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ORIGINAL PAPER

First U–Pb geochronology on detrital zircons from Early-Middle Cambrian strata of the Torgau-Doberlug Syncline (eastern Germany) and palaeogeographic implications

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Abstract LA-ICP-MS U–Pb data from detrital zircons of the Ediacaran to Cambrian siliciclastic sequence of the Torgau-Doberlug Syncline (TDS, Saxo-Thuringia, Germany) are reported for the first time. The majority of 203 analysed zircon grains is Proterozoic with minor amount of Archean and Palaeozoic grains. The U–Pb ages fall into three groups: 2.8–2.4 Ga (3%), Neoarchean to earliest Palaeoproterozoic; 2.3–1.6 Ga (46%), early to late Palaeoproterozoic; 1.0–0.5 Ga (47%), Neoproterozoic to Cambrian. This age distribution is typical for the West African Craton as the source area and for Cadomian orogenic events in northwestern Gondwana. The samples show an age gap between 1.6 and 1.0 Ga, which is characteristic for West African provenance and diagnostic in distinguishing this unit from East Avalonia and Baltica. The dataset shows clusters of Palaeoproterozoic ages at 2.2–1.7 Ga, that is typical for western Gondwana, which was affected by abundant magmatic intrusions (ca. 2.2–1.8 Ga) during the Eburnean orogeny (West African craton). Neoarchean zircon ages (3%) point to recycling of magmatic rocks formed during the Liberian and Leonian orogenies. Ediacaran to earliest Cambrian rocks of the TDS originated in an active margin regime of the Gondwanan shelf. The following early Palaeozoic overstep sequence was deposited within rift settings that reflects instability of the West-Gondwanan shelf and the separation of terranes from Ordovician onward. The results of this study demonstrate distinct northwestern African provenance of the Cambrian siliciclastics of the TDS. Due to Th–U ratios from concordant zircon analysis, igneous origin from felsic melts is concluded as the source of these grains.

Keywords Saxo-Thuringia · Torgau-Doberlug Syncline · West African Craton · Cambrian · Zircon geochronology · Provenance

Introduction

Clastic sedimentary rocks provide relevant information related to their provenance and the tectono-sedimentary processes during their original deposition (Oliveira et al. 2015). In last decades, the U–Pb dating on detrital zircon grains from clastic sediments by Laser Ablation and Inductive Coupled Plasma Mass Spectrometry (LA-ICP-MS) became a powerful tool in provenance analysis, and has been successful in discriminating between different source regions (e.g. Friedl et al. 2000; Jeffries et al. 2003; Gerdes and Zeh 2006; Frei and Gerdes 2009; Bahlburg et al. 2010; Linnemann et al. 2011, 2014). In this paper, we present new U–Pb data from siliciclastic rocks from eastern Germany (Torgau-Doberlug Syncline, Saxo-Thuringian Zone) and we review the tectono-stratigraphic setting of the area for the Ediacaran-Cambrian succession.

Whereas sedimentary rocks of Ediacaran age are widely distributed in the Saxo-Thuringian Zone, Cambrian successions focused in this paper show a rather spotty geographic

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occurrence. Stratigraphically intact successions are practically absent mainly due to later Variscan overprint. A special challenge consists in the determination of the stratigraphic position of non-fossiliferous sedimentary portions and in the reconstruction of the depositional history especially of the siliciclastics. Whereas for some Early (carbonates) and Middle Cambrian (siliciclastics) horizons of the Torgau-Doberlug Syncline the stratigraphic age and for the mentioned early Cambrian ones also the depositional conditions have already been concluded reasonably, absolute ages as well as the source areas of the clastic material, in contrast, have hitherto not yet been investigated. Objective of this paper is to start the filling of this gap.

In this paper, the U–Pb detrital zircon ages are used to conclude the provenance of Cambrian siliciclastic rocks of the TDS and to evaluate the tectono-stratigraphic framework during Ediacaran–Cambrian time.

Geological setting

The Saxo-Thuringian Zone was defined (together with the other Variscan zones) by Kossmat (1927). It consists of several Cadomian basement units overlain by Palaeozoic sediments. The Saxo-Thuringian Zone is a part of the Armorican microplate (van der Voo 1979), a para-autochthonous terrane at the northern margin of Gondwana, which is also mentioned the Armorican Terrane Assemblage (Tait et al. 1997) or part of Cadomia (Linnemann et al. 2004; Bahlburg et al. 2010). The Torgau-Doberlug Syncline (TDS) represents a subunit situated in the northeastern part of the Saxo-Thuringian Zone and is composed of Ediacaran to Cambrian, and locally of Viséan sediments (Fig. 1). This filling resulted from sedimentary processes in marginal basin and continental arc environments of the Cadomian orogenic belt, which persisted until the earliest Cambrian time (Buschmann et al. 2006).

The TDS, which is a subsurface unit only known from boreholes, comprises the Ediacaran Rothstein Formation, unconformably overlain by Cambrian sedimentary rocks (Buschmann et al. 1995). The Rothstein Formation represents a fragment of a Cadomian back-arc basin, which has been slightly deformed during the Cadomian orogeny (Buschmann 1995). Overlying Cambrian strata, in contrast, are undeformed (Linnemann and Buschmann 1995; Elicki 1997; Buschmann et al. 2006).

The Rothstein Formation is characterized by thick layers of massive black chert and dark-gray to black distal turbidites, composed of graywacke and mudstone beds. Sedimentological and geochemical data point to an origin within the center of a back-arc basin developed on thinned continental crust (Buschmann 1995; Linnemann et al. 2000, 2007). The depositional age of the Rothstein Formation comes from zircon dating (ash layers), because the only fossil content is of non-significant pyritized spherical and filamentous, probably palynomorph microforms (Buschmann 1990). The U–Pb dating of zircon grains from Rothstein Formation yielded a concordant age of 570–565 Ma (Linnemann et al. 2000, 2007; Buschmann et al. 2001), which assigns the depositional time to the Late Ediacaran.

In the Cambrian time, several major continents (Gondwana, Laurentia, Siberia, Baltica) existed (Linnemann et al. 2000; Elicki and Wotte 2003). During the Early to Middle Cambrian, the TDS was situated on the European shelf of the western Gondwanan margin (Fig. 2). The general sedimentological evolution during the Early-Middle Cambrian produced a rather uniform stratigraphic pattern over most of the Mediterranean region, which includes the Cambrian deposits today in Spain, France, Sardinia and Germany, and showing strong similarity to successions in Morocco and Turkey, too (Elicki 1997; Linnemann et al. 2000; Elicki and Wotte 2003).

Cambrian strata of the TDS are unconformably on top of the Cadomian basement and are estimated to be of about 1500 m in thickness. They are represented by the Lower Cambrian Zwethau Formation and the Middle Cambrian Tröbitz and Delitzsch formations (Arenzhain Group) (Fig. 3) (Brause and Elicki 1997; Elicki 1999; Geyer et al. 2014). These formations consist of (rare) conglomerates, of shallow marine carbonates and peritidal to shelf siliciclastics. Generally, the units represent the first post-Cadomian sedimentary sequence. Following them, a remarkable and widespread gap in sedimentation is characteristic for most of the Upper Cambrian time (Linnemann 2007).

The Lower Cambrian Zwethau Formation is unconformable on top of the Ediacaran rocks (Cadomian basement). The thickness of the Zwethau Formation is approximately 700 m. It consists of two members, the lower member (Torgau Member) is dominated by carbonates, the upper member (Rosenfeld Member) consists of alternating carbonate-siliciclastic and pure siliciclastic sediments (Fig. 3). The Torgau Member consists of fossiliferous oolitic limestone, dolomite, claystone, and increasing siltstone intercalations in the upper part. Common sedimentary structures (small-scale ripples, cross bedding, bioturbation, mud cracks, sulfate nodules) point to shallow subtidal to intertidal conditions and the existence of migrating oolite shoals and lagoons (Elicki 1994, 1999; Buschmann et al. 1995). Elicki (1994, 1999) interpreted the sedimentary environment of the Torgau Member as a carbonate-dominated subtidal ramp with calcimicrobial-archaeocyathan buildups succeeded by a mixed intertidal ramp environment with oolite shoal complexes and partly restricted areas. The archaeocyaths correlate with Lower Ovetian archaeocyathan zones of the Ossa-Morena Zone (SW Iberia) which corresponds with the

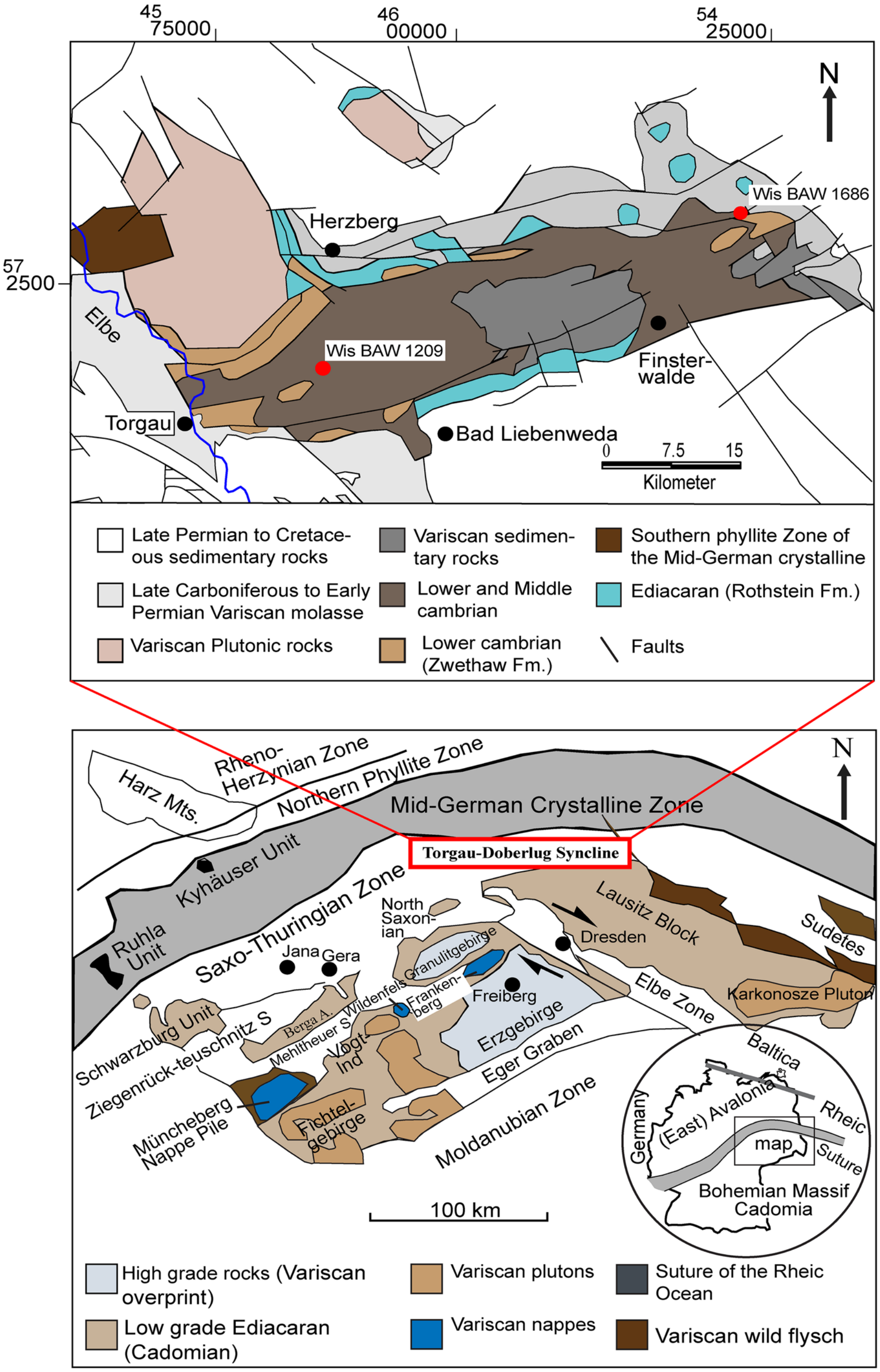


Fig. 1 Location map of the study area. **a** Geological map of Torgau-Doberlug Syncline TDS (modified from Linnemann et al. 2010) with core localities shown by circle notations. **b** Sketch map of the Saxo-Thuringian Zone and location of the study area (modified from Linnemann et al. 2010)

Middle Issendalenian of Morocco due to their trilobite content. This in turn assigns the Torgau Member to the mid-Early Cambrian (Elicki 1997; Geyer and Landing 2004). The upper member of the Zwethau Formation (Rosenfeld Member) mainly consists of alternations of limestone, dolostone, and siliciclastic sediments. In contrast to the Torgau Member, here the amount of siliciclastic sediments is distinctly larger, and redispositional features such as slump structures and fining upward cycles within the carbonates are often present (Freyer and Suhr 1987). Fossils include cyanobacteria, shell remains, and poorly preserved archaeocyaths. The depositional environment is poorly constrained and was assigned to a deeper basinal area by Freyer and Suhr (1987), although the occurrence of coarser siliciclastic sediments might rather reflect climatically and related run-off changes

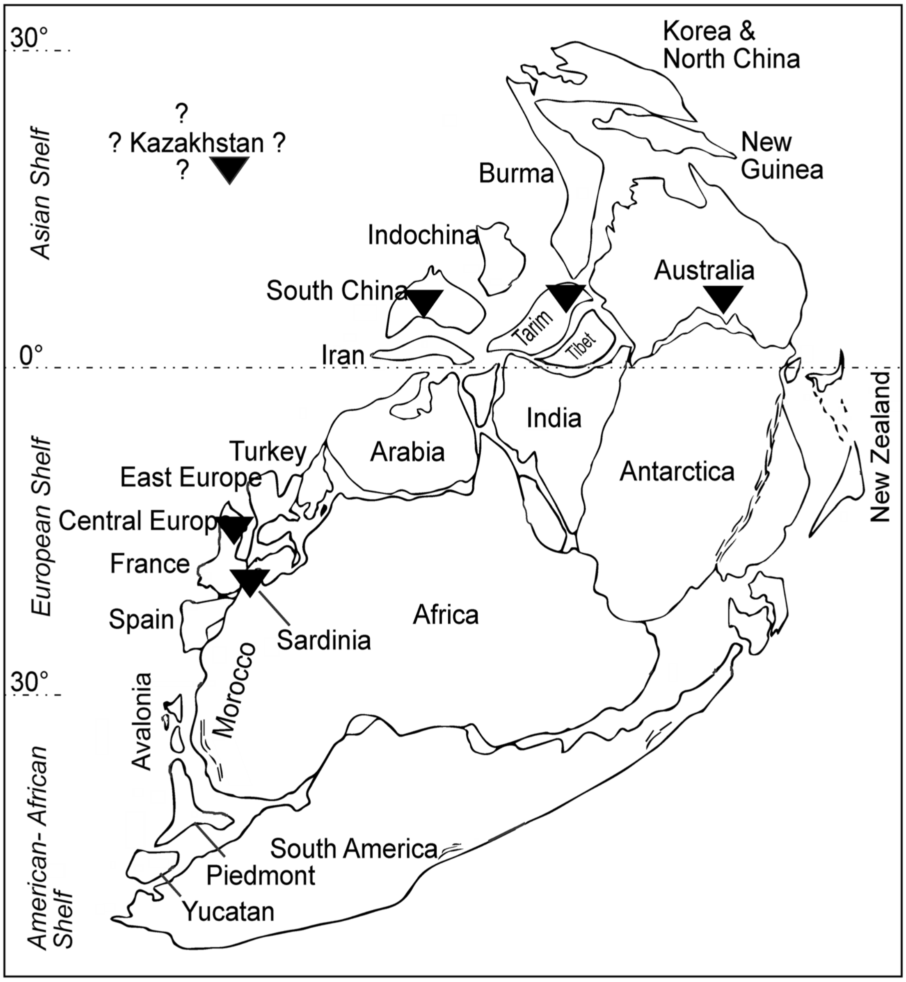


Fig. 2 Palaeogeographic sketch of the Gondwana craton during the late Early to early Middle Cambrian times (modified after Elicki and Wotte 2003). Location of Torgau-Doberlug Syncline indicated by a *black triangle*

under neritic conditions and a palaeogeographic dislocation of the area (Elicki 2003).

The Middle Cambrian sediments of the TDS consist of two units summarized as the Arenzhain Group (composed of the Tröbitz and Delitzsch formations) (Fig. 3). This group is represented by siliciclastic sediments with very few carbonate intercalations at its base (Brause 1969, 1970; Elicki 1997; Geyer et al. 2014). The Tröbitz Formation is dominated by alternating quarzitic sandstones with minor dark grey micaceous claystone. Several thin calcareous layers occur near the transition to the overlying Delitzsch Formation (Brause 1970). The Tröbitz Formation is assigned to the lower Middle Cambrian by "*Paradoxides*" *insularis* biozone fossils, which corresponds to the Middle Agdzian (Celtiberian) of western Gondwana (Buschmann et al. 2006). The overlying Delitzsch Formation is dominated by alternating quarzitic sandstone and micaceous claystone with decreasing sandstone intercalations towards the top. In contrast to the Tröbitz Formation, the claystone is mostly greenish and more micaceous. Small-scale sedimentary cycles of up to 10 cm thickness were observed in the upper parts where cross bedding and abundant trace fossils also occur (Brause 1970). Several thin calcareous horizons occur in the middle part of the Delitzsch Formation. The Delitzsch Formation is assigned to the Middle Cambrian ("*Paradoxides*" *insularis* to lowest *Paradoxides paradoxissimus* biozones) corresponding to the late Agdzian to Early Caesaraugustan (Celtiberian) of western Gondwana (Buschmann et al. 2006).

Analytical procedures

Detrital zircon grains of three samples from TDS were collected and investigated. These samples were taken from two drilling cores (Wis BAW 1209-78 and Wis BAW 1686-81), which represent the Ediacaran–Cambrian interval. These boreholes were drilled for exploration in mineral resources and cores are today deposited in a central repository of the Brandenburg State Office for Mining, Geology and Raw Materials (LBGR) in Wünsdorf near Berlin.

The selected samples were first fragmented with the SelFrag laboratory equipment at the Geological Institute of Freiberg University. They were sieved for

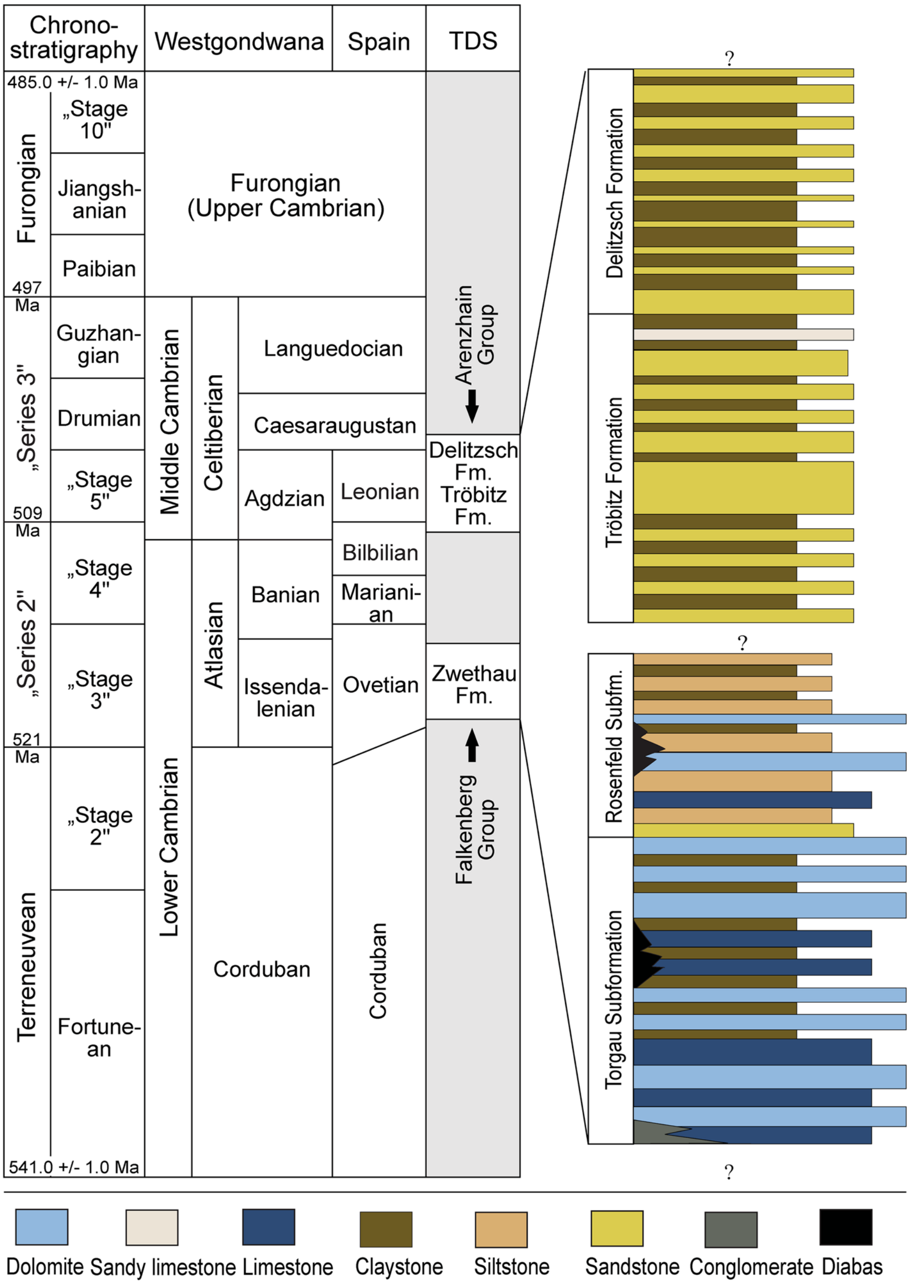


Fig. 3 Lithological column and detailed profiles of sedimentary rocks of the Torgau-Doberlug Syncline TDS Central Germany (from Elicki 2015)

fraction 80–400 µm, separated by magnetic separation of the extracted heavy minerals in a Frantz Isodynamic Separator and followed by density separation using a heavy liquid method. The final selection of zircon grains for U–Pb dating was carried out by hand-picking under a binocular microscope. Zircons of each sample were randomly picked to get a representative selection of the overall zircon populations. The selected zircons were mounted in epoxy and polished to approximately half of their thickness to expose their internal structure. Transmitted and reflected light photomicrographs were made along with CL images to select grains and choose sites for analysis. To avoid mixed U–Pb ages resulting from postmagmatic or metamorphic influences only zircon grains showing monophase growth patterns were selected for isotope analyses.

The selected zircon grains were analyzed for U, Th and Pb isotopes by LA-ICP-MS techniques at the Museum of Mineralogy and Geology (GeoPlasma Lab, Senckenberg Natural History Collections, Dresden) using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a RESOLUTION Excimer Laser System and a large volume cell (LAURIN TECHNIC S-155). The settings of the Laser and the ICP-MS instrument are given in Table 1. Each analysis consisted of 15 s background acquisition

Table 1 LA-ICP-MS operating conditions and instrument settings for U–Pb analyses

Laboratory and sample	
Laboratory name	GeoPlasma Lab, Senckenberg Natural History Collections, Dresden, Germany
Sample type/mineral	Sandstone/Zircons
Sample preparation	Conventional mineral separation: Frantz magnetic separator, heavy liquids, handpicking under binocular microscope. 1 cm resin mount, 1um polish to finish
ICP-MS Instrument	Thermo-Scientific, Finnigan Element 2 XR
Make, Model and type	1390 W
Forward power	15.0 L min-1 (plasma)
Gas flow rate	1.07 L min-1 (aux)
Scan mode	E-scan
Scanned masses	202, 204, 206, 207, 208, 232, 235, 238
Mass resolution	300
Integration time per peak	1.4 s (=25 scans)
Oxide UO+/U+	<1%
Dwell time	4 ms
Dead time	18 ns
Settling time	≤1 ms/amu
Number of scans	1500
Laser ablation system	RESOLUTION
Laser system	LAURIN TECHNIC S-155
Large volume cell	193 nm
Laser wavelength	25%
Attenuator	4–5 mJ
Fluence	5 mJ
Laser energy	4 Hz
Repetition rate	25 µm (rims, cores unknowns)–35 µm (non-complex unknowns), 35 µm (standard)
Spot size	560 ml min^{-1} He, 7.0 ml min^{-1} N2
Carrier gas and flow	15 s
Blank	26 s
Ablation time	20 s
Wash-out time	30 s prior to each ablation spot
Data processing	GJ-1 used as primary reference material, Plesovice used as secondary reference material
Gas blank	Plesovice (Sláma et al. 2008)
Calibration strategy	In-house spreadsheet data processing
Reference material information	Mass bias correction normalized to the primary reference material
Data processing package used	^{204}Pb signal and a model Pb composition (Stacey and Kramers 1975)
Mass discrimination	Ages are quoted at 95% conf., propagation is by quadratic addition
Common Pb correction	Plesovice: Wtd ave. ^{206}Pb/^{238}U age = 337 ± 8 Ma, 336.5 ± 5 Ma, 338 ± 4 Ma (95% conf.)
Uncertainty level and propagation	For details on analytical protocol and data processing, see Gerdes and Zeh (2006)
Quality control/validation	
Other information	

followed by 26 s data acquisition, using a laser spot size 35 µm for standards and non-complex unknown zircon grains. In some cases, for smaller domains of the unknown grains (rims and cores) a smaller diameter of 25 µm was used. As primary zircon standard the GJ1 zircon was used. According to the recommendation of Horstwood et al. (2016) a secondary zircon standard (Plesovice zircon) was analysed. Sequences started with the analysis of five GJ1, one Plesovice and 10 unknowns followed by a repetition of a succession of three measurements of the GJ1 standard, one measurement of the Plesovice standard and 10 unknowns. Per sample (120 unknowns) 41 GJ1 and 13 Plesovice were analysed. The secondary standard (Plesovice) shows in the three sample sets (this paper) weighted averages of ^{206}Pb-^{238}U ages of 337 ± 8, 336.5 ± 5, and 338 ± 4 Ma (Tables 2–4, electronic supplement), which are in the recommended range of Sláma et al. (2008). Raw data were corrected for background signal, common Pb correction, laser-induced elemental fractionation, instrumental mass discrimination, and time-dependent elemental fractionation of Pb-Th and Pb-U is applied using an Excel ® spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann-Wolfgang-Goethe University Frankfurt, Frankfurt am Main, Germany). Where necessary, a common Pb correction was carried out based on the interference and background corrected ^{204}Pb signal and a model Pb composition (Stacey and Kramers 1975). The necessity of the correction is judged on whether the corrected ^{207}Pb/^{206}Pb ratio lies outside the internal errors of the measured ratios. Interpretation with respect to the obtained ages was done for all grains within a range of 90–110% of concordance (Gerdes and Zeh 2006). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (~0.6 and 0.5–1% for $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia diagrams (2σ error ellipses) and Concordia dates (95% confidence level) were produced using Isoplot/Ex 2.49 (Ludwig 2001), and frequency and relative probability plots using AgeDisplay (Sircombe 2004). The $^{207}Pb/^{206}Pb$ date was taken for interpretation for all zircons > 1.0 Ga, and the $^{206}Pb/^{238}U$ dates for younger grains. For further details on analytical protocol and data processing, see Gerdes and Zeh (2006).

Results

In this study, 370 grains were analysed. The results of LA-ICP-MS U–Pb zircon dating are shown on the concordia diagrams in Figs. 5, 6, and 7 and listed in tables 2–4 (electronic supplement). The frequency and probability density distribution plots are shown in Figs. 5, 6 and 7. CL images of representative detrital zircons from the three quarzitic sandstone samples collected from the TDS unit are shown in Fig. 4. In this study, the concordance in the range of 90–110% was use. The errors reported in the text are 2σ.

Sample T02, borehole 1209-78, Torgau-Doberlug (r5719848, h4581980 UTM)

This sample is fine–medium quartzitic sandstone, which mainly made of quartz and plagioclase, mica, and very scarce accessory components. This sample was collected from borehole 1209-78 at depth 151 m, which penetrated Lower-Middle Cambrian rocks in TDS and located west of the town of Doberlug-Kirchhain and south of Herzberg (Fig. 1). The selected zircon grains are mostly homogeneous and have internal textures that are supposed to be typical for high-grade metamorphic rocks (Corfu et al. 2003; Sagawe et al. 2016) (Fig. 4). A total of 120 detrital zircon grains were analysed, from which 76 grains were concordant (Table 2, electronic supplement). The age of the youngest concordant grain yields a date of 558 ± 18 Ma. The oldest zircon yields a date of 2756 ± 22 Ma. From these 76 grains, four grains are of Archaean age (2756 ± 22 Ma, 2691 ± 36 Ma, 2620 ± 34 Ma, 2591 ± 19 Ma). Thirty-eight grains are Palaeoproterozoic (50%), ranging from 2470 ± 28 Ma to 1682 ± 44 Ma. The majority, 44% of all grains are Neoproterozoic and range from 904 ± 31 Ma to 558 ± 18 Ma. No Mesoproterozoic zircons were detected (Fig. 5). The probability plot shows distinct peaks at c. 660, 625, 560 and 533 Ma (Fig. 5). Measured Th–U elemental ratios for concordant zircons are between 0.04 and 2.84 (Fig. 8). Three grains yield Th–U values below 0.1 and show metamorphic overprint (e.g., Gärtner et al. 2014). The Th–U ratio of 92% of grains are in the range of 0.1–1.50, which indicates their origin as from magmas of intermediate to felsic composition (e.g., Hoskin and Schaltegger 2003; Linnemann et al. 2007).

Sample T07, borehole 1209-78, Torgau-Doberlug (r5719848, h4581980 UTM)

This sample is fine–medium quartzitic sandstone. The main components of this sample are quartz, plagioclase, mica, and very scarce accessory components.The sample was collected from borehole 1209-78 at depth 266 m below the sample T02 (see previous paragraph). Seventy zircon grains from this sample were concordant (Table 3, electronic supplement). Their CL images mostly show large areas of homogenization, suggesting attributes of high-grade metamorphism (Corfu et al. 2003; Sagawe et al. 2016) (Fig. 4). The youngest concordant grain yields a date of 541 ± 11 Ma and the oldest zircon yields a date of 2532 ± 14 Ma. One grain is Archaean in age (2532 ± 14 Ma). About 46% of grains are Palaeoproterozoic, in the range 2424 ± 176 Ma to 1717 ± 73 Ma. Only two Mesoproterozoic zircons were detected in this sample (1435 ± 76 Ma, 1320 ± 26 Ma). Around 50% of all zircons in the sample are Neoproterozoic, in the range 820 ± 15 Ma to 541 ± 11 Ma (Fig. 6). The probability plot is dominated by peaks at c. 670, 630, 525, and 560 Ma (Fig. 6). Obtained Th–U values varies from 0.07 to 2.12 for all concordant grains (Fig. 8). Almost 96% of grains are in the range of 0.1–1.50, which indicates their origin from magmas of intermediate to felsic composition (e.g., Hoskin and Schaltegger 2003; Linnemann et al. 2007).

Sample T15, borehole 1686-78, Herzberg (r 5716577, h 5421637 UTM)

This sample is of fine–medium quartzitic sandstone, dominated by quartz, plagioclase, mica, and some accessory components. This sample was collected from borehole 1686-78 at depth 329 m, which is located near Herzberg (Fig. 1). The 120 zircons extracted from this rock are characterized by internal textures like fir-tree and sector zoning, as well as homogenization (Fig. 4). From 120 grains, only 57 grains gave concordant ages varying between 2705 ± 15 and 506 ± 07 Ma (Fig. 7, Table 4, electronic supplement). One zircon shows Archaean age (2705 ± 15 Ma). A remarkable proportion of 47% is Palaeoproterozoic in age. Such dates range from 2453 ± 16 Ma to 1609 ± 39 Ma. Three Mesoproterozoic zircons were detected (1473 ± 48 Ma, 1193 ± 25 Ma, 1110 ± 20 Ma). Around 42% of all zircons

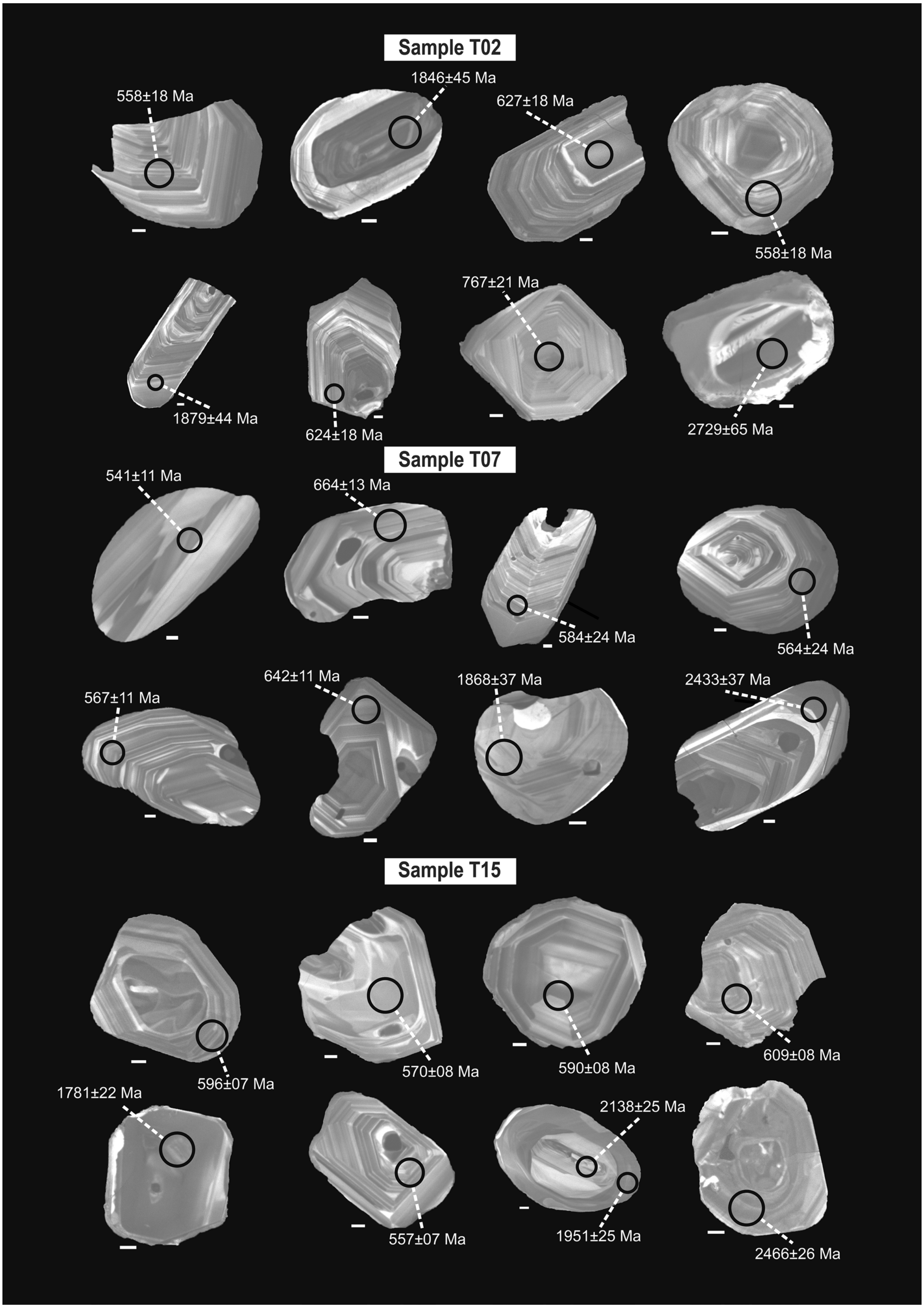
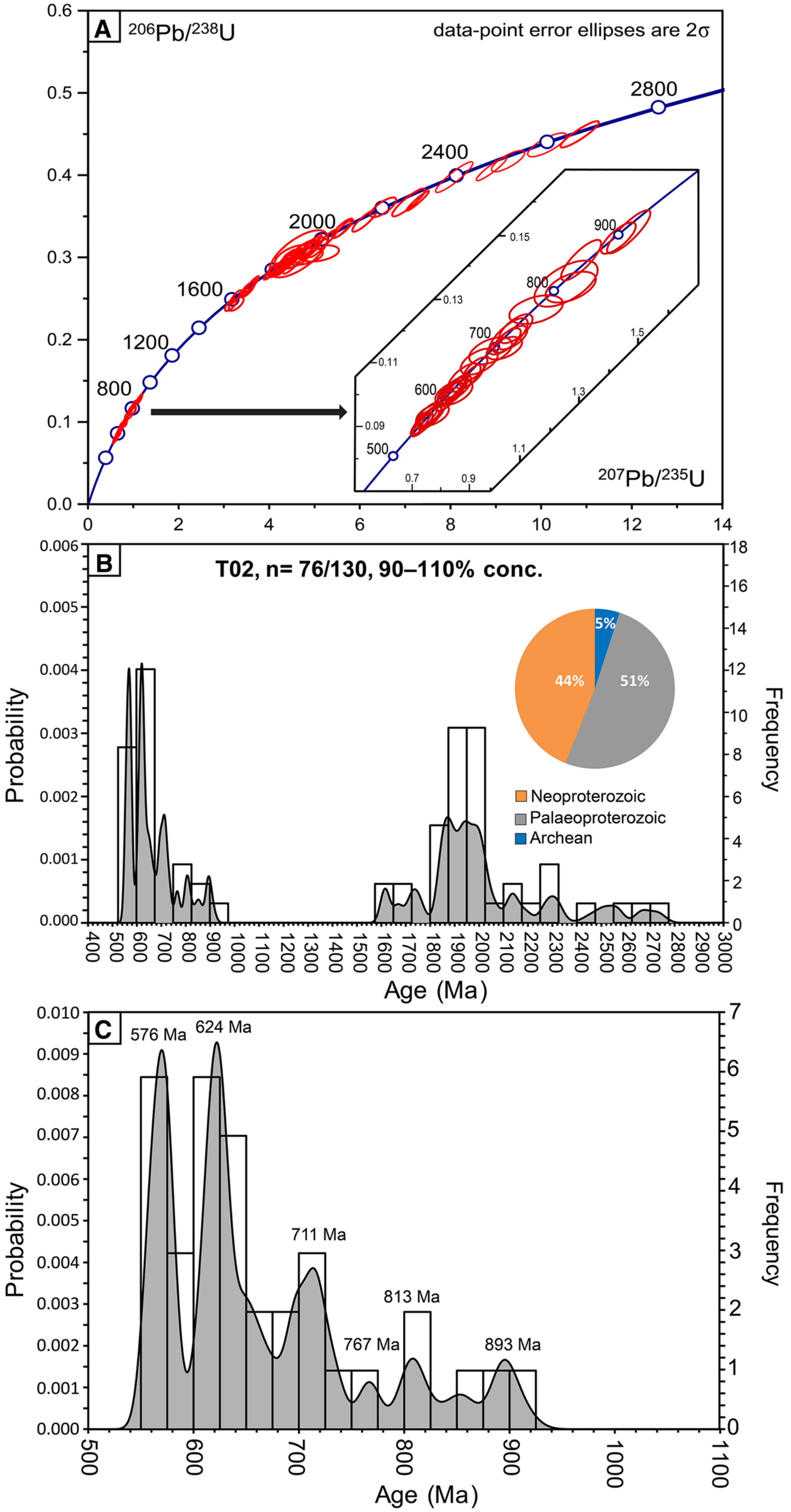


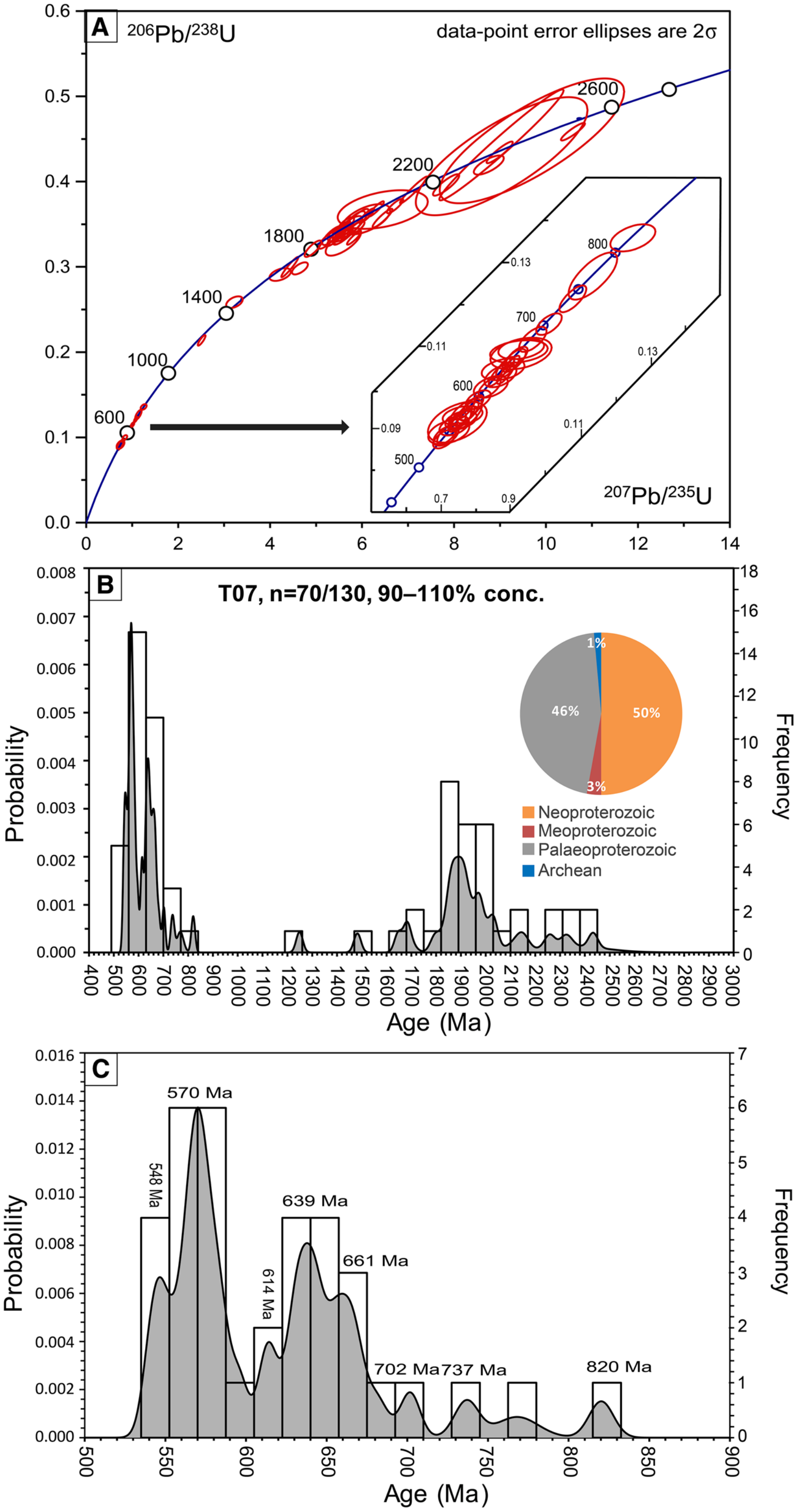
Fig. 4 Cathodoluminescence (CL) images of zircon grains obtained from samples T02, T07 and T15 showing their internal texture, laser spots (*red circles*), and apparent ages in Ma (2σ-error). All *scale bars* are 10 µm

Fig. 5 U–Pb ages of a detrital zircon grain from sample T02. **a** Concordia diagram. **b**, **c** Combined binned frequency and probability density plots of detrital zircon grains. **b** 400–3000 Ma. **c** 500–1100 Ma



in sample T15 are Neoproterozoic, in the range from 944 ± 14 Ma to 506 ± 07 Ma. Two grains yield early Cambrian dates (506 ± 07 Ma, 507 ± 08 Ma) (Table 4, electronic supplement). The probability plot shows distinct peaks at c. 660, 590, 570, and 560 Ma (Fig. 7). Measured Th–U values of concordant grains show a spread of 0.11 to 1.50 (Fig. 8).

Fig. 6 U–Pb ages of detrital zircon grains from sample T07. **a** Concordia diagram. **b**, **c** Combined binned frequency and probability density plots of detrital zircon grains. **b** 400–3000 Ma. **c** 500–900 Ma

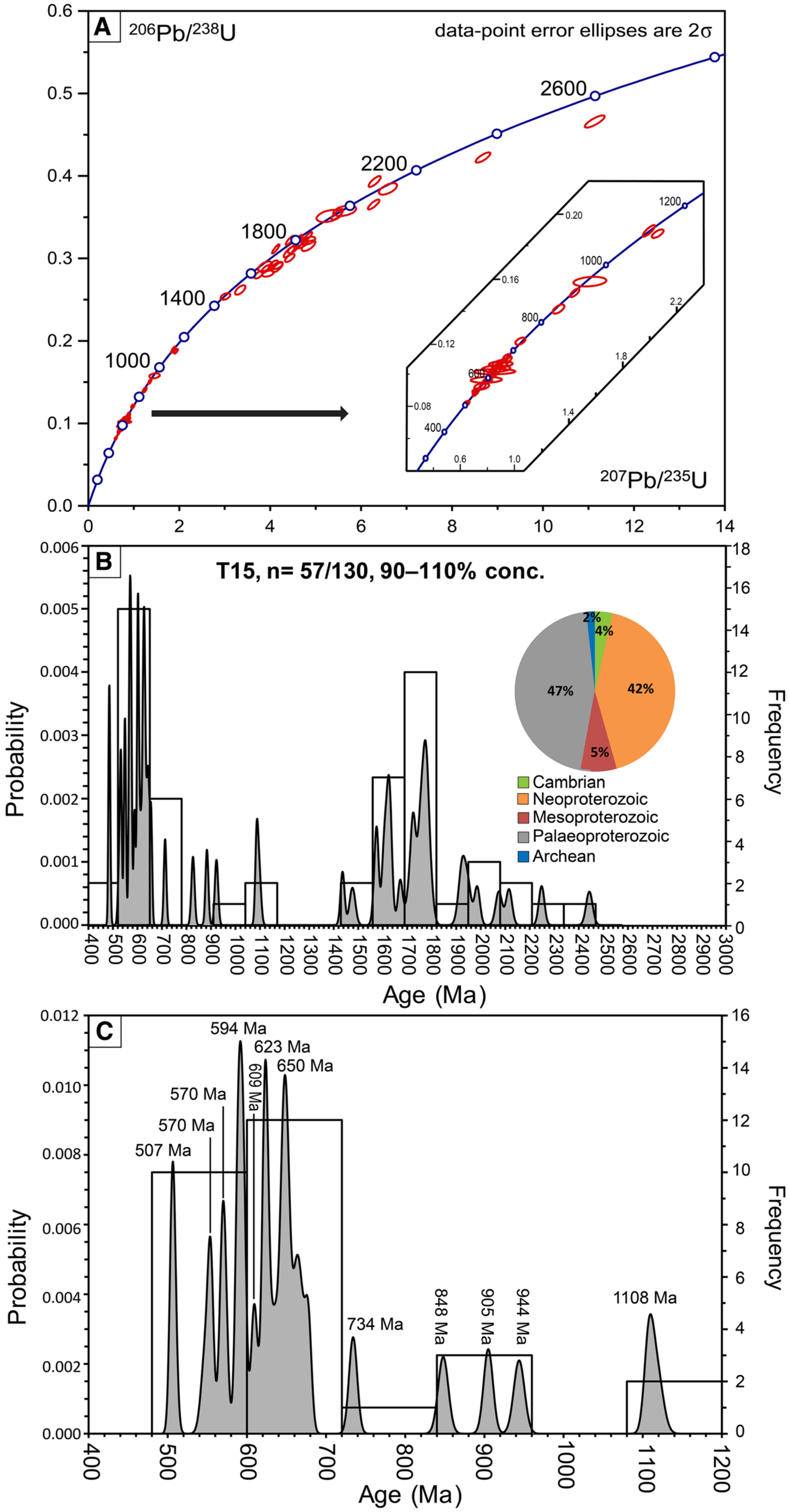


All the grains are in the range of 0.1–1.50, which indicates their origin from magmas of intermediate to felsic chemistry (e.g., Hoskin and Schaltegger 2003; Linnemann et al. 2007).

Discussion

The scarcity of geologic data from TDS presents a major limitation in understanding the Proterozoic and Early to

Fig. 7 U–Pb ages of detrital zircon grains from sample T15. **a** Concordia diagram. **b**, **c** Combined binned frequency and probability density distribution plots of detrital zircon grains. The range of **b** 400–3000 Ma. **c** 400–1200 Ma



Middle Cambrian evolution of this region. The geochronological ages of 204 inherited zircons from siliciclastic rocks were determined to review the palaeogeographic history, the source areas and the timing of geotectonic events in the TDS during Proterozoic to Early–Middle Cambrian time. A total amount of 370 zircon grains has been collected and analysed from three samples in TDS.

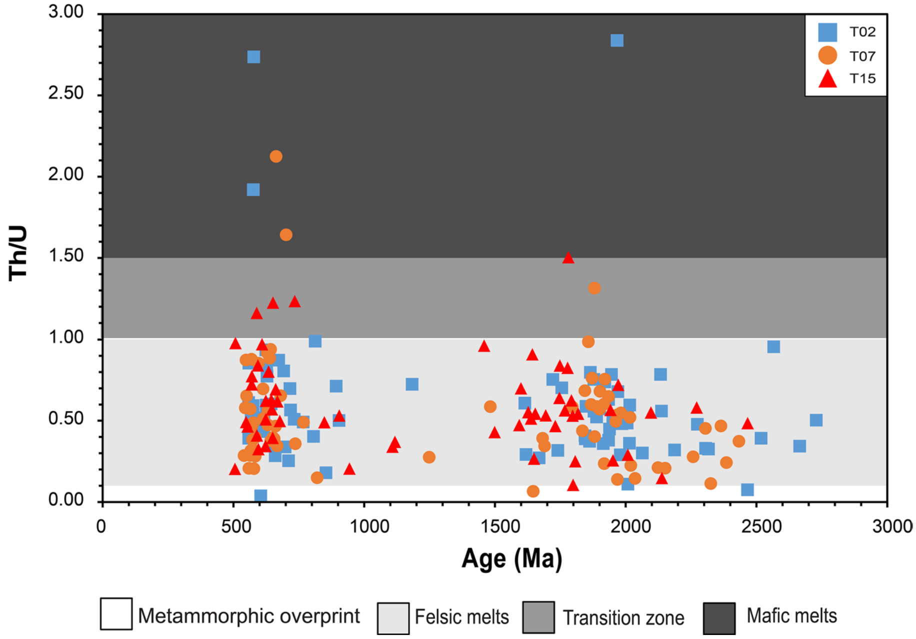


Fig. 8 Th/U ratio versus concordant U–Pb age of detrital zircon grains from TDS

The U–Pb dating ages obtained from the analysed samples show a common pattern regarding the source area. The ages are predominantly Neoproterozoic to Cambrian (1.0–0.5 Ga; 47%) and Palaeoproterozoic (2.3–1.6 Ga; 48%) with a smaller fraction of Neoarchean age (3%). The age spectrum of the samples is comparable to those reported from other Cadomian terranes (e.g., Linnemann et al. 2004, 2008; Drost et al. 2011; Mazur et al. 2015), which formed along the West African margin by recycling the old West African crust by magmatic activity during Cadomian orogenic processes (Linnemann et al. 2000, 2014; Nance et al. 2008; Mazur et al. 2015). The main feature of all investigated samples is the scarcity of a detrital record of Mesoproterozoic source rock (1.6–1 Ga) (Fig. 9). This phenomenon is typical of West African provenance. It indicates derivation of the clastic material from the West African craton and is diagnostic in distinguishing from East Avalonia and Baltica as a possible source (Nance and Murphy 1994; Friedl et al. 2000; Murphy et al. 2000; Linnemann et al. 2004; Bahlburg et al. 2010). Three age clusters

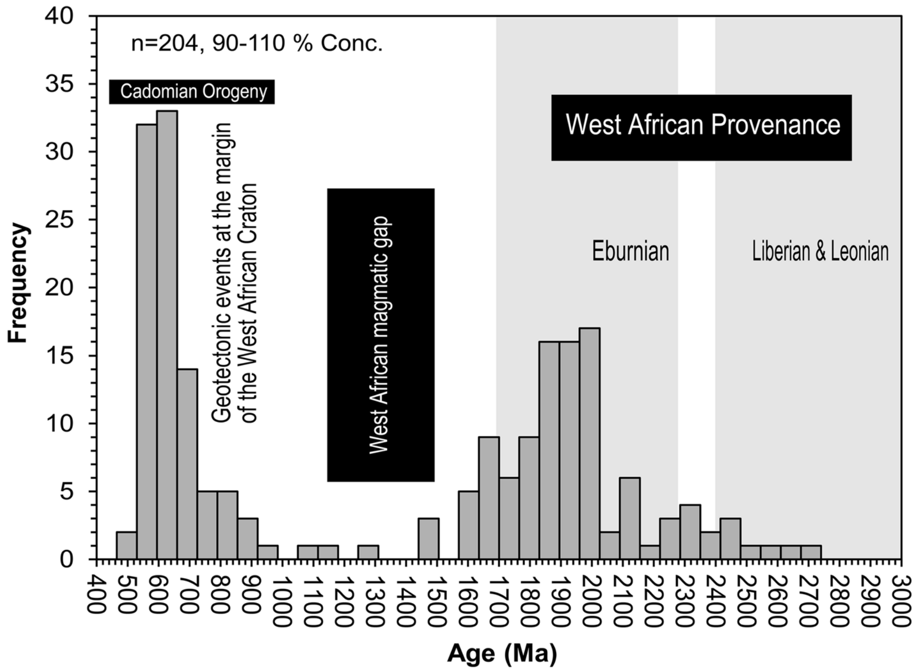


Fig. 9 Age compilation for detrital zircon grains from three Ediacaran–Cambrian sandstone of the TDS (Saxo-Thuringian Zone). Ages older than 1.7 Ga clearly indicate the West African provenance (modified from Linnemann et al. 2010)

have been obtained from this study 2.8–2.4 Ga, 2.3–1.7 Ga, and 1.0–0.5 Ga (Fig. 9). The few Archean zircon grains (2.8–2.4 Ga) point to recycling of magmatic rocks formed during the Liberian and the Leonian orogenies, respectively. Both orogenies affected the West African craton during the Archean (Rocci et al. 1991). An orogenic activity taken place at 2.3–1.7 Ga is typical for the western part of the Gondwana supercontinent, which was affected by abundant magmatic intrusions during the Eburnean orogeny (West African craton) (Hirdes and Davis 2002; Bahlburg et al. 2010). The third age cluster 1.0–0.5 Ga follows the Eburnean orogeny after the mentioned West African magmatic gap by a period of orogenic quiescence lasting for about 900 Ma, which was terminated by Neoproterozoic crust forming events starting at c. 750 Ma (Hirdes and Davis 2002; Linnemann et al. 2004; Stern 2008; Bahlburg et al. 2010).

The oldest sediments in TDS have been deposited at about 570–565 Ma (Rothstein Formation) (Linnemann 2007). Linnemann et al. (2007) suggested that the Rothstein Formation was deposited within a back-arc basin, which predominantly consisted of thinned continental crust and was flanked by a magmatic arc to the “North” and by a cratonic source to the “South” (Linnemann et al. 2000; Buschmann et al. 2001). Field data and geochemical information suggest that the 566 ± 10 Ma old Rothstein Formation comprises a low-grade metamorphic suite of intrusive and effusive enriched mid-ocean ridge basalts, andesites, calc-alkaline metabasalts, and subordinate alkaline metabasalts (Buschmann 1995; Buschmann et al. 2001). The submarine effusive character of these rocks is indicated by pillow structures that may have formed during seafloor spreading. This interpretation is additionally supported by the occurrence of black cherts, which are assumed to be the product of hydrothermal activity at a spreading center that caused alteration of the submarine volcanic and sedimentary rocks. According to Buschmann (1995), deposition of the Rothstein Formation was accompanied by strike-slip faulting, that produced submarine pull-apart basins and led to the re-sedimentation of older unconsolidated sediments.

Cambrian sediments in the Saxo-Thuringian Zone are restricted to the Lower and Middle Cambrian, with the onset of sedimentation in the higher Early Cambrian at about 530 Ma (Elicki 1997). These successions are characterized by carbonates with archaeocyatha, siliciclastic sediments, and red beds. The last were likely derived from erosion of laterite horizons generated on the denuded Cadomian orogeny and the cratonic hinterland at ca. 540–530 Ma (Linnemann and Romer 2002). These occurrences suggest a general uplift of the Cadomian basement that was probably due to the rapid changes in plate-tectonic settings. In addition, the laterites and the occurrence of archaeocyatha point to deposition at low palaeolatitudes. The overall change of the plate-tectonic regime is reflected by the onset of Cambrian sedimentation. Detritus of the Cambrian deposits was predominantly (~80%) derived from the Cadomian orogen.

Finally, the plate-tectonic model for TDS in the Saxo-Thuringian Zone during Early to Middle Cambrian proposed by Linnemann et al. (2007) suggests that during Precambrian time an active margin leaded to thinning of the Cadomian crust and transcurrent faulting, which may have led to the opening of a rift basin subsequently filled by Lower to Middle Cambrian sediments.

Conclusions

The geochronological data from Torgau-Doberlug Syncline in combination with results of previous studies lead to the following conclusions:

1. The U–Pb data obtained from this study are highly consistent and fit very well with data from other units of the Saxo-Thuringian Zone and in northwestern Gondwana.
2. The common Eburnian age peak (2000–2200 Ma) and the occurrence of the West African magmatic gap (1.0–1.6 Ma) indicates a significant input of sediments from the West African Craton as a source area.
3. The Ediacaran (Neoproterozoic) and the Orosirian (Palaeoproterozoic) represent the dominant ages of zircon populations. A pronounced age peak exists at about 600 Ma and a smaller peak at about 900–950 Ma. These peaks are characteristic for West African provenance.
4. The scarcity of Mesoproterozoic detrital zircons in the samples from the Torgau-Doberlug Syncline indicates that the sources of the sediments were derived from the eroded Cadomian orogen and the West African craton. Zircon populations form the TDS exclude a sediment source from Avalonia and Baltica areas.
5. The Neoarchean age indicate the recycling the magmatic rocks during the Liberian and Leonian orogenies, which affected the West African Craton during the Archaean.
6. The age groups: 2.8–2.4 Ga (3%), 2.3–1.6 Ga (43%), and 1.0–0.5 Ga (47%) are typical of the West African Craton and of Cadomian orogenic events in the northwestern Gondwana palaeogeographic region.
7. The Th–U ratio from concordant zircon analysis lies between 0.1 and 1.0, which indicates the source of the zircon as an igneous origin from felsic melts. Th–U > 1.0 probably originate from mafic melts, whereas Th–U < 0.1 shows a metamorphic overprint.

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