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ORIGINAL PAPER

New insights into Cadomian basin evolution and stratigraphic affiliation of sedimentary units of Saxo-Thuringia, Germany: Part 2—detrital zircon U–Pb ages

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Abstract

New LA-ICP-MS detrital zircon U–Pb age data from Saxo-Thuringia provide improved constraints on the evolution of Neoproterozoic to Early Ordovician sedimentary basins along the northern margin of Gondwana. Several investigated quartzitic successions previously assigned to the Neoproterozoic have robust maximum depositional ages (RMDA) of 499 ± 5 Ma (member 2 of the Clanzschwitz Group) and 485 ± 5 Ma (Seidewitz Formation), requiring their reassignment to the upper Cambrian–Lower Ordovician. The immature greywacke units of the Cadomian basement yield robust maximum depositional ages between 551 and 546 Ma, consistent with uniform deposition during the Late Neoproterozoic in a broad active continental margin setting. In contrast, Ordovician quartzites reveal variable source signatures. Some reflect exclusively recycling of Neoproterozoic (Avalonian–Cadomian orogenic belt) and older crustal material (West African Craton), while others show additionally significant input from younger Cambro–Ordovician magmatic rocks in the Saxo-Thuringian hinterland, highlighting diverse sediment sources along the Ordovician shelf margin. The detrital zircon U–Pb data confirm a West African provenance for all analysed units. Despite its younger age, a Carboniferous greywacke from the Görlitzer Schiefergebirge was also studied here due to its close lithological resemblance to Neoproterozoic greywackes and the absence of established differentiation criteria. Its detrital zircon assemblage reflects a recycled Cadomian basement signature, along with admixtures of Cambro–Ordovician zircons and juvenile grains (~ 375–370 Ma) derived from Upper Devonian magmatic rocks. In the absence of fossil evidence, this provides clear criteria to distinguish Neoproterozoic from Carboniferous greywackes in this part of Saxo-Thuringia.

Keywords Neoproterozoic · Ordovician · Stratigraphy · Detrital zircon · LA-ICP-MS · Peri-Gondwana

Introduction

The oldest sedimentary rocks of Saxo-Thuringia are of Upper Neoproterozoic age and belong to the Cadomian sedimentary units of the Lausitz, Leipzig, Weesenstein, Clanzschwitz and Katzhütte groups (e.g. Linnemann et al. 2000, 2014, 2018) (Fig. 1). The sediments were deposited along the periphery of the West African Craton (e.g. Linnemann et al. 2000, 2014, 2018; Linnemann and Romer 2002; Stephan et al. 2019b) and later transferred to their current position during plate tectonic reorganisations largely in the frame of the closure of the Rheic Ocean and the formation of the Variscan Orogen (e.g. Stephan et al. 2019b; Kroner et al. 2022, 2023). The current understanding of the evolutionary development of the Neoproterozoic units of Saxo-Thuringia is largely based on the previous study by Linnemann et al. (2000), which was later supplemented by additional zircon age and isotopic data (Buschmann et al. 2001; Linnemann et al. 2004, 2014, 2018; Table 1).

In recent studies by Kühnemann et al. (2025a) and Meinhold et al. (2025), petrographic features and the discovery of trace fossils suggest that the established age classification of some units previously assigned to the

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Neoproterozoic must be reconsidered. This, in turn, challenges key aspects of the prevailing model of Cadomian basin evolution. Of special interest are units that are interpreted to have been deposited during an Ediacaran glacial event, as found in the Clanzschwitz and Weesenstein groups (see Linnemann et al. 2018 for details).

In the present study, U–Pb age dating of detrital zircons from Cadomian sedimentary units in Saxo-Thuringia is carried out using laser ablation-inductively coupled plasma-magma spectrometry (LA-ICP-MS). The youngest age population of detrital zircon grains provides robust maximum depositional ages, offering important constraints on the timing of sedimentation (e.g. Talavera et al. 2012). However, especially in passive margin settings, significant time gaps between zircon crystallisation and final sediment deposition may occur due to distal source areas and limited juvenile input (Cawood et al. 2012). Statistical analysis of zircon age spectra allows for grouping of samples with similar provenance and sedimentary histories (e.g. Vermeesch et al. 2016; Stephan et al. 2019a, b). In addition to upper Cambrian–Lower Ordovician quartzitic lithologies, this study also includes previously undated, sparsely exposed greywacke deposits from East Thuringia, as well as a biostratigraphically constrained Carboniferous greywacke from the Görlitzer Schiefergebirge, which was sampled as a reference due to its close lithological resemblance to Neoproterozoic greywackes.

Recent re-evaluations of the oldest sedimentary units in Saxo-Thuringia have already challenged key aspects of the established model for Neoproterozoic basin development and early Palaeozoic sedimentation (Kühnemann et al. 2025a, c; Meinhold et al. 2025). Within this context, the present study aims to refine and expand the existing detrital zircon dataset in order to reassess the timing, provenance and geodynamic setting of sediment deposition along the northern margin of Gondwana. By integrating the new U–Pb data with the recent petrographic and stratigraphic evidence, this work aims to contribute to the ongoing debates (Linnemann and Gärtner 2025; Kühnemann et al. 2025b) on the evolution of the early sedimentary basins in Saxo-Thuringia. A thorough understanding of the regional geology is essential before large-scale geotectonic models are put forward.

Geological setting

The sedimentary units investigated in this study are part of the tectonostratigraphic unit of Saxo-Thuringia, which is bounded in the north by the Mid-German Crystalline Zone and in the south by the Moldanubian Zone (including Teplá-Barrandia). In the Late Neoproterozoic, both Saxo-Thuringia and Teplá-Barrandia were constituents of the peri-Gondwana belt in the northern periphery of the supercontinent Gondwana (Nance and Murphy 1994, 1996; Linnemann et al. 2000; Linnemann and Romer 2002). These Neoproterozoic terrane units are composed of a Cadomian basement and uncomformably overlying Palaeozoic successions (e.g. Linnemann et al. 2000, 2007; Linnemann and Romer 2002; Figs. 1b, 2). The evolution of Saxo-Thuringia is associated with the development of a magmatic arc system—the Avalonian–Cadomian orogenic belt—along the northern margin of Gondwana between 650 and 600 Ma. Enhanced thermal activity within this arc system caused crustal thinning, ultimately leading to the formation of a backarc basin (Murphy and Nance 1991; Buschmann 1995; Linnemann et al. 2000, 2004, 2007, 2008). Composed primarily of erosional debris from the magmatic arc, the Cadomian sedimentary rocks began to accumulate in the basin around 565 Ma. These deposits are dominated by turbiditic greywackes, but also mineralogically mature lithologies (today quartz schists and quartzites), massive chert layers and isolated magmatic intrusions with mid-ocean ridge basalts (MORB) signatures (e.g. Linnemann 1991; Bankwitz and Bankwitz 1995; Linnemann and Buschmann 1995b; Buschmann 1995; Buschmann et al. 1995). Among these oldest Cadomian units in Saxony are, in addition to parts of the Kernzone Complex—a tectonically decoupled melange of Proterozoic and Lower Palaeozoic rock units (Linnemann et al. 1999, 2000; Heuse et al. 2001)—the Altenfeld Formation (both part of the Schwarzburg Anticline) and the Rothstein Formation (Torgau-Doberlug Syncline; Figs. 1b, 2). Detrital zircon ages from both equivalent greywacke units and their overlying stratigraphic successions constrain the timing of sedimentation in the backarc basin to approximately 570–560 Ma (Linnemann et al. 2007, 2014). One of only two direct age determinations from the Late Neoproterozoic basin system comes from sensitive high-resolution ion microprobe (SHRIMP) analyses of two zircons extracted from a 2 mm-thick tuff layer within the Rothstein Formation. According to Buschmann et al. (2001), this tuff yields an age of 566 ± 10 Ma, providing evidence for continued magmatic arc activity during this period.

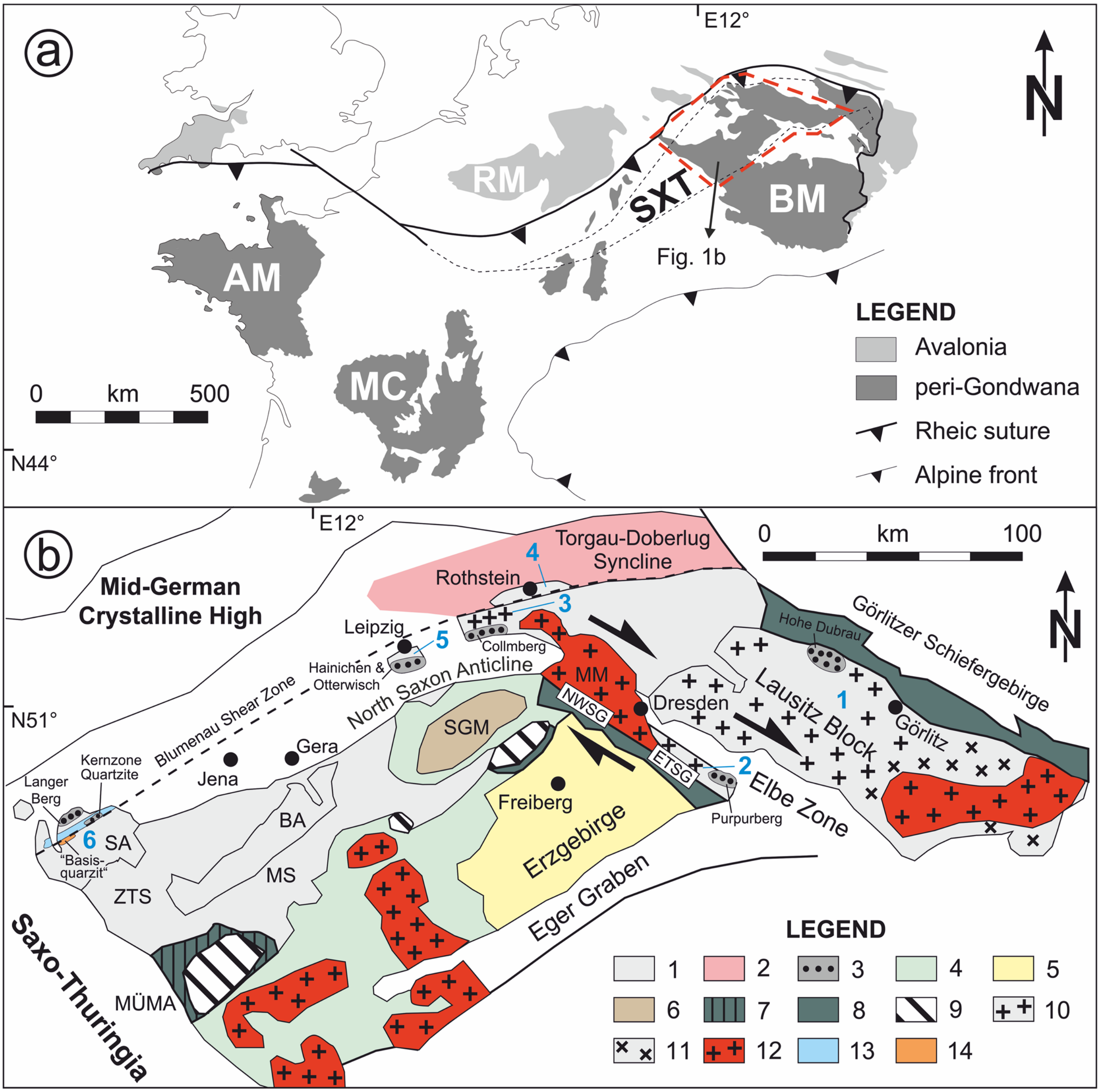
Due to their high maturity, the Weesenstein Group (Elbe Zone) and the Clanzschwitz Group (North Saxon Anticline) were initially assigned to the shelf deposits of the passive margin of the Neoproterozoic backarc basin (Linnemann 1994; Linnemann et al. 2007). Both groups are regarded as an initially coherent unit and were later separated by the tectonic activity of the Elbe Zone around 335–327 Ma (Linnemann 1994; Hofmann et al. 2009). The older parts of the Clanzschwitz Group, members 1 and 2, consisting of quartzites and quartz schists, can be correlated with the quartzitic Seidewitz Formation of the Weesenstein Group (Linnemann et al. 2018). The detrital zircon ages of member 2 from the Clanzschwitz Group previously indicated Neoproterozoic sedimentation with a maximum depositional age (MDA) of around 565 Ma (Linnemann et al. 2018). The immature greywackes of member 3 of the Clanzschwitz Group and the Müglitz Formation from the Weesenstein Group, on the other hand, were interpreted as slightly younger, glaciomarine-deposited, pebble-bearing units (Linnemann et al. 2018). Detrital zircon grains yield a MDA of 562 ± 5 Ma for the Müglitz Formation (Linnemann et al. 2018). However, the stratigraphic positioning of both units is revised by recent studies (Kühnemann et al. 2025a, c) based on petrographic and geochemical features. Additionally, Meinhold et al. (2025) presented biostratigraphic evidence confirming that the Seidewitz Formation, previously the older part of the Weesenstein Group, is a Lower Ordovician deposit (Fig. 2).

Convergence processes between the magmatic arc and the cratonic mainland led to the closure of the Neoproterozoic backarc basin from around 560 Ma (Linnemann et al. 2007). In consequence of the model established in the literature so far, a retroarc basin has developed into which the eroded sediments of the former backarc basin were deposited as massive, monotonous turbiditic greywacke sequences. The chert fragments, which are found in the Lausitz Group (Lausitz Block; e.g. loose rock fragments around Petershain and temporary outcrop in Kunnersdorf) and whose origin is attributed to the massive chert layers of the older Rothstein Formation (Linnemann et al. 2007), served as evidence for this assumption. However, Kühnemann et al. (2025c) have demonstrated that the chert lithoclasts of the Lausitz Group deposits do not constitute eroded fragments of the Rothstein Formation. Consequently, no evidence currently exists to support the concept of a short-lived retroarc basin, and the established two-stage basin model requires revision through more extensive analyses. Established models further suggest that the greywackes of the Leipzig Group (North Saxon Anticline), Frohnberg Formation (Katzhütte Group, Schwarzburg Anticline) and parts of the eastern Thuringian region are equivalent to those of the Lausitz Group and also were deposited within the retroarc basin. The youngest detrital zircons from the greywacke matrix provide a MDA of 542 ± 3 Ma for the Frohnberg Formation and 543 ± 4 Ma for the Lausitz Group (Linnemann et al. 2007). A direct sedimentation age is supposed to be provided by the Wüsteberg Tuff, sampled from a dump of a technical shaft at the Wüsteberg hill (ca. 3 km to the SW of Kamenz, Lausitz Block). The two Pb–Pb zircon evaporation age analyses by Gehmlich et al. (1998) and Linnemann et al. (2000) yielded ages of 564 ± 3 Ma and 565 ± 3 Ma, respectively. The SHRIMP age according to Buschmann et al. (2001) is slightly older at 574 ± 8 Ma but also indicates Late Neoproterozoic sedimentation and synsedimentary volcanic activity. The end of the Cadomian-related sedimentation was finally sealed by the extensive intrusions caused by the slab break-off at around 540 Ma (Linnemann et al 2007). The Cambrian uplift and intense weathering phase resulted in significant chemical alteration and recycling of the Neoproterozoic units. The now more mature material was subsequently deposited unconformably over the Cadomian basement in the course of the Early Ordovician (Tremadocian) transgression, caused by the opening of the Rheic Ocean (Linnemann et al. 2000).

Sample material and methods

The selection of greywacke and quartzitic samples for zircon dating is based on the investigations by Kühnemann et al. (2025a), which also provide detailed petrographic descriptions and locality information (see also Online Resource ESM1). When selecting the sample locations, an attempt was made to represent the low-grade metamorphosed Neoproterozoic units of Saxo-Thuringia as comprehensively as possible (Fig. 3). Localities from the Lausitz Block, the Elbe Zone, North Saxon Anticline, and the Schwarzburg Anticline were considered (Fig. 1b). In addition to 21 Neoproterozoic greywackes (see Kühnemann et al. 2025a for the usage of the term greywacke) and a few Lower Ordovician mineralogically mature siliciclastics (today quartz schists and quartzites), a Carboniferous sample (B155/72-P6) from the Görlitzer Schiefergebirge was examined for comparison and as a reference, as it is lithologically indistinguishable from the adjacent Neoproterozoic Lausitz greywackes. Up to ca. 3 kg of sample material was used to prepare the analyses and was processed at the Institute of Geology (TU Bergakademie Freiberg). Note that in contrast to earlier studies concerning the Neoproterozoic sedimentary units (e.g. Linnemann et al. 2000, 2018), the present study focuses exclusively on the detrital zircons originating directly from the greywacke silt- to sand-sized clasts and matrix. Individual large magmatic pebbles were not dated.

Sample preparation was performed at the Institute of Geology of the TU Bergakademie Freiberg (TUBAF). Heavy mineral concentrates were obtained by standard separation techniques. After using a jaw crusher, the fractions were first dry and afterwards wet sieved. For zircon dating, the non-magnetic heavy mineral fraction between 80–250 µm was first separated by a Frantz magnetic separator at 1.2 A and 20° inclination of the guide rail. The isolation of the heavy mineral fraction enabled the further separation of zircon. Heavy mineral concentrates were first enriched using bromoform (2.84 g/cm^3) and then using diiodomethane (3.32 g/cm^3) as the heavy liquids. The zircons to be dated were selected manually under a binocular microscope. To avoid sampling bias, zircons of different shapes and sizes were randomly separated, mounted on a doubly sided tape and embedded in epoxy resin. Finally, the grain mounts were grinded and polished. Scanning electron microscopy (SEM) images of the zircons were taken at the Institute of Geology of the TU Bergakademie Freiberg (TUBAF) by using cathodoluminescence (CL) and backscattered-electron (BSE) mode to document the grain shapes and visualise


a
E12°
N44°
RM
SXT
BM
AM
MC
Fig. 1b
0 km 500
LEGEND
Avalonia
peri-Gondwana
Rheic suture
Alpine front
b
E12°
N51°
Mid-German Crystalline High
Torgau-Doberlug Syncline
Rothstein
Leipzig
Collmberg
Hainichen & Otterwisch
North Saxon Anticline
Blumenau Shear Zone
Gera
Jena
Kernzone Quartzite
Langer Berg
"Basis-quarzit"
SA
BA
MS
ZTS
SGM
MM
NWSG
ETSG
Dresden
Freiberg
Erzgebirge
Purpurberg
Elbe Zone
Lausitz Block
Görlitz
Hohe Dubrau
Görlitzer Schiefergebirge
Eger Graben
MÜMA
Saxo-Thuringia
0 km 100
LEGEND
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◂**Fig. 1** **a** Saxo-Thuringia (SXT) within the pre-Alpine framework of Central Europe. Grey areas represent Precambrian and Palaeozoic units (light grey: Avalonia-related; dark grey: peri-Gondwana-related. The red dashed polygon indicates the approximate extent of the study area shown in **b**. *AM* Armorican Massif, *MC* Massif Central, *RM* Rhenish Massif, *BM* Bohemian Massif. Modified after Meinhold et al. (2025). **b** Simplified geological map of Saxo-Thuringia (modified after Linnemann et al. 2010). *BA* Berga Anticline, *ETSG* Elbtalschiefergebirge, *MM* Meissen Massif, *MS* Mehltheuer Syncline, *MÜMA* Münchberg Massif, *NWSG* Nossen Wilsdruffer Schiefergebrige, *SA* Schwarzburg Anticline, *SGM* Saxonian Granulite Massif, *ZTS* Ziegenrück–Teuschnitz Syncline. *1* General distribution of Cadomian basement and overlying Palaeozoic sedimentary rocks of the 'Thuringian Facies', *2* Lower to middle Cambrian of the 'Thuringian Facies', *3* External segment of the Saxo-Thuringia where Ordovician rocks are present only as very thick, bedded, and highly mature Tremadocian quartzites, *4* Metamorphosed Palaeozoic rocks of the 'Thuringian Facies' (phyllites and garnet phyllites of the mid-pressure/low-temperature and the low-pressure/low-temperature units of the Erzgebirge nappes and adjoining areas), *5* Mid-pressure/mid-temperature metamorphosed Cadomian basement rocks of the Freiberg and Reizenhain gneiss domes and Palaeozoic rocks of the high-pressure/high-temperature nappes of the Erzgebirge, *6* High-grade metamorphosed rocks of the Saxonian Granulite Massif, *7* Palaeozoic sedimentary rocks of the 'Bavarian Facies', *8* Palaeozoic sedimentary rocks with mixed distribution of 'Thuringian and Bavarian Facies', *9* High-grade metamorphic rocks of the nappes of the Münchberg Massif and the Zwischengebirge of Wildenfels and Frankenberg, *10* Cadomian granitoids (~ 540 Ma), *11* Lower Ordovician granitoids (~ 490–480 Ma), *12* Variscan granitoids (~ 335–325 Ma), *13* Kernzone Complex, *14* Upper Cambrian to Lower Ordovician sedimentary rocks. Blue numbers 1–6 representing Neoproterozoic sedimentary units: *1* Lausitz Group, *2* Weesenstein Group, *3* Clanzschwitz Group, *4* Rothstein Formation, *5* Leipzig Group (Thuringian region adjoins in the eastern extension), *6* Katzhütte Group. Detailed map of the sampling locations is provided in the Fig. 3

growth zones and inclusions for the subsequent laser spots. Zircons of the distinct sedimentary units of Saxo-Thuringia were analysed at the Institute for Applied Geosciences at the Karlsruhe Institute of Technology (KIT) for their U, Pb and Th isotopes. A total of 3498 measurements were performed to determine the crystallisation ages of the minerals (Online Resource ESM2). Most zircon grains were dated by single spot analyses. For some samples, however, the youngest grains were analysed multiple times, with up to six spot analyses per grain (Fig. 4b, c). To estimate the maximum age of deposition, the study considers the average age of the youngest zircon population, defined as a coherent group of three to six crystals overlapping within the 2σ error (Table 2). Recrystallised domains were avoided during laser spot analyses. Furthermore, also only analyses containing no or negligible levels of common lead were considered. The spots were commonly positioned within the zircon mantle area of undisturbed magmatic zircons, and for selected zircons, the cores that were recognizable in the CL images were also measured. A second control measurement was carried out for the youngest zircon crystals, where repeated measurements were made along a profile. Laser spots with diameters of 20, respectively, 25 µm were used. Analyses were carried out using a Thermo-Scientific ELEMENT XR (sector field) mass spectrometer, coupled to an Excimer laser (Analyte Excite+, Teledyne Photon Machines). The measurements were performed during 4 sessions. Processing of the raw data was done by applying an in-house spreadsheet (Gerdes and Zeh 2006, 2009). Further processing parameters, as well as the results of the measurement of reference materials and unknown zircon grains can be accessed in the Online Resource ESM3. For calculation of robust maximum depositional ages, the R-freeware package "Provenance" (Vermeesch et al. 2016) was applied. The package "detzrcr" was additionally used for data visualization and statistic comparison. For evaluation and interpretation of the age data, e.g. for kernel density estimates (KDE) and multidimensional scaling plots, only analyses with a concordance between 90 and 110 % were considered, following common practise (e.g. Meinhold et al. 2021; Zeh et al. 2024). Caution should be further exercised regarding the interpretation of the zircon age data with respect to statements on the maximum sedimentation age, as younger ages caused by Pb loss can also be concordant with the filter methods used in the data analysis. For this purpose, the analyses were filtered for common lead and zircons with a metamorphic Th/U ratio (~ 0.01) were also excluded. The degree of concordance was determined by the following equation: $^{206}Pb/^{238}U$ age/$^{207}Pb/^{206}Pb$ age x 100. Due to the natural gap in the typical zircon age data for the extended regional study area around 1.2 Ga, the $^{206}Pb/^{238}U$ age was used for the age display of zircons younger than 1.2 Ga and the $^{207}Pb/^{208}Pb$ age for zircons older than 1.2 Ga.

Results of detrital zircon U–Pb dating

A total of 3126 concordant zircon ages (~ 89 % of all analyses) were determined from the 28 analysed Upper Neoproterozoic to Lower Ordovician samples from the (meta-) sedimentary units of Saxo-Thuringia and the Carboniferous sample from the Görlitzer Schiefergebirge (Table 2). Thereof 101 concordant ages were subsequently recorded in a second measurement sequence to verify the youngest zircon ages obtained in the first sequence. The full set of data can be accessed in the Online Resource (ESM2).

The zircon crystals are typically transparent and without visible inclusions. Zircons with a reddish to slightly brownish or yellowish colour shade also appear occasionally. Rounded and (sub-)rounded grain shapes are dominant, while idiomorphic, mainly long-prismatic crystals are less common. The zircon populations in all samples show

Table 1 Summary of zircon age dating already performed on the Upper Neoproterozoic to Lower Ordovician sedimentary units and their associated tuffs in Saxo-Thuringia. The number and variability of the samples analysed in previous studies concerning zircon age dating are not overly large and are essentially limited to a few selected, recurring locations without going further in terms of spatial distribution

Author	Year	Location	Analytical methods
Linnemann et al.	2000	Wüsteberg (tuff, Lausitz Group, Lausitz Anticline) Weesenstein railway station (Weesenstein Group, Elbe-zone) Schlangenberg, Wellerswalde (Clanzschwitz Group, North Saxon Anticline) Grendel Mountain, Sachsendorf (Frohnberg Formation, Schwarzburg Anticline)	$^{207}Pb/^{206}Pb$ single zircon evaporation ages of Wüsteberg Tuff and detrital zircons from granite pebbles from different Neoproterozoic greywackes
Buschmann et al.	2001	Wüsteberg (tuff, Lausitz Group, Lausitz Anticline) drill cores from near Herzberg (Brandenburg), Rothstein Formation, Torgau-Doberlug Syncline	SHRIMP U/Pb zircon dating on zircons from: Wüsteberg Tuff 2 mm thick ash layer + turbiditic greywacke from Rothstein Formation
Linnemann et al.	2004	Wurzelberg, Goldisthal (Schwarzburg Anticline) Oßling quarry (Lausitz Group)	SHRIMP U/Pb zircon dating on detrital zircons in greywacke matrix
Linnemann et al.	2014	Altenfeld (Altenfeld Formation, Schwarzburg Antiform) Wurzelberg (Frohnberg Formation, Schwarzburg Antiform)	LA-SF-ICP-MS U-Pb zircon age dating on detrital zircons in greywacke matrix
Linnemann et al.	2018	Kleiner Steinberg (Clanzschwitz Group, North Saxon Anticline) Großer Steinberg (Clanzschwitz Group, North Saxon Anticline) Müglitz valley (Weesenstein Group, Elbe Zone), partly same locations as in Linnemann et al. (2000)	LA-SF-ICP-MS U-Pb zircon age dating on granitoid pebbles from greywackes and few detrital zircons directly from matrix

a wide range in sizes and shapes, but no significant differences were observed among the individual samples. Most crystals reveal undisturbed oscillating zoning in CL images (Fig. 4), suggesting a felsic magmatic origin. This is further supported by Th/U ratios between 0.1 and 1.0 (e.g. Da Silva et al. 2000; Rubatto 2002; Scherstén et al. 2004; Grant et al. 2009). Some grains show clear core-rim relationships (Fig. 4f, h) and other indications for partial dissolution and/or recrystallisation at the rims.

Within a unit, there are no significant differences in the selected sample locations. Also, the peak distribution of zircon ages up to the Neoproterozoic Era proves to be quite consistent for all units. With the exception of the Carboniferous greywackes, Neoproterozoic ages represent ~ 58 % of all concordant ages in all other units, with the main peak between 600–580 Ma. Stenian zircon grains with ages of 1100–950 Ma occur very sparsely (< 2 %), but recurrently. The three minor peaks in the Palaeoproterozoic at ~ 1900, ~ 2050 and ~ 2200 Ma, display distinct variations across the individual units. The Palaeoproterozoic population represent ~ 29 % of the concordant ages, whereas Archaean ages, at ~ 6 %, only occur to a subordinate extent in all samples. The oldest zircon with an age of 3560 ± 17 Ma originates from the Lausitz Group (sample LG21-21A), whereby two further zircons with a Palaeoarchaean age of >3500 Ma were dated across the units. When excluding the juvenile input from the Cadomian arc (<700 Ma), the more quartzitic samples (e.g. Collmberg Quartzite, Clanzschwitz Group member 2, Seidewitz Formation) and also the Müglitz Formation show a higher proportion (~90 %) of zircon populations older than 700 Ma compared to the typical greywackes (~ 82 %). The KDE plot reveals three types of zircon spectra that can be clearly distinguished from each other in terms of their youngest zircon ages (Fig. 5). KDE plots of the individual sample locations are compared in Online Resource ESM4.

Neoproterozoic–lower Cambrian units

As proposed by previous studies, deposition at the Ediacaran–Cambrian boundary encompasses immature greywackes of the Lausitz and Leipzig groups (Lausitz Block), along with those from East Thuringia (Eleonorental, Eisenberg). The Müglitz Formation (Elbe Zone) may also correspond to this group, although the exact depositional timing remains open (see discussion below). A total of 14 samples were analysed from the Lausitz Group, three samples from East Thuringia, two from the Müglitz Formation and one sample from the Leipzig Group. The age spectra exhibit an almost identical peak distribution. The samples from the conglomeratic member 3 of the Clanzschwitz Group, the Katzhütte Group, as well as the conglomeratic arkose from the Eleonorental (sample ELEO-V, East Thuringia), also exhibit a strikingly similar pattern. Based on the discussion of the youngest zircon age in the Introduction section, the current

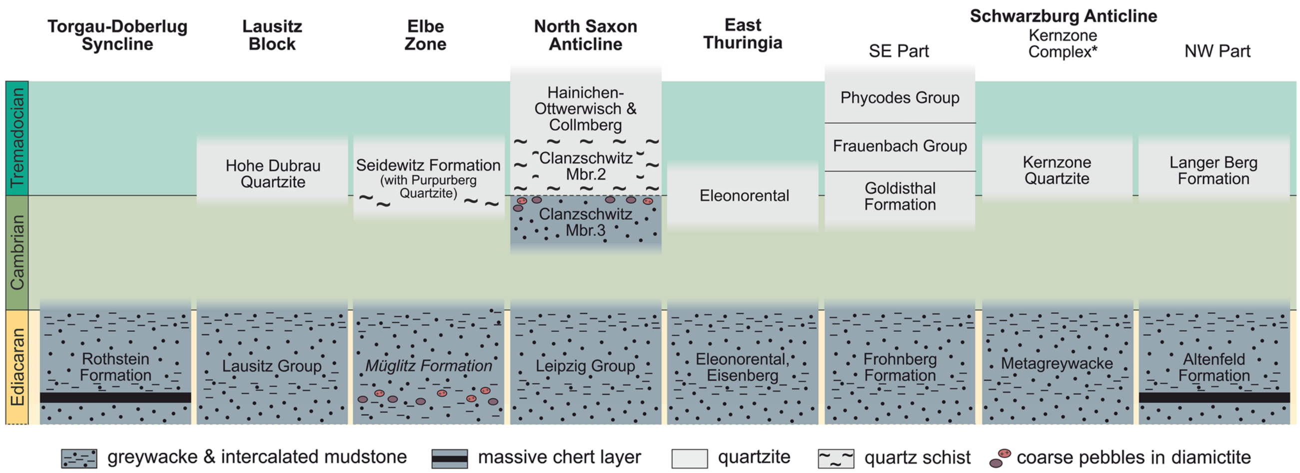


Fig. 2 Simplified representation of stratigraphic profiles limited only to the Upper Neoproterozoic and (upper Cambrian to) Lower Ordovician sedimentary units, based on the latest revisions by Kühnemann et al. (2025a, c) and Meinhold et al. (2025). *Note that the Kernzone Complex, as interpreted by Linnemann et al. (1999, 2000) and Heuse et al. (2001), likely represents a tectonically decoupled melange unit composed of Proterozoic and Lower Palaeozoic metasedimentary and metamagmatic rocks. For the complete stratigraphic sequence, see Fig. 8

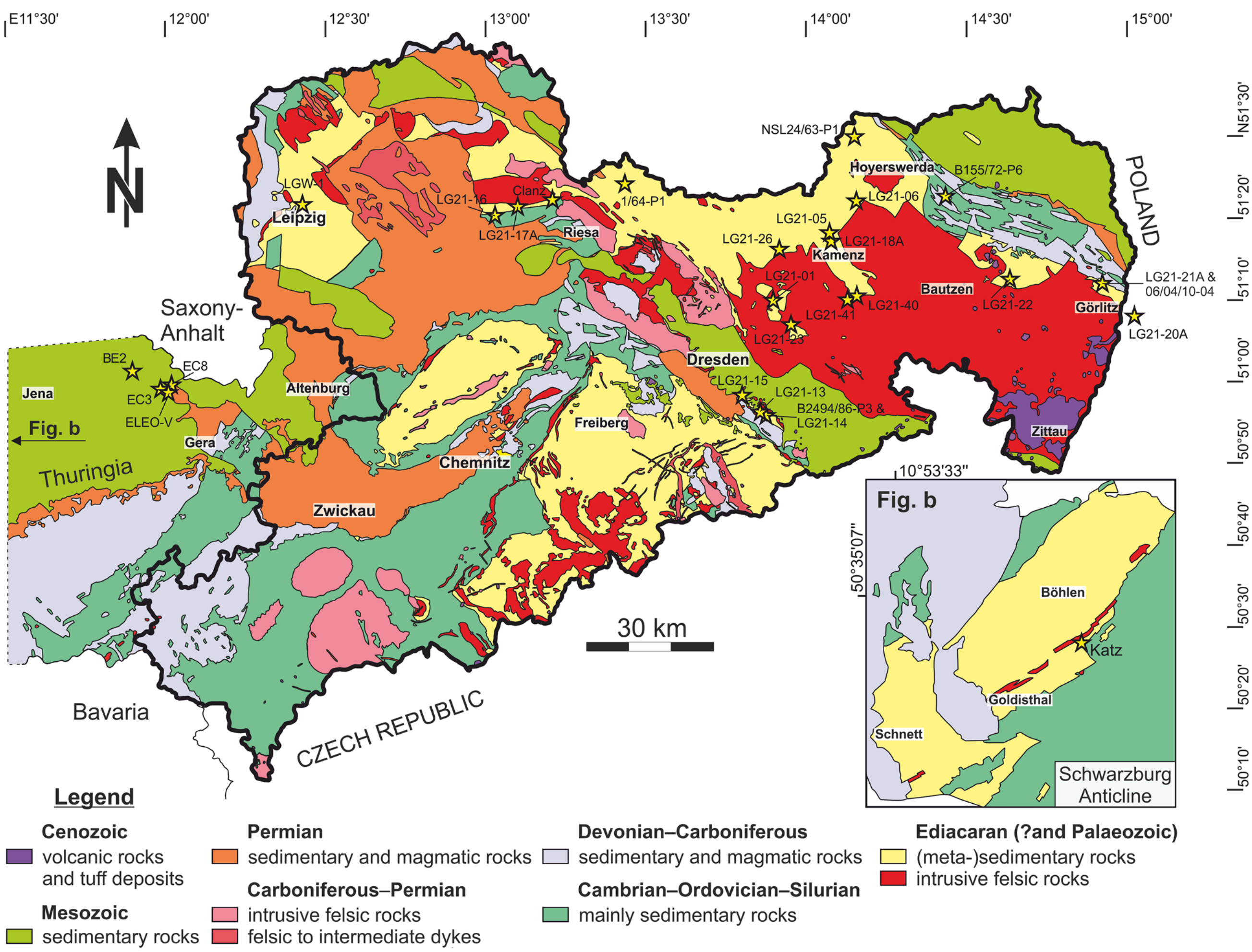


Fig. 3 Map of sampling locations (coordinates are provided in ESM1). It should be noted that the Cadomian basement units, particularly in the Eastern Thuringian area, are only very locally exposed or drilled over small areas and therefore cannot be adequately represented on the map

stratigraphic assignment and the typical petrographic and geochemical characteristics (e.g. von Gaertner 1944; Kühnemann et al. 2025c) conducted in previous studies, we suggest that these samples, so far assigned to the Neoproterozoic–lower Cambrian, are rather consistent with the group of upper Cambrian–Lower Ordovician units described below.

The youngest zircon populations of the Lausitz Group and the Leipzig Group, including the Thuringian area, with their maximum ages of 547 ± 6 (sample LG21-05) and 537 ± 6 (sample EC8), indicate a sedimentation extending into the lowermost Cambrian (Figs. 5, 6). Younger Cambrian zircon ages (lower Series 2 to Lower Furongian) occur occasionally in the study area. Although these youngest individual grains are concordant and exhibit low common lead, they are excluded from further interpretation due to their rarity and incongruence with the geological context. The youngest zircon population of the Müglitz Formation, with an average age of 558 ± 6 Ma (sample LG21-15), points towards a Late Neoproterozoic maximum age of deposition. Notably, sample LG21-13 yielded a single 493 ± 16 Ma zircon with common lead below detection limit and a 98 % concordance, which would be consistent with a late Cambrian or younger depositional age. The presence of the otherwise early Cambrian zircon populations in the Lausitz Group (0.6 %), the eastern Thuringian area (0.4 %) and the Müglitz Formation (1.4 %) is therefore rather subordinate. The Leipzig Group does not comprise any Phanerozoic zircons. Detrital zircons from the Neoproterozoic Era represent the majority of the total zircon population (58.8–64.9 %), with a peak maximum at ~ 580 Ma (Figs. 5, 6). All units further reflect a Palaeoproterozoic sediment source, as evidenced by the recurrent peaks at ~ 1900, ~ 2050, and ~ 2200 Ma described above, with the ~ 1900 Ma peak being the most prominent. Palaeoproterozoic zircons in the Lausitz Group, the Thuringian area with Leipzig Group and the Müglitz Formation are constituted of about 26 %, 32 % and 36 %, respectively. The proportion of Archaean zircons in the units is 8.3 %, 5.1 % and 7.0 %.

Upper Cambrian–Lower Ordovician units

The Collmberg Quartzite, Seidewitz Formation, and Clanzschwitz Group (member 2) contrast with the Neoproterozoic greywackes by their higher Phanerozoic zircon content (Ø 23.6 %), thus providing evidence of sedimentation during the early Palaeozoic (Figs. 5, 6). As previously stated, despite the absence of Phanerozoic zircon populations, we propose that the samples from member 3 of the Clanzschwitz Group as well as those from the upper part of the Frohnberg Formation of the Katzhütte Group and the Eleonorental ('Basisquarzit' and its equivalents) can be assigned to the upper Cambrian–Lower Ordovician units too.

The zircon age spectrum of the Collmberg Quartzite (sample LG21-16A, North Saxon Anticline) substantiates earlier biostratigraphic assignments to the Tremadocian (e.g. Deutsche Stratigraphische Kommission 1997). The youngest zircon population is determined at 494 ± 3 Ma, although some analyses indicate a late Early Ordovician (Floian) age. The magmatic zoning and the rounded shape of some of the youngest zircons, likely due to preceding transport, indicate that the sediment may be younger than the youngest zircon population age would suggest. Ordovician zircons represent 2.1 % of the concordant ages of sample LG21-16A. The most prominent age peak is at ~ 500 Ma and a second at ~ 580 Ma (Fig. 5). In this sample, Cambrian zircons predominate with an abundance of 31.0 %, whereby the proportion of Neoproterozoic zircons decreases comparatively to 42.3 %. The proportion of Palaeoproterozoic and Archaean ages is lower than in the Neoproterozoic greywackes at 21.5 % and 3.1 % respectively, although here as well the three Palaeoproterozoic peaks are apparent. The quartzitic lithologies of the Seidewitz Formation and the Clanzschwitz Group (member 2) were previously classified as Neoproterozoic (e.g. Linnemann et al. 2018). However, their youngest zircon populations of 485 ± 5 Ma (sample B2494/86-P3) and 499 ± 5 (sample LG21-17A) Ma point to a late Cambrian to Early Ordovician age of deposition. The proportion of Cambrian zircons is significantly lower than in the Collmberg Quartzite sample, with values of 12.6 % for the Clanzschwitz Group and 22.8 % for the Seidewitz Formation (Fig. 6). In addition to the peak between 580 and 600 Ma, which is characteristic of all groups, there is also a further peak around 500 Ma for the Seidewitz Formation and around 550 Ma for the Clanzschwitz Group. The proportion of Neoproterozoic zircons in both units is comparable to the immature greywackes, at 48.4 % and 64.0 %. The age ranges of the Palaeoproterozoic and Archaean zircons in the Seidewitz Formation and the Clanzschwitz Group are 23.4 % and 3.3 % and 20.7 % and 2.7 %, respectively, and coincide with those of the Collmberg Quartzite. The zircon age patterns observed in the quartz schist sample from the Frohnberg Formation (Katzhütte Group), the conglomeratic greywacke of the Clanzschwitz Group (member 3) and the conglomeratic arkose from the Eleonorental in East Thuringia are strikingly similar to those recorded in the Neoproterozoic greywackes. The high proportion of Neoproterozoic zircons, at 57.3 %, 65.8 % and 60.7 %, respectively, is remarkable. The Palaeoproterozoic zircon population is similarly well represented at 30.8 %, 29.7 % and 32.8 %, and is thus also significantly higher than in the other Ordovician units. The proportion of Archaean zircons is highest in these units, with an average of 7.7 %. In contrast, no Phanerozoic zircons could be found in the samples.

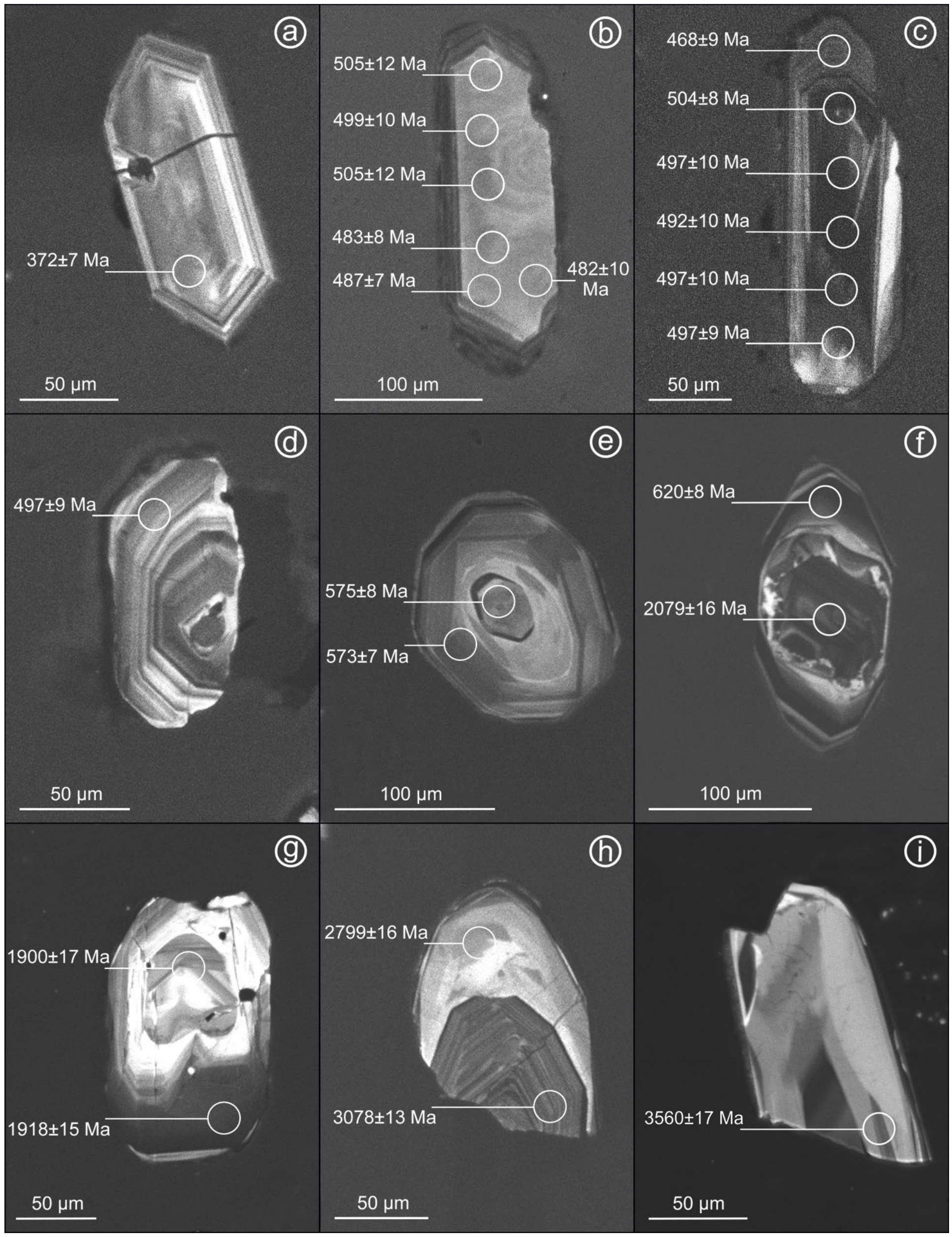


Fig. 4 Cathodoluminescence images of selected zircon grains picked for LA-ICP-MS analyses. Shown are the analysis spots selected with the corresponding $^{206}Pb/^{238}U$ ages for samples <1.2 Ga and $^{207}Pb/^{206}Pb$ for ages >1.2 Ga. **a** Upper Devonian zircon (sample B155/72; Görlitzer Schiefergebirge, Lausitz Block). **b** Upper Cambrian–Lower Ordovician zircon (sample LG21-16A; Collmberg quartzite, North Saxon Block). **c** Upper Cambrian zircon (sample LG21-17A; Großer Steinberg, Clanzschwitz Group, North Saxon Block). **d** Upper Cambrian zircon (sample LG21-14; quartzitic lithology of Seidewitz valley, Elbe Zone). **e** Neoproterozoic zircon (sample LG21-41; Tanneberg, Lausitz Group). **f** Palaeoproterozoic zircon with younger Neoproterozoic grown rim (LG21-26; Reichenau, Lausitz Group). **g** Palaeoproterozoic zircon (sample BE2, East Thuringia). **h** Archean zircon with slightly younger growth hem (sample 06/04/10-04, Kunnersdorf, Lausitz Group). **i** Oldest measured Archean zircon in the study (LG21-21A; Kunnersdorf, Lausitz Group)

Carboniferous unit

The Carboniferous greywacke sample B155/72-P6 from the Görlitz Schiefergebirge occupies a distinctive position, as it does not originate from the Cadomian basement of Saxo-Thuringia. It serves as a reference sample in order to develop differentiation criteria that have hitherto not been available in comparison with the neighbouring Neoproterozoic Lausitz greywacke. Although the youngest zircon population in the greywacke sample from the Görlitzer Schiefergebirge dates to the Upper Devonian (373 ± 4 Ma), biostratigraphic data confirm that sedimentation extended into the early Carboniferous (Brause et al. 1962; Brause and Hirschmann 1964). The age spectrum displays two prominent peaks: one at ~ 490 Ma (late Cambrian) and another at ~ 370 Ma (Late Devonian; Fig. 5). Devonian zircons account for a substantial portion of the concordant age population (25.9 %; Fig. 6), while Ordovician and Cambrian ages constitute 10.3 % and 31.0 %, respectively. In contrast, Neoproterozoic zircons lack a distinct peak and are reduced to 20.7 % of the total. Among the Palaeoproterozoic ages (10.3 %), the typical ~ 1900 Ma peak is missing, although two smaller peaks are present at approximately 2000 and 2050 Ma. Archaean zircons are rare, comprising only 1.7 % of the concordant ages.

Table 2 Maximum depositional ages of investigated samples

Sample	Lithology	n-prov.[a]	Age[b] (Ma) (youngest conc. zircon)	± 2σ	conc. %	Age[c] (Ma) (youngest zircon population)	± 2σ	MSWD[d]	*n*[e]
Lausitz Carboniferous (Görlitzer Schiefergebirge)									
B155/72-P6	Greywacke	58/71	367	7	101	372.5	3.6	0.07	4
Lausitz Group (Lausitz Block)									
LG21-01	Greywacke	130/141	498	16	99	551.5	4.4	1.29	6
LG21-05	Greywacke	99/103	541	15	97	546.7	5.5	0.26	5
LG21-06	Greywacke	48/56	517	8	98	567.8	5.0	0.41	3
LG21-18A	Greywacke	69/77	487	9	98	572.2	6.8	0.18	3
LG21-20A	Greywacke	105/124	545	14	100	553.4	4.6	0.81	4
LG21-21A	Greywacke	120/134	497	10	101	548.5	5.6	0.37	4
LG21-22	Greywacke	113/128	549	12	100	562.3	5.4	0.08	5
LG21-23	Recrystallised greywacke	113/131	526	8	99	549.2	5.2	1.76	3
1/64-P1	Greywacke	96/108	556	12	96	560.4	5.1	0.66	5
NSL24/63-P1	Greywacke	142/158	558	10	98	573.2	3.8	0.05	5
LG21-26	Greywacke	134/141	554	10	97	566.6	4.6	0.13	4
LG21-40	Greywacke	134/140	541	9	100	553.8	5.8	0.34	3
LG21-41	Greywacke	152/160	554	8	98	555.3	6.1	0.11	3
06/04/10-04	Microconglomeratic greywacke	128/136	560	12	98	564.6	4.9	0.44	4
Seidewitz Formation (Elbe Zone)									
LG21-14	Quartzite	79/94	495	8	103	499.7	4.5	0.61	5
B2494/86-P3	Quartzite	106/130	476	11	98	485.1	4.6	0.06	4
Müglitz Formation (Elbe Zone)									
LG21-13	Quartzitic greywacke	102/117	493	16	98	559.4	5.5	0.49	4
LG21-15	Greywacke	122/133	537	11	96	557.6	5.6	1.40	5
Collmberg Quartzite (North Saxon Anticline)									
LG21-16A	Quartzite	184/198	492	7	96	494.7	3.4	0.17	6
multiple (18 grains, n = 61)[f]						500.5	4.9	1.30	3
Clanzschwitz Group—member 2 (North Saxon Anticline)									
LG21-17A	Quartz schist	153/169	486	9	95	499.3	4.8	0.09	5
multiple (9 grains, n = 22)[f]						498.1	4.1	0.92	5
Clanzschwitz Group—member 3 (North Saxon Anticline)									
Clanz #	Conglomeratic greywacke	111/142	544	16	96	548.2	5.3	0.05	3
Leipzig Group (North Saxon Anticline)									
LGW-1	Greywacke	75/90	561	9	101	568.4	5.1	2.02	3
East Thuringia									
EC3	Quartzitic greywacke	88/94	562	11	102	573.6	4.8	0.39	5
EC8	Greywacke	95/108	485°	11	99	537.5	5.5	1.12	3
multiple (6 grains, n = 18)[f]						573.1	5.6	1.02	3
BE2	Greywacke	87/95	571	10	98	574.0	5.4	0.21	4
ELEO-V#	Conglomeratic arkose	61/70	567	11	101	572.0	4.0	0.30	6
Katzhütte Group (Frohnberg Formation; Schwarzburg Anticline)									
Katz#	Quartz schist	121/149	558	8	101	557.5	5.4	0.20	4

Although samples marked with # do not contain Phanerozoic zircons, they have been classified as younger due to their increased maturity and their equivalence to the basal sequences of the Goldisthal Formation (Schwarzburg Anticline). Full information on the sample list and zircon age data can be accessed in Online Resource ESM1, ESM2 and Fig. 3. Further information on the petrography and whole-rock geochemistry of the analysed samples can be accessed in Kühnemann et al. (2025a, c)

[a]Number of analysed grains for provenance analyses (concordant/total) with concordance level 90–110 %

[b]Age of youngest concordant zircon grain (concordance level 95–105 %)

[c]Robust maximum depositional age (RMDA; defined by youngest zircon population)

[d]Mean standard weighted deviation

[e]number of analysed grains for RMDA

[f]Results of multiple U-Pb dating of the youngest zircon grains (up to 6 analyses per grain)

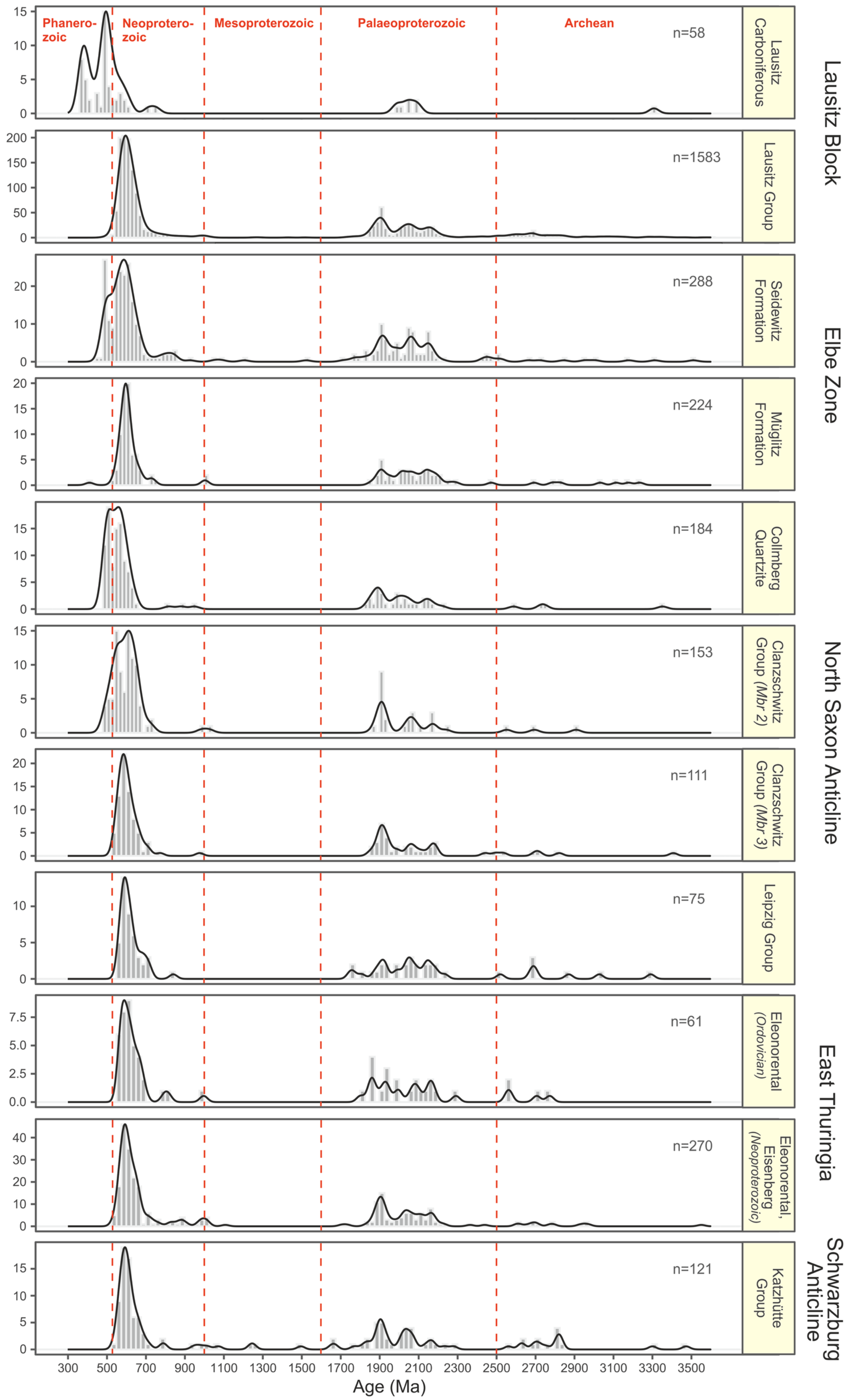


Fig. 5 Histograms and kernel density estimate (KDE) plots of the zircon age spectra of the units previously assigned to the Cadomian basement of Saxo-Thuringia, as well as the greywackes of the Görlitzer Schiefergebirge. Only analyses with a concordance between 90 and 110 % were selected for presentation. n = number of concordant zircon ages. KDE plots of the individual sample locations are compared in ESM4

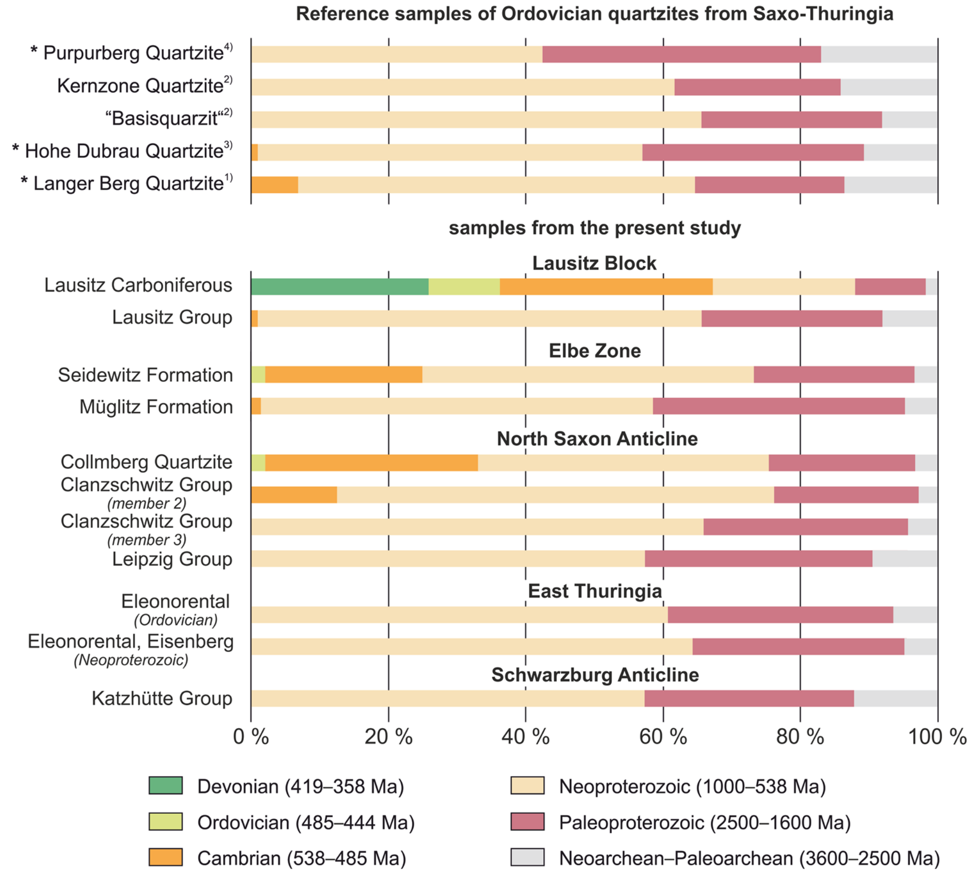


Fig. 6 Illustration of the relative presence of certain stratigraphic age groups within the analysed sedimentary units of Saxo-Thuringia. A Lower Ordovician age is biostratigraphically proven for the samples marked with an asteristk (*). Biostratigraphic age constraints from the literature: Langer Berg Quartzite (Linnemann 1996); Dubrau Quartzite (Linnemann 2003); Purpurberg Quartzite (Meinhold et al. 2025). Zircon reference data for Ordovician quartzites: [1]Linnemann et al. (2007); [2]Linnemann et al. (2014); [3]Franz et al. (2013); [4]Linnemann et al. (2018). Respective lithologies of the units are explained in the text

Discussion

Detrital zircon age record

The detrital zircon age spectra of all Saxo-Thuringian units examined in this study consistently point to a West African provenance, in agreement with earlier findings by Linnemann et al. (2000, 2014, 2018) and Stephan et al. (2019a, b). This interpretation is now extended to both the East Thuringian greywackes and the Carboniferous greywacke from the Görlitzer Schiefergebirge, for which detrital zircon data confirming a West African source are presented here for the first time. For the latter, the data indicate reworking and redeposition of the Cadomian rocks during post-Cadomian sedimentary processes. With the exception of the Collmberg Quartzite and the Carboniferous greywacke sample, all other units were previously assigned to the Cadomian basement and were classified as Neoproterozoic. Nevertheless, the re-dating of detrital zircons has demonstrated that distinct groups can be distinguished, exhibiting younger sedimentation ages in some units.

Neoproterozoic–early Cambrian sedimentation

Despite minor local variations in the occurrence (including their complete absence in some samples), the Lausitz and Leipzig greywackes exhibit consistent zircon age patterns, thereby confirming a Late Neoproterozoic–early Cambrian age of deposition, as previously established by Linnemann et al. (2000, 2007). The presence of Phanerozoic zircons, though sparse, indicates that sedimentation extended at least into the earliest Cambrian. A comparable time lag between the crystallisation age of detrital zircons and the actual deposition of the host sediments has also been demonstrated for other peri-Gondwanan successions, such as the Schist–Greywacke Complex of the Iberian Massif (Talavera et al. 2012). Similar age patterns occur in the Müglitz Formation and the greywackes of East Thuringia, where the sedimentary age had long been debated for the latter. The new data support a Neoproterozoic to Cambrian age as posited by Meinhold (2004), resolving earlier suggestions ranging from Ordovician (Pfeiffer 1970; Sehm 1973, 1976; Lange et al. 1999) to Carboniferous (Timmermann 1978; Pfeiffer 1995). The available zircon age data suggest that some samples from the Leipzig–Thuringia region could be slightly older on average, whereas those from the Müglitz

Formation may be younger. It can therefore be assumed that locally distinct sedimentation conditions prevailed within the Cadomian backarc basin. Nevertheless, the close genetic relationship proposed by the zircon age data is further corroborated by overlapping geochemical and petrographic characteristics (see Kühnemann et al. 2025a, c). Exceptionally young single zircon ages (e.g. 487 ± 9 Ma in sample LG21-18A, Lausitz Group; Table 2) might be explained by a partial "concordia-parallel" Pb loss during post-Cadomian structural–metamorphic overprint, as suggested by several discordant $^{206}Pb/^{238}U$ ages in the same sample down to ~ 325 Ma. Similar effects likely explain offsets of up to 50 Ma between the youngest grains and the youngest zircon populations (RMDA) in samples like LG21-01 and EC8 (Table 2).

The stratigraphic separation of the Müglitz and Seidewitz formations proposed by Kühnemann et al. (2025a) and Meinhold et al. (2025) is validated by the new zircon age data. As a result, the Neoproterozoic Weesenstein Group cannot be defined following the previous definition established by Linnemann et al. (2018). It is necessary to invert the stratigraphic arrangement of both formations. The Seidewitz Formation, which was defined as the older unit by Linnemann et al. (2018), proves to be significantly younger than previously assumed based on the presence of Early Ordovician and late Cambrian zircons. This revised interpretation is further supported by trace fossil evidence from the Purpurberg Quartzite as a part of the Seidewitz Formation (see Meinhold et al. 2025). In contrast, the Müglitz Formation, with a youngest zircon population of 557 ± 6 Ma and a single concordant grain dated at 493 ± 16 Ma, provide evidence of a late Ediacaran maximum depositional age or slightly later. Considering the late Cambrian zircon age and the slightly different petrographic features (cf. Online Resource ESM5), it remains debatable whether the Müglitz Formation can be considered equivalent to the other Neoproterozoic–lower Cambrian units.

Late Cambrian–Early Ordovician sedimentation

The new detrital zircon age data demand a revision of the established model that assigned the Clanzschwitz Group (North Saxon Anticline) and the Seidewitz Formation (Elbe Zone) to the shallow marine environment of the passive margin of the Cadomian backarc basin (Linnemann 1991; Linnemann et al. 2007, 2018). The local occurrence of the two quartzitic, highly mature units, particularly the Purpurberg Quartzite (Seidewitz Formation), within the Late Neoproterozoic is difficult to reconcile with the previous model. Studies of other former Cadomian-influenced peri-Gondwanan terranes (e.g. Iberian Massif, Teplá-Barrandian unit) have so far detect only the typical immature greywacke and mudstone sequences (Valladares et al. 2000; Pereira et al. 2006; Drost et al. 2004, 2011). Former detailed provenance analyses of the source area of the cratonic hinterland did not recognise widespread mature lithologies. An exception is represented by pebbles of mature clasts (quartzites) in Upper Neoproterozoic metaconglomerates from the Barrandian part of the Teplá–Barrandian Unit (Sláma et al. 2008). However, mature units characterised by low or absent feldspar content first appear in Saxo-Thuringia during the Cambrian (Linnemann et al. 2000, 2004; Linnemann and Romer 2002), which is marked by intense weathering processes that provided reworked and recycled sedimentary material for the Tremadocian transgression (Linnemann and Buschmann 1995a; Linnemann et al. 2000). The comparatively high proportion of Palaeoproterozoic to Archaean zircons may therefore be indicative both of recycling of the Neoproterozoic greywacke deposits and of mixing with older cratonic sources. Such upper Cambrian–Lower Ordovician mature siliciclastic rocks share characteristic features with the quartzitic lithologies of the Clanzschwitz Group (member 2) and the Seidewitz Formation (Kühnemann et al. 2025a, c). Moreover, zircon age spectra (Fig. 5) confirm sedimentation during the early Palaeozoic. The quartzitic lithologies of the Seidewitz Formation and members 1 and 2 of the Clanzschwitz Group (according to Linnemann et al. 2018), which exhibit similar petrographic compositions, appear to be equivalent and were likely separated later, presumably due to tectonic activity within the Elbe Zone during the late Carboniferous to Early Permian (335–327 Ma; Hofmann et al. 2009).

The occurrence of widespread highly mature quartzites in Saxo-Thuringia—including the Dubrau Quartzite (Lausitz Block), the Purpurberg Quartzite (Elbe Zone), the Frauenbach Group and Kernzonen Quartzite (both Schwarzburg Anticline), as well as the quartzites from Otterwisch-Hainichen and Collmberg (both North Saxon Anticline)—supports a broader regional pattern of early Palaeozoic transgressive deposition. Their zircon age spectra often reveal a time lag between crystallisation and deposition, which is common for passive margin settings (Cawood et al. 2012). In such settings, the detritus typically does not derive from juvenile magmatic arc material, but rather consists of erosional products transported over varying distances from a distal hinterland. Consequently, the detrital zircons can represent a broad spectrum of ages, including idiomorphic older grains introduced depending on the transport distance. Although the youngest detrital zircons in some Saxo-Thuringian siliciclastics, such as the Purpurberg and Dubrau quartzites as representative examples, indicate a Late Neoproterozoic to early Cambrian maximum depositional age (Franz et al. 2013; Linnemann et al. 2018), biostratigraphic data suggest at least an Early Ordovician age for both units (e.g. Linnemann 2003; Meinhold et al. 2025). Similarly, the 'Basisquarzit'

(Schwarzburg Anticline) has traditionally been assigned to the lower Palaeozoic based on its higher maturity compared to other Neoproterozoic units and interpreted as the basal unit of the Goldisthal succession (von Gaertner 1944; Falk and Wiefel 2003), despite the youngest detrital zircon age of 557 ± 14 Ma obtained from this conglomeratic arkose (Linnemann et al. 2014). Even in cases where both Phanerozoic zircons and biostratigraphic evidence are absent (e.g. Purpurberg and Kernzonen quartzites; Linnemann et al. 1999, 2000, 2014, 2018; see Fig. 6), the combination of high lithological maturity and characteristic geochemical properties can still justify an interpretation as upper Cambrian to Lower Ordovician equivalents in Saxo-Thuringia (Mingram 1998; Kühnemann et al. 2025c). In contrast to several of these units lacking Phanerozoic zircon populations, the Collmberg Quartzite is clearly distinguished by a high proportion of late Cambrian to Early Ordovician detrital zircons. These are most likely derived from the numerous granitoid bodies emplaced during the tectonic transition from Cadomian collisional to Ordovician rift setting (e.g. Rumburk granite: 496 ± 2 Ma; Vogt et al. 2023), or time equivalent magmatic rocks.

Although the ELEO-V sample exhibits a zircon population distribution similar to that of the other dated Neoproterozoic greywackes of the Eleonorental in East Thuringia and does not contain Phanerozoic zircons, its petrographic and isotopic characteristics are different. These features indicate a probable correlation with the Tremadocian basal succession of the Goldisthal Formation (Schwarzburg Anticline; cf. Kühnemann et al. 2025c) and implies the presence of Lower Ordovician sequences exposed at the surface in East Thuringia (e.g. Eleonorental near Bad Köstritz). Similarly, the quartz schist (sample Katz) from the Frohnberg Formation (Katzhütte Group, Schwarzburg Anticline) suggests an early Palaeozoic deposition due to its high maturity (Kühnemann et al. 2025c).

Coming back to the Saxo-Thuringian part in northern Saxony, as the conglomeratic greywacke of member 3 of the Clanzschwitz Group only occurs locally as loose rocks and has been strongly affected by tectonic overprint and metamorphism, the lithostratigraphic framework of this unit is difficult to resolve. According to the prevailing model by Linnemann et al. (2018), member 3 represents the stratigraphically uppermost part of the Clanzschwitz Group and should therefore postdate the Lower Ordovician quartzitic member 2. However, the significantly lower maturity, in addition to the lack of Phanerozoic zircons, contradicts this interpretation. We therefore propose that member 3 represents the basal layer of the Clanzschwitz Group. Although its zircon age spectrum resembles that of Neoproterozoic greywackes, a slightly younger depositional age is inferred, as rounded greywacke fragments are also present within the pebble assemblage (Schmidt 1960).

Carboniferous sedimentation

The greywacke from the Görlitzer Schiefergebrige provides a useful reference for distinguishing post-Cadomian from Cadomian-related greywacke successions in Saxo-Thuringia. During the early Carboniferous, distal greywacke sequences were deposited in Saxo-Thuringia, with relicts preserved today in the Ziegenrück-Teuschnitz Syncline (southeast Thuringia and northern Bavaria) and in the Görlitzer Schiefergebirge at the northern margin of the Lausitz Block. These deposits formed in a geological setting influenced by the Variscan orogeny and the closure of the Rheic Ocean (Göthel 2001). The zircon age spectrum of the Carboniferous greywacke points to multiple sediment sources. Evidence for contributions from the Cadomian basement and its recycled products is provided by the characteristic detrital zircon age peaks in the Palaeoproterozoic and Archaean (Fig. 5). A prominent age peak at ~ 490 Ma reflects input from Cambrian–Ordovician rift-related felsic magmatic rocks of Saxo-Thuringia. The abundant ~ 370 Ma zircon population further suggests Late Devonian magmatic activity in Saxo-Thuringia or its vicinity. This magmatism is recorded, for example, in granitoids and rhyolites of the Berga Anticline of Saxo-Thuringia and adjacent areas (Neumühle, Hirschberg, Gefell areas; e.g. Gehmlich et al. 2001; Gehmlich 2003). Rare detrital zircons of similar age were also identified in the Prasinit-Phyllite-Series of the Münchberg Massif (Koglin et al. 2018). Together with the population around ~ 490 Ma, this implies that both Cambro–Ordovician and Late Devonian magmatic rocks were increasingly subject to erosion and reworking during the early Carboniferous.

Sample comparison

To provide a more detailed visual representation of the age relationships within the analysed zircon populations, multidimensional scaling (MDS) plots with different display focuses are presented (Fig. 7). Samples with more similar age spectra plot in closer proximity, whereby nearest neighbours are connected by continuous lines and second-nearest by dashed lines. As the Carboniferous greywacke is not relevant to the pre-Variscan evolution of Saxo-Thuringia, it is excluded. The Lower Ordovician quartzitic units of the Collmberg Formation, Seidewitz Formation and member 2 of the Clanzschwitz Group are distinctly separated from the immature greywackes of the Lausitz and Leipzig groups, the Thuringian region and the Müglitz Formation (Fig. 7a). The quartz schist of the Katzhütte Group, the conglomeratic arkose equivalent from the Eleonorental (sample ELEO-V), and member 3 of the Clanzschwitz Group also plot in close proximity, primarily due to the shared absence of Phanerozoic zircons. However, despite their similarity in detrital zircon age spectra, these three units are not coeval with the Neoproterozoic greywackes. The protolith sediment was rather deposited during the late Cambrian–Early Ordovician. This highlights the limitations of age pattern-based clustering alone and underscores the necessity of incorporating petrographic and (isotope-)geochemical data for reliable stratigraphic interpretations.

Even when considering additional zircon age data from Late Neoproterozoic to Lower Ordovician sedimentary units in Saxo-Thuringia reported in the literature, a clear temporal distinction between immature greywackes and quartzitic lithologies remains evident (Figs. 7b–d). However, the limited data available for some of the units may bias the quantitative comparison of age distributions and individual sample positions in the plot should therefore be interpreted with caution. Despite these limitations, the clustering of Neoproterozoic greywacke reference samples from the Rothstein Formation (Torgau-Doberlug Syncline), the Frohnberg Formation (SW Schwarzburg Anticline, Katzhütte Group), and the Altenfeld Formation (NW Schwarzburg Anticline, Katzhütte Group) with units analysed in this study offers robust evidence for a common genetic linkage (Figs. 7b, c). It remains likely that all units were deposited quasi-synchronously, as proposed by Buschmann (1995) and Linnemann et al. (2000, 2007), in a backarc basin from partly slightly divergent, locally different composed supply areas of the cratonic mainland. The MDAs of the greywacke units, which are overall closely grouped, do not allow for a temporally resolved distinction that would support the development of a subsequent retroarc basin.

A comparison of the Lower Ordovician units studied here with Tremadocian quartzites from Hohe Dubrau (Lausitz Block), Langer Berg, Kernzone (both Schwarzburg Anticline), and Purpurberg (Elbe Zone) reveals two main groupings in the MDS plot (Fig. 7d). The quartzites from Hohe Dubrau, Purpurberg and the Kernzone, characterised by a near absence of Phanerozoic zircons (Fig. 6), form one cluster on the right side of the plot. The Katzhütte Group quartz schist, basal conglomerates from the Eleonorental (sample ELEO-V) and member 3 of the Clanzschwitz Group plot in between (Fig. 7d), sharing the absence of Phanerozoic zircons but exhibiting slight disparities in composition. Notably, member 3 contains a more pronounced Neoproterozoic population and fewer Archaean zircons (Fig. 6). On the left side of the plot, Collmberg Quartzite, Langer Berg Quartzite, as well as the Seidewitz Formation and member 2 of the Clanzschwitz Group are grouped together based on a high proportion of Ordovician and particularly Cambrian zircons and lower Palaeoproterozoic proportions (Fig. 6).

The Collmberg Quartzite (sample LG21-16A) occupies a special position among the Ordovician quartzites (Figs. 6, 7d). The distinctive character is likely due to derivation from a more juvenile-influenced source area, as evidenced by a high proportion of Cambrian–Ordovician detrital zircons and a comparatively low content of Palaeoproterozoic ages. Together with its high feldspar content (cf. Online Resource ESM3 in Kühnemann et al. 2025a) and only sparse fossil record, these features argue against the previously assumed equivalence to the quartzites of Hainichen–Otterwisch and Hohe Dubrau (e.g. Linnemann 1995). These quartzites, including also the Purpurberg Quartzite, are feldspar-poor, highly mature, and fossil-bearing units and are presumed to correspond to the Upper Frauenbach Quartzite of the Schwarzburg Anticline. These units probably represent reworked sediments of the Cambrian weathering phase and recycled Cadomian basement of Gondwana. The observed trend of increasing feldspar, Na and Ni content (Kühnemann et al. 2025a, c) in combination with the high young zircon input in the Collmberg Quartzite, rather suggests a slightly younger stratigraphic position and deeper erosion level in the source area, potentially around the Tremadocian–Floian boundary. A similar trend was previously described in the sedimentary rocks of the Phycodes Group stratigraphically above the Upper Frauenbach Quartzite (Hahne et al. 1984; Mingram 1998). Nevertheless, a correlation between the mature Lower Ordovician quartzites is challenging to establish in the absence of fossil evidence, particularly when relying solely on detrital zircon ages.

Despite these differences, all quartzites of the Lower Ordovician probably represent a largely concurrent deposition whose supply of sedimentary material may differ depending on the lithologies present in the source region, as well as the erosion and transport processes occurring in the hinterland. Their common feature, a dominance of zircons older than 570 Ma, reflects significant input from older cratonic sources and recycling of Neoproterozoic greywackes. This signature could assist in classifying similar Saxo-Thuringia passive margin sequences lacking fossil evidence.

Implications for the Late Neoproterozoic Saxo-Thuringian basin model

The recent detrital zircon data from Cadomian basement units and Lower Ordovician quartzites in Saxo-Thuringia challenge aspects of the established Cadomian basin evolution model. The prominent zircon age peak between ~ 580 and 600 Ma in immature Neoproterozoic–lower Cambrian units supports sedimentation in a Late Neoproterozoic–early Cambrian backarc basin (e.g. Linnemann et al. 2000; Buschmann et al. 2001). Direct evidence of synsedimentary activity of the Cadomian magmatic arc, for example manifesting as ash layers, could not be provided. Given the low thickness, limited distribution and high proportion of rounded zircons (20 %; Linnemann et al. 2000), the ash layer of the Wüsteberg Tuff is most likely to represent reworked material. The introduction of partially idiomorphic zircons with an age of approximately 570 Ma into the sedimentary rock may also have been attributed to the erosion of hinterland granitoids. Unlike other peri-Gondwanan terranes such as the Central Iberian Zone (Rodríguez-Alonso et al. 2004), the absence of tuffs may suggest either a distal basin position or arc inactivity during greywacke deposition; or alternatively, ongoing arc activity with turbiditic sedimentation preventing the preservation of coherent ash layers. Additionally, the detrital zircon record does not support the existence of a short-lived retroarc basin related to Cadomian convergence (Linnemann et al. 2007), consistent with recent doubts (Kühnemann et al. 2025c).

Although the Müglitz Formation (Elbe Zone) displays broad similarities in detrital zircon age spectra compared to the Neoproterozoic greywackes, it also contains isolated late Cambrian zircon ages and differs slightly in petrographic features. A key point of discussion is the nature of its contact with the Seidewitz Formation, which Linnemann et al. (2018) described as gradual—leading them to assign to the Müglitz Formation a younger stratigraphic position. However, Meinhold et al. (2025) re-evaluated this interpretation, integrating new fossil constraints and questioning the relative ages of the two units. They present two competing hypotheses: one proposes a Neoproterozoic (Ediacaran) origin for the Müglitz Formation, implying a distinct stratigraphic hiatus (i.e. Cadomian unconformity, Linnemann and Buschmann 1995a, b) to the overlying Lower Ordovician Seidewitz Formation. The other hypothesis assumes an upper Cambrian to lowermost Ordovician age, which aligns with the apparently gradual transition between the formations observed in the field. The recent zircon data and the fossil evidence from the Seidewitz Formation (Meinhold et al. 2025) tend to support a continuous, post-Cadomian sedimentary succession, suggesting that the Müglitz Formation was not deposited in the Neoproterozoic backarc basin and does not constitute part of the Cadomian basement. Nevertheless, further work is required to fully clarify the nature of this contact and its sedimentary implications. Contrary to the prevailing consensus (e.g. Linnemann et al. 2000, 2014, 2018), both the Seidewitz Formation and the Clanzschwitz Group, similar to other Lower Ordovician quartzites, were deposited on the passive margin shelf of northern Gondwana after the Cadomian orogeny.

The stratigraphic arrangement within the Clanzschwitz Group proposed by Linnemann et al. (2018) merits reconsideration. Given its immature character in comparison to member 2 and the absence of Phanerozoic zircon populations, it is postulated that member 3 represents the basal conglomeratic layer of the unit. Its geochronological, geochemical and petrographic characteristics resemble those of the Goldisthal Formation (Schwarzburg Anticline), suggesting the possibility of a younger, potentially early Palaeozoic age for member 3. This revised stratigraphy of the Clanzschwitz, but also the former Weesenstein Group has implications for the model of the "Weesenstein glaciation", which postulates the deposition of glaciomarine diamictites towards the end of the Ediacaran in both the Müglitz Formation and member 3 of the Clanzschwitz Group (Linnemann et al. 2018). However, significant heterogeneity in the composition and quantity of the pebble assemblage (Kühnemann et al. 2025a) and the presence of rounded greywacke fragments (Schmidt 1960) contradict an Ediacaran age of deposition. Instead, member 3 of the Clanzschwitz Group could represent an upper Cambrian–Lower Ordovician succession, and also the Müglitz Formation could be younger than Late Neoproterozoic. Further research is required to evaluate whether glaciomarine sedimentation occurred in Saxo-Thuringia at the end of the Ediacaran or whether the glacial interpretation as a whole need to be reconsidered.

The new zircon data also provide temporal constraints on sedimentation and basin development by revising previous interpretations of thermal overprinting in the Clanzschwitz Group and the Müglitz Formation. The early Cambrian age of the Laas granodiorite (537 ± 5 Ma; Linnemann et al. 2018) rules out that this magmatic rock was the source of metamorphism in the Clanzschwitz Group, given the new post-Cadomian age for the deposition of the protoliths of the Clanzschwitz Group metasedimentary rocks. Kühnemann et al. (2025a) instead link the metamorphic overprint to a Permo-Carboniferous event, supported by structural and mineralogical evidence (Fig. 8). The high level of tectonic deformation of the Clanzschwitz Group indicates that the contact between the Laas granodiorite and metasediments is more likely tectonic than intrusive, placing a lower limit of ~ 537 Ma on sedimentation and an upper limit prior to Permo–Carboniferous metamorphism. A comparable scenario applies to the Dohna granodiorite in the Elbe Zone (538 ± 2 Ma; Linnemann et al. 2018), whose age excludes it as the source of thermal metamorphic overprint in the Lower Ordovician Seidewitz Formation (Fig. 8). Whether it affected the Müglitz Formation remains unclear, given the uncertain stratigraphic position of that unit. Additionally, Schmidt (1960) characterises the present-day contact surfaces as subsequently overprinted, hence there is no conclusive evidence of early Cambrian contact metamorphism. Younger intrusive bodies related to the Meissen Pluton (~ 330 Ma; Hofmann et al. 2009) are present in the region and may have been responsible for the thermal overprinting.

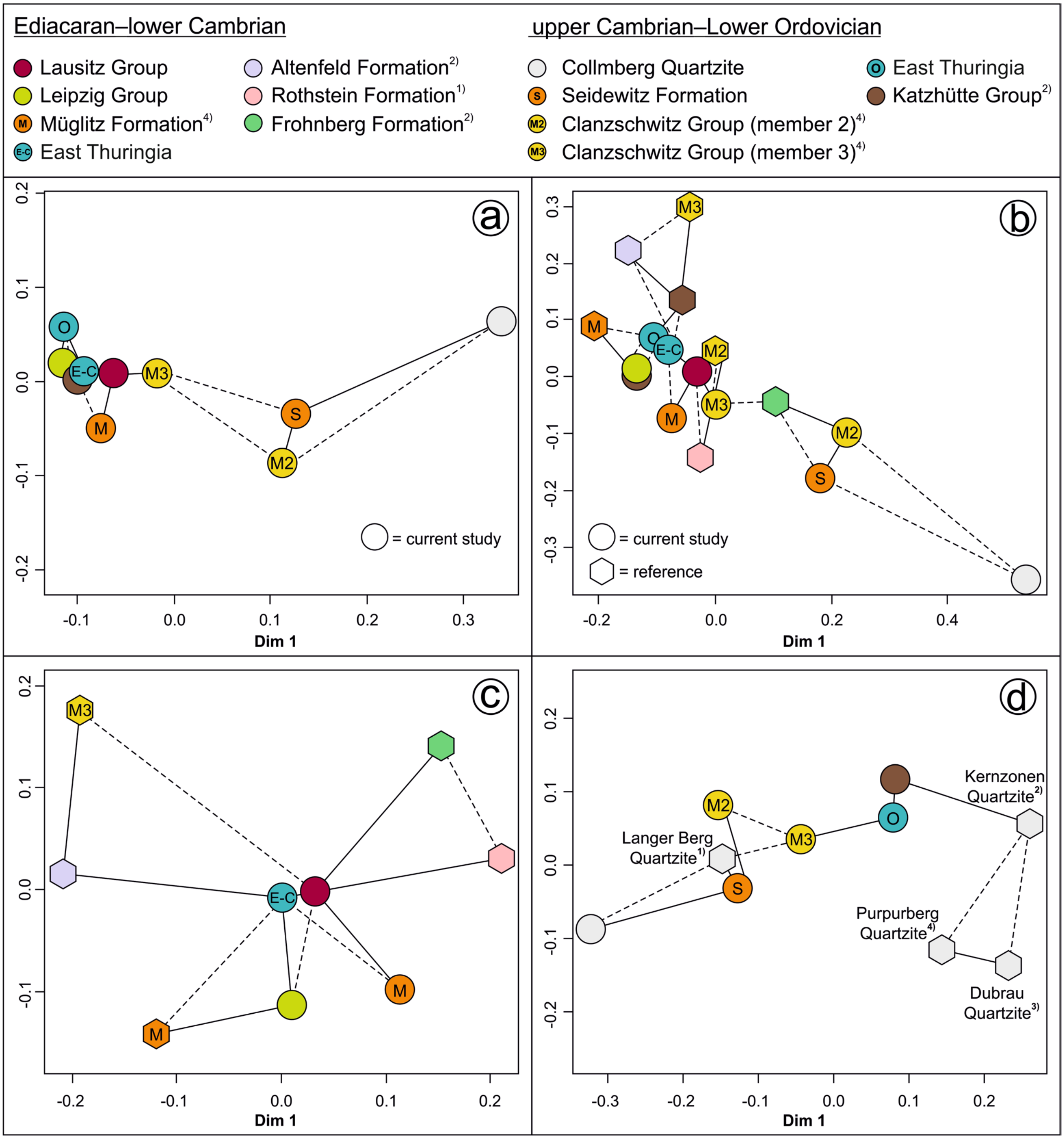
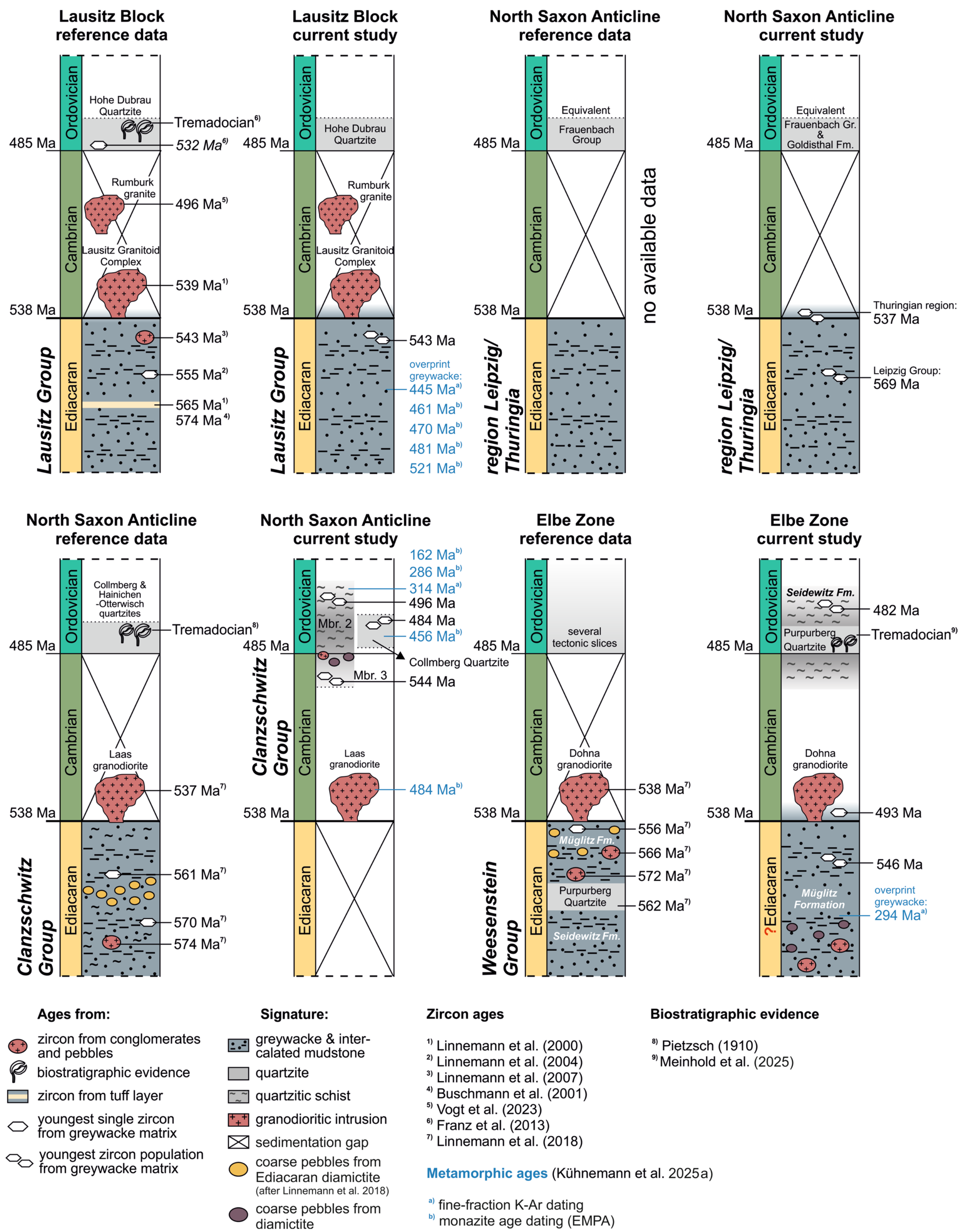


Fig. 7 Multidimensional scaling (MDS) maps for the detrital zircon age spectra of the Upper Neoproterozoic to Lower Ordovician units of Saxo-Thuringia investigated in the present study and references from the literature. The respective lithologies of the units are explained in the text. **a** Relationship between all units investigates in the present study. **b** Relationship between all available zircon age data from the current study and those known from literature. **c** Comparison of the Neoproterozoic greywacke units. **d** Comparison between the Lower Ordovician basal conglomerates and quartzites. The colours of the reference samples refer to the colours of the samples shown as circles of the present study. Zircon reference data: [1] Linnemann et al. (2007); [2] Linnemann et al. (2014); [3] Franz et al. (2013); [4] Linnemann et al. (2018)


Lausitz Block
reference data
Lausitz Block
current study
North Saxon Anticline
reference data
North Saxon Anticline
current study
Ordovician
Cambrian
Ediacaran
485 Ma
538 Ma
Hohe Dubrau Quartzite
Tremadocian[6]
532 Ma[6]
Rumburk granite
496 Ma[5]
Lausitz Granitoid Complex
539 Ma[1]
543 Ma[3]
555 Ma[2]
565 Ma[1]
574 Ma[4]
Lausitz Group
543 Ma
overprint greywacke:
445 Ma[a]
461 Ma[b]
470 Ma[b]
481 Ma[b]
521 Ma[b]
Equivalent
Frauenbach Group
no available data
region Leipzig/ Thuringia
Frauenbach Gr. & Goldisthal Fm.
Thuringian region:
537 Ma
Leipzig Group:
569 Ma
North Saxon Anticline
reference data
North Saxon Anticline
current study
Elbe Zone
reference data
Elbe Zone
current study
Collmberg & Hainichen -Otterwisch quartzites
Tremadocian[8]
Laas granodiorite
537 Ma[7]
561 Ma[7]
570 Ma[7]
574 Ma[7]
Clanzschwitz Group
162 Ma[b]
286 Ma[b]
314 Ma[a]
496 Ma
Mbr. 2
484 Ma
456 Ma[b]
Collmberg Quartzite
Mbr. 3
544 Ma
484 Ma[b]
several tectonic slices
Dohna granodiorite
538 Ma[7]
556 Ma[7]
Müglitz Fm.
566 Ma[7]
572 Ma[7]
Purpurberg Quartzite
562 Ma[7]
Seidewitz Fm.
Weesenstein Group
Seidewitz Fm.
482 Ma
Purpurberg Quartzite
Tremadocian[9]
493 Ma
546 Ma
Müglitz Formation
overprint greywacke:
294 Ma[a]
?Ediacaran
Ages from:
zircon from conglomerates and pebbles
biostratigraphic evidence
zircon from tuff layer
youngest single zircon from greywacke matrix
youngest zircon population from greywacke matrix
Signature:
greywacke & intercalated mudstone
quartzite
quartzitic schist
granodioritic intrusion
sedimentation gap
coarse pebbles from Ediacaran diamictite
(after Linnemann et al. 2018)
coarse pebbles from diamictite
Zircon ages
[1] Linnemann et al. (2000)
[2] Linnemann et al. (2004)
[3] Linnemann et al. (2007)
[4] Buschmann et al. (2001)
[5] Vogt et al. (2023)
[6] Franz et al. (2013)
[7] Linnemann et al. (2018)
Biostratigraphic evidence
[8] Pietzsch (1910)
[9] Meinhold et al. (2025)
Metamorphic ages (Kühnemann et al. 2025a)
[a] fine-fraction K-Ar dating
[b] monazite age dating (EMPA)

◂**Fig. 8** Schematic stratigraphic profiles of the analysed Upper Neoproterozoic to Lower Ordovician units of Saxo-Thuringia. Zircon age data previously published in the literature are compared in the individual units with the age data from the youngest zircon populations of the present study. The combined results of the most recent investigations (this study; Kühnemann et al. 2025a, c; Meinhold et al. 2025) necessitate a reassignment of the origin of the quartzites from the Seidewitz Formation (Elbe Zone) and the Clanzschwitz Group (North Saxon Anticline) from the Neoproterozoic to the upper Cambrian to Lower Ordovician. Also, the stratigraphic affiliation of the Müglitz Formation of the Weesenstein Group to the Ediacaran–lower Cambrian or upper Cambrian–Lower Ordovician remains uncertain (see text for discussion). Consequently, the presumed Late Neoproterozoic glaciomarine origin of the conglomerates and diamictites locally represented in the Clanzschwitz and Weesenstein groups is contested. The Collmberg Quartzite is assumed to be stratigraphically slightly younger compared to the other Lower Ordovician quartzites, due to the overall younger zircon population. As observed in the recent study by Kühnemann et al. (2025c), conglomeratic arkoses, equivalent to the lower Tremadocian Goldisthal Formation (Schwarzburg Anticline), occur in East Thuringia alongside Neoproterozoic greywackes

Conclusion

The zircon age spectra of all investigated sedimentary units from Saxo-Thuringia confirm a detritus supply from two major sources, the West African Craton and the Avalonian–Cadomian orogenic belt (e.g. Linnemann et al. 2000, 2004). Some Lower Ordovician quartzites, along with the Carboniferous greywacke of the Görlitzer Schiefergebirge, provide evidence for sediment input from Cambro-Ordovician magmatic sources. In the case of the latter, an additional juvenile contribution from felsic magmatic rocks—most likely rhyolites—dated to the Upper Devonian (~ 375–370 Ma) is also recorded (Fig. 9). When considered alongside recent studies on the stratigraphy of pre-Variscan units in Saxo-Thuringia (Kühnemann et al. 2025a, c; Meinhold et al. 2025), the detrital zircon age data presented here call for a revision of the Cadomian-related stratigraphic framework (Figs. 8, 9). Importantly, this study demonstrates that stratigraphic classification based solely on detrital zircon geochronology—especially for highly mature quartzitic units

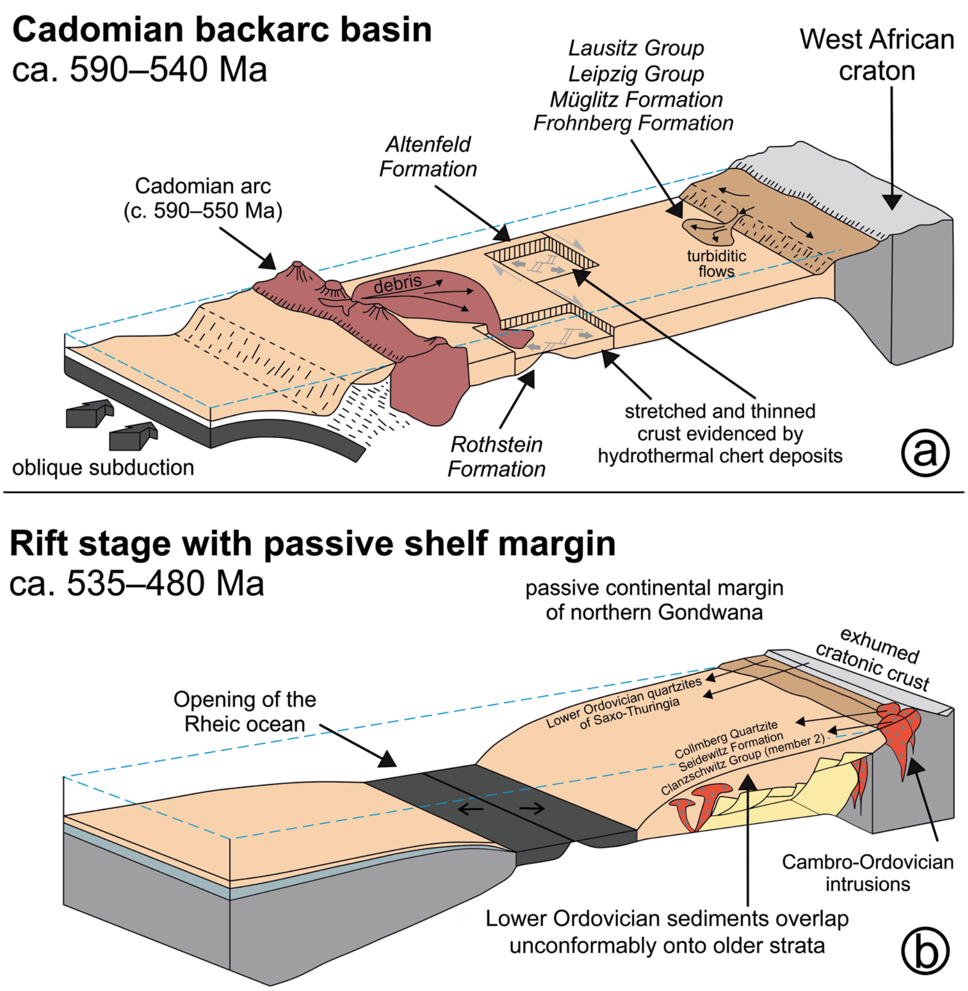


Fig. 9 Basin constellation in the Late Neoproterozoic and Early Ordovician at the northern margin of Gondwana. Model of the Cadomian backarc basin ca. 590–540 Ma ago (**a**) and of the post-Cadomian evolution into a passive continental margin (**b**). Modified after Linnemann et al. (2007). The revised stratigraphic age assignment of the Seidewitz Formation is according to Kühnemann et al. (2025a), Meinhold et al. (2025) and the present study and that of the Clanzschwitz Group (member 2) is according to Kühnemann et al. (2025a) and the present study

in passive margin settings—can be misleading due to the lack of juvenile zircon input. A comprehensive approach integrating petrographic, geochemical, and palaeontological evidence alongside geochronology is essential for accurately resolving sediment provenance and basin evolution in the complex Saxo-Thuringian region.

1. The detrital zircon populations provide evidence that all Neoproterozoic units of Saxo-Thuringia were deposited simultaneously within a backarc basin system on the northern continental margin of Gondwana, without a short-lived intermediate stage of a retroarc basin before the climax of the Cadomian orogeny. However, the stratigraphic position of the Müglitz Formation (Weesenstein Group, Elbe Zone), previously described as Neoproterozoic, requires further investigation in future studies.
2. Despite the youngest zircon populations indicating a Neoproterozoic age, the samples from member 3 of the Clanzschwitz Group, the Katzhütte Group and sample ELEO-V from the Eleonorental (East Thuringia) can be considered equivalents of the basal layers of the Goldisthal Formation (Frohnberg Formation, Schwarzburg Anticline) due to their petrographic and geochemical characteristics. Accordingly, they are probably of upper Cambrian to Lower Ordovician age.
3. The affiliation of the quartzitic units of the Seidewitz Formation (Weesenstein Group, Elbe Zone) and member 2 of the Clanzschwitz Group (North Saxon Anticline) is revised from the Neoproterozoic to the upper Cambrian–Lower Ordovician (Fig. 8). Hence, contrary to previous models, it can be concluded that these units do not constitute part of the Cadomian basement and were not deposited simultaneously along with the immature greywackes within a backarc basin. It is therefore proposed that these lithologies are best interpreted as passive margin deposits on the broad Gondwana shelf after the Cadomian orogeny (Fig. 9b).
4. The stratigraphic classification of the highly mature Lower Ordovician quartzites of Saxo-Thuringia based on detrital zircon age populations alone is challenging, primarily due to the limited juvenile zircon input from active magmatic sources. The absence of Phanerozoic zircons in the quartzites of the Purpurberg, Kernzone and Hohe Dubrau formations points to a dominant contribution from old cratonic sources and recycled Neoproterozoic material. In contrast, the presence of Cambrian and Ordovician zircon populations in the Collmberg Quartzite, the Seidewitz Formation (quartz schist samples adjacent to the Purpurberg Quartzite), and member 2 of the Clanzschwitz Group suggests a more juvenile source area, likely associated with sediment supply from Cambro–Ordovician magmatic rocks within Saxo-Thuringia. It is therefore plausible that these highly mature sediments were deposited more or less synchronously along the northern Gondwanan margin adjacent to the West African Craton, but in different facies zones and with distinct source regions (Fig. 9b).
5. Based on the differing zircon age population, the decreasing maturity, and the limited fossil record of the Collmberg Quartzite, we conclude that the previously assumed equivalence to the Hohe Dubrau and Hainichen-Otterwisch quartzites is invalid, and a slightly younger stratigraphic age (i.e. Phycodes Group) may be valid.

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Data availability All data are available within this article and its supplementary material.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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