



# A juvenile arc terrane in the Mid-German Crystalline Zone: constraints from zircon U–Pb–Hf isotope data and implications for pre- to syn-Variscan evolution

Marius Beck<sup>1</sup> · Armin Zeh<sup>2</sup> · Matthias Hinderer<sup>1</sup> · Henri P. Meinaß<sup>1</sup> · Dirk Scheuven<sup>1</sup> · Axel Gerdes<sup>3</sup>

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## Abstract

Presently, little is known about the zircon age–Hf isotope record of (meta)sedimentary rocks exposed in the southernmost part of the Mid-German Crystalline Zone and adjacent Rhenohercynian Domain, preventing detailed reconstructions of the geodynamic evolution in Central Europe. In this study, such data are presented from Late Devonian to Viséan greywackes and granite gneisses of the Palatinate Forest (Mid-German Crystalline Zone) and the Harz Mountains (Rhenohercynian). These provide evidence that clastic sedimentary rocks in both realms were sourced from a so far unrecognized, juvenile oceanic arc terrane, which was initially formed at 490–570 Ma ( $\epsilon\text{Hf}_t$  up to +13.0), and internally reworked at ca. 500, 400, 370 and 335 Ma ( $\epsilon\text{Hf}_t = +2.0$  to +8.4), prior to Variscan collision and post-collisional magmatism at 330 Ma. Late Devonian arc reworking is indicated by zircon U–Pb ages of ca. 370 Ma estimated for the Albersweiler granite gneiss ( $\epsilon\text{Hf}_t = +3.6$  to +7.7) and an amphibolite-facies paragneiss; other reworking events are indicated by the detrital zircon record. The results of data compilation further suggest that the oceanic arc terrane remained widely isolated from continental input within the Prototethys–Rheic oceanic realm until its collision with Avalonia at 335 Ma. The relics of the arc system became widely dispersed within the Saxothuringian, Rhenohercynian, Teplá-Barrandian, and Moldanubian domains during the Variscan collision and collapse.

**Keywords** Variscides · Mid-German Crystalline Zone · Palatinate Forest · U–Pb–Hf zircon · Juvenile arc · Rheic Ocean · Provenance

## Introduction

The detrital zircon record of clastic sedimentary rocks provides a powerful tool, which enables geoscientists to discriminate and correlate low- to high-grade metasedimentary rock units in mountain belts, which have been affected by a complex structural–metamorphic overprint during orogenic

accretion. Based on the zircon record, it is possible to gain detailed information not only about the age of sedimentation (e.g., Fedo et al. 2003; Linnemann et al. 2007; Gehrels et al. 2011), but also about the magmatic–metamorphic evolution in the hinterland prior to, and during, amalgamation (Eckelmann et al. 2014; Zeh et al. 2020). The maximum depositional age (MDA) is commonly reflected by the U–Pb age of the youngest detrital zircon grain or population (e.g., Vermeesch et al. 2023; Zeh et al. 2025a), and the timing of magmatic and metamorphic events in the source regions by the zircon age spectrum and related Th/U ratios (e.g., Kirchner and Albert 2020). In addition, the nature of magmatism in the hinterland is constrained by the Hf isotope record of zircon grains, allowing discrimination between juvenile crust formed from depleted mantle sources, internal reworking of ancient crust, and/or crust–mantle interaction (e.g., Gerdes and Zeh 2006, 2009; Hawkesworth and Kemp 2006; Laurent and Zeh 2015), although there are limits with

✉ Armin Zeh  
armin.zeh@kit.edu

<sup>1</sup> Institute of Applied Geosciences, Technical University of Darmstadt, Schnittspahnstr. 9, 64287 Darmstadt, Germany

<sup>2</sup> Institute for Applied Geosciences, Mineralogy and Petrology, KIT—Karlsruhe Institute of Technology, Adenauerring 20B, Geb. 50.4, 76131 Karlsruhe, Germany

<sup>3</sup> Frankfurt Isotope and Element Research Center (FIERCE), Goethe-University Frankfurt, 60438 Frankfurt am Main, Germany

respect to enriched mantle-derived (ultra-)potassic suites (Couzinié et al. 2016).

For unravelling the geodynamic evolution of the Variscides, such information is essential, in particular as many rock units, which initially were formed in well-defined geotectonic settings, became seriously modified by structural–metamorphic overprint, and additionally dispersed during syn- to post-collisional processes (e.g., Kroner and Romer 2013). In this study, the first combined set of in situ zircon U–Pb ages and Hf isotope data is presented for metasedimentary rocks and related granitoids from the southernmost part of the Mid-German Crystalline Zone (MGCZ), from the Palatinate Forest and, for comparison, from Devonian to Viséan greywackes of the Harz Mountains of the adjacent Rhenohercynian Domain. These new data, in addition to those compiled from adjacent Variscan basement units, provide new insights into the pre- to syn-Variscan geotectonic evolution, and lead to the definition of a so far unrecognized terrane within the MGCZ.

## Geological setting

### Mid-German Crystalline Zone

The Mid-German Crystalline Zone (MGCZ) represents an NE-trending alignment of basement units within the Central European Variscides, exposed from the NE to the SW in the Kyffhäuser Mountains, Ruhla Crystalline Complex, Spessart Crystalline Complex, Odenwald Crystalline Complex, Palatinate Forest and the northern Vosges (Fig. 1). Classically, it has been interpreted as a Variscan suture zone, separating the Saxothuringian Domain in the southeast from the Rhenohercynian Domain in the northwest (e.g., Kossmat 1927; Franke 1989).

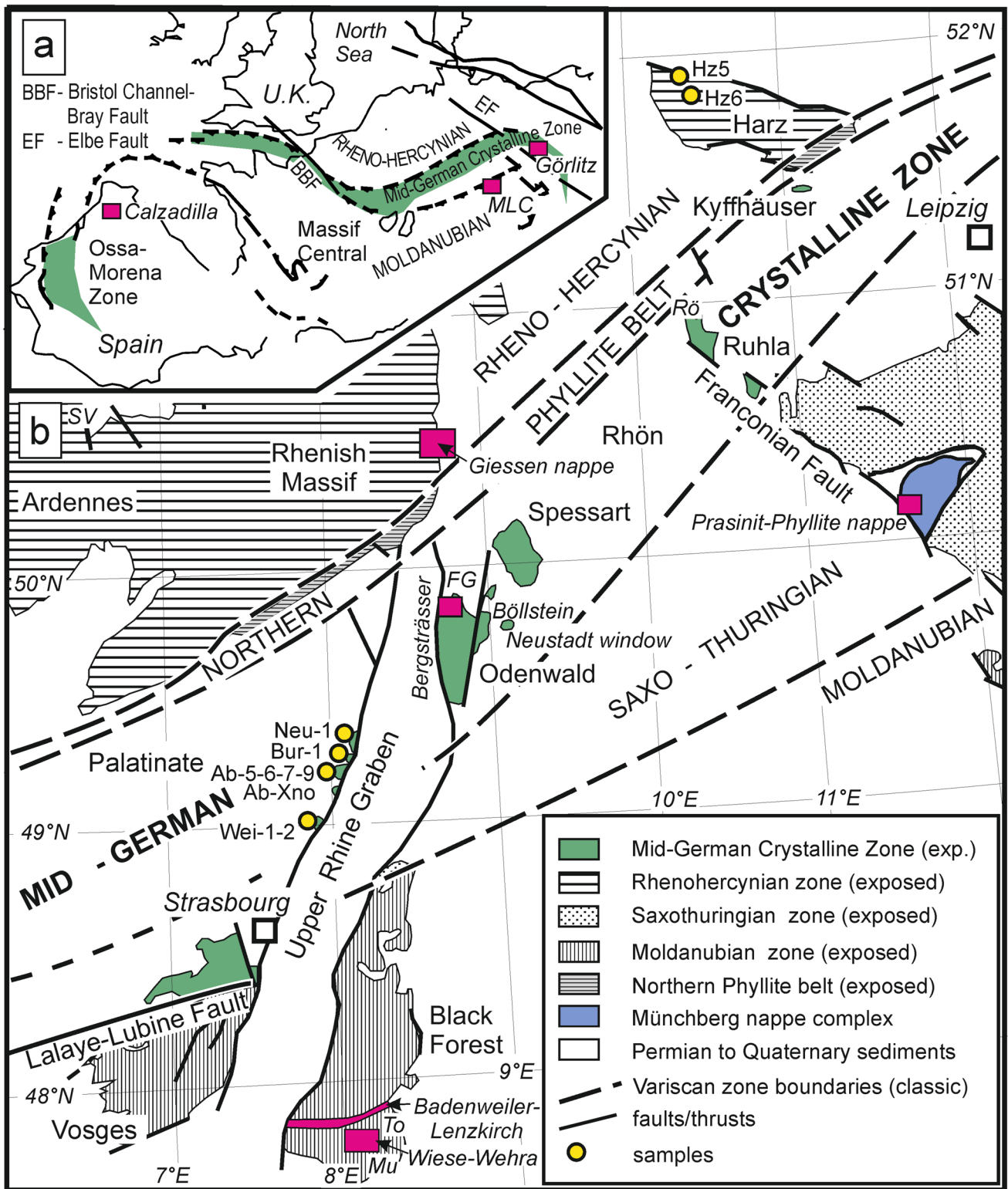
This simplistic interpretation, however, has been modified significantly over the past 15 years. Based on contrasting zircon age–Hf isotope spectra in metasedimentary rock units of the Ruhla Crystalline Complex, Zeh and Gerdes (2010) concluded that the MGCZ represents a composite terrane made up of at least two distinct basement units of different origin. Unit 1 hosts Silurian metasedimentary rocks with an N-Gondwana (Armorica–Cadomia) affinity, and Unit 2 Silurian/Devonian metasedimentary rocks sourced from SW-Baltica (Sveconorwegian). The metasedimentary rocks of Unit 2 were intruded by Silurian–Devonian granites (now orthogneisses) at 425–395 Ma in a magmatic-arc setting (Brätz 2000), perhaps related to NW-directed subduction of the Rheic Ocean beneath Avalonia (e.g., Zeh and Gerdes 2010; Eckelmann et al. 2014; Zeh et al. 2024b). The age spectra and Hf isotope compositions of detrital zircon populations of Unit 1 overlap those found in most (meta) sedimentary rocks exposed in the Saxothuringian Domain southeast of the MGCZ (e.g., Zeh et al. 2001; Bahlburg et al.

2010; Linnemann et al. 2013; Kühnemann et al. 2025), and those of Unit 2 overlap with most Devonian (meta)sandstones and greywackes of the Rhenohercynian Domain to the northwest of the MGCZ (Eckelmann et al. 2014; Linnemann et al. 2024; Zeh et al. 2024b; Dörr et al. 2025).

The twofold subdivision of the MGCZ suggested by Zeh and Gerdes (2010) was subsequently modified by new dating results, carried out on metasedimentary and magmatic rocks from both the Spessart and Odenwald Crystalline complexes by Dörr et al. (2017, 2022), Dörr and Stein (2019), Kirchner and Albert (2020), and Nesbor (2021). Zircon age spectra obtained from these basement complexes yielded MDAs ranging from the Neoproterozoic (550–530 Ma), through Ordovician (470–480 Ma) and Silurian (420 Ma), to Devonian (365 Ma), and provided evidence for the involvement of at least four distinct sediment sources, comprising (1) N-Gondwana (Cadomia), (2) SW-Baltica (Sveconorwegian), (3) Avalonia, and (4) SE-Baltica (Malopolska region). According to Kirchner and Albert (2020), SW-Baltica/Avalonia-derived metasedimentary rocks are predominant in the Spessart Crystalline Complex, whereas those of SE-Baltica (or exotic) provenance are restricted to the Böllstein Odenwald and the adjacent Neustadt window (i.e., Neustädter Fenster: Kirchner and Albert 2020; Dörr et al. 2022). We note that rocks of “exotic” provenance show a pronounced age peak at ca. 1500 Ma and Ordovician MDAs of ca. 475 Ma, and occur in close vicinity of metasedimentary rocks with Devonian MDAs, either showing SW-Baltica/Avalonia (Nesbor 2021) or Saxothuringian/Teplá-Barrandian (= Cadomian) age spectra (Dörr et al. 2017; Drost et al. 2010).

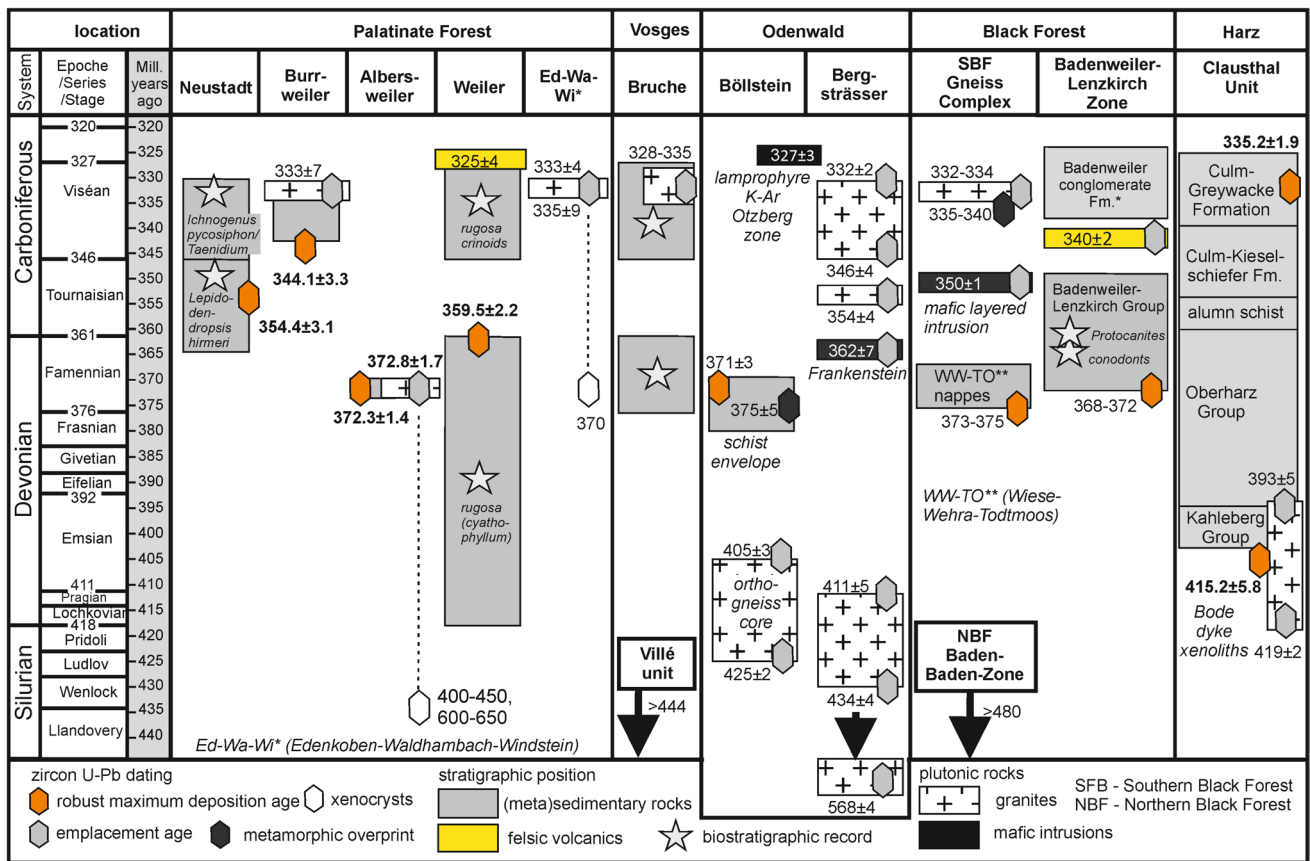
Dörr and Stein (2019) found the first unambiguous evidence for the existence of a Cadomian basement in the MGCZ. Based on comprehensive zircon U–Pb dating of rocks from the northern Bergsträsser Odenwald, these authors identified orthogneisses with protolith emplacement ages of ca. 570 Ma. These rocks were deformed until ca. 540 Ma, intruded by late Neoproterozoic (ca. 540 Ma), and Silurian to early Devonian (435–410 Ma) granites, and affected by the Variscan structural–metamorphic overprint at 385–370 Ma (Fig. 2). Dörr and Stein (2019) postulated that the orthogneisses represent relics of a Cadomian magmatic arc, which was intensely reworked by southward-directed subduction of the Rheic Ocean during Silurian–Devonian, prior to the Variscan collision with Avalonia. In contrast to the aforementioned basement units of the MGCZ, nothing is known about provenance and magmatic evolution in the hinterland of sedimentary rocks exposed in the southwestern-most continuation of the MGCZ, in the Palatinate Forest (Fig. 1b), which is the target of this study.

The crystalline basement of the Palatinate Forest, which comprises only a few small outcrops (Fig. 1b), is predominantly made up of siliciclastic rocks, commonly



**Fig. 1** **a** Position of the Mid-German Crystalline Zone (MGCZ) in Europe, MLC—Mariánské Lázně Complex. **b** Exposed basement units of the MGCZ and of adjacent realms, and position of stud-

ied samples (modified after Reischmann and Anthes 1996). SV—Stavelot-Venn Massif, FG—Frankenstein gabbro, To—Todtmoos Unit, Mu—Murgtal Unit, Rö—Rögis quartzite



**Fig. 2** Event-chronological table, summarizing the timing of sediment deposition and magmatic events in the Palatinate Forest, the northern Vosges, the Odenwald Crystalline Complex, the Southern Black Forest (SFB), and the northwestern Harz Mountains. Data sources: Palatinate Forest (this study; Daubree 1852; Münzing 1956; Genser 1965; Häntzschel 1972; Reischmann and Anthes 1996), N-Vosges (Dubois 1946; Corsin et al. 1960; Hess et al. 1995; Boutin

et al. 1995; Altherr et al. 2000; Skrzypek et al. 2007, 2014), Böllstein Odenwald (Hess and Schmidt 1989; Reischmann et al. 2001; Dörr et al. 2017, 2022), Bergsträsser Odenwald (Kirsch et al. 1988; Siebel et al. 2012; Dörr and Stein 2019; Stein et al. 2022), Black Forest (Hegner et al. 2001; Schaltegger 2000; Zeh et al. 2024a, 2025a), Harz Mountains (Linnemann et al. 2024)

metagreywackes, locally intercalated by the Albersweiler granite gneiss. The latter has been dated at  $368.6 \pm 7.1$  Ma by Pb–Pb single zircon evaporation technique (Reischmann and Anthes 1996). Subsequently, the basement rocks were intruded by Viséan post-tectonic granites at ca. 333 Ma, as is reflected by single zircon Pb–Pb ages of the granodiorites of Waldhambach ( $333.1 \pm 4.4$  Ma) and Windstein ( $333.7 \pm 3.7$  Ma), the Edenkoben granite ( $335.0 \pm 9.0$  Ma), and a granite dike cutting the metapelite at Burrweiler ( $333.0 \pm 6.9$  Ma). The felsic pyroclastic rocks associated with the Weiler metagreywackes yielded slightly younger Sm–Nd and Rb–Sr isochron ages of  $327 \pm 21$  Ma and  $325 \pm 4$  Ma, respectively (Reischmann and Anthes 1996).

For some metagreywackes the depositional age is indicated by the fossil record. For the Neustadt metagreywacke, sediment deposition is constrained as Viséan by the trace fossils *Ichnogenus Pycosiphon/Taenidium* (Häntzschel 1972), and Tournaisian by the plant fossil *Lepidodendropsis*

*hirmeri* (Münzing 1956), respectively. For the Weiler metagreywackes, the Devonian to Viséan ages are supported by a few rugose corals (*Cyathophyllum*) and crinoid stem segments (Daubree 1852; Genser 1965)—(Fig. 2). These data show that metasedimentary rocks of the Palatinate Forest were deposited coevally with siliciclastic rocks in the Rhenohercynian Domain, exposed in the adjacent Rhenish Massif and the Harz Mountains (Figs. 1b, 2).

The results of recent research show that the Rhenohercynian Domain is underlain by a Cadomian (Neoproterozoic) basement of Eastern Avalonia, e.g., the Wartenstein gneiss in the Northern Phyllite Zone (Dörr and Stein 2019). This basement was subsequently covered by Cambro–Ordovician sedimentary sequences, which are well exposed in the Stavelot-Venn Massif of the Ardennes (Willner et al. 2013; Herbosch and Boulvain 2025 and references therein). These were affected by Ordovician magmatic activity at 490–445 Ma (see summary in Herbosch and Boulvain 2025) and, at its

SE margin, were intruded by calc-alkaline magmatic rocks during Late Silurian to Lower Devonian (435–390 Ma), perhaps related to NW-directed subduction of the Rheic Ocean (Zeh and Gerdes 2010; Zeh et al. 2024b; Dörr et al. 2025). This final magmatic activity occurred contemporaneously to the opening of the Rheohercynian Basin, which has been interpreted as a back-arc basin (Zeh and Gerdes 2010).

Detailed detrital zircon U–Pb provenance studies of Eckelmann et al. (2014), Linnemann et al. (2024), and Dörr et al. (2025) showed that, during the Devonian to Viséan, the Rheohercynian Basin was filled by sedimentary detritus from three major sources: (1) SE-Baltica, (2) Avalonia, and (3) Cadomia. The data also reveal that SE-Baltica–Avalonia sources were predominant during the Devonian to Lower Carboniferous (Tournaisian), while Viséan sedimentary rocks (flysch and greywackes) indicate a Cadomian provenance and, therefore, are assumed to have been supplied from the nearby MGCZ (Linnemann et al. 2024). Presently, a large number of zircon age spectra exist for Devonian to Viséan sandstones and greywackes of the Rheohercynian Domain, whereas nothing is known about their Hf isotope composition. This prevents a detailed assessment of the tectono–magmatic–metamorphic evolution in the hinterland, in particular of the relationships between the MGCZ and the Rheohercynian Zone.

## Samples

Siliciclastic metasedimentary rocks from three outcrops of the Palatinate Forest were investigated, comprising meta-greywackes from small outcrops at Neustadt (sample Neu-1), from abandoned quarries northwest of Weiler (Wei-1 and Wei-2) and metapelites near Burrweiler (Bur-1)—(Fig. 1b). In addition, five samples were taken from an operating quarry west of Albersweiler, four from the Albersweiler granite gneiss (Ab-3, Ab-5, Ab-7 and Ab-9), and one from a black lenticular xenolith of approximately 1 m length within the granite gneiss (Ab-Xno).

The samples Neu-1, Wei-1 and Wei-2 are low-grade metagreywackes, consisting of predominantly angular to sub-rounded grains of submillimetre size in a clayish matrix (now sericite, chlorite and, in the Weiler samples, biotite as well; Fig. 3). This indicates a maximum metamorphic overprint of the samples at the greenschist-facies conditions. The grains mostly consist of quartz and feldspar prevailing over lithic clasts accounting for less than 20 vol. % (Figs. 3a–c, 4a), mostly of magmatic (> 70 vol. %) and sedimentary (15–20 vol. %), and, subordinately of volcanic and metamorphic origin (Fig. 4b).

In contrast, samples Bur-1 and Ab-Xno were affected by a higher degree of metamorphic overprint, perhaps caused by contact metamorphic heating, which erased all primary sedimentary structures. Sample Bur-1 is characterized by

intensively altered porphyroblasts of presumably retrograde cordierite (pinite) and plagioclase, resting in a fine-grained, well-foliated matrix of quartz, muscovite, chlorite and opaque minerals, in addition to accessory zircon (Fig. 3d). In contrast, sample Ab-Xno is a coarse-grained, well-foliated biotite–plagioclase gneiss with minor hornblende and accessory apatite, zircon and opaque phases (Figs. 3e, 4c).

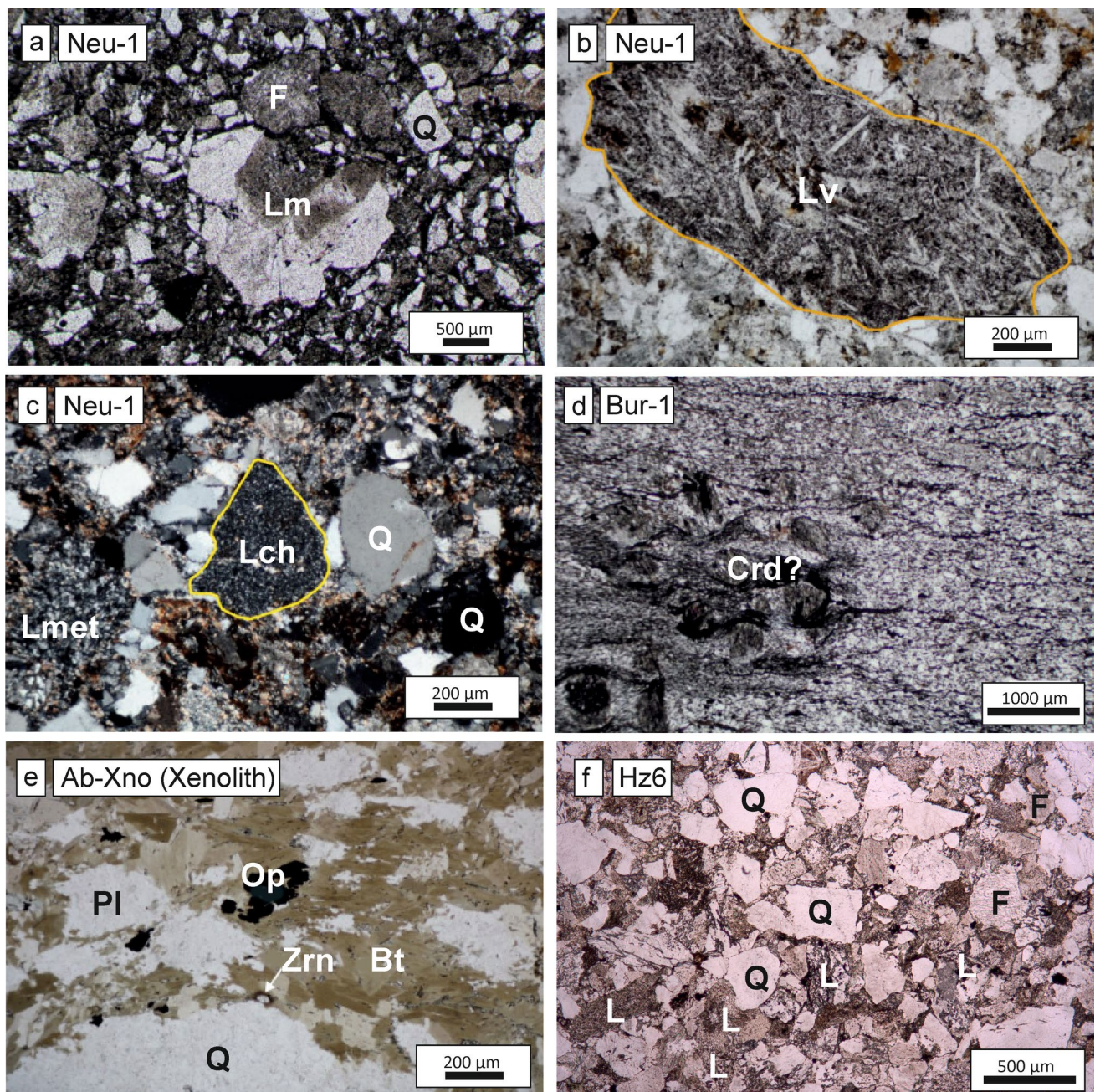
The Albersweiler granite gneiss samples are grey to dark grey, and weakly foliated. They mainly consist of quartz, K-feldspar, plagioclase and minor biotite, and contain accessory apatite, zircon and an opaque phase (Fig. 4c). Based on modal content, they can be classified as monzogranite and granodiorite in the Qz–Afs–Pl diagram (Fig. 4d), as has already been noted by Laue and Reischmann (1994). Plagioclase commonly shows typical albite twinning and myrmekite microstructures when in contact with K-feldspar. The latter is commonly developed as microcline, closely intergrown with recrystallized quartz grains showing 120° triple point junctions.

For comparison, two metasedimentary rock samples from the northwestern part of the Harz Mountains were investigated as well (Fig. 1b). The first is a fine-grained, Lower Devonian (Emsian) sandstone of the Kahleberg Group (sample Hz5) underlying the Wissenbach schists with the famous Rammelsberg SEDEX deposit, and the second is an Upper Carboniferous (Viséan), coarse-grained greywacke belonging to the Culm-Greywacke Formation (sample Hz6; Fig. 1b). Sample Hz5 was taken from the Rammelsberg quarry near Goslar, and sample Hz6 from a road cut close to the southern dam of the Oker water reservoir. Both samples were only affected by a low-grade metamorphic overprint during Variscan folding and thrusting. Sample Hz5 is a relatively mature sandstone (quartz-arenite), consisting mainly of well-rounded quartz grains, and minor chert and detrital mica. In contrast, greywacke sample Hz6 is dominated by angular grains of quartz, feldspars (both plagioclase and K-feldspar), and abundant lithic clasts (ca. 55 vol. %) of mainly plutonic, sedimentary, and metamorphic origin, and subordinate volcanic origin (Figs. 3f, 4a–b). In addition, it contains detrital muscovite, biotite and chlorite flakes, as well as chlorite, illite, and calcite of diagenetic origin. Metamorphic clasts commonly consist of sericite schist, quartz-mica schist, and quartzite. For sample coordinates see Table 1.

## Analytical techniques

### Zircon separation and imaging

Representative zircon populations were recovered from (meta)sedimentary rocks and granite gneiss samples of ca. 2 kg weight each. The samples were crushed with a jaw crusher (< 3 mm) and pulverized with a steel disc

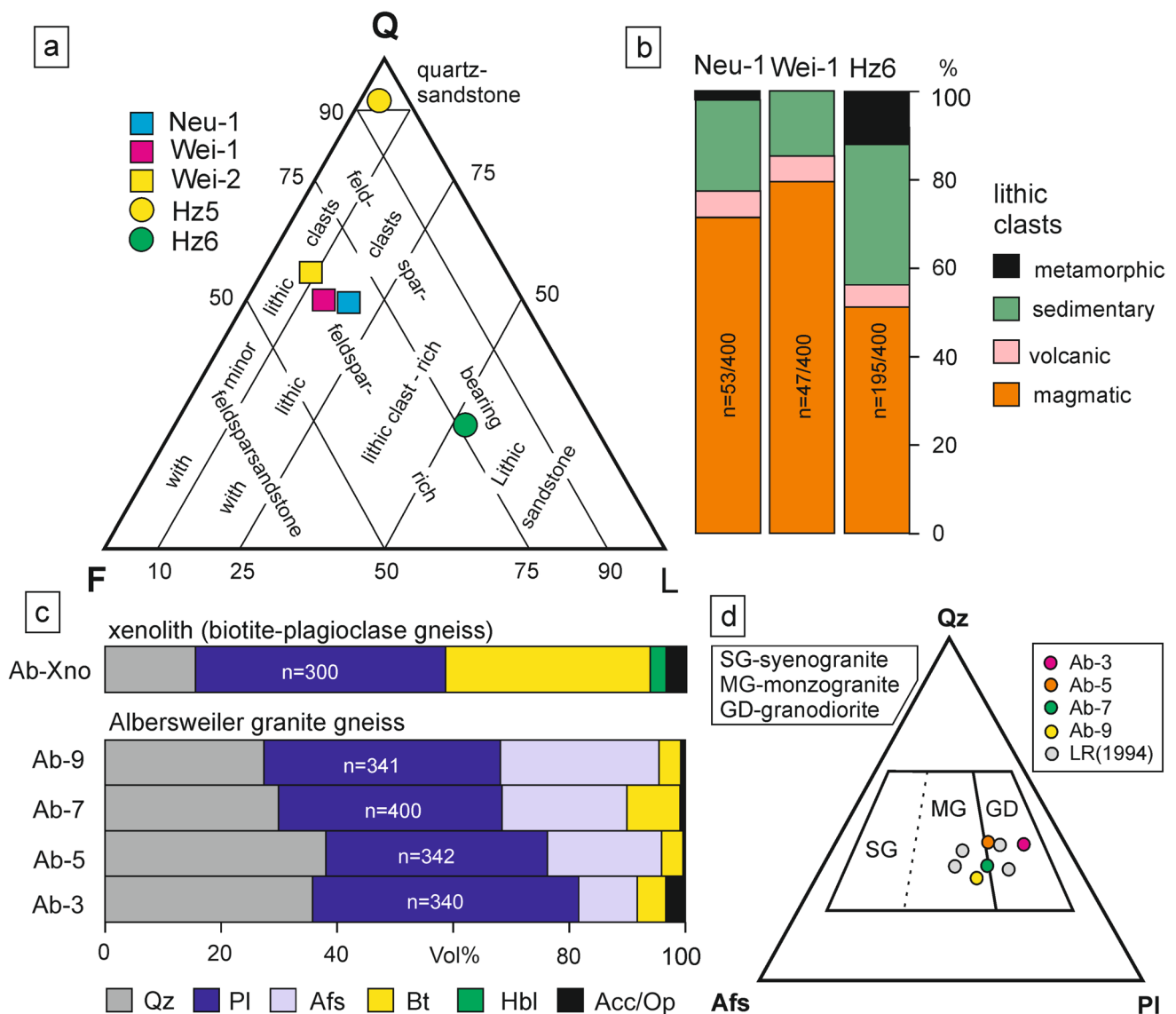


**Fig. 3** Selected photomicrographs of metasedimentary rocks from the **a–e** Palatinat Forest and **f** Harz Mountains. **a–c** Low-grade metagreywacke from Neustadt (sample Neu-1) consisting of angular to sub-rounded grains of quartz (Q) and feldspar (F), as well as lithic clasts of magmatic (Lm), volcanic (Lv), metamorphic (Lmet), and chert (Lch) origin. **d** Medium-grade metapelite from Burrweiler (Bur-1) with porphyroblasts of cordierite (Crd; pinitized) and/or

plagioclase in a fine-grained sericite–chlorite–quartz-rich matrix. **e** Coarse-grained biotite–plagioclase gneiss; a xenolith in Albersweiler granite gneiss (sample Ab-Xno: Bt—biotite, Pl—plagioclase, Q—quartz, Op—opaque, Zrn—zircon). **f** Low-grade greywacke from the Clausthal Unit of the Harz Mountains (sample Hz6) made up of angular particles of Q, F and lithic clasts (L, undifferentiated)

mill to grain sizes  $< 500 \mu\text{m}$  (2 min in the disc mill), and the heavy mineral fraction was enriched by panning only. Finally, zircon grains were manually selected with a brush from the panning concentrates under ethanol. The selected populations were pipetted with ethanol on

double-sided tape, sputtered with Au for 15 s, and imaged for their morphologies (Fig. 5) by back-scattered electron (BSE) microscopy using a TESCAN VEGA2 scanning electron microscope at the Department of Mineralogy and Petrology at Karlsruhe Institute of Technology (KIT).



**Fig. 4** Results of petrographic observations of **a–b** sandstones and greywackes, and **c–d** Albersweiler granite gneiss and a xenolith within. **a** Q–F–L (Quartz–Feldspar–Lithic clasts) diagram after Füchtbauer (1988), showing the composition of low-grade sedimentary rocks from the Palatinate Forest (samples Neu-1, Wei-1, Wei-2), and the Harz Mountains (Hz5, Hz6). **b** Spectrum of lithic clasts in greywackes. **c** Mineral mode of Albersweiler granite gneiss and

related xenolith (biotite–plagioclase gneiss)—Qz—quartz, Pl—plagioclase, Afs—Alkalifeldspar, Bt—biotite, Hbl—hornblende, Acc/Op—accessory/opaque minerals. **d** Composition of Albersweiler granite gneiss samples in Qz—Afs—Pl diagram of Streckeisen (1974) [data from this study and LR (1994)—Laue and Reischmann 1994]

Subsequently, the same grains were mounted with epoxy and ground to expose their centre parts. The polished grains were imaged by BSE again, to gain information about their internal zoning. Subsequently, each population was investigated for U–Th–Pb dating, and Lu–Hf isotope analyses (only grains with concordance level 90–110%).

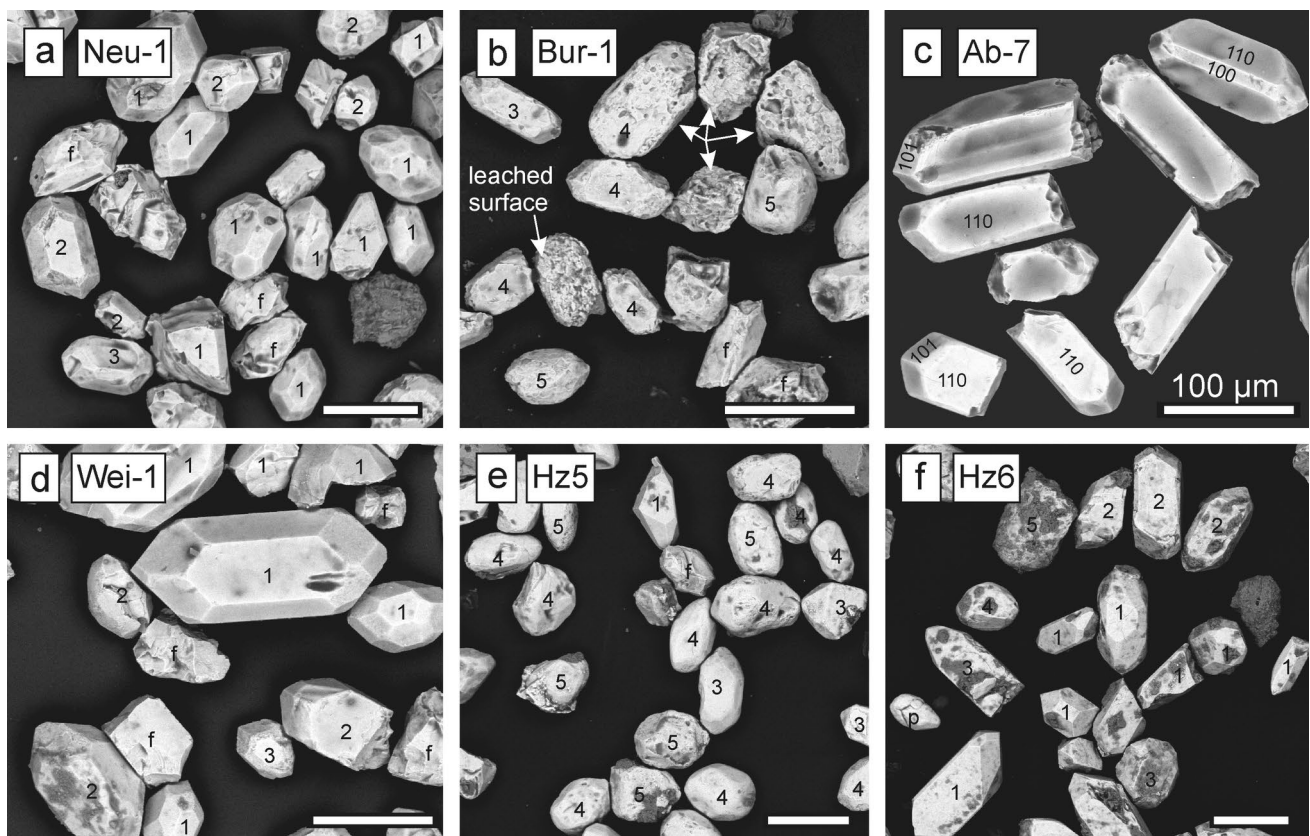
### Zircon U–Th–Pb analyses

Uranium–Th–Pb analyses were performed by laser ablation—sector field—inductively coupled plasma—mass spectrometry (LA-SF-ICP-MS) during five sessions, using a 193 nm ArF Excimer laser (Analyte Excite+, Teledyne

**Table 1** Co-ordinates of rock samples

Sample	Rock type	Location	Sample co-ordinates	
			longitude N	latitude E
<i>Palatinate Forest</i>				
Neu-1	greywacke	Neustadt	49°21'01.90"	8°07'32.23"
Bur-1	metagreywacke (with Crd)	Burrweiler	49°15'35.04"	8°04'23.37"
Wei-1	greywacke	quarry Weiler	49°02'36.15"	7°54'14.94"
Wei-2	greywacke	quarry Weiler	49°02'36.40"	7°54'06.95"
Ab-5	granite gneiss	quarry Albersweiler	49°13'23.92"	8°01'15.77"
Ab-6	granite gneiss	quarry Albersweiler	49°13'21.54"	8°01'13.59"
Ab-7	granite gneiss	quarry Albersweiler	49°13'20.09"	8°01'14.01"
Ab-9	granite gneiss	quarry Albersweiler	49°13'17.26"	8°01'24.45"
Ab-Xno	metagreywacke (Bt-Pl-gneiss)	quarry Albersweiler	49°13'17.26"	8°01'24.45"
<i>Harz Mountains</i>				
Hz5	quartz sandstone	Rammelsberg quarry	51°53'32.93"	10°25'20.36"
Hz6	coarse-grained greywacke	Oker water reservoir	51°49'19.46"	10°26'49.59"

Crd—cordierite, Bt—biotite, Pl—plagioclase



**Fig. 5** Morphology of zircon populations in greywackes (Neu-1, Wei-1, Bur-1, Hz6), sandstone (Hz5), and granite gneiss (Ab-7) from the Palatinate Forest and Harz Mountains. The numbers (1–5) charac-

terize the degree of roundness according to the classification of Zeh and Cabral (2021). Note that many zircon grains in the Burrweiler metapelite (Bur-1) are strongly corroded at their surface (arrows)

Photon Machines) coupled to a Thermo-Scientific Element XR instrument at KIT, Karlsruhe, Germany. Zircon grains of unknown age were analysed together with the

reference zircon BB (primary standard), Plešovice and KA1 (KaapValley), using a laser spot diameter of 20 µm, a laser fluence of 2.0 Jcm<sup>-2</sup>, at 10 Hz repetition rate, RF

power of 1240 W, a mixed Ar–He–N<sub>2</sub> carrier gas consisting of Ar = 0.95 Lmin<sup>-1</sup>, He = 0.3cell + 0.2cup (both Lmin<sup>-1</sup>), and N<sub>2</sub> = 0.0011 Lmin<sup>-1</sup>. Three pulses of pre-ablation were obtained prior to each analysis of 15 s duration following 15 s background measurement.

All raw data were corrected offline using an in-house MS Excel<sup>®</sup> spreadsheet program (Gerdes and Zeh 2006, 2009). A common Pb correction based on the interference and background-corrected <sup>204</sup>Pb signal and a model Pb composition were applied (Stacey and Kramers 1975) when required. More detailed information about analytical conditions is presented in ESM-Table S1, and the results of measurements of reference zircons and unknowns in ESM-Table S2. Concordia diagrams were plotted by the software ISOPLOT 3.75 (Ludwig 2012), and age spectra by AgeDisplay (Sircombe 2004), using <sup>206</sup>Pb/<sup>238</sup>U ages for zircons younger than 1000 Ma, and <sup>207</sup>Pb/<sup>206</sup>Pb ages for zircons older than 1000 Ma, and a concordance level of 90–110%.

### Lu–Hf isotope analyses

Lutetium–Hf isotope analyses were carried out with a Resolution M-50 193 nm ArF Excimer laser system coupled to a Thermo-Scientific multicollector (MC)-SF-ICP-MS (Neptune Plus) at FIERCE in Frankfurt am Main, Germany. The analytical protocols used are the same as described in Gerdes and Zeh (2006). Detailed operating conditions for Lu–Hf isotope analyses, and results of standard measurements are presented in ESM (Tables S1 and S3). Multiple measurements of reference zircon GJ1 and Temora-1 during the analytical session yielded <sup>176</sup>Hf/<sup>177</sup>Hf ratios of 0.282005 ± 0.000023 (2σ S.D.), and 0.282667 ± 0.000031 (2σ S.D.) respectively, in agreement with published values (Woodhead and Hergt 2005).

For calculation of initial epsilon Hf values ( $\epsilon Hf_i$ ), the chondritic uniform reservoir (CHUR) used was that recommended by Bouvier et al. (2008), <sup>176</sup>Lu/<sup>177</sup>Hf of 0.0336 and <sup>176</sup>Hf/<sup>177</sup>Hf of 0.282785, and a decay constant of 1.867 × 10<sup>-11</sup> (Scherer et al. 2001; Söderlund et al. 2004). All two-stage Hf model ages ( $T_{DM}$ ) were calculated by applying <sup>176</sup>Hf/<sup>177</sup>Hf = 0.283181 ± 0.00023 ( $n = 46$ ) and <sup>176</sup>Lu/<sup>177</sup>Hf = 0.038055 for the depleted mantle (DM) evolutionary line (average MORB composition from the Atlantic and Indian oceans of Chauvel and Blichert-Toft 2001), resulting in a depleted mantle (DM) evolutionary line ranging from +14 (today) to zero (at 4.56 Ga). Crustal evolutionary trends were modelled by applying <sup>176</sup>Lu/<sup>177</sup>Hf = 0.0113 for continental crust (average of Taylor and McLennan 1985 and Wedepohl 1995). For all detrital zircon grains, initial <sup>176</sup>Hf/<sup>177</sup>Hf,  $\epsilon Hf_i$  and  $T_{DM}$  were calculated using the ages obtained for the respective zircon domains (ESM-Table S3).

## Results

### Zircon U–Pb dating and imaging

From metasedimentary rock samples, about 100–300 zircon grains were selected (upon availability) for in situ U–Pb dating by LA-SF-ICP-MS. Of those, between 96 and 150 grains per sample were analysed (Table 2), mostly grains with no visible alteration and fractures, guided by BSE images. Most of the analysed grains show a (relic) oscillatory or banded zoning in BSE images and Th/U ratios between 0.1 and 1.3 (ESM-Table S2), indicating an igneous origin. The only exception is reflected by many zircon grains in sample Ab-Xno with a blurred zoning and Th/U < 0.1, pointing to a metamorphic origin. An igneous origin is also suggested by the perfect euhedral shape of most zircon grains abundantly found in all low-grade metagreywackes (Neu-1, Wei-1, Wei-2, Hz6; Fig. 5a, d, f), whereas those in the mature sandstone sample Hz5 are mostly round (Fig. 5e), showing a degree of roundness of mostly 4 to 5, according to the classification of Zeh and Cabral (2021). Zircon grains separated from the xenolith sample Ab-Xno have variable shapes from angular to completely rounded (not shown), and detrital zircon grains in the Burrweiler metapelite are mostly corroded at their surface (Fig. 5b), perhaps due to interaction with muscovite during contact metamorphism (for discussion about the zircon dissolution process see Zeh et al. 2025b).

Between 66 and 89% of the analysed detrital zircon grains yielded concordant ages (concordance level of 90–110%; Table 2; ESM-Table S2). These are the ones considered for further interpretation. The zircon age spectra obtained from all metasedimentary rocks of the Palatinate Forest, but also from the Viséan Harz greywacke (Hz6) are dominated by Paleozoic zircon grains. More than 95% of the populations show ages less than 600 Ma. In contrast, 85% of grains in the Emsian Harz sandstone (Hz5) are older than 700 Ma (Fig. 6).

All Palatinate samples show a pronounced age peak at ca. 375 Ma, as well as at 400 Ma, and peaks of variable size at 500 Ma. Pronounced peaks at 375 Ma and 500 Ma are also reflected by the age spectrum of sample Hz6, which additionally shows a younger significant age peak at ca. 340 Ma (Fig. 6a). In most samples the MDA, defined by the age of the youngest detrital zircon grain of 98–102% concordance, is close to the robust MDA (R-MDA), which is defined by the youngest cluster of concordant zircon analyses following five criteria: (1) Th/U ratio > 0.1, (2) concordance level of 90–110%, (3) MSWD < 1.1 (mean square weighted deviation), (4) Probability exceeding 0.4, (5) number of grains analysed is greater than two. The oldest R-MDA is obtained from

**Table 2** Results of U–Pb zircon dating

Sample	n <sup>a</sup>	n <sup>b</sup>	%	max.dep.Age <sup>c</sup>	± 2σ	y. Age cluster <sup>d</sup>	± 2σ	MSWD <sub>CE</sub>	Prob <sub>CE</sub>	n <sup>e</sup>
	(all)	(90–110%)		(Ma)		(Ma)				
<i>Burrweiler</i>										
Bur-1	96	66	69	341	6	<b>344.1</b>	<b>3.3</b>	0.52	0.89	6
<i>Neustadt</i>										
Neu-1	119	92	77	341	9	<b>354.4</b>	<b>3.1</b>	0.79	0.69	8
<i>Weiler</i>										
Wei-1	120	107	89	347	9	<b>359.5</b>	<b>2.2</b>	0.79	0.79	15
Wei-2	120	107	89	353	10	<b>361.2</b>	<b>2.2</b>	0.52	0.99	17
<i>Albersweiler (Xenolith)</i>										
Ab-Xno	123	82	67	418	7	metamorphic age (zircon Th/U < 0.1)				
						<b>372.3</b>	<b>1.4</b>	1.04	0.41	22
<i>Albersweiler Granite Gneiss</i>										
Ab-7	55					371.9	2.3	0.38	0.99	16
Ab-9	48					373.9	2.4	1.11	0.33	10
all data						<b>372.8</b>	<b>1.7</b>	0.67	0.96	26
<i>Harz Mountains</i>										
H5	148	102	69	414	7	<b>415.0</b>	<b>5.8</b>	0.11	0.55	2
H6	150	96	64	331	6	<b>335.2</b>	<b>1.9</b>	0.54	0.97	13

a—number of all analyses per sample

b—number of analyses with concordance level 90–110%

c—maximum depositional age defined by youngest zircon grain of 98–102% concordance

d—maximum depositional age defined by youngest zircon age cluster

e—number of grains of cluster

Prob<sub>CE</sub>—Probability (of concordance and equivalence)

bold numbers—best age estimates

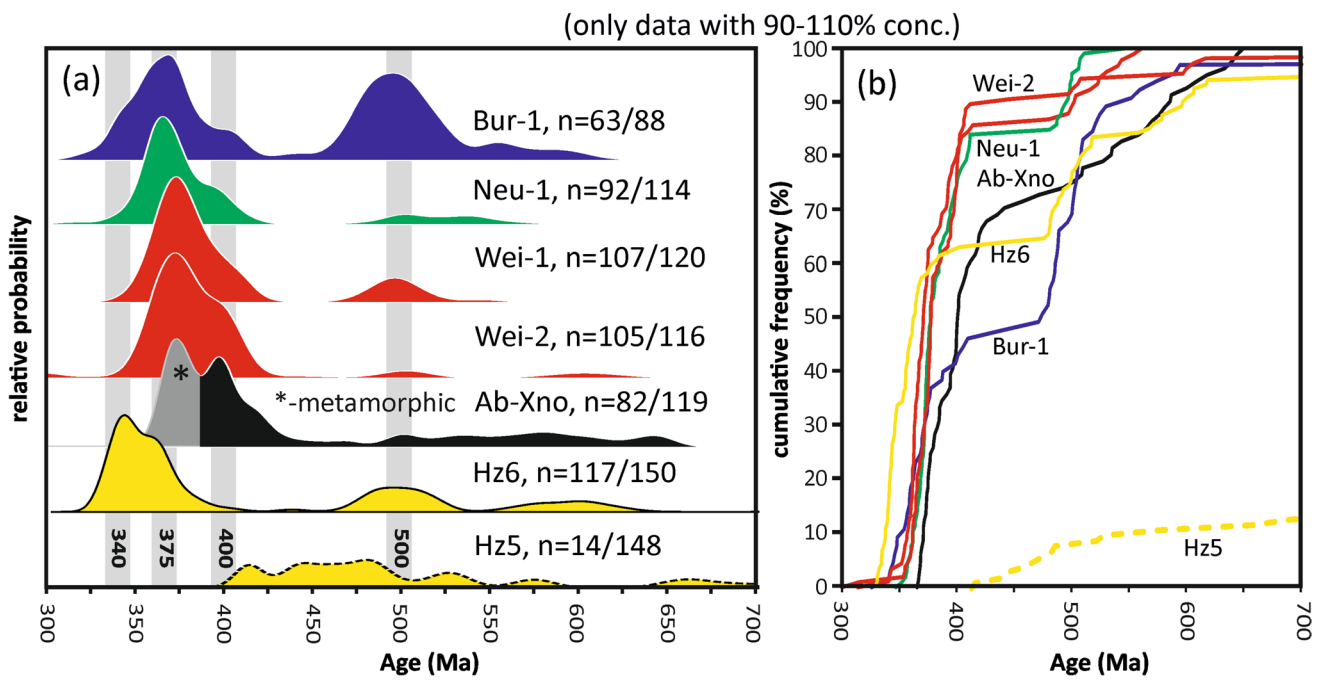
Emsian sandstone sample H5 (415.0 ± 5.8 Ma), and the youngest from Viséan Harz greywacke H6 (335.2 ± 1.9 Ma), whereas R-MDAs of all Palatinate metasediments fall in between (Wei-2: 361.2 ± 2.2 Ma; Wei-1: 359.5 ± 2.2 Ma; Neu-1: 354.4 ± 3.1 Ma; Bur-1: 344.1 ± 3.3 Ma; Fig. 7 and Table 2). The youngest age of 372.3 ± 1.4 Ma, derived from zircon grains in the xenolith sample Ab-Xno, most likely reflects the age of metamorphic zircon growth, as all 22 zircon grains analysed show very low Th/U < 0.1 (Fig. 7a). The youngest concordant zircon grain with Th/U > 0.1 in sample Ab-Xno yields a concordant age of 418 ± 7 Ma, representing the MDA.

Zircon grains separated from Albersweiler gneiss samples Ab-7 and Ab-9 are mostly euhedral and dominated by {110} prisms and {101} pyramids (Fig. 5c), corresponding to the low-T zircon typology class P1 of Pupin (1980). Some of these grains show CL-bright, oscillatory zoned cores with highly variable U contents (40–398 µg/g) and Th/U ratios (0.97 to 0.01), surrounded by CL-dark rims also with variable Th/U (1.36–0.01). Most rims, but also some core domains, show high U contents (400–5000 µg/g), and were obviously affected by alteration and recrystallization, as indicated by reaction fronts cross cutting the original

zircon growth zoning (not shown). From sample Ab-7, 55 zircon analyses were obtained on 43 grains. Sixteen core analyses yielded a concordia age of 371.9 ± 2.3 Ma, and six xenocrysts older ages of 2590, 2060, 600–650 (n = 3) and 420 Ma (n = 1, Fig. 8a–b). Analyses of CL-dark rims and recrystallized core domains mostly yielded highly discordant ages < 370 Ma, and high common Pb levels (up to 8.5% of the <sup>206</sup>Pb; ESM-Table S2). Zircon grains of sample Ab-9 show very similar results (Fig. 8c–d). From 48 analyses (on 42 zircon grains), ten analyses yielded within uncertainties the same concordia age of 373.9 ± 2.4 Ma, and five core analyses gave older ages close to concordia at 600–650 Ma (n = 4) and at 450 Ma (n = 1). CL-dark rims, with high U contents, and recrystallized core domains also yielded ages less than 370 Ma (ESM-Table S2). The best-preserved magmatic zircon domains of both samples (Ab-7 and Ab-9) yielded a concordant age of 372.8 ± 1.7 Ma (Table 2).

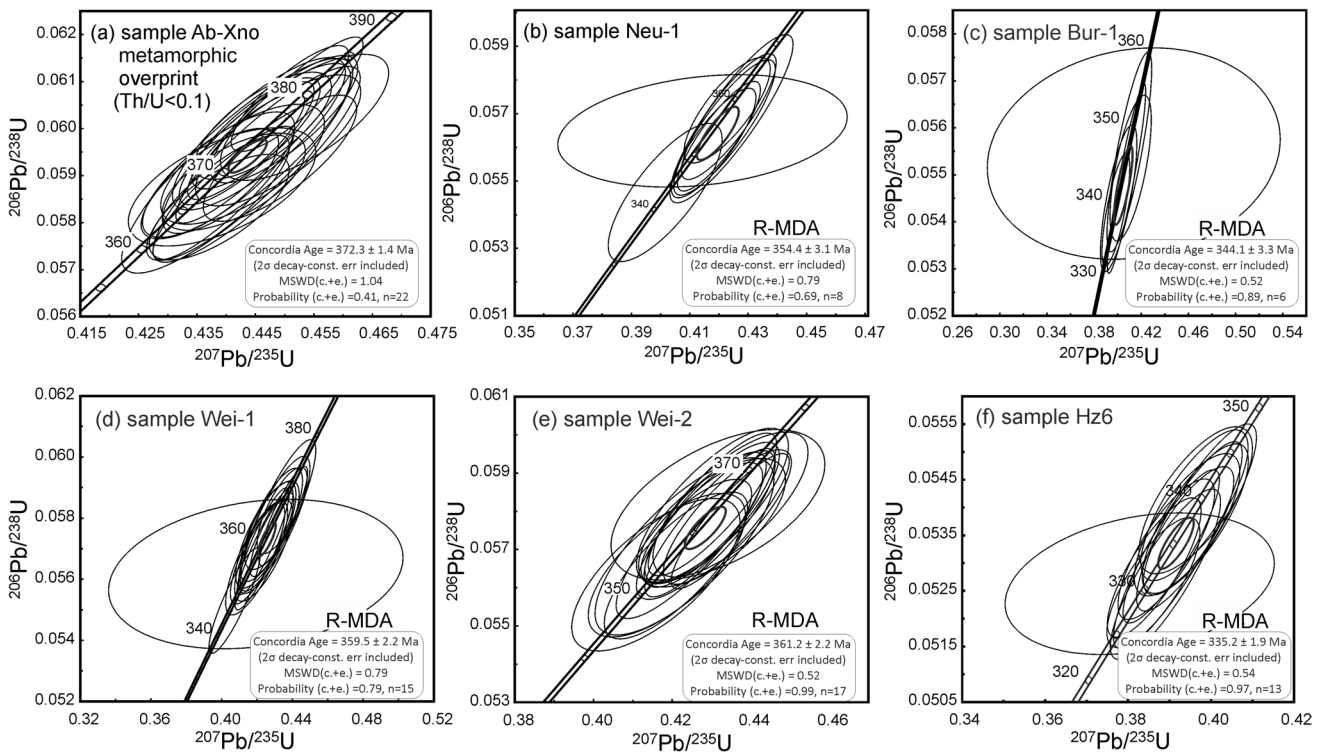
## Hf–isotope analyses

Hafnium isotope analyses of the detrital zircon grains in the metagreywackes and metapelites from the Palatinate Forest mostly yield superchondritic εHf<sub>t</sub> values between + 1.0



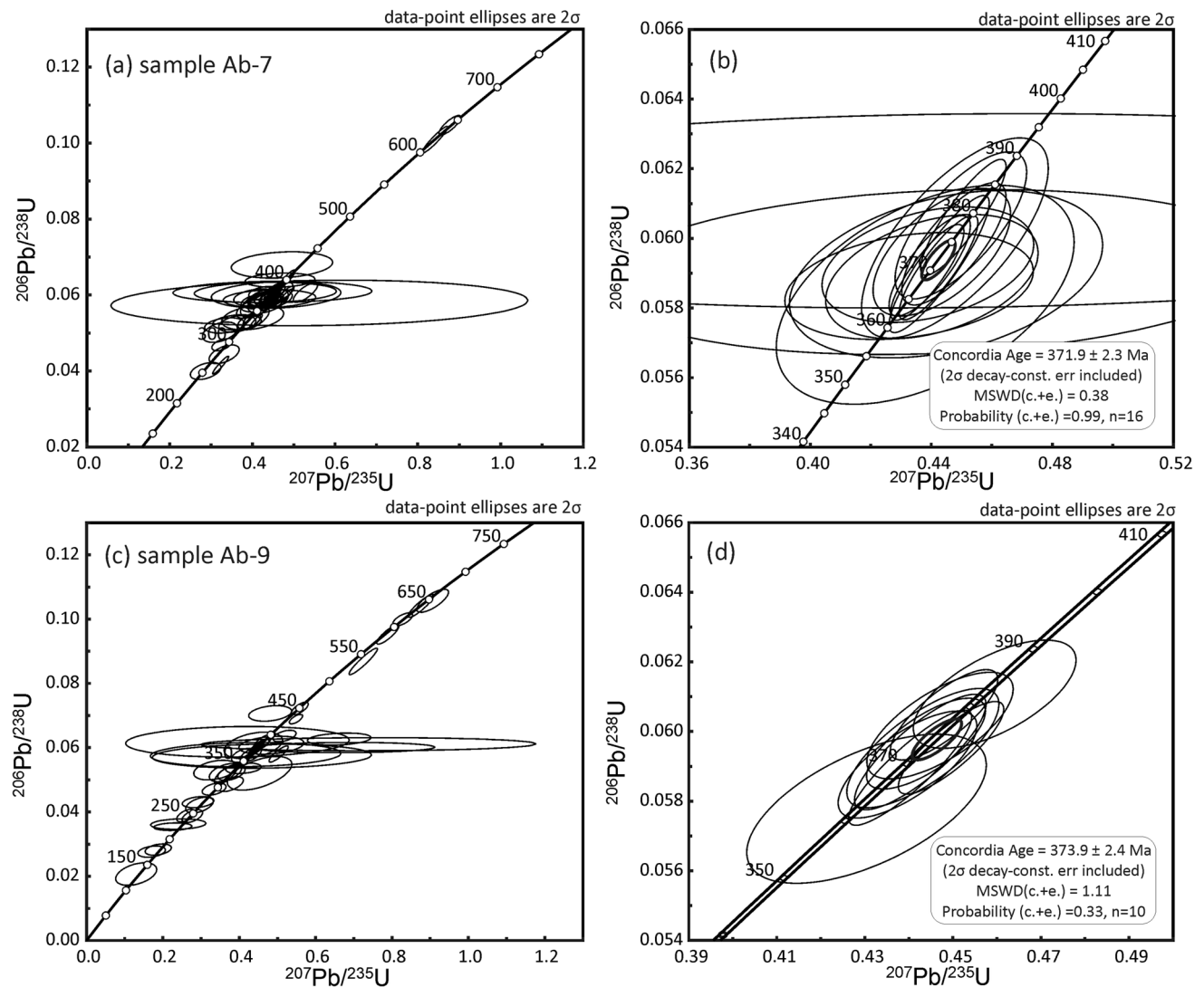
**Fig. 6** Age spectra of detrital zircon populations in metasedimentary rocks from the Palatinate Forest and Harz Mountains, presented in **a** as population density plots, and **b** in cumulative age plots in the age

range 300–700 Ma. Note that for sample Hz5 only less than 15% of the data are shown, and that the spectrum of sample Ab-Xno comprises detrital and metamorphic zircon analyses



**Fig. 7** Wetherilla diagrams showing the robust maximum depositional ages (R-MDAs) obtained from the youngest cluster of concordant zircon grains in metasedimentary rocks from the Palatinate Forest

and Harz Mountains. Note that all zircon analyses of sample Ab-Xno show Th/U < 0.1, dating the time of metamorphic overprint



**Fig. 8** Results of U–Pb dating of zircon populations in the Albersweiler granite gneisses, **a–b** sample Ab-7, **c–d** sample Ab-9. Many analyses of both samples form a cluster at ca. 372 Ma, which is interpreted to reflect the timing of protolith emplacement. In addition, there is evidence for inherited grains (at 650–600 Ma and 450–400 Ma), and for significant Pb-loss

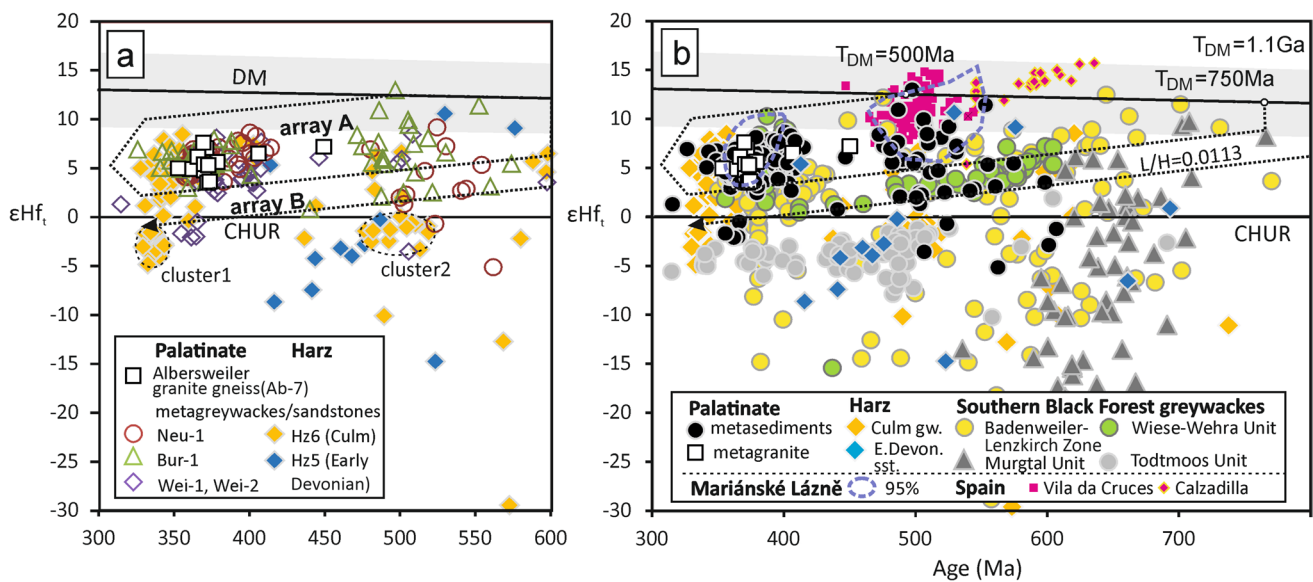
and +13.0 (Fig. 9a; ESM-Table S3), except for seven analyses of zircon grains from the Weiler and Neustadt metagreywackes with slightly subchondritic  $\epsilon\text{Hf}_t$  values ranging down to  $-5.0$ . Most analyses ( $\sim 80\%$ ) define a crustal array which starts from the depleted mantle (DM) evolutionary line between 750 and 500 Ma (array A in Fig. 9), while most other data follow a parallel trend (array B), which intersects the DM-line at ca. 1.1 Ga (Fig. 9b). Analyses of magmatic and inherited zircon grains of the Albersweiler granite gneiss also show superchondritic  $\epsilon\text{Hf}_t$  (+3.7 to +7.8) and plot on array A (Fig. 9). The same holds true for  $\sim 60\%$  of the zircon grains of the Viséan Harz greywacke (sample Hz6), which define the youngest end of array A. The remaining 40% form two clusters below array B: cluster 1 at ca. 340 Ma ( $\epsilon\text{Hf}_t = -0.5$  to  $-5.0$ ), and cluster 2 at ca. 500

Ma ( $\epsilon\text{Hf}_t = 0.0$  to  $-4.0$ ; Fig. 9a). The zircon analyses of the Emsian sandstone Hz5 mostly show subchondritic values at  $< 700$  Ma ( $\epsilon\text{Hf}_t = 0.0$  to  $-15$ ), except for three grains overlapping with array A (Fig. 9). Most Hf analyses with ages between 900 and 1700 Ma in sample Hz5 show chondritic to superchondritic  $\epsilon\text{Hf}_t$  (0 to +10,  $\sim 70\%$ ), and the remaining show subchondritic  $\epsilon\text{Hf}_t$  down to  $-15$  (Fig. 10a).

## Discussion

### Age of deposit, intrusion and metamorphism

The results of this study show that the sedimentary protoliths of all metagreywackes and metapelites in the Palatinate



**Fig. 9** **a** Results of Hf isotope analyses of zircon populations in clastic sedimentary rocks from the Palatinat Forest and Harz Mountains, as well as from the Albersweiler granite gneiss. **b** Comparison of age– $\epsilon\text{Hf}_i$  data of this study with those from the Southern Black Forest; Badenweiler–Lenzkirch Zone (data from Zeh et al. 2025a), Wiese–Wehra, Todtmoos, and Murgtal units (data from Zeh et al. 2024a), the Mariánské Lázně Complex of the Teplá–Barrandian Zone (the fields comprise about 95% of the data from Collett et al. 2022) and Spain (data from Arenas et al. 2007; Sánchez Martínez et al. 2021). We

note that most data from the Palatinat (ca. 85%) and the Viséan Harz greywacke Hz6 (ca. 60%) define a crustal array, which starts from the depleted mantle (DM) evolutionary line at 750–500 Ma and develops until ca. 335 Ma (array A). Most other data plot on a subparallel array (array B), which starts from the DM at ca. 1.1 Ga. Many zircon analyses of the Harz greywacke Hz6 (ca. 35%) form clusters below array B (clusters 1 at ca. 335 Ma, cluster 2 at ca. 500 Ma). CHUR—Chondritic Uniform Reservoir,  $T_{\text{DM}}$ —two-stage hafnium model age

Forest were deposited during the Devonian to Early Carboniferous (Viséan), consistent with field relationships and biostratigraphic records (Fig. 2). The oldest MDA of  $418 \pm 7$  Ma is indicated by a detrital zircon grain (with  $\text{Th}/\text{U} > 0.1$ ) of the biotite–plagioclase gneiss xenolith in the Albersweiler granite gneiss (Ab–Xno). Most other zircon grains (with  $\text{Th}/\text{U} < 0.1$  and blurred zoning) in this paragneiss yielded a precise age of  $372.3 \pm 1.4$  Ma ( $n = 22$ ), which most likely date the time of amphibolite-facies metamorphic overprint. Magmatic zircon grains of the Albersweiler orthogneiss gave a protolith emplacement age of  $372.8 \pm 1.7$  Ma (Table 2), which is within uncertainties identical to the metamorphic age, but also to a Pb–Pb single zircon evaporation age of  $368.5 \pm 5.4$  Ma, previously obtained by Reischmann and Anthes (1996) for the same orthogneiss. In combination, the data suggest that deposition of the biotite–plagioclase gneiss protolith (greywacke) occurred between ca. 420 and 370 Ma, and that its amphibolite-facies metamorphic overprint was nearly contemporaneous with the syntectonic emplacement of the Albersweiler granite gneiss.

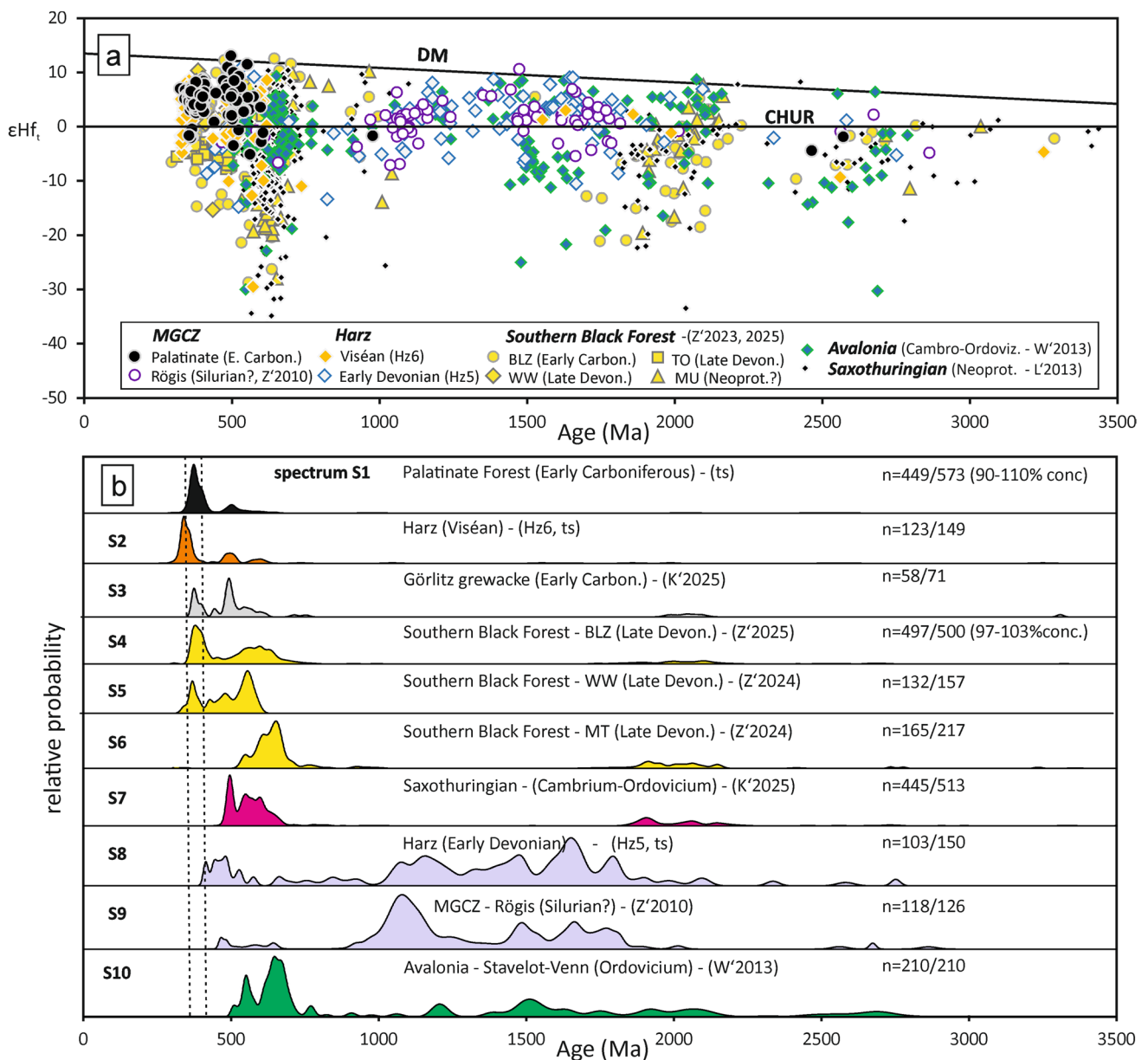
Deposition of the greywackes at Neustadt, Weiler and of the metapelites of Burrweiler occurred later. The R-MDAs of all these sediments (360–345 Ma; Table 2) are in accordance with the biostratigraphic record (Fig. 2), and with the fact that the Burrweiler metapelite was intruded by granite

dikes at  $333.0 \pm 6.9$  Ma (Reischmann and Anthes 1996). Deposition of the Weiler metagreywackes occurred probably much later than is reflected by the R-MDA (ca. 360 Ma). This interpretation is backed up by Viséan fossils and an Rb–Sr isochron age of  $325 \pm 4$  Ma obtained from ignimbrites and tuffs intercalating the metagreywackes in the Weiler region (Reischmann and Anthes 1996).

For the two samples from the Harz Mountains, the R-MDAs are also in accordance with the litho-biostratigraphic record (Schneider 1954; Ribbert 1975; and summaries in Schwab 2008 and Linnemann et al. 2024), suggesting deposition of sandstone Hz5 during Emsian (R-MDA =  $415.0 \pm 5.8$  Ma), and of the greywacke Hz6 during Viséan (R-MDA =  $335.2 \pm 1.9$  Ma). The R-MDA of the Emsian sandstone Hz5 is significantly younger than the MDA of  $471 \pm 7$  Ma previously obtained by Linnemann et al. (2024) on the same unit. The R-MDA of the Clausthal Culm greywacke (Hz6) overlaps the MDA of  $339 \pm 6$  Ma published by Linnemann et al. (2024).

## Provenance

Results of U–Pb dating indicate that most of the detrital zircon grains in the Late Devonian to Viséan metagreywackes and metapelites of the Palatinat Forest (Neu-1, Bur-1,



**Fig. 10** Comparison of **a** age- $\epsilon Hf_t$  data and **b** detrital zircon age spectra of Devonian to Viséan metagreywackes, metapelites and sandstones from the Palatinate Forest and the Harz Mountains (this study), with data from Avalonia (W'2013: Willner et al. 2013), Saxothuringia (L'2013: Linnemann et al. 2013), Görlitz grewacke

(K'2025: Kühnemann et al. 2025), Rögis quartzite of the MG CZ (Z'2010: Zeh and Gerdes 2010), Southern Black Forest (BLZ—Badenweiler—Lenzkirch Zone, WW—Wiese—Wehra Unit, TO—Todmoos Unit, MT—Murgtal Unit; Z'2024: Zeh et al. 2024a, Z'2025: Zeh et al. 2025a)

Wei-1, Wei-2, Ab-Xno) and greywackes of the Harz Mountains (Hz6) were derived from igneous rocks younger than 600 Ma (>95%, Fig. 6b), predominantly from Cambro-Ordovician (520–490 Ma), Early Devonian (410–390 Ma; only Palatinate), and Late Devonian to Early Carboniferous (375–340 Ma) sources. Harz greywacke Hz6 additionally received abundant input from magmatic rocks formed during the Viséan (340–327 Ma; this study and Linnemann et al. 2024). In the age- $Hf$  isotope data diagram, most

detrital zircon grains from the Late Devonian to Viséan metasedimentary rocks define a crustal array, which starts from the depleted mantle evolutionary line between 750 and 500 Ma, and ends at ca. 335 Ma (array A in Fig. 9a–b). This array, along with zircon age spectra, suggests that: (1) the oldest zircon grains (570–480 Ma) were formed in a Late Neoproterozoic to Cambro-Ordovician oceanic arc system, which was predominantly derived from depleted mantle, and barely influenced by detritus from the continental basement

of the Avalonian–Cadomian Belt, (2) until 335 Ma, the oceanic arc system remained isolated, and was only internally reworked by magmatic processes.

Isolation of the oceanic arc system from the Avalonian–Cadomian Belt, which formed a cordillera along the northern margin of Gondwana during the Neoproterozoic–Cambrian (e.g., Nance and Murphy et al. 1994; Zeh et al. 2001; Linnemann et al. 2007, 2010 and references therein), is supported by the high contrast of the zircon age– $\epsilon\text{Hf}_t$  spectra (for comparison see Fig. 10). Age spectra of sedimentary rocks derived from Cadomian (Saxothuringian) and Avalonian basement sources are commonly dominated by Neoproterozoic–Cambrian zircon populations forming age peaks between 520 and 750 Ma (age spectra S4, S6, S7, S10 in Fig. 10b). In addition, these spectra contain abundant populations with Paleoproterozoic (1700–2200 Ma) and Archean (2500–3300 Ma) ages, which are barely seen in the Palatinate sediments (spectrum S1 in Fig. 10b). Avalonia-derived sediments additionally contain abundant Mesoproterozoic zircon grains with ages between 1000 and 1700 Ma, commonly forming clusters at ca. 1200 and 1500 Ma (spectrum S10 in Fig. 10b). The combined zircon age– $\epsilon\text{Hf}_t$  patterns of Cadomia- and Avalonia-derived sediments are characterized by highly variable  $\epsilon\text{Hf}_t$  values at 520–750 Ma (+13 to –55), 1700–2200 Ma (+10 to –35), and 2500–3300 Ma (+8 to –30), in addition to super- and subchondritic clusters between 1000 and 1700 Ma (only reflected by Avalonia-derived detritus; Fig. 10a).

Furthermore, the age spectra of all metasedimentary rocks from the Palatinate Forest and Harz Mountains are extremely different from those derived from Devonian and most Tournaisian sedimentary rocks of the Rhenohercynian realm (Rhenish Massif and Harz Mountains) and the Northern Phyllite Zone, as is well reflected by cumulative age spectra and kernel density plots shown in Figs. 11 and 12, respectively. Most of the Rhenohercynian Devonian to Tournaisian sedimentary rocks are dominated by zircon grains with ages between 1000 and 1700 Ma (> 85%; i.e. age spectrum AS1 in Fig. 11a–b), interpreted to reflect mixed Avalonia–Baltica sources (for discussions see Geisler et al. 2005; Zeh and Gerdes 2010; Eckelmann et al. 2014; Kirchner and Albert 2020; Linnemann et al. 2024; Dörr et al. 2025).

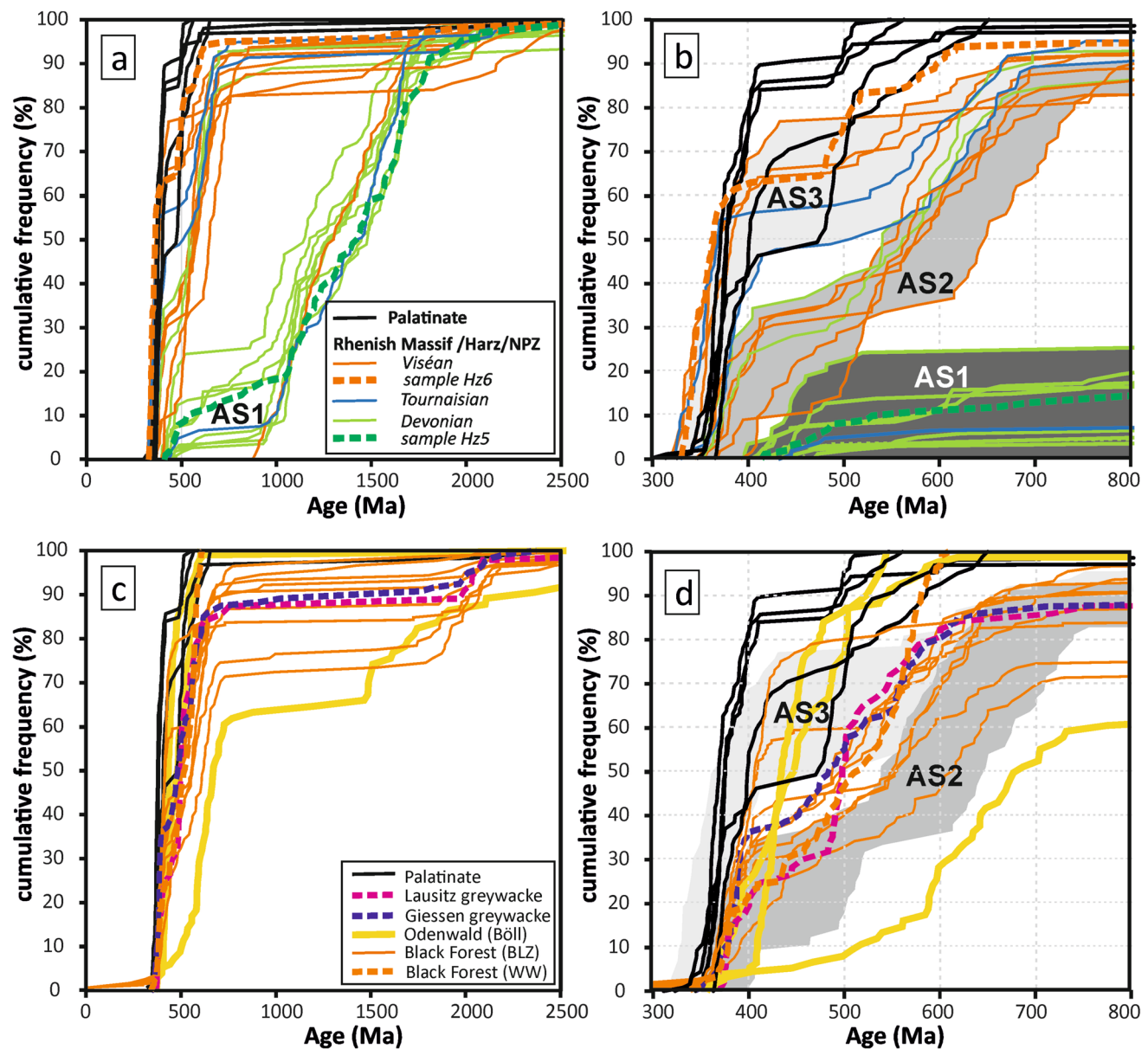
The age spectrum AS1 is also reflected by sample Hz5 (Emsian sandstone), showing an overwhelming overlap with the zircon age– $\epsilon\text{Hf}_t$  spectrum of the Silurian Rögis quartzite in the Ruhla Crystalline Complex of the MGCZ (Fig. 10a–b). The absence of any clear Avalonia–Baltica signal in the metagreywackes and metapelites of the Palatinate Forest and the Viséan greywacke Hz6 in the Harz Mountains suggests that: (1) the oceanic arc terrane was completely disconnected from the Rhenohercynian realm (Avalonia) until the Viséan at ca. 335 Ma, (2) Devonian sedimentary rocks of Avalonia–Baltica affinity in the Rhenohercynian

realm, exemplified by sample Hz5, were overlain by oceanic arc-derived sediments without any significant mixing. We note that the predominance of zircon grains of Viséan age (335–328 Ma) in the Harz greywacke Hz6 is also reflected by the data set of Linnemann et al. (2024; for comparison see Fig. 12d). It is likely that the two subchondritic  $\epsilon\text{Hf}_t$  clusters found in the Harz greywacke Hz6 (clusters 1 and 2 in Fig. 9a) resulted from the admixing of detritus from an additional source, perhaps from the Saxothuringian realm during Viséan greywacke deposition.

Results of comprehensive data compilation, summarized in the Figs. 9, 10, 11, 12, further reveal that zircon age and Hf isotope data of metasedimentary rocks from the Palatinate Forest and Harz Mountains show a great overlap with those obtained from eclogites, mafic and felsic orthogneisses of the Mariánské Lázně Complex (Fig. 9b), forming the base of the Teplá-Barrandian Zone (e.g., Collett et al. 2022). Isotope-geochemical data suggest the Mariánské Lázně Complex to host relics of a MORB to intra-oceanic arc system, which mainly developed during the Devonian between 390 and 365 Ma (Deiller et al. 2021), but also Neoproterozoic to Early Paleozoic relics (c. 550–450 Ma), as indicated by zircon xenocrysts with highly superchondritic  $\epsilon\text{Hf}_t$  (Collett et al. 2022).

Great overlap is further shown by Late Devonian to Early Carboniferous (meta)greywackes exposed in the southern domain of the Black Forest, part of the Moldanubian Domain *sensu* Kossmat (1927), in particular with those from the Badenweiler–Lenzkirch Zone and the Wiese–Wehra Unit (Zeh et al. 2024a, 2025a). The spectra of both units are characterized by significant age peaks at ca. 370 Ma and 400 Ma (Fig. 12c), and superchondritic  $\epsilon\text{Hf}_t$  values between +1 and +10 (Fig. 9b). We note that the zircon data of the Wiese–Wehra metagreywackes define a crustal trend located between array A and B shown in Fig. 9b. However, in contrast to Palatinate Forest, the zircon age spectrum of the Wiese–Wehra Unit reveals an additional large age peak at ca. 550 Ma (Fig. 12c).

Age spectra with a significant age peak at ca. 370–390 Ma were also reported from greywackes of the Giessen nappe (Dörr et al. 2017; Fig. 12b) and, more recently, from the Lausitz Block (Görlitz greywacke; Kühnemann et al. 2025), which forms part of the Saxothuringian Domain (Fig. 1a). However, due to the lack of any Hf isotope data, the assignment of these zircon populations to the suggested oceanic arc system remains speculative. The same holds true for clastic (meta)sedimentary rocks of Devonian age (MDA < 375 Ma) reported from the schist envelope of the Böllstein Odenwald (Dörr et al. 2017), as well as from the Prasinite-Phyllite Unit forming the lowermost nappe unit of the Münchberg Massif (Fig. 1b). Geochemical and zircon age data of Koglin et al. (2018) show that the Prasinite-Phyllite Unit hosts calc-alkaline magmatic rocks, which were



**Fig. 11** Comparison of cumulative age spectra of metasedimentary rocks from the Palatinate Forest (this study) with those of sedimentary rocks from the: **a–b** Rhenohercynian Domain and NPZ–Northern Phyllite Zone [Rhenish Massif (Eckelmann et al. 2014; Dörr et al. 2025), Harz Mountains (Linnemann et al. 2024), NPZ (Dörr et al. 2025)], and **c–d** the Moldanubian–Saxothuringian domains: [BLZ—

Badenweiler–Lenzkirch Zone, WW—Wiese–Wehra Zone of the Southern Black Forest (Zeh et al. 2024a, 2025a), Görlitz greywacke (Kühnemann et al. 2025), Giessen nappe greywacke (Dörr et al. 2017), Böll–Böllstein Odenwald (Dörr et al. 2017, 2022)]. AS1, AS2, AS3 (in **b, d**) mark fields of distinct age spectra mentioned in text

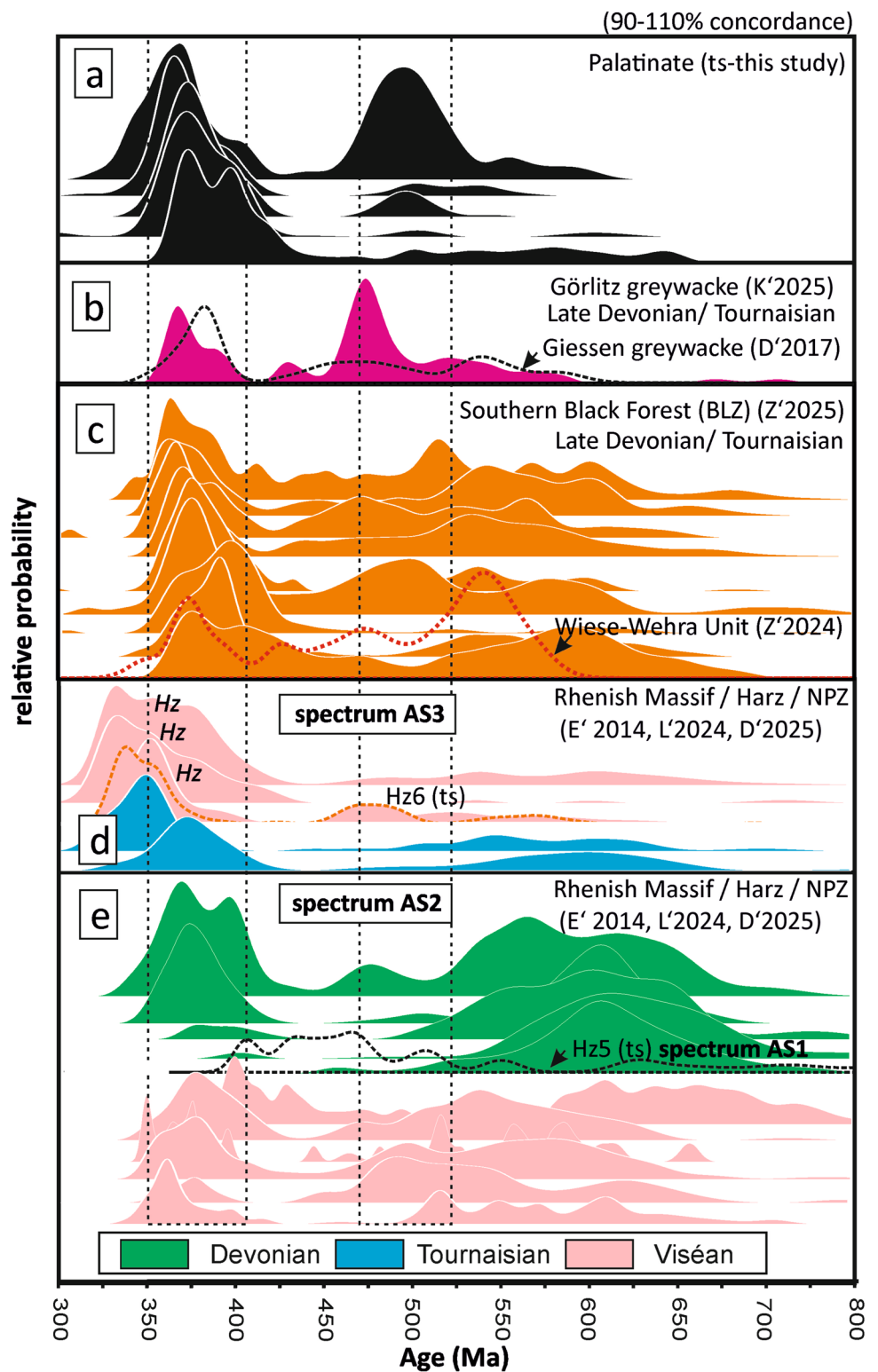
emplaced in a primitive oceanic arc setting at ca. 405 Ma, and that related volcanosedimentary rocks were deposited before  $371 \pm 6$  Ma.

In summary, the results of data compilation suggest that the juvenile arc terrane became widely dispersed during accretion and subsequent orogenic collapse of the Variscan Belt, leaving traces in the Rhenohercynian, Saxothuringian, Teplá–Barrandian, and Moldanubian domains. Alternatively, it cannot be excluded that the Variscan Belt of

Central Europe hosts several oceanic arc terranes, although this option appears less likely.

Finally, the age spectra obtained from Late Devonian to Early Carboniferous (meta)greywackes of the southern Black Forest, the Giessen and Görlitz greywackes, and the Rhenohercynian realm (Rhenish Massif, Harz Mountains, Northern Phyllite Zone) show a much higher proportion of detrital zircon grains with ages  $> 600$  Ma (commonly  $> 20$ – $50\%$ ), compared to those from the Palatinate

**Fig. 12** Comparison of age spectra, presented in Kernel density plots, of metasediments from **a** Palatinate Forest (this study) with those of Devonian to Viséan sedimentary rocks of **b** Görlitz and Giessen greywackes (D'2017; Dörr et al. 2017; K'2025: Kühnemann et al. 2025), **c** the Southern Black Forest (BLZ—Badenweiler–Lenzkirch Zone, Z'2025: Zeh et al. 2025a; WW—Wiese–Wehra Unit, Z'2024: Zeh et al. 2024a), and **d–e** from the Rhenohercynian Domain and NPZ—Northern Phyllite Zone (E'2014; Eckelmann et al. 2014; L'2024; Linnemann et al. 2024; D'2025: Dörr et al. 2025). Diagrams in **(d)** represent plots with age spectrum (AS3), and in **(e)** with age spectrum (AS2), as defined in Fig. 11. For clarity, plots with age spectrum AS1 are not shown, except for sample Hz5. We note that the age spectrum AS2 is restricted to Devonian sediments, whereas those of Tournaisian and Viséan ages reflect age spectra AS2 and AS3. Viséan greywackes from the Harz Mountains (marked with Hz, including Hz6) always show the youngest age peaks at ca. 335 Ma (data from Linnemann et al. 2024)



Forest (<5%), suggesting admixing of detritus from additional sources outside of the arc terrane. Age spectra variations are well reflected by the cumulative age plots shown in Fig. 11b and d. Based on these plots, two age spectra can be distinguished: age spectrum AS2 with <35% of Devonian/

Carboniferous grains, and 30–60% older than >600 Ma, and age spectrum AS3 with 50–80% of Devonian/Carboniferous grains, and <50% older than >600 Ma.

For the greywackes of the Badenweiler–Lenzkirch Zone of the southern Black Forest, mixing of detritus from

three different sources was recently discussed by Zeh et al. (2025a): (1) an oceanic arc–back-arc system (exemplified by the Wiese–Wehra Unit, Fig. 1b), (2) Cadomian greywackes (exemplified by the Murgtal Unit), and (3) an evolved continental arc of Cambro–Ordovician age (exemplified by the Todtmoos Unit). For the Giessen and Görlitz greywackes, abundance of Cadomian (Saxothuringian) detritus from the Lausitz Block and adjacent Saxothuringian basement units was discussed by Dörr et al. (2017), and Kühnemann et al. (2025), respectively.

## Geotectonic implications

The combined zircon age–Hf isotope data of this and previous studies reveal that most of the detritus found in the Palatinate Forest and Viséan Harz greywackes were derived from a juvenile oceanic arc terrane, initially formed in the Neoproterozoic to Ordovician (570–480 Ma). This timing requires that arc formation started prior to opening of the Rheic Ocean, which resulted from the break off of Avalonia from the northwestern margin of Gondwana at ca. 500 Ma (e.g., Žák et al. 2023 and references therein). Taking this into account, the oceanic arc terrane must have been located within the Prototethys to the north of Gondwana (e.g., Kroner and Romer 2013), in the realm not affected by Avalonia rifting between 500 and 430 Ma. Hafnium model ages further imply that the oceanic arc terrane resulted from continuous subduction of oceanic crust derived from the depleted mantle between 750 and 500 Ma (Fig. 9b).

Older Hf model ages up to 1.1 Ga, reflected by array B in Fig. 9, but also by the data from the Wiese–Wehra Unit of the Black Forest, might be interpreted to result from collision–amalgamation with an even older oceanic arc terrane. Five data points below array B in Fig. 9 ( $T_{DM}$  up to 1.45 Ma; ESM-Table S3), and five zircon grains (out of 550) with ages between 980 and 2570 Ma (ESM-Table S2), additionally indicate minor input from even older sources, albeit of unknown origin. The very small number of these exotic ancient grains suggests that the oceanic arc terrane perhaps never amalgamated to the Avalonian–Cadomian Belt. In that case abundant zircon detritus with ages between 750 and 530 Ma, and a wide range in  $\epsilon Hf_t$  values from +13 to –55 would be expected (see Fig. 10a; Saxothuringian spectrum). Abundant detrital zircon grains with subchondritic  $\epsilon Hf_t$  in the Harz greywacke Hz6 (clusters 1 and 2 in Fig. 9a) may be explained by admixing of detritus from the presumed Saxothuringian part of the MGCZ during Viséan sediment deposition.

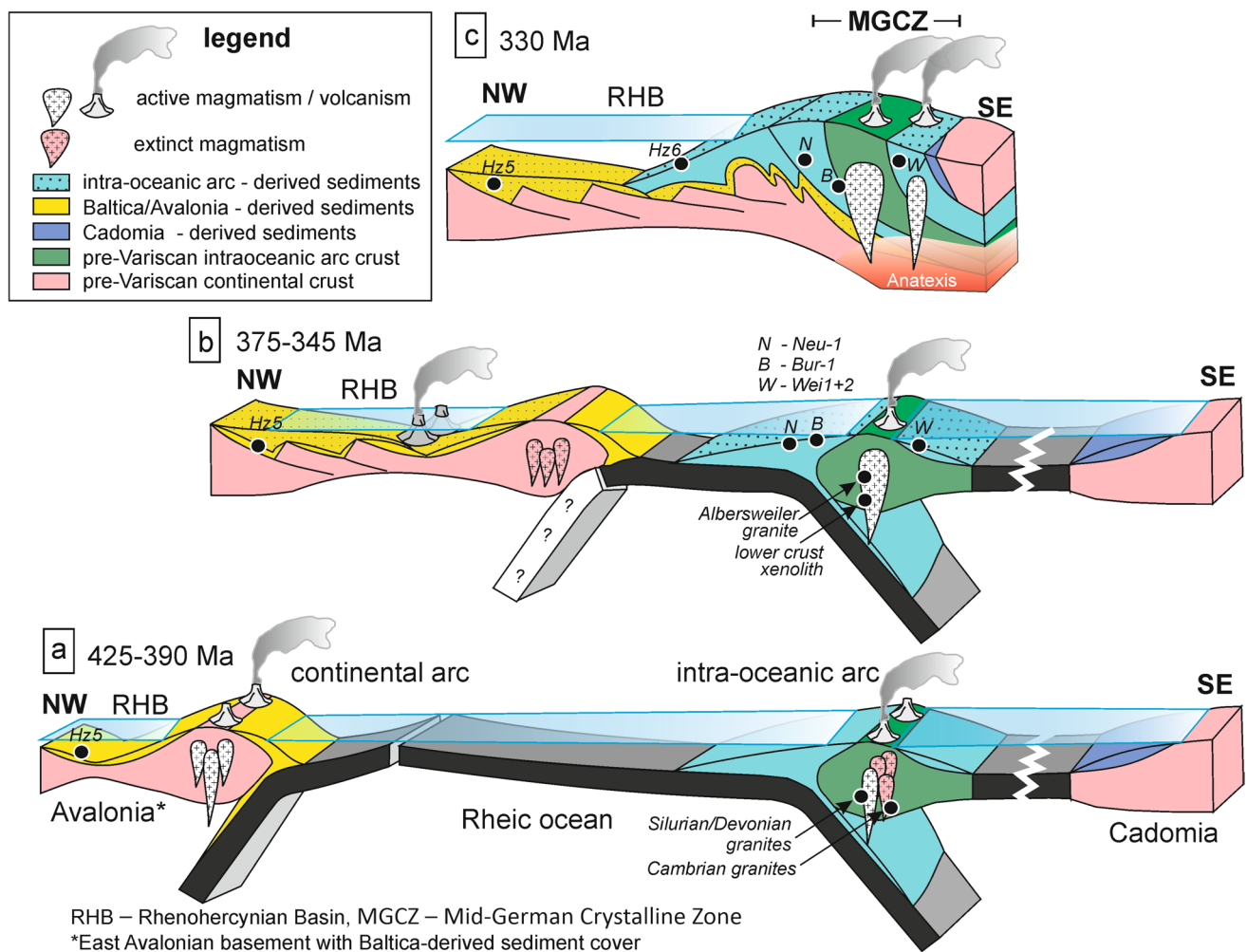
The general absence of Cadomian (Saxothuringian) and Avalonia–Baltica detritus in the Palatinate metagreywackes and metapelites (Figs. 10, 11, 12), and the age–Hf arrays A and B (Fig. 9) hint that the oceanic arc terrane remained isolated from the other, pre-Variscan basement units, and

that it was only affected by internal reworking until its amalgamation with Avalonia at ca. 335 Ma. Reworking occurred periodically at ca. 500, 400 and 370 Ma, as is reflected by the detrital zircon age record derived from the Palatinate metasediments (Fig. 6), and the age–Hf isotope signature of the Albersweiler granite gneiss. Crust reworking was initiated most likely by subduction beneath the oceanic arc (Fig. 13a). The position of all Hf isotope data on array A, or below it, further indicates that crust reworking prevailed over crustal growth between 500 and 335 Ma.

Crust reworking perhaps occurred by two major processes: (1) Subduction-recycling of volcano-sedimentary detritus derived from the evolving oceanic arc, causing successive enrichment of the sub-arc mantle by incompatible trace elements like Zr and Hf (see Nebel et al. 2011); (2) Periodic melting within the (enriched) mantle wedge and overlying arc crust. The combination of both processes and the resulting age– $\epsilon Hf_t$  array resemble the Pietersburg Terrane in Southern Africa, where subduction-related sediment recycling, and periodic granitoid formation lasted for ca. 350 Myr (Laurent and Zeh 2015).

In the present case, reworking of the isolated oceanic arc terrane at 420–390 Ma occurred coeval with the establishment of a continental magmatic arc along the southern margin of Avalonia, which is well documented by studies from the Ruhla and Spessart crystalline complexes, the Northern Phyllite Zone, and the Harz Mountains (e.g., Sommermann et al. 1994; Dombrowski et al. 1995; Kirchner and Albert 2020; Zeh and Gerdes 2010; Zeh et al. 2024b; Dörr et al. 2025). This continental arc is commonly explained as resulting from NW-directed subduction of the Rheic Ocean beneath Avalonia during the Silurian to Early Devonian and the related opening of the Rhenohercynian back-arc basin (Zeh and Gerdes 2010). Taking this into account, the oceanic basin located between the suggested oceanic arc terrane and Avalonia, i.e., the merged Prototethys–Rheic Ocean, underwent a bipolar subduction during the Silurian to Early Devonian (Fig. 13a), as originally suggested by Eckelmann et al. (2014). Nevertheless, the absence of any arc-related magmatic rocks in the period between 390 and 300 Ma on Avalonia suggests that NW-subduction ceased during the Early Devonian, while SE-subduction beneath the oceanic arc terrane continued. The latter is well reflected by the Albersweiler granite gneiss (Fig. 13b), and by the Frankenstein gabbro in the Odenwald (see discussion in Eckelmann et al. 2014). Zeh and Gerdes (2010) ascribed slab break-off as a reason for subduction to stop, although any conclusive evidence is lacking.

During Viséan, ongoing SW-subduction resulted in collision of the oceanic arc terrane with the Rhenohercynian realm, comprising Avalonia basement and overlying Baltica-derived sedimentary rocks. This collision resulted in fast uplift and erosion of the arc terrane, and deposition of



**Fig. 13** Plate-tectonic model showing the evolution of the juvenile intra-oceanic arc terrane in relation to Avalonia and Cadomia from the Early Devonian until the Viséan. **a** A juvenile oceanic arc terrane, isolated from Avalonia and Cadomia, becomes internally reworked by magmatic processes due to SE-directed subduction of the Protethys–Rheic Ocean. Contemporaneous NW-directed subduction led to the formation of a continental magmatic arc at the southeastern margin of Avalonia, and to opening of the Rheohercynian back-arc basin, successively filled with pre- to syn-Devonian detritus derived from Avalonia and Baltica (exemplified by sample Hz5). **b** Internal magmatic reworking, volcanism and sediment supply from the oceanic arc terrane continued until the Viséan (ca. 335 Ma), as is indicated by the syn-kinematic intrusion of the Albersweiler granite at

ca. 372 Ma, hosting xenoliths of Devonian greywackes (MDA=415 Ma), as well as by arc-related detritus found in Devonian to Viséan metasedimentary rocks of the Palatinate Forest (samples Neu-1, Bur-1, Wei-1 and Wei-2). NW-directed subduction ceased for an unknown reason. **c** Collision of the oceanic arc terrane with Avalonia caused fast uplift and erosion, as well as deposition of oceanic arc-derived detritus into the Rheohercynian Basin (exemplified by sample Hz6) during the Viséan. These sediments buried Avalonia–Baltica-derived sediments. Collision further resulted in underplating and anatexis of Avalonia- and oceanic arc-related basement rocks, reflected by widespread magmatism (I- and S-type) within the MGCZ realm. Collision with Cadomian basement along the southern margin of the oceanic arc terrane caused admixing of “Saxothuringia”-derived detritus

arc-related detritus in the Rheohercynian realm (exemplified by greywacke sample Hz6), on top of sedimentary rocks previously derived from mixed Avalonia–Baltica sources (exemplified by sample Hz5; Fig. 13c). Collision also caused underplating and partial anatexis of Avalonia basement, producing the S-type and hybrid granites. This interpretation is backed by a switch from superchondritic to subchondritic Nd–Hf isotopic signature in magmatic rocks (gabbros, granites, volcanics) of the MGCZ between 370 and 330 Ma. For the Palatinate Forest this is well reflected by the

Albersweiler granite gneiss ( $\epsilon\text{Hf}_t = +3.4$  to  $+7.8$  at 370 Ma), and the Viséan granites and felsic volcanics ( $\epsilon\text{Nd}_t = -2.1$  to  $-4.2$  at 333 Ma; Reischmann and Anthes 1996). For the adjacent Bergsträsser Odenwald, the switch is reflected by data from the Frankensteiner gabbro ( $\epsilon\text{Nd}_t = +3.4$  to  $+3.8$  at 362 Ma) and several Viséan granites ( $\epsilon\text{Nd}_t = -0.3$  to  $-4.0$  at 340–335 Ma; for a summary see Altherr et al. 1999). Altherr et al. (1999) excluded Avalonia-derived rocks as sources or contaminants for the Viséan granites in the Odenwald. The subchondritic  $\epsilon\text{Hf}_t$  values ( $-1$  to  $-5$ ) of many zircon grains of

Viséan age in the Harz greywacke Hz6 (cluster 1 in Fig. 9a) might also be explained by syn-collisional plutonism/volcanism in the adjacent MGCZ, related to partial anatexis of Avalonian basement at ca. 335 Ma. In contrast, cluster 2 in sample Hz6 (at 500 Ma) suggests input of detritus from an external source, perhaps from evolved Saxothuringian (Cadomian) basement, which was thrust contemporaneously over the southeastern margin of the oceanic arc terrane (Fig. 13c).

In the Odenwald Crystalline Complex of the MGCZ, closure of an Ediacarian-Silurian oceanic basin and back-arc system is suggested by the geochemical signatures of amphibolites (back-arc tholeiites) and eclogites (N- to E-MORB's), showing Nd-model ages of 610–600 Ma and 470–425 Ma, respectively (Will et al. 2015). The eclogites (Will and Schmädicke 2001) additionally yielded a garnet-whole isochrone age of  $357 \pm 6$  Ma ( $\epsilon_{\text{Hf}_t} = +11.3$ ), perhaps dating the climax of the metamorphic overprint (Scherer et al. 2002).

Finally, we note that the juvenile oceanic arc terrane perhaps was not restricted to the MGCZ in Central Europe, but extended further to the east and west. Eastwards, the juvenile arc terrane might be correlated with parts of the Mariánské Lázně Complex of the Teplá-Barrandian domain, as suggested by similar age- $\epsilon_{\text{Hf}_t}$  signatures of zircon grains in eclogites, felsic and mafic rocks (Fig. 9b). Westwards, it might be correlated with the Calzadilla Ophiolite in NW-Spain, which, according to Arenas et al. (2018, 2021) was derived from depleted mantle ( $\epsilon_{\text{Hf}_t} = +13$ ) in a fore-arc setting at ca. 600 Ma (for data compilation see Fig. 9b). Juvenile oceanic crust formation until 500 Ma is also reflected by the Vila da Cruces Ophiolite (Sánchez Martínez et al. 2021). In summary, the existing data suggest the existence of an Ediacarian to Devonian juvenile oceanic arc system, which extended from NW-Spain to the Teplá-Barrandian in the Czech Republic.

## Conclusions

- (1) Results of this study indicate that the MGCZ hosts relics of a so far unrecognized juvenile oceanic arc terrane, which was initially formed at 570–480 Ma, and had been reworked by magmatic processes until ca. 335 Ma.
- (2) The arc system initiated in the Prototethys Ocean north of Gondwana, and remained isolated from other pre-Variscan basement units until its Viséan amalgamation with Avalonia and Cadomia.
- (3) Due to Variscan collision and collapse, the arc terrane became widely dispersed, leaving traces in the Rhenohercynian, Saxothuringian, Teplá-Barrandian and the Moldanubian domains.

- (4) A continuation of the juvenile arc terrane towards the east and west is suggested by zircon age-Hf isotope signatures of the Mariánské Lázně Complex (Czech Republic) and the Calzadilla Ophiolite Complex (NW-Spain).
- (5) The results show that the combination of detrital zircon U-Pb ages and Hf isotope analyses provides a powerful tool to reconstruct the Variscan basement puzzle in Central Europe.

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## Declarations

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

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