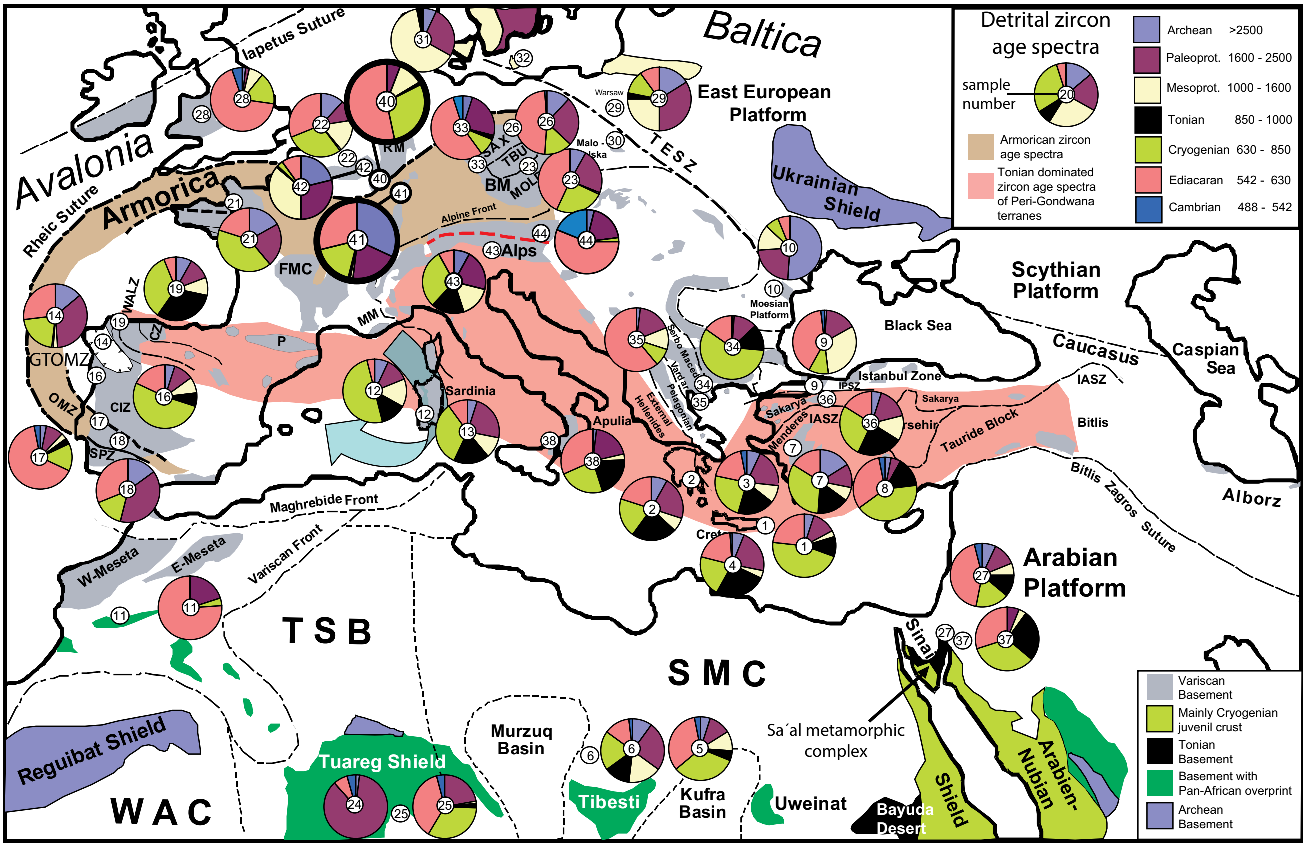


Fig. 13 Map is showing the recent outlines of Europe with the different age spectra of the detrital zircons during Late Ediacaran/Cambrian time (modified after Dörr et al. 2015). BM, Bohemian Massif; BV, Brunovestulicum; CIZ, Central Iberian Zone; CZ, Cantabrian Zone; FMC, French Massif Central; GTOMZ, Galicia Tras-Os-Montes Zone; IASZ, Izmir Ankara shear zone; IPSZ, Intra Pontide shear zone; MM, Maures Massif; OMZ, Ossa-Morena Zone; P, Pyrenees; RM, Rhenish Massif; Sax, Saxothuringikum; SPZ, South Portuguese Zone; TBU, Tepla–Barrandian Unit; TESZ, Trans-European Suture Zone; WALZ, West Asturian Leonese Zone. Sample number/reference: 40, Wartenstein Crystalline, this study; 41, Odenwald Crystalline, this study; 42, Willner et al. (2013); 43, Heinrichs et al. (2012); 44 and Mandl et al. (2018). Red dashed line marks the supposed northern boundary of the Minoan terrane in the Alps. References locations 1–39, see Dörr et al. (2015) or electronic supplement number 6

fit with the age spectrum of number 22 of the Brabant Massif (green curve in Fig. 4, Linnemann et al. 2012) and of number 42 of the Ardennes (Fig. 13, Willner et al. 2014). The U–Pb age spectrum of detrital zircons of paragneiss from the Wartenstein Crystalline correlates with all the provenance analyses of Neoproterozoic and Cambrian sediments of Wales (number 28, Fig. 13, Murphy et al. 2004a, b) and Newfoundland (Willner et al. 2014 and references therein) which all belong to the Avalonian and related terranes delivering their detritus from the Amazonian Craton.

Cadomian basement

The wall rock east of Auerbach is composed of grey biotite–plagioclase gneiss which is intercalated by a variegated series of calc-silicate rock, micaschist, amphibolite, and metapsamite. Kupfahl et al. (1972) interpreted the whole sequence as paragneiss constituted of greywacke, marl and basalt. Despite the subhedral habitus of the zircons analyzed from the biotite–plagioclase gneiss (sample 2), they form a uniform zircon population with similar Th/U ratios around 0.4 (Fig. 6c), with a U–Pb concordia age at 566 ± 2 Ma ($n = 66$, Fig. 7) and a TuffZirc Age at 568 + 3/− 4 Ma (coherent group of 84/112, 95% conf.). The few analyses with younger U–Pb ages ($n = 8$) could result from a lead loss during high-grade metamorphic overprint. Zircons with an age around 600 Ma ($n = 5$) are probably inherited from older igneous rocks. No older zircons could be detected. Because of such a homogenous zircon population, the protolith of the biotite–plagioclase gneiss (sample 2) could be interpreted as magmatic in origin. Plutonic rocks could have intruded into a Cadomian basement or volcanic layers could be intercalated into the metasediment sequence. The latter is more plausible, because the biotite–plagioclase orthogneiss displays a banded layering (10–30 cm) as a result of different modal composition. The age of the biotite–plagioclase orthogneiss (sample 2) of the Odenwald correlates with the U–Pb age of zircons from granitoid pebbles of the Ediacaran Weesenstein tillite of the Müglitz formation at 566 ± 4 Ma, 572 ± 2 Ma, and 576 ± 7 Ma (Elbe Zone, Saxothuringian Zone, Linnemann et al. 2018) which point to an magmatic arc at around 560–576 Ma in their provenance area. Similar U–Pb ages at around 570–585 Ma from boulders of volcanic origin are detected in the late Ediacaran flysch of the Tepla–Barrandian Unit (Dörr et al. 2002).

The biotite–plagioclase gneiss (sample 3) displays a complex geochronological history. The Th/U ratios and the U–Pb ages of the zircons scatter from 0.004 to 1.1 (Fig. 6b) and from 380 to 580 Ma (Fig. 8a). Concordant U–Pb ages between 480 and 550 Ma may be interpreted as detrital zircon population of an Ordovician sediment, but a granite dyke (sample 4) with a concordia age of 542 ± 3 Ma (Fig. 9c, see text below) intruded both biotite–plagioclase gneiss (samples 2 and 3). The U–Pb ages between 480 and 545 Ma could not represent the age of detrital zircons, but a partly opened U–Pb system of overprinted magmatic zircons. Seven zircons with low Th/U ratios of 0.004–0.2, typical for metamorphic zircons (Hartmann and Santos 2004), define a $^{206}Pb/^{238}U$ mean age at 386 ± 5 Ma (Fig. 6a). The zircon population at 568 ± 4 (Fig. 8c) Ma could be interpreted as the protolith age of the orthogneiss similar to the sample 2. The U–Pb age around 386 Ma (Fig. 8b) could be interpreted as the age of the metamorphic grown zircons.

The foliation of the Cadomian basement east of the village Auerbach is crosscut by granitoid dykes of 10 cm–40 cm thickness. The orthogneiss is intruded perpendicular to their gneissic foliation (160°/60°) by a ± vertical N–S trending, 15 cm-thick, white granite dyke (sample 4) which contains again two concordant zircon populations. A small zircon population defines a concordia age of 384 ± 4 Ma (Fig. 9b). An older population of 16 zircons defines a concordia age of 542 ± 3 Ma (Fig. 9c). A second granite dyke (sample 6 Fig. 2) with an intrusion age of 545 ± 6 cuts the Cadomian basement's foliation (140°/70°) at a high angle (120°/60°). The Ediacaran protolith age of the orthogneiss and the Cambrian age of the dykes prove the existence of a Cadomian crystalline basement in the Odenwald for the first time.

The Dieburg granite intruded into the basement of the northern Frankenstein Massif at 540 ± 8 Ma (Fig. 11b). The Th/U ratios together with the oscillatory zoning of the zircons are typical for magmatic zircons. Their U–Pb age could be interpreted as the intrusion age, because the granite suffered only greenschist facies overprint below a temperature of 500 °C.

Three metagranites of the Odenwald intruded at 542 ± 3 Ma (sample 4), at 540 ± 8 Ma (sample 7) and at 545 ± 6 Ma (sample 6) into the metavolcano-clastic sequence of the Cadomian basement. The low $^{87}Sr/^{86}Sr$ value of apatites from the Dieburg granite (sample 7) of 0.7045 (ESM Table 11) could be related to a mixing of partial melt from a depleted mantle source with a melt generated in the lower crust, probably indicate a subduction-related origin of the melt. The slightly higher $^{87}Sr/^{86}Sr$ value of 0.7054 (ESM Table 11) from apatite of the two granite dykes of the Cadomian basement east of Auerbach either suggests a higher influence of a crustal source rock during magma mixing with a melt from a depleted mantle source or may represent a hybrid magma. Both interpretations are compatible with an active magmatic continental arc setting of the Cadomian granites. The intrusion age of 542 Ma of the metagranites from the Odenwald fits with that of granodiorites of the Saxothuringian Zone (Kröner et al. 2001; Dörr et al. 2002; Zelazniewicz et al. 2004, Linnemann et al. 2013). Slightly (3%) older gneiss (calc-alkaline plutonic rocks) intruded at ca. 552 Ma into a Cadomian basement in the Münchberger nappe of the

Saxothuringian Zone (Koglin et al. 2018). Subduction-related plutons with Late Ediacaran ages could also be detected in the Moldanubian Zone yielding U–Pb zircon ages at 549 ± 6 Ma and 555 ± 12 Ma (Teipel 2003). Further to the West, the large Mancellian batholith intruded at 540 ± 10 Ma (U–Pb on monazite, Pasteels and Dore 1982) into the submarine fan sediments of the Cadomian Brioverian Group (Armorican Massif).

The precambrian para- and orthogneiss of the Odenwald show a strong foliation. The Cambrian metagranite dykes display a stretching lineation of the dark minerals with a weak foliation. The Cadomian deformation and metamorphism is bracketed between the protolith age of the orthogneiss at around 567 Ma and the intrusion age of the granite dykes at around 543 Ma. Late Ediacaran metamorphism and deformation of the Cadomian basement of the West Odenwald could be correlated with the age of the high-grade overprinted Tepla–Barrandian Unit (Zulauf et al. 1999) and is also known from the migmatite of the St.Malo terrane of the Armorican Massif (541 ± 5 Ma, Peucat 1983, 1986).

In the Odenwald, Cadomian basement could be detected at three locations: (1) north of the Weschnitz pluton; (2) in the centre of the Flasergranitoid Zone east of Auerbach; and (3) north of the Frankenstein Massif (Fig. 2, magenta color = Cadomian basement). The Cadomian crust of the northern Frankenstein Massif is in contrast to the interpretation of the Frankenstein gabbro and related rocks as a Devonian magmatic arc in a thin crust (Kirsch et al. 1988). There must be a fault between the Cadomian basement and the Devonian Frankenstein gabbro.

Silurian–Devonian active margin

Granite dykes intruded east of the village Eberstadt (location sample 8, Fig. 2) at 434 ± 4 Ma into paragneiss, amphibolite, and diabase which probably represent Cadomian basement. The dykes are the first igneous rocks known from the MGCZ which intruded during Silurian time into metasediments with Armorican affinity. The U–Pb age of 434 ± 4 Ma on zircons matches within its error with the Silurian granite gneiss of the northern Ruhla Crystalline Complex (423 ± 6 Ma and 426 ± 4 Ma, Brätz 2000), but they intruded into Early Palaeozoic metasediments with Baltica affinity (Zeh and Gerdes 2009). Zeh and Will (2010) interpreted these Silurian calc-alkaline granites of Ruhla as volcanic-arc granitoids, which might indicate an NW-directed subduction of the Rheic ocean underneath the former Laurussia continental shelf. Probably, the granitoids represent the plutonic equivalent of the Silurian volcanic arc (metarhyolite and metaandesite, 433 ± 9 Ma) described by Sommermann et al. (1994) from the Northern Phyllite Belt (Fig. 14). In the central part of the Spessart antiform, metagranodiorites intruded also in the Silurian (Dombrowski et al. 1995) into metasediments but with unknown provenance.

Younger, Devonian igneous rocks intruded into the basement of the Odenwald. The granite protolith of the Lower Devonian orthogneiss of Wembach (Fig. 2, sample 9) intruded at 411 ± 5 Ma into metasediments with probably Armorican affinity. In the East Odenwald metagranodiorite intruded into paragneiss and amphibolite at 405 ± 3 Ma (Reischmann et al. 2001, Fig. 2, unit IV), which are interpreted as a remnant of an Early Devonian magmatic arc

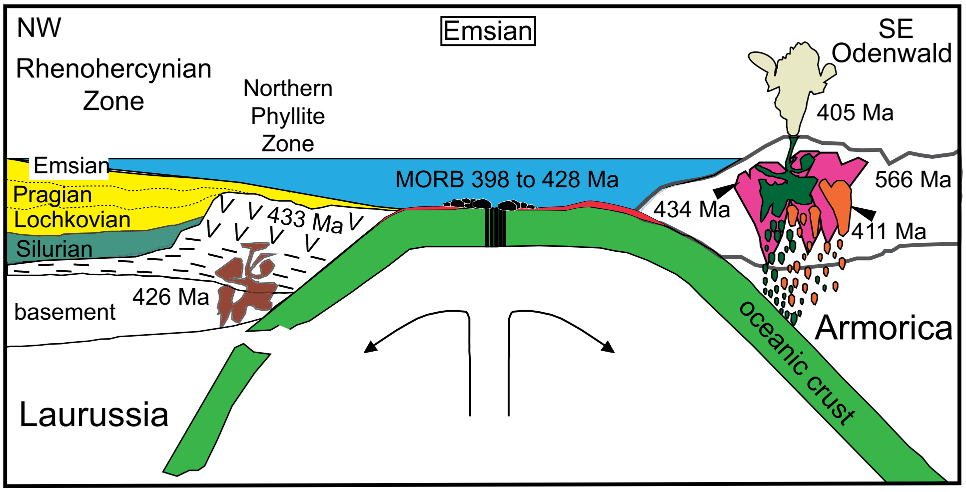


Fig. 14 Tentative model of the Lower Devonian active continental margin of Armorica. Numbers represent the U–Pb age of zircons of the igneous rocks: 433 ± 9 Ma, Sommermann et al. (1994); 426 ± 4 Ma, Brätz (2000); 405 ± 3 Ma, Reischmann et al. (2001); 566 ± 2 Ma, samples 2 and 3, this study; 434 ± 4 Ma, sample 8, this study; 411 ± 5 Ma, sample 9, this study. The educt ages of the oceanic crust: 387–407 Ma, Dörr (1986); 397 ± 2 Ma, Clark et al. (1998); 400 −420 Ma, Oliver et al. (1993); Dubińska et al. (2004); 428 ± 6 Ma, Finger and von Quadt (1995)

similar to the nearby Spessart Crystalline (Altenberger and Besch 1993; 410±18 Ma, U–Pb on zircon, Dombrowski et al. 1995; Oncken 1997). Similar Devonian ages are known from metaigneous rocks of the Central Gneiss Unit of the Ruhla Crystalline Complex at 413 ± 5 Ma and 398 ± 3 Ma (Brätz 2000, Fig. 1). A nearly continuous succession of granite and granodiorite intrudes into the basement of the MGCZ from the Silurian to Lower Devonian times. U–Pb zircon ages at 434 Ma, 418 Ma, 411 Ma, 410 Ma, 405 Ma, and 398 Ma could be interpreted as a magmatic arc at the northern boundary of Armorica pointing to a subduction beneath the MGCZ to the southeast. Taking the Silurian-to-Devonian plutons of the Odenwald, the Silurian volcanic arc at the southern edge of the Rhenohercynian Zone and the Silurian-to-Devonian ocean crust (428–398 Ma) into account, a simple tentative model with a subduction zone to the northwest beneath Laurussia and to the southeast beneath Armorica could be assumed during the Silurian, which vanished in the Lower Devonian (Fig. 14) in the Northern Phyllite Belt.

Early Variscan imprint

A second, Devonian, metamorphism overprinted the whole Cadomian basement. Zircons grown under solid-state metamorphic condition could be detected in both, the orthogneiss at 386 ± 7 Ma (Fig. 8b) and the metagranite at 384 ± 4 Ma (Fig. 9b). Similar U–Pb data on zircons at 375 ± 2 Ma (lower intercept age) are interpreted as the age of the amphibolite facies metamorphism of the mantle sequence (Beerfurth paragneiss, Fig. 2, unit IV, brown color) in the East Odenwald (Todt et al. 1995). U–Pb ID-TIMS analyses of single titanite grains of the variegated series of the Cadomian basement prove also a second metamorphism at 369 ± 1 Ma (Fig. 10b) and a slow cooling below 600 °C. Similar K–Ar ages of amphibole at 371 Ma (Kreuzer and Harre 1975) of the Cadomian basement east of Auerbach also point to a Devonian metamorphism and no later heating of the basement above a temperature of 450 °C. This Devonian thermal event is widespread in crystalline basement of the Saxothuringian Zone. In the Münchberger nappe, Ar–Ar and K–Ar ages on muscovite and hornblende of 372–390 Ma (Kreuzer et al. 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. The Cadomian basement of the West Odenwald displays similar Ediacaran and Devonian magmatic and metamorphic events such as the Münchberger nappe and could also be interpreted as a nappe. Devonian U–Pb zircon and monazite ages (380–387 ± 3 Ma, ID-TIMS) are also detected in Moldanubian Zone (Timmermann et al. 2004, 2006). Further to the West, in the Armorican Massif, Devonian monazites (405–370 Ma) from the Brioverian micaschists prove also an Early Variscan overprint of Cadomian basement (Schulz 2013).

Conclusions

Provenance

South of the Rheic suture zone the Mid-German Crystalline Zone, the Saxothuringian Zone and the Tepla–Barrandian Unit belong to Armorica. Armorican U–Pb age spectra of detrital zircons (Mesoproterozoic age gap) of the Mid-German Crystalline Zone have been detected from Ediacaran to Ordovician times. The Wartenstein Crystalline basement (Mesoproterozoic ages) in the Rheic suture zone can be correlated with the London–Brabant high. The boundary of the Armorica to Laurussia is between the West Odenwald and the Wartenstein Crystalline. The southern boundary of the Armorican to the Minoan continent can be traced in the East Alps (Armorica, Mandl et al. 2018; Minoean, Heinrichs et al. 2012).

Cadomian basement

A part of the Cadomian volcanic arc is located in the Mid-German Crystalline Zone. This is the link between the Bohemian Massif and the Armorican Massif. Cadomian orthogneiss (567 Ma) and paragneiss are overprinted by a Late Ediacaran metamorphism. Granite dykes intruded at 542 Ma into this metamorphic Cadomian basement. The plutons of the northern Frankenstein Massif, which intruded at 540 Ma into the paragneiss, could be correlated with the Cadomian Mancellian batholith (Armorican Massif). The Silurian and Devonian plutons, which intruded at 434 Ma and 411 Ma into the Cadomian basement, point to an active Armorican continental margin (Fig. 14). During the Devonian, the Cadomian basement was overprinted at 382 ± 3 Ma by a high-grade metamorphism and never reached a temperature above 450 °C after 370 Ma.

The newly discovered Cadomian basement of the Mid-German Crystalline Zone can be correlated with the Tepla–Barrandian Unit and the Sudetes to the East and with the St. Malo-Mancellian terrane (North Armorican terrane) to the West.

Acknowledgements We are grateful to Janina Schastok and Linda Marko (Universität Frankfurta.M.) for their invaluable help with the isotopic analyses. The quality of the paper was improved by the comments of Jiří Žák (Praha) and Friedrich Finger (Salzburg). All of these are kindly acknowledged.

References

Adusumalli CI, Schubert W (2001) Geochemistry of metabauxites in the Bergsträsser Odenwald (Mid German Crystalline Rise) and palaeoenvironmental. Implic Mineral Petrol 72:45–62

Ahrendt H, Clauer N, Hunziker JC, Weber K (1983) Migration of folding and metamorphism in the Rheinisches Schiefergebirge deduced from K–Ar and Rb–Sr age determinations. In: Martin H, Eder FW (eds) Intracontinental fold belts. Springer, Berlin, pp 323–338

Altenberger U, Besch T (1993) The Böllstein Odenwald: evidence for pre- to early Variscan plate convergence in the Central European Variscides. Geol Rundsch 82:475–488

Altenberger U, Besch T, Mocek B, Zaipeng Y, Yong S (1990) Geochemie und Geodynamik des Böllsteiner Odenwaldes. Mainzer geow Mitt 19:183–200

Altherr R, Henes-Klaiber U, Hegner E, Satir M, Langer C (1999) Plutonism in the Variscan Odenwald (Germany): from subduction to collision. Int J Earth Sci 88:422–443

Anderle H-J, Franke W, Schwab M (1995) Stratigraphy of the phyllite zone in tectonostratigraphic evolution of the Central and East European orogens. In: Dallmeyer RD, Franke W, Weber K (eds) Pre-Permian geology of Central and Eastern Europe. Springer, Berlin, pp 99–107

Anthes G, Reischmann T (2001) Timing of granitoid magmatism in the eastern mid-German crystalline rise. J Geodyn 31:119–143

Bachtadse V, Torsvik TH, Tait JA, Soffel HC (1995) Paleomagnetic constraints on the paleogeographic evolution of Europe during the Paleozoic. In: Dallmeyer RD, Franke W, Weber K (eds) Prepermian geology of Central and Eastern Europe. Springer, Berlin, pp 567–578

Bahlburg H, Vervoort JD, Du Frane SA (2010) Plate tectonic significance of Middle Cambrian and Ordovician siliciclastic rocks of the Bavarian Facies, Armorican Terrane Assemblage, Germany—U–Pb and Hf isotope evidence from detrital zircons. Gondwana Res 17:223–235

Belka Z, Ahrendt H, Franke W, Wemmer K (2000) The Baltica-Gondwana suture in central Europe: evidence from K–Ar ages of detrital muscovites and biogeographical data. In: Franke W, Haak V, Oncken O, Tanner D (eds) Orogenic processes: quantification and modelling in the Variscan Belt, vol 179. Geological Society, London, Special Publications, London, pp 87–102

Belka Z, Valverde-Vaquero P, Dörr W, Ahrendt H, Wemmer K, Franke W, Schäfer J (2002) Accretion of first Gondwana-derived terranes at the margin of Baltica. In: Winchester JA, Pharaoh TC, Verniers J (eds) Palaeozoic amalgamation of Central Europe, vol 201. Geological Society, London, Special Publications, London, pp 19–36

Bierther W (1941) Geologie des unteren Hahnenbachtales bei Kirn a. d. Nahe. Jahresber Reichsst Bodenforsch 61:109–156

Brätz H (2000) Radiometrische Altersdatierungen und geochemischen Untersuchungen von Orthogneisen, Granite und Granitporphyren aus dem Ruhlaer Kristallin, Mitteldeutsche Kristallinzone. Dissertation Univ. Würzburg, Germany, pp 1–151

Brinkmann R (1948) Die mitteldeutsche Schwelle. Geol Rundsch 36:55–66

Buschmann B (1995) Geotectonic facies analysis of the Rothstein Formation (Neoproterozoic, Saxothuringian Zone, Germany). Unpublished Thesis Bergakademie Freiberg

Clark AH, Scott DJ, Sandeman HA, Bromley AV, Farrar E (1998) Siegenian generation of the Lizard ophiolite: U–Pb zircon age data for plagiogranite, Porthkerries, Cornwall. J Geol Soc Lond 155:595–598

Cocks LRM, Fortey RA (2009) Avalonia—a long-lived terrane in the Lower Palaeozoic? Geol Soc Lond Spec Publ 325:141–154

Dickinson WR, Gehrels GE (2009) Use of U–Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database. Earth Planet Sci Lett 288:115–125

Dittmar U, Oncken O (1992) Anatomie und Kinematik eines passiven varistischen Kontinentalrandes—zum Strukturbau des südwestlichen Rheinischen Schiefergebirges. Frankf Geowiss Arb Ser A 11:34–37

Dombrowski A, Henjes-Kunst F, Höhndorf A, Kröner A, Okrusch M, Richter P (1995) Orthogneisses in the Spessart Crystalline Complex, north-west Bavaria: Silurian granitoid magmatism at an active continental margin. Geol Rundsch 84:399–411

Dörr W (1986) Stratigraphie, Stoffbestand und Fazies der Giessener Grauwacke (E' Rheinisches Schiefergebirge). Diss Universität Giessen, pp 1–134

Dörr W, Zulauf G, Fiala J, Franke W, Vejnar Z (2002) Neoproterozoic to Early Cambrian history of an active plate margin in the Teplá-Barrandian unit—a correlation of U–Pb isotopic-dilution-TIMS ages (Bohemia, Czech Republic). Tectonophysics 352:65–85

Dörr W, Zulauf G, Gerdes A, Lahaye J, Kowalczyk G (2015) A hidden Tonian basement in the eastern Mediterranean: age constraints from U–Pb data of magmatic and detrital zircons of the External Hellenides (Crete and Peloponnesus). Precambrian Res 258:83–108

Dörr W, Zulauf G, Gerdes A, Loeckle F (2017) Provenance of Upper Devonian clastic (meta)sediments of the Böllstein Odenwald (Mid-German-Crystalline-Zone, Variscides). Int J Earth Sci 106:2927–2943

Drost K (2008) Sources and geotectonic setting of Late Neoproterozoic-Early Paleozoic volcano-sedimentary successions of the Teplá-Barrandian unit (Bohemian Massif): evidence from petrographical, geochemical, and isotope analyses. Geologica Saxonica 54:1–165

Dubińska E, Bylina P, Kozlowski A, Dörr W, Nejbert K (2004) U–Pb dating of serpentinization: hydrothermal zircon from a metasomatic rodingite shell (Sudetic ophiolite, SW Poland). Chem Geol 203:183–203

Eckelmann K, Nesbor D, Königshof P, Linnemann U, Hofmann M, Lange J-M, Sagawe A (2013) Plate interactions of Laurussia and Gondwana during the formation of Pangaea-Constraints by U–Pb LA-SF-ICP-MS detrital zircon ages of Devonian and Early Carboniferous siliciclastics of the Rheinisches Schiefergebirge. (Rhenohercynian zone, Central European Variscides). Gondwana Res 25:1484–1500

Fedo CM, Sircombe KN, Rainbird RH (2003) Detrital zircon analysis of the sedimentary record. In: Hanchar JM, Hoskin PWO (eds) Zircon. Mineralogical Society of America and Geochemistry Society, reviews in mineralogy and geochemistry, vol 53. Washington, DC, pp 277–303

Finger F, von Quadt A (1995) U/Pb ages of zircons from a plagiogranite-gneiss in the south-eastern Bohemian Massif, Austria—further evidence for an important early Paleozoic rifting episode in the eastern Variscides. Schweiz Mineral Petrogr Mitt 75:265–270

Franke W (1989) Tectonostratigraphic units in the Variscan belt of central Europe. Geol Soc Am Spec Pap 230:67–89

Franke W, Oncken O (1990) Geodynamic evolution of the north-central Variscides: a comic strip. In: Freeman R, Giese P, Mueller S (eds) The European geotraverse: integrative studies. European Science Foundation, Strasbourg, pp 187–194

Frei D, Gerdes A (2008) Accurate and precise in situ zircon U–Pb age dating with high spatial resolution and high sample through put by automated LA-SF-ICP-MS. Chem Geol 261(3–4):261–270

Geisler T, Vinx R, Martin-Gombojav N, Pidgeon RT (2005) Ion microprobe (SHRIMP) dating of detrital zircon grains from quartzites of the Eckergneiss Complex, Harz Mountains (Germany):

implications for the provenance and the geological history. Int J Earth Sci (Geol Rundsch) 94:369–384

Hajná J, Žák J, Dörr W (2017) Time scales and mechanisms of growth of active margins of Gondwana: a model based on detrital zircon ages from the Neoproterozoic to Cambrian Blovice accretionary complex, Bohemian Massif. Gondwana Res 42:63–83

Hartmann LA, Santos JOS (2004) Predominance of high Th/U, magmatic zircon in Brazilian Shield sandstones. Geology 32:73–76

Haverkamp J (1991) Detritusanalyse unterdevonischer Sandsteine des Rheinisch-Ardennischen Schiefergebirges und ihre Bedeutung für die Rekonstruktion der sedimentliefernden Hinterländer. Thesis Techn Univ Aachen, p 156

Heinrichs T, Siegesmund S, Frei D, Drobe M, Schulz B (2012) Provenance signatures from whole-rock geochemistry and detrital zircon ages of metasediments from the Austroalpine basement south of the Tauern Window (Eastern Tyrol, Austria). Geo Alp 9:156–185

Henes-Klaiber U (1992) Zur Geochemie der variszischen Granitoide des Bergsträsser Odenwalds. Thesis, University of Karlsruhe

Hindel R (1975) Geochemische Untersuchung der Paragneise zwischen Heppenheim und Lindenfels/Odenwald. In: Amstutz GC, Meisl S, Nickel E (eds) Mineralien und Gesteine im Odenwald, vol 27. Aufschluß Sonderband, Heidelberg, pp 135–139

Kirsch H, Kober B, Lippolt HJ (1988) Age of intrusion and rapid cooling of the Frankenstein gabbro (Odenwald, SW-Germany) evidenced by ^{40}Ar/^{39}Ar and single zircon ^{207}Pb/^{206}Pb measurements. Geol Rdsch 77(3):693–711

Klemm G (1918) Erläuterungen zur geologischen Karte. Großherzogthum Hessen, 1:25 000, Blatt Neunkirchen, 2nd edn. Großherzoglicher Staatsverlag, Darmstadt, p 81

Klemm DD, Weber-Diefenbach K (1975) Zur Genese du Odenwälder Amphibolite, Gneise und Basite. In: Amstutz GC, Meisl S, Nickel E (eds) Mineralien und Gesteine imOdenwald, vol 27. Aufschluß Sonderband, Heidelberg, pp 141–148

Koglin N, Zeh A, Franz G, Schüssler U, Glodny J, Gerdes A, Brätz H (2018) From Cadomian magmatic arc to Rheic ocean closure: the geochronological-geochemical record of nappe protoliths of the Münchberg Massif, NE Bavaria (Germany). Gondwana Res 55:135–152

Kossmat F (1927) Gliederung des varistischen Gebirgsbaues. Abh d Sächs Geol Landesamts 1:1–39

Kreher B (1994) Petrologie und Geochemie der Gabbrointrusionen des Frankensteins (Odenwald). Geol Jb Hessen 122:81–122

Kreuzer H, Harre W (1975) K/Ar-Altersbestimmungen an Hornblenden und Biotiten des Kristallinen Odenwaldes. In: Amstutz GC, Meisl S, Nickel E (eds) Mineralien und Gesteine im Odenwald, vol 27. Aufschluß Sonderband, Heidelberg, pp 71–77

Kreuzer H, Seidel E, Schüssler U, Okrusch M, Lenz K-L, Raschka H (1989) K–Ar geochronology of different tectonic units at the northwestern margin of the Bohemian massif. Tectonophysics 157:149–178

Krohe A (1994) Verformungsgeschichte in der mittleren Kruste eines magmatischen Bogens. Geotekt Forsch 80:1–147

Krohe A, Willner AP (1995) The Odenwald crystalline complex. In: Dallmeyer RD, Franke W, Weber K (eds) Pre-permian geology of Central and Eastern Europe. Springer, Berlin, pp 174–181

Kröner A, Jaeckel P, Hegner E, Opletal M (2001) Single zircon ages and whole-rock Nd isotopic systematics of early Palaeozoic granitoid gneiss from the Czech and Polish Sudetes (Jizerske hory, Krkonose Mountains and Orlice-Sneznik Complex). Int J Earth Sci 90:304–324

Kupfahl HG, Meisl S, Kümmerle E (1972) Erläuterungen zur Geologischen Karte von Hessen 1:25000 Blatt Nr. 6217 Zwingenberg a. d. Bergstraße. Hessisches Landesamt für Bodenforschung, Wiesbaden, pp 1–276

Linnemann U, Gemlich M, Tichomirowa M, Buschmann B, Nasdala L, Jonas P, Lützer H, Bomback K (2000) From Cadomian subduction to Early Paleozoic rifting: the evolution of Saxo-Thuringia at the margin of Gondwana in the light of single zircon geochronology and basin development (Central European Variscides, Germany). Geol Soc Lond Spec Publ 179:131–153

Linnemann U, McNaughton NJ, Romer RL, Gehmlich M, Drost K, Tonk C (2004) West African provenance for Saxo-Thuringia (Bohemian Massif): did Armorica ever leave pre-Pangean Gondwana?—U/Pb-SHRIMP zircon evidence and the Nd isotopic record. Int J Earth Sci 93:683–705

Linnemann U, Gerdes A, Drost K, Buschmann B (2007) The continuum between Cadomian Orogenesis and opening of the Rheic Ocean: constraints from LA–ICP–MS U–Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, NE Bohemian massif, Germany). In: Linnemann U, Nance RD, Kraft P, Zulauf G (eds) The evolution of the Rheic Ocean: From Avalonian–Cadomian Active Margin to Alleghenian–Variscan Collision. Geological Society of America Special Paper, vol 423, pp 61–96

Linnemann U, Pereira F, Jeffries TE, Drost K, Gerdes A (2008) The Cadomian Orogeny and the opening of the Rheic Ocean: the diachrony of geotectonic processes constrained by LA-ICP-MS U–Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). Tectonophysics 461:21–43

Linnemann U, Herbosch A, Liégeois J-P, Pin C, Gärtner A, Hofmann M (2012) The Cambrian to Devonian odyssey of the Brabant Massif within Avalonia: a review with new zircon ages, geochemistry, Sm–Nd isotopes, stratigraphy and palaeogeography. Earth Sci Rev 112:126–154

Linnemann U, Gerdes A, Mandy Hofmann M, Marko L (2013) The Cadomian Orogen: neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton—constraints from U–Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). Precambrian Res 244:236–278

Linnemann U, Pidal AP, Hofmann M, Drost K, Quesada C, Gerdes A, Marko L, Gärtner A, Zieger J, Ulrich J, Krause R, Vickers-Rich P, Horak J (2018) A ~ 565 Ma old glaciation in the Ediacaran of peri-Gondwanan West Africa. Int J Earth Sci (Geol Rundsch) 107:885–911

Lippolt HJ (1986) Nachweis altpaläozoischer Primäralter (Rb–Sr) und karbonischer Abkühlungsalter (K–Ar) der Muskovit-Biotit-Gneise des Spessarts und der Biotit-Gneise des Böllsteiner Odenwaldes. Geol Rundsch 75(3):569–583

Ludwig KR (2001) User's manual for Isoplot/Ex version 2 49, a geochronological toolkit for microsoft excel. Berkley Geochronology Center Special Publication 1a, Berkley CA USA

Ludwig KR, Mundil R (2002) Extracting reliable U–Pb ages and errors from complex populations of zircons from Phanerozoic tuffs. Geochim Cosmochim Acta 66:463

Mandl M, Kurz W, Hauzenberger C, Fritz H, Klötzli U, Schuster R (2018) Pre-alpine evolution of the Seckau Complex (Austroalpine basement/Eastern Alps): constraints from in situ LA-ICP-MS U\Pb zircon geochronology. Lithos 296–299:412–430

Massonne H-J (1995) III.C.4 Metamorphic evolution. In: Dallmeyer RD, Franke W, Weber K (eds) Pre-Permian geology of central and eastern Europe, IGCP 233. Springer, Berlin, pp 132–137

Massonne H-J, Schreyer W (1983) A new experimental phengite barometer and its application to a Variscan subduction zone at the southern margin of the Rhenohercynicum. Terra Abstr 3:187

Matte P (1986) Tectonics and plate tectonics model for the Variscan Belt of Europe. Tectonophysics 126:329–374

Matthes S, Okrusch M, Richter P (1972) Zur Migmatitbildung im Odenwald. N Jb Mineral Abh 116:225–267

Meisl S (1990) Metavolcanic rocks in the Northern Phyllite Zone at the southern margin of the Rhenohercynian belt. In: Field guide: mid-German crystalline rise and Rheinisches Schiefergebirge. Int Conf Paleozoic orogens in central Europe, Göttingen Giessen, pp 25–42

Meisl S, Kreuzer H, Höhndorf A (1989) Metamorphose Bedingungen und -Alter des Kristallins am Wartenstein bei Kirn/Nahe. Vortrag, 5. Rundgespräch "Geodynamik des europaischen Variszikums". Braunschweig 16.-18.11.1989

Molzahn M, Anthes G, Reischmann T (1998) Single zircon Pb/Pb age chronology and isotope systematics of the Rhenohercynian basement. Terra Nostra 98(1):67–68

Murphy JB, Fernández-Suárez J, Jeffries T, Strachan RA (2004a) U–Pb (LA–ICP-MS) dating of detrital zircons from Cambrian clastic rocks in Avalonia: erosion of a Neoproterozoic arc along the northern Gondwanan margin. J Geol Soc Lond 161:243–254

Murphy JB, Pisarevsky SA, Nance D, Keppie JD (2004b) Neoproterozoic-Early Palaeozoic evolution of peri-Gondwanan terranes: implications for Laurentia-Gondwana connections. Int J Earth Sci 93:659–682

Okrusch M (1995) Metamorphic evolution. In: Dallmeyer RD, Franke W, Weber K (eds) Pre-Permian geology of Central and Eastern Europe. Springer, Berlin, pp 201–213

Okrusch M, Raumer JV, Matthes S, Schubert W (1975) Mineralfazies und Stellung der Metamorphite im kristallinen Odenwald. In: Amstutz GC, Meisl S, Nickel E (eds) Mineralien und Gesteine im Odenwald, vol 27. Aufschluß Sonderband, Heidelberg, pp 109–134

Okrusch M, Geyer G, Lorenz J (2011) Sammlung geol Führer 106: Spessart: 386, Berlin (Borntraeger)

Oliver GJH, Corfu F, Krogh TE (1993) U–Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. J. Geol Soc Lond 150:355–369

Oncken O (1997) Transformation of a magmatic arc and an orogenic root during oblique collision and it's consequences for the evolution of the European Variscides (Mid-German Crystalline Rise). Geol Rundschau 86:2–20

Oncken O, Winterfeld CV, Dittmar U (1999) Accretion of a rifted passive margin: the late Paleozoic Rhenohercynian fold and thrust belt (Middle European Variscides). Tectonics 18:75–91

Pasteels P, Dore F (1982) Age of the Vire Carolles granite. In: Odin GS (ed) Numerical dating in stratigraphy. Wiley, New York, pp 784–790

Peucat JJ (1983) Géochronologie des roches métamorphiques (Rb–Sr and U– Pb). Exemples choisis au Groenland, en Laponie, dans le Massif Armoricain et en Grande Kabylie. Mémoire de la Société Géologique et Minéralogique de Bretagne, p 28

Peucat JJ (1986) Behaviour of Rb–Sr whole rock and U–Pb zircon systems during partial melting as shown in migmatitic gneisses from the St. Malo Massif, NE Brittany, France. J Geol Soc Lond 143:875–886

Pupin JP (1980) Zircon and granite petrology. Contrib Mineral Petrol 73:207–220

Raumer vJ (1973) Die mineralfazielle Stellung der Metapelite und Metagrauwacken zwischen Heppenheim und Reichelsheim (Odenwald). N Jb Mineral Abh 118:313–336

Reischmann T, Anthes G, Jaekel P, Altenberger U (2001) Age and origin of the Böllsteiner Odenwald. Miner Petrol 72:29–44

Schafft R (1985) Makro- und mikrostrukturelle Untersuchungen der Metamorphen Zone im südlichen Hunsrück. Thesis Univ Göttingen

Scholtz H (1934) Die Tektonik des Steinkohlenbeckens im Saar-Nahe-Gebiet und die Entstehungsweise der Saar-Saale-Senke. Z Dtsch Geol Ges 85:316–382

Schubert W (1968) Die Amphibolite des prävaristischen Schieferrahmens im Bergsträsser Odenwald. N Jb Mineral Abh 108:69–110

Schubert W, Lippolt HJ, Schwarz W (2001) Early to middle Carboniferous hornblende ^{40}Ar/^{39}Ar ages of amphibolites and gabbros from the Bergsträsser Odenwald. Mineral Petrol 72:113–132

Schulz B (2013) Monazite EMP-Th–U–Pb age pattern in Variscan metamorphic units in the Armorican Massif (Brittany, France). Z Dt Ges Geowiss 164(2):313–335

Siebel W, Eroglu S, Shang CK, Rohrmüller J (2012) Zircon geochronology, elemental and Sr–Nd isotope geochemistry of two Variscan granitoids from the Odenwald-Spessart crystalline complex (Mid-German Crystalline Rise). Mineral Petrol 105:187–200

Sláma J, Dunkley DJ, Kachlík V, Kusiak MA (2008) Transition from island-arc to passive setting on the continental margin of Gondwana: U–Pb zircon dating of Neoproterozoic metaconglomerates from the SE margin of the Teplá–Barrandian Unit, Bohemian Massif. Tectonophysics 461(1–4):44–59

Söllner F, Köhler H, Müller-Sohnius D (1981) Rb/Sr-Altersbestimmungen an Gesteinen der Münchberger Gneismasse (MM), NE Bayern—Teil 2, Mineraldatierungen. N Jahrb Miner Abh 142(2):178–198

Sommermann A-E, Anderle H-J, Todt W (1994) Das Alter des Quarzkeratophyrs der Krausaue bei Rüdesheim am Rhein (Blatt 6013 Bingen, Rheinisches Schiefergebirge). Geol Jahrb Hessen 122:143–157

Stein E (1996) Untersuchungen zur Genese der Flasergranitoid-Zone des zentralen Odenwaldes—Magmatische und/oder tektonische Gefüge. Z Geol Wiss 24(5/6):573–583

Stein E (2000) Zur Platznahme von Granitoiden—Vergleichende Fallstudien zu Gefügen und Platznahmemechanismen aus den White-Inyo Mountains, California, USA und dem Bergsträsser Odenwald. Geotekt Forsch 93:1–344

Stein E (2001) The geology of the Odenwald crystalline complex. Mineral Petrol 72:7–28

Tait JA, Bachtadse V, Franke W, Soffel H (1997) Geodynamic evolution of the European Variscan fold belt:palaeomagnetic and geological constraints. Geol Rundsch 86:585–598

Tait JA, Schatz M, Bachtadse V, Soffel H (2000) Palaeomagnetism and Palaeozoic palaeogeography of Gondwana and European terranes. In: Franke W, Haak V, Oncken O, Tanner D (eds) Orogenic processes: quantification and modelling in the Variscan Belt, vol 179. Geological Society, London, Special Publications, London, pp 21–34

Teipel U (2003) Obervendischer und Unterordovizischer Magmatismus im Bayerischen Wald: Geochronologische (SHRIMP), geochemische und isotopen-geochemische Untersuchungen an Metamagmatiten aus dem Westteil des Böhmischen Massivs. Münchner Geol Hefte 33:1–98

Timmermann H, Štědrá V, Gerdes A, Noble SR, Parrish RR, Dörr W (2004) The problem of dating high-pressure metamorphism: a U–Pb isotope and geochemical study on eclogites and related rocks of the Mariánské Lázně Complex, Czech Republic. J Petrol 45:1311–1338

Timmermann H, Dörr W, Krenn E, Finger F, Zulauf G (2006) Conventional and in situ geochronology of the Teplá Crystalline unit, Bohemian Massif: implications for the processes involving monazite formation. Int J Earth Sci 95:629–647

Todt WA, Altenberger U, von Raumer J (1995) U-Pb data on zircons for the thermal peak of metamorphism in the Variscan Odenwald, Germany. Geologische Rundschau 84:466–472

Valverde-Vaquero P, Dörr W, Belka Z, Franke W, Wiszniewska J, Schastok J (2000) U–Pb single-grain dating of detrital zircon in the Cambrian of central Poland: implications for Gondwana versus Baltica provenance studies. Earth Planet Sci Lett 184:225–240

van Breemen O, Henderson J B, Loveridge W D, Thompson P H (1987) U–Pb zircon and monazite geochronology and zircon morphology of granulites and granite from the Thelon Tectonic

Zone, Healey Lake and Artillery Lake map areas, NWT. Current research part A, Geological survey of Canada paper, vol 87, no 1A, pp 783–801

Weber K, Behr H-J (1983) Geodynamic interpretation of the mid European Variscides. In: Martin H, Eder FW (eds) Intracontinental fold belts—case studies in the Variscan Belt of Europe and in the Damara Belt in Namibia. Springer, Berlin, pp 427–469

Weber-Diefenbach K (1974) Geochemische Untersuchungen an Biotit-Dioriten, Hornblende-Dioriten und Metamorphiten des mittleren kristallinen Odenwaldes. N Jb Mineral Abh 120:119–146

Will TM, Lee S-H, Schmädicke E, Frimmel HE, Okrusch M (2015) Variscan terrane boundaries in the Odenwald-Spessart basement, Mid-German crystalline zone: new evidence from ocean ridge, intraplate and arc-derived metabasaltic rocks. Lithos 220–223:23–42

Will TM, Schulz B, Schmädicke E (2017) The timing of metamorphism in the Odenwald-Spessart basement, Mid-German crystalline zone. Int J Earth Sci 106(5):1631–1649

Will TM, Schmädicke E, Ling X-X, Li X-H, Li Q-L (2018) New evidence for an old idea: geochronological constraints for a paired metamorphic belt in the central European Variscides. Lithos 302–303:278–297

Willner AP, Massone H-J, Krohe A (1991) Tectono-thermal evolution of a part of a Variscan magmatic arc: the Odenwald in the Mid-German Crystalline Rise. Geol Rundsch 80:369–389

Willner AP, Barr SM, Gerdes G, Massonne HJ, White CE (2013) Origin and evolution of Avalonia: evidence from U–Pb and Lu–Hf isotopes in zircon from the Mira terrane, Canada, and the Stavelot-Venn Massif, Belgium. J Geol Soc Lond 170:769–784

Willner AP, Gerdes A, Massonne HJ, van Staal CR, Zagorevski A (2014) Crustal evolution of the Northeast Laurentia Margin and the Peri-Gondwanan Microcontinent Ganderia Prior to and during closure of the Iapetus Ocean: U–Pb and Hf isotope evidence from Newfoundland. Geosci Can 41:345–363

Zeh A (1996) Die Druck-Temperatur-Deformations-Entwicklung des Ruhlaer Kristallins (Mitteldeutsche Kristallinzone). Geotekton Forsch 86:1–214

Zeh A, Gerdes A (2009) Baltica- and Gondwana-derived sediments in the Mid-German Crystalline Rise (Central Europe): implications for the closure of the Rheic ocean. Gondwana Res 17:254–263

Zeh A, Will TM (2010) The Mid-German crystalline zone. In: Linnemann U, Romer RL (eds) Pre-Mesozoic geology of Saxo-Thuringia—from the Cadomian active margin to the Variscan Orogen. Schweizerbart, Stuttgart, pp 195–220

Zelazniewicz A, Dörr W, Bylina P, Franke W, Franke W, Haack U, Heinisch H, Schastok J, Grandmontagne N, Kulicki C, Haack U, Heinisch H, Schastok J, Kulicki C (2004) The eastern continuation of the Cadomian orogen: U–Pb zircon evidence from Saxo-Thuringian granitoids in south-western Poland and the northern Czech Republic. Int J Earth Sci (Geol Rundsch) 93:773–781

Ziegler PA (1986) Geodyamic model for the Paleozoic crustal consolidation of Western and Central Europe. Tectonophysics 126:303–328

Zulauf G, Schitter F, Riegler G, Finger F, Fiala J, Vejnar Z (1999) Age constraints on the Cadomian evolution of the Teplá Barrandian unit (Bohemian Massif) through electron microprobe dating of metamorphic monazite. Z Deutsch Geol Ges 150:627–639

Zulauf G, Dörr W, Fiala J, Romano SS (2007) Crete and the Minoan Terranes: age constraints from U–Pb dating of detrital zircons. In: Linnemann U, Nance RD, Kraft P, Zulauf G (eds) The evolution of the Rheic Ocean: from Avalonian-Cadomian active margin to Alleghenian-Variscan collission. Geological Society of America Special Paper, vol 423, pp 401–409

Zulauf G, Dörr W, Fisher-Spurlock SC, Gerdes A, Chatzaras V, Xypolias P (2014) Closure of the paleotethys in the external hellenides: constraintsfrom U–Pb ages of magmatic and detrital zircons (Crete). Gondwana Res. https://doi.org/10.1016/j.gr.2014.06.011