Geological Magazine

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Original Article

Cite this article: Meinhold G, Arslan A, Jensen S, and Kühnemann V. Discovery of trace fossils in the Weesenstein Group, Elbe Zone, Germany, and its significance for revising the Ediacaran and Ordovician stratigraphy of Saxo-Thuringia. *Geological Magazine* **162**(e10): 1–12. https://doi.org/10.1017/S0016756825000032

Received: 8 October 2024
Revised: 10 December 2024
Accepted: 31 January 2025

Keywords:
Ediacaran; Ordovician; trace fossils; Elbtalschiefergebirge; Saxo-Thuringia; peri-Gondwana

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Discovery of trace fossils in the Weesenstein Group, Elbe Zone, Germany, and its significance for revising the Ediacaran and Ordovician stratigraphy of Saxo-Thuringia

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Abstract

Trace fossils are described for the first time from the Purpurberg Quartzite of the Weesenstein Group, where deposition is so far considered to be glacio-eustatic controlled during the ~565 Ma-old Weesenstein–Orellana glaciation. The mineralogically mature quartzites are locally rich in trace fossils, but the bedding plane bioturbation index is commonly less than 3. The trace fossil assemblage is of low diversity and comprises abundant *Palaeophycus* isp. and *Palaeophycus tubularis* and rare *Phycodes*, likely *Phycodes* cf. *palmatus*. One large *Lockeia siliquaria* and likely also a poorly preserved *Rusophycus*? isp. were found. Based on these findings and regional correlation with quartz-rich sequences of Saxo-Thuringia, an Early Ordovician age is suggested for the Purpurberg Quartzite, which can be regarded as a facies equivalent to shallow marine, quartz-rich sequences of southwestern Europe deposited along the northern Gondwanan margin during the Early Ordovician. In the light of this new insight, stratigraphic implications for the Weesenstein diamictite are also briefly discussed.

1. Introduction

The Ediacaran Period is an important interval of Earth's history following upon the famous Cryogenian 'Snowball Earth' glaciations and comprising the time when macroscopic life (metazoans) started to flourish globally as represented by the Ediacara biota, trace fossils and the first biomineralized animals (Cunningham *et al.* 2017; Wood *et al.* 2019, and references therein). The extreme climate of the Cryogenian Period may have created conditions amenable to the radiation of metazoans (e.g. Shields, 2023). Glacial conditions persisted also into the Ediacaran Period, but of much shorter duration and lesser distribution. The best known of these is the ~580 Ma Gaskiers glaciation, which approximates the appearance of the Ediacara biota (e.g. Pu *et al.*, 2016). Recently, there has been increased interest in putative late Ediacaran glacial deposits although generally with loose age control and uncertainties in a glacial origin of the diamictites (see Wang *et al.* 2023 for review). Ediacaran sedimentary rocks have therefore been the focus of intensive research and are studied in detail on many palaeocontinents.

In the northern Bohemian Massif – a part of peri-Gondwana – Ediacaran sedimentary rocks with only low-grade metamorphic overprint occur in Saxo-Thuringia (also named Saxothuringian Zone, originally defined by Kossmat, 1927; see Meinhold, 2017 for the English translation) (Figure 1a, b). Here, Ediacaran sedimentary rocks are known from the Schwarzburg Anticline, North Saxon Anticline, Doberlug Syncline, Lausitz Anticline and the Elbtalschiefergebirge of the Elbe Zone (Linnemann, 1995; Linnemann & Schauer, 1999; Linnemann, 2007; Linnemann *et al.* 2007, 2008, 2010a; Kemnitz *et al.* 2018) – just to name the most prominent locations. The Ediacaran rocks are unconformably overlain by Lower Ordovician marine overstep sequences, with Cambrian (Series 2 and Miaolingian) strata present only locally. The hiatus between the Ediacaran and younger strata is commonly interpreted to represent the Cadomian unconformity, first described in Saxo-Thuringia in drillcore 5507/70 near Gera by Linnemann & Buschmann (1995a), with its type area being placed at the Monumentenberg in the Hohe Dubrau, Upper Lusatia (Linnemann & Buschmann, 1995b).

In the present study, the focus is on the Elbtalschiefergebirge of the Elbe Zone where the Ediacaran rock record is represented by the up to 2500-m-thick Weesenstein Group (Figure 1c) which comprises two formations: the older (but see below) Seidewitz Formation overlain with gradual transition by the Müglitz Formation (Linnemann *et al.* 2018) (Figure 2a). The former comprises quartzite and quartz schist horizons as well as a thick quartzite unit, named the Purpurberg Quartzite (or Purpurberg Quartzite Member), with ~70 m at its type locality at the hill of Purpurberg, interpreted to be a glacio-eustatic controlled low-stand deposit (Linnemann, 1992, Kurze *et al.* 1992; Linnemann, 1995, 2007; Linnemann *et al.* 2010a, 2018). Because of its

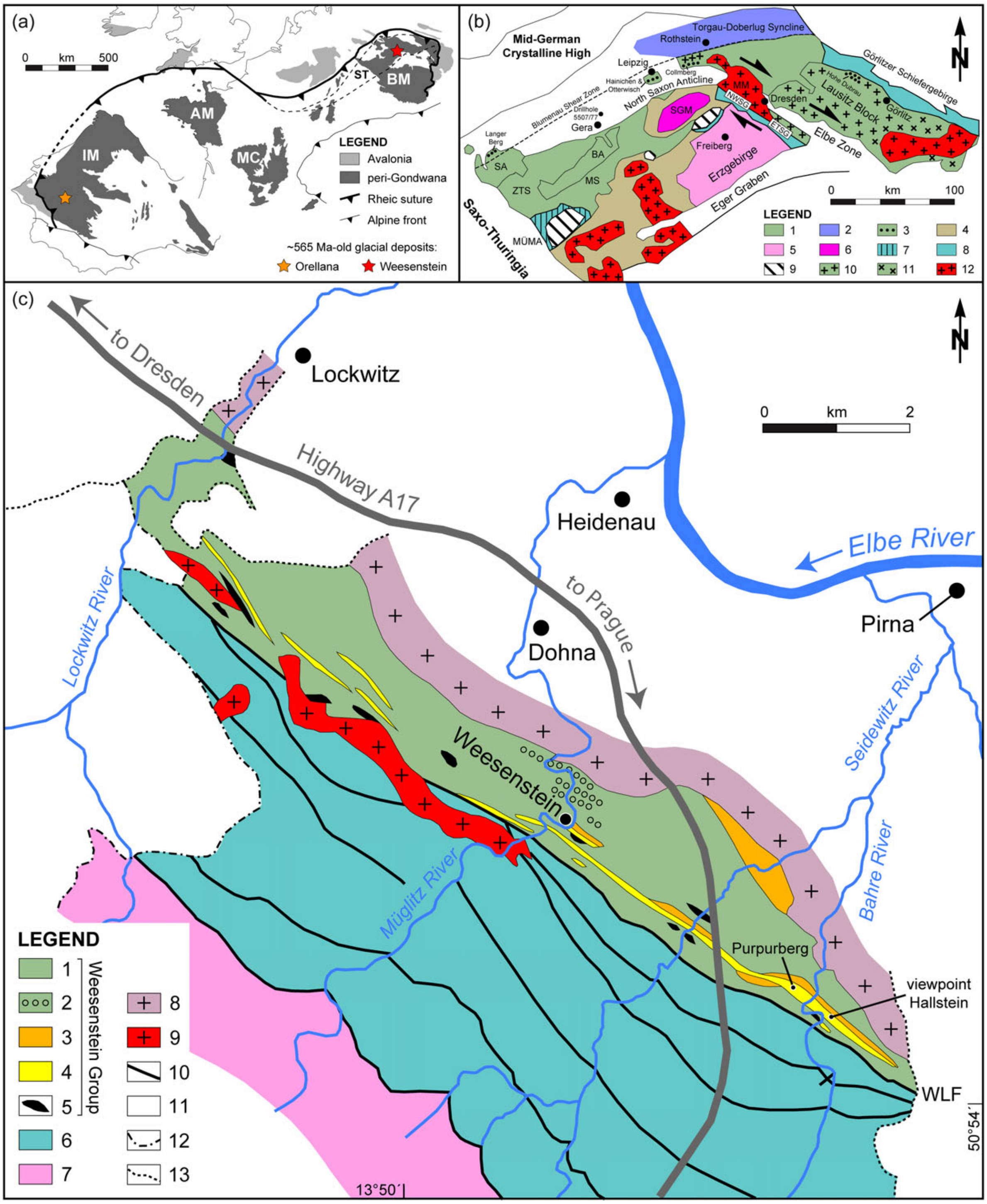

Figure 1. **(a)** Location of Saxo-Thuringia (ST) in a pre-Alpine setting of Central Europe. Exposures of Precambrian and Palaeozoic rocks are shown in grey shades: Avalonia-related units in pale grey and Gondwana-related units in dark grey. Red and orange stars indicate locations of deposits interpreted to belong to the ~565 Ma-old Weesenstein–Orellana glaciation (after Linnemann *et al.* 2018). AM – Armorican Massif, BM – Bohemian Massif, IM – Iberian Massif, MC – Massif Central. **(b)** Location of the Elbtalschiefergebirge (ETSG), which together with the Nossen-Wilsdruffer Schiefergebirge (NWSG) is part of the Elbe Zone, in a simplified geological map of Saxo-Thuringia (modified from Linnemann *et al*. 2010b). BA – Berga Anticline, MM – Meissen Massif, MS – Mehltheuer Syncline, MÜMA – Münchberg Massif, 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). **(c)** Location of the Weesenstein Group in a simplified geological map of the Elbtalschiefergebirge (modified from Linnemann *et al.* 2018). The location of Highway A17 was drawn after Google Maps. 1 – Weesenstein Group containing the Seidewitz and Müglitz formations, 2 – Isolated pebbles and conglomerates (Müglitz Formation, Weesenstein Group), 3 – Quartz schists often under- and overlying the Purpurberg Quartzite (Seidewitz Formation, Weesenstein Group), 4 – Purpurberg Quartzite and its equivalents (Seidewitz Formation, Weesenstein Group), 5 – Meta-basalts (Weesenstein Group), 6 – Ordovician to Carboniferous metasedimentary and igneous rocks of the Elbtalschiefergebirge of 'Thuringian and Bavarian Facies' overprinted under greenschist-facies conditions during the Variscan orogeny, 7 – Cadomian metasedimentary rocks of the Erzgebirge overprinted under upper greenschist- to amphibolite-facies conditions during the Variscan orogeny, 8 – Dohna granodiorite (~538 Ma), 9 – Variscan (lower Carboniferous) granitoids of the Meissen Massif (~335 Ma), 10 – Major faults and dextral shear zones of the Elbtalschiefergebirge originated during the Variscan orogeny, 11 – Permian and younger sedimentary cover, 12 – Limit of Permian (Rotliegend) sedimentary rocks, 13 – Limit of Cretaceous (Cenomanian–Turonian) sedimentary rocks. WLF – West Lausitz Fault.

(a) Stratigraphic concept after Linnemann *et al.* (2018)

Chronostratigraphy	Lithostratigraphy		Rock lithologies
	Group	Formation	
Ediacaran	Weesenstein Group	Müglitz Formation	Weesenstein diamictite, mudstone, greywacke & quartz wacke
		Seidewitz Formation	Purpurberg Quartzite, quartz schist & quartzite

(b) Revised stratigraphic concept based on the present study

Chronostratigraphy	Lithostratigraphy		Rock lithologies
	Group	Formation	
Lower Ordovician		Seidewitz Formation	Purpurberg Quartzite, quartz schist & quartzite
Lower Ordovician/ Cambrian[1] or Ediacaran[2]	Weesenstein Group	Müglitz Formation	Weesenstein diamictite, mudstone, greywacke & quartz wacke

[1]According to hypothesis 1 in the Discussion section; [2]According to hypothesis 2 in the Discussion section

Figure 2. **(a)** Lithostratigraphy of the Weesenstein Group after Linnemann *et al.* (2018). **(b)** Revised lithostratigraphy of the study area after the results of the present study. The lithologies are not given in stratigraphic order among the formations. For example, the Weesenstein diamictite can be underlain and overlain by quartz wacke. Note that the meta-basalts are not shown here (see Fig. 1c for details).

hardness, the Purpurberg Quartzite is a prominent morphological feature in the landscape and is considered to be of lithostratigraphic importance for the subdivision of the Weesenstein Group (Alexowsky *et al.* 1997). The Müglitz Formation comprises mainly greywacke, partly pebble bearing, of the Weesenstein diamictite; the latter has been interpreted to belong to the Ediacaran glaciomarine diamictites of Cadomia for which Linnemann *et al.* (2018) proposed the term Weesenstein–Orellana glaciation and based on zircon U–Pb data age of ~565 Ma for this glacial event. Linnemann *et al.* (2022) extended the late Ediacaran Cadomian glaciation to include deposits from France and the Czech Republic in addition to those of Germany and Spain (Orellana) and suggested a relationship with similarly aged diamictites from north-western Africa, Iran and the Arabian Peninsula.

Given the significance of the Ediacaran Period in Earth's history, a closer look at the Weesenstein Group was required, with particular emphasis on the stratigraphic age constraints. During several days of reconnaissance fieldwork, trace fossils were discovered in the Weesenstein Group, i.e. in the Purpurberg Quartzite of the Seidewitz Formation. These fossil findings indicate an age of more than 80 Myr younger than currently estimated for these rocks. Consequently, previous stratigraphic and palaeoenvironmental concepts of the Ediacaran rock record of Saxo-Thuringia are therefore questioned, and alternatives are proposed based on our field observations and trace fossil data (Figure 2b).

2. Geological setting

The Elbtalschiefergebirge is a complex geological zone tectonically situated between the Erzgebirge nappe pile in the SW and the Lausitz Block in the NE (Figure 1b). It is part of the Elbe Zone, a Variscan dextral strike-slip zone where Neoproterozoic and Palaeozoic rocks are nowadays – in some cases tectonically – situated adjacent to each other (Pietzsch, 1917; Linnemann & Schauer, 1999). The oldest rocks are considered to be those of the Weesenstein Group (e.g. Linnemann *et al.* 2010a, 2018), cropping out in a ~13 km long and up to ~1.8 km wide strip, striking in NW–SE direction (Figure 1c). A local exposure of contact metamorphosed greywacke in the valley of the Gottleuba River at Langenhennersdorf, ~6 km to the southeast of the type locality of the Purpurberg Quartzite, is also considered to belong to the Weesenstein Group (Pietzsch, 1913a, 1917, 1919).

The Weesenstein Group has been contact metamorphosed (Pietzsch, 1916; Schmidt, 1960; Kurze *et al.* 1992; Linnemann, 1992; Alexowsky *et al.* 1997). It was intruded after the Cadomian deformation by the 538 ± 2 Ma-old Dohna granodiorite and later by Variscan granitoids of the Meissen Massif (e.g. Linnemann *et al.* 2018). However, whether or not both magmatic events caused contact metamorphic overprint in the Weesenstein Group remains to be clarified. The following sections provide a synopsis of the geological work in the study area from the 19th century to the present day.

2.a. Geological work until 1990

Geological studies around the village and castle of Weesenstein started to flourish in the 19th century (e.g. Naumann & Cotta, 1845, 1846a,b; Mietzsch, 1871, 1874; Geinitz, 1872). On a hand specimen of a spotted slate (Knotenschiefer in German), Geinitz (1872) described from the Weesenstein area a structure of regular fine parallel ridges (Figure 3). He interpreted it as a compressed stem of likely *Calamites* or a leaf of *Cordaites* but also discussed its similarity with '*Eophyton linnaeanum*', originally named by Torell (1868). The type locality of '*Eophyton linnaeanum*' is in south-central Sweden where the 'Eophyton sandstone' is a trace fossil-rich clastic succession, nowadays known as the Mickwitzia Sandstone Member (lower Cambrian; e.g. Jensen, 1997). '*Eophyton*' is interpreted as a tool mark (e.g. Häntzschel, 1975; Jensen, 1997). Ordovician examples from Estonia probably were created by corals or crinoid stems dragged across the substrate (Vinn & Toom, 2016). Other possible tools have been discussed in the literature (see Savazzi, 2015 for details). The specimen from Weesenstein resembles very much an '*Eophyton*'-type tool mark (cf. fig. 11C in Jensen, 1997; fig. 3 in Vinn & Toom, 2016). Regardless of the uncertainty of the specimen's nature, the description of Geinitz (1872) already illustrates the likelihood of finding fossils or interesting sedimentary structures in the weakly metamorphosed metasedimentary rocks of the Weesenstein Group.

Besides a geological overview map in 1:120,000 scale (Naumann & Cotta, 1846a,b), the first detailed geological mapping of the study area, i.e. map sheet Pirna in 1:25,000 scale, was done by Beck (1889); the corresponding explanatory booklet was published three years later (Beck, 1892). Beck (1892) named the metasedimentary rocks of the Weesenstein area simply as 'Metamorphische Grauwackenformation von Weesenstein' and 'Metamorphisches Grauwackengebirge von Weesenstein' which translates into English as 'Metamorphic Greywacke Formation of Weesenstein' and 'Metamorphic Greywacke Mountains of Weesenstein' respectively. A wide range of stratigraphic ages was postulated for these rocks, e.g. Cambrian or Devonian (Beck, 1897) or Kulm (early Carboniferous) (Lepsius, 1910). The second edition of the geological map was prepared by Pietzsch (1913b), with the explanatory booklet being published three years later (Pietzsch, 1916). Pietzsch (1914) named the weakly metamorphosed metasedimentary rocks around Weesenstein as 'Weesensteiner Grauwackenformation'. Due to lithological similarities with some of the Precambrian rocks of the Barrandian area, Pietzsch (1914) was the first to argue for a Precambrian age. Note that at that time, Bohemian geologists used the term 'Algonkium' (Algonkian in English) instead of Precambrian (Pietzsch, 1914).

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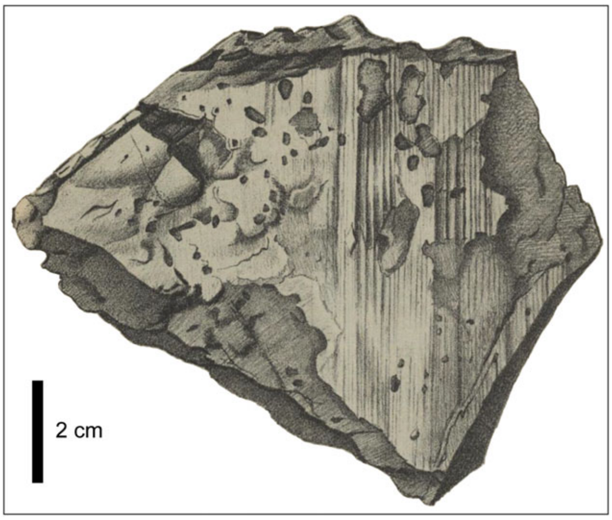

Figure 3. '*Eophyton*'-type tool mark illustrated in Geinitz (1872) from a spotted slate (Knotenschiefer) of the Weesenstein area. For illustration purposes, the grey-ochre background in the original illustration is shown here in white colour. No scale bar is given in Geinitz (1872) for this specimen but assuming all specimens illustrated in Geinitz (1872) were drawn in the same scale and for some specimens the size was mentioned, it is possible to provide a scale bar.

Kossmat (1916) followed Pietzsch's interpretation and also assumed a Precambrian age.

Besides greywacke, partly pebble bearing, there is also quartz schist and quartzite in the 'Weesensteiner Grauwackenformation'. First descriptions of the quartz schist and quartzite (called simply 'Quarz' in some of the older German literature and geological maps) are given in von Raumer (1811), Naumann & Cotta (1845), Mietzsch (1871, 1874), and Beck (1892). A prominent quartzite, i.e. the Purpurberg Quartzite as named in later studies, has a varying thickness of 20 to 120 m and dips steeply to the SW (Pietzsch, 1916) (Figure 4a, b). Pietzsch (1916, 1917) interpreted it as a quartz vein similar to the famous 'Pfahl' in northeastern Bavaria. Gallwitz (1929), however, found poorly preserved ripple structures in the quartzite at Purpurberg and thus first proved the quartzite's sedimentary origin. Based on Gallwitz's work and comparison with Lower Palaeozoic quartzites from Thuringia and Saxony, von Gaertner (1932) speculated a Tremadocian age for the quartzites of the 'Weesensteiner Grauwackenformation'.

Schmidt (1960) studied in detail the pebbles of the Weesenstein greywacke. The pebbles, however, do occur only at a few locations, mainly N and NW of Weesenstein (e.g. Pietzsch, 1916; Schmidt, 1960). The largely rounded pebbles have a size of a few centimetres, rarely up to ~20 cm (Pietzsch, 1916; Schmidt, 1960). They are derived from quartz, quartzite and greywackes as well as granitoids, pegmatites and felsic as well as mafic volcanic rocks (Pietzsch, 1916; Schmidt, 1960).

From 1976 onward, the 'Weesensteiner Grauwackenformation' was subdivided into an older 'Seidewitzer Serie' and a younger 'Weesensteiner Serie' (see Kurze *et al.* 1992 for details). Alder (1987) separated the 'Purpurberg Quartzite' from the 'Weesensteiner Serie' and correlated the former based on lithostratigraphic and petrographical characteristics with Lower Ordovician (Tremadocian) marine overstep sequences of Saxo-Thuringia. Especially, the occurrence of tourmaline-bearing quartzite (hornfels) pebbles in the basal conglomerate of the Purpurberg Quartzite as well as in the Collmberg Quartzite (corresponds today to the Collmberg Formation) and Dubrau Quartzite (corresponds today to the Dubrauquarzit Formation) was taken as a line of evidence that these quartzites have a similar stratigraphic age. Alder (1987) was the first to mention trace fossils from the Purpurberg Quartzite: bedding parallel feeding structures and poorly preserved *Skolithos*-like traces, but only in text form without illustrations nor giving location names. Until the present study, no further mention of trace fossils occurred in the literature; Alder's diversion from the commonly accepted Precambrian age of the Purpurberg Quartzite was ignored in all follow-up publications.

2.b. Geological work between 1990 and 2022

Intensive fieldwork including mapping of the area and sedimentological studies was done as part of a doctoral thesis (U. Linnemann, unpub. Ph.D. thesis, Bergakademie Freiberg, 1990), largely published in Linnemann (1992) and Kurze *et al.* (1992). A third, revised version of the geological map and explanatory booklet of the area was presented by Alexowsky *et al.* (1997) who used much of the data from Linnemann (1992) and Kurze et al. (1992). Linnemann (1992, 1995), according to published Pb–Pb zircon evaporation ages, originally suggested a Cryogenian age, Alexowsky *et al.* (1997) assumed an early Vendian (Varanger) age, and the German Stratigraphic Commission (2022) gave an age of 580 Ma (or older) to 540 Ma for the Weesenstein Group. In general, a Neoproterozoic (Ediacaran) age for the Weesenstein Group has been manifested in the literature, based on U–Pb ages from detrital zircon grains and zircon grains from igneous pebbles (e.g. Linnemann *et al.* 2007, 2018).

The area's stratigraphy has continued to undergo changes of which only the most important are briefly mentioned here. Kurze *et al.* (1992) introduced the 'Weesensteiner Gruppe' (= Weesenstein Group) to represent Pietzsch's 'Weesensteiner Grauwackenformation' and subdivided it into an older 'Niederseidewitzer Folge' (corresponds today to the Müglitz Formation) and a younger 'Oberseidewitzer Folge' (corresponds today to the Seidewitz Formation). Originally, it was thought that the steeply dipping succession is becoming continuously younger from the NE to the SW (Linnemann, 1992; Kurze *et al.* 1992; Alexowsky *et al.* 1997). In later work, however, this model was revised and proposed that the succession becomes continuously younger from the SW to the NE which led to the currently accepted subdivision of the Weesenstein Group (Linnemann *et al.* 2018): the older Seidewitz Formation and the younger Müglitz Formation (Figure 2a). The reasoning for this reversal of the stratigraphy of the Weesenstein Group remains elusive.

The Seidewitz Formation comprises the Purpurberg Quartzite and quartz schists. Some amphibolites and meta-basalts are mentioned to occur within the Seidewitz Formation (e.g. Linnemann *et al.* 2018). The Purpurberg Quartzite, named by Alder (1987), is the most prominent lithostratigraphic unit comprising mature quartzite and a locally occurring conglomerate consisting of weathering-resistant components such as mainly white vein quartz and quartzite and minor dark quartzite (hornfels) pebbles. Although originally placed by Linnemann (1992, 1995) and Kurze *et al.* (1992) at the base of the Purpurberg Quartzite, the conglomerate has more recently been placed at the top of the Purpurberg Quartzite (fig. 4 in Linnemann *et al.* 2018). The mature deposits were interpreted to have formed during glacio-eutstatic sea-level low-stand during an Ediacaran glacial event (see Linnemann *et al.* 2018).

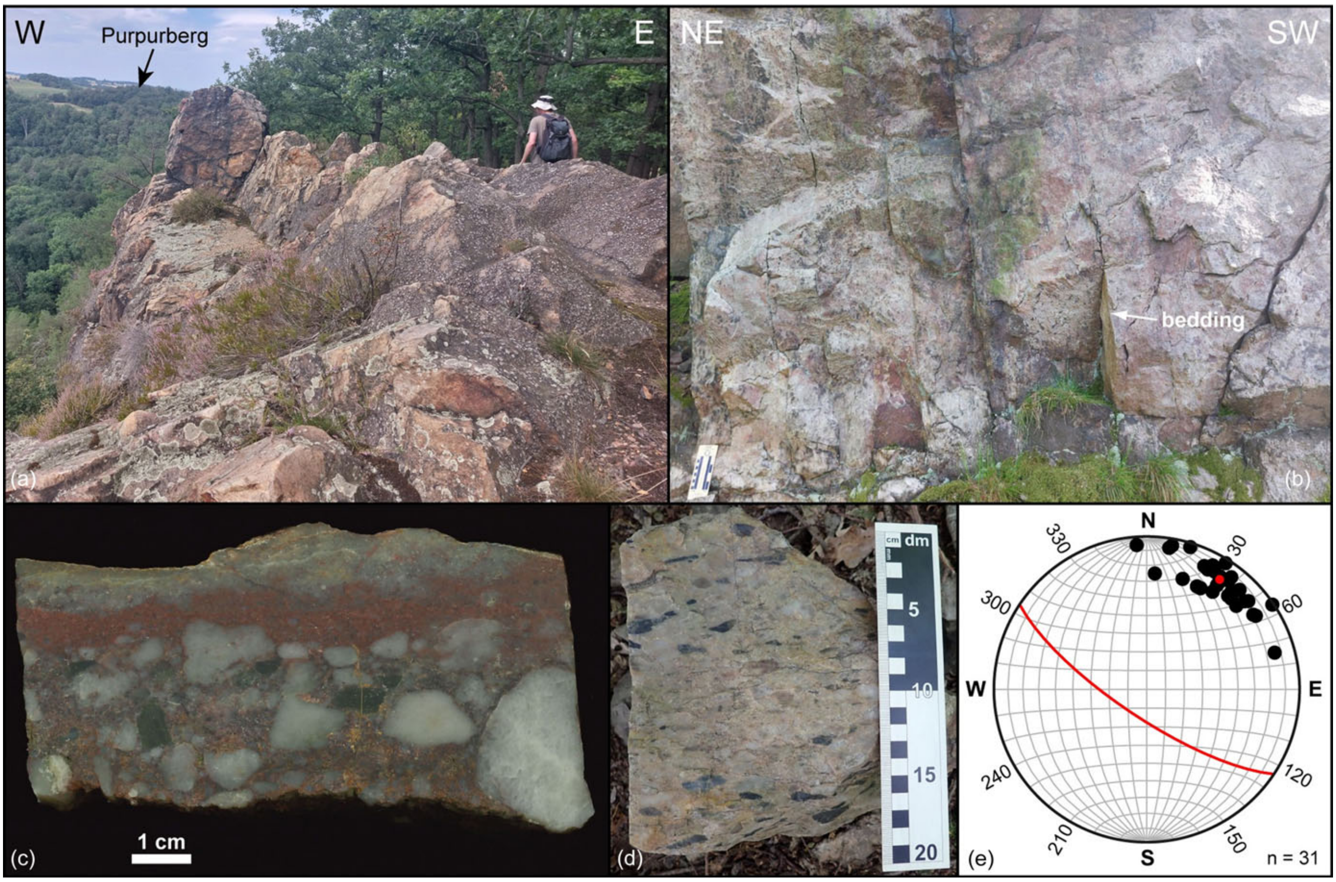

Figure 4. **(a)** Field photograph showing rock exposure around the eastern side of the Bahre River valley, at the viewpoint Hallstein, with the view toward the Purpurberg in the NW. Person for scale. **(b)** Field photograph showing steeply dipping, thickly-bedded quartzite in the lower part of the Purpurberg Quartzite at the eastern side of the Bahre River valley, ~450 m to the NW of the viewpoint Hallstein. Scale bar lower left = 10 cm. **(c)** Conglomerate with sub- to well-rounded clasts of vein quartz, quartzite, and dark tourmaline-bearing quartzite (hornfels) from the basal part of the Purpurberg Quartzite from the eastern side of the Bahre River valley (sample number ESG2). Haematite is omnipresent. The rock specimen was cut perpendicular to the plane of bedding. **(d)** Field photograph of conglomerate from the Purpurberg area, western side of the Bahre River valley (sample number ESG4). **(e)** Stereonet plot showing the bedding orientation of the Purpurberg Quartzite. Lower hemisphere Schmidt net projection created using the Orient software (Vollmer, 2015). Black dots – Poles to bedding planes. Red dot – Pole of calculated average bedding plane. Red curve – Great circle of calculated average bedding plane. n – total number of bedding plane measurements.

The Müglitz Formation comprises mainly greywacke, partly pebble bearing of the Weesenstein diamictite (see Linnemann *et al.* 2018 for details). The Weesenstein diamictite has been interpreted to belong to the glaciomarine diamictites of Cadomia, and the term Weesenstein–Orellana glaciation with an age of ~565 Ma was proposed for this glacial event (Linnemann *et al.* 2018).

2.c. New field observations

Fieldwork was carried out in the study area from 2022 onward to figure out the stratigraphic orientation (base and top) of the sedimentary succession and position of the conglomerate, as different views exist in the literature in which direction the strata become younger and where the conglomerate occurs. In addition, we aimed to explore whether Alder's observations of the presence of trace fossils within the quartzitic succession of the Weesenstein Group can be confirmed.

Our field observations along the eastern and western sides of the Bahre River valley revealed that the sedimentary strata become younger toward the SW because the discovered trace fossils (discussed later) occur as convex hyporeliefs on lower bedding planes of the Purpurberg Quartzite. A conglomerate occurs locally in the basal part of Purpurberg Quartzite. The conglomerate is clast supported, comprising rounded and minor subangular clasts (often flattened and deformed) of up to 2 cm in average size of mainly white vein quartz and quartzite and minor dark tourmaline-bearing quartzite (hornfels) (Figure 4c, d). In parts, extensive haematite staining is common. On the eastern side of the Bahre River valley, the conglomerate is ~5 cm thick and forms the base of the Purpurberg Quartzite. On the western side of the Bahre River valley, it is at least 20 cm, probably up to 30 cm thick and occurs approximately 1.10 m above the base. It is either a single wide channel-fill deposit with varying thickness or the conglomerate represents several channel-fill deposits occurring in slightly different stratigraphic positions, but always in the lowermost (basal) part of the Purpurberg Quartzite. The Purpurberg Quartzite is largely a thickly-bedded quartzite unit (Figure 4b). In parts, thin silty beds occur. The quartzites of the Purpurberg Quartzite are mineralogically mature. Major constituents are medium to coarse sand-sized monoquartz and minor polyquartz. The bedding within the Purpurberg Quartzite dips on average steeply with ~75° toward the SW (Figure 4e). Below and above the

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Figure 5. Trace fossils from the Purpurberg Quartzite (Seidewitz Formation of the Weesenstein Group). All are base of bed views. **(a)** Straight and curved specimens of *Palaeophycus* isp. and *Palaeophycus tubularis* from the western side of the Bahre River valley, 4.10 m above the base of the Purpurberg Quartzite. Note the abundance of traces. Some burrows cross each other, but branching does not occur, and that burrow fill is identical to host sediment above. Scale bar = 20 cm. **(b)** Detail view of Fig. 5a. Note that some burrows cross each other (indicated with arrows). **(c)** Straight and curved specimens of *Palaeophycus* isp., *Palaeophycus tubularis* and *Phycodes* cf. *palmatus* (lower right side) from a loose block at the eastern side of the Bahre River valley (sample number ESG5). **(d)** Detail view of Fig. 5c. Note the abundance of traces. **(e)** Close-up from a *Palaeophycus tubularis* trace showing coarse quartz grains as first burrow filling.

Purpurberg Quartzite are quartz phyllites and quartzite horizons. Some quartz phyllites show contact metamorphism, visible by newly formed minerals such as andalusite.

During fieldwork trace fossils were discovered in the Purpurberg Quartzite (Figures 5 and 6). They occur on lower bedding planes. In two examples, approximately 40–60 % of the bedding is covered, with many burrows overlapping each other, and some are not always well defined, pointing toward a bedding plane bioturbation index of 4, using the scheme of Miller & Smail (1997). However, in most cases where trace fossils are visible their abundance is low (indices of 1 to 3).

3. Material and methods

The majority of the trace fossils were observed at several quartzite outcrops in the lower (older) part of the thick quartzite succession forming the Purpurberg Quartzite sensu stricto, along the eastern and western side of the Bahre River valley, including also the type locality at Purpurberg. Very faint, poorly preserved horizontal structures (probably trace fossils) were also observed at one locality at the north-western side of the Seidewitz River valley and the north-western side of the Müglitz River valley, opposite Weesenstein Castle but are not discussed further here due to their uncertain nature. Photographs were taken from the trace fossils with digital cameras for documentation. Because of the hardness of the rock and to avoid damage to the trace fossils, no attempt was made to extract rock slabs from outcrops. Hand specimens were collected in the field from the most prominent lithologies for rock description. The hand specimens shown in Figure 4c, d and the loose rock slab shown in Figure 5c are stored at the Institute of Geology, TU Bergakademie Freiberg.

4. Systematic ichnology

Because of the biostratigraphic importance of the trace fossil findings in the Purpurberg Quartzite, some systematic ichnology is given. Alder (1987) mentioned the presence of *Skolithos*-like structures which we do not question. However, no *Skolithos* nor *Skolithos*-like traces could be found during fieldwork. Therefore, a detailed description of *Skolithos* is not given here.

The use of open nomenclature follows Bengtson (1988).

Horizontal simple burrows

Ichnogenus *Palaeophycus* Hall, 1847

Type ichnospecies. Palaeophycus tubularis Hall, 1847, by subsequent designation of Miller (1889).

Palaeophycus tubularis Hall, 1847

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Figure 6. Trace fossils from the Purpurberg Quartzite (Seidewitz Formation of the Weesenstein Group). All are base of bed views. **(a)** Straight and curved specimens of *Palaeophycus* isp. and *Palaeophycus tubularis* from the eastern side of the Bahre River valley, 4.40 m above the base of the Purpurberg Quartzite. Some specimens cross each other, but branching does not occur, and that burrow fill is identical to the host sediment above. **(b)** Poorly-preserved traces of likely *Palaeophycus* isp. from the basal part of the Purpurberg, western side of the Bahre River valley. **(c–d)** Straight and curved specimens of *Palaeophycus* isp. from a loose block at Purpurberg, western side of the Bahre River valley. **(e)** Although the determination is problematic due to poor preservation, this trace resembles an arthropod trace fossil, being a possible *Rusophycus*, eastern side of the Bahre River valley, 4.40 m above the base of the Purpurberg Quartzite. A thin fracture cuts the specimen. **(f)** A large single specimen of *Lockeia siliquaria* from the eastern side of the Bahre River valley, 2 m above the base of the Purpurberg Quartzite. A fracture cuts the specimen.

Figures 5, 6a–d

Material. Several specimens as convex hyporeliefs within the Purpurberg Quartzite; the eastern and western sides of the Bahre River valley.

Description. Straight to curved, cylindrical to subcylindrical burrows preserved as convex hyporelief. Outer surface smooth, without ornamentation. Burrows parallel to subparallel to bedding, with diameter of 1.5–2.5 cm and length often greater than 10 cm. Locally, specimens intersect each other producing apparent branching; real branching does not occur. Burrow fill is identical to host rock; in some cases, coarser quartz grains mark the first filling, which can be taken as an indication of passive fill.

Remarks. Many of the specimens are too poorly preserved to be determined to species level, and are referred to *Palaeophycus* isp., but some can be referred to *P. tubularis* as defined by Pemberton & Frey (1982). *P. tubularis* is seemingly common in two to three horizons of the thickly-bedded Purpurberg Quartzite, in which few other, very distinct simple traces are rarely associated with the assemblage. *Palaeophycus* represents passive infilling of open-dwelling burrows commonly interpreted as formed by predaceous or suspension-feeding animals (Pemberton & Frey, 1982). This cosmopolitan ichnotaxon is common in shallow marine sand-dominated environments from the Cambrian to Recent (e.g. Häntzschel, 1975; Jensen, 1997). There are reports of latest Ediacaran *Palaeophycus* although rare and with a size not exceeding 8 mm in diameter (e.g. Nowlan et al. 1985; Narbonne & Aitken, 1990).

On the same surface as *Palaeophycus* are found more strongly curved burrow segments, in places forming hairpin turns. This morphology is not attributable to *Palaeophycus* but because they are rare they are not treated separately. Further deviation from a typical *Palaeophycus* morphology is seen in a near polygonal development (Figure 5d).

Branched burrows

Ichnogenus *Phycodes* Richter, 1850

Remarks. Phycodes is essentially a branched form of horizontally bundled burrows without annulation, preserved as convex hyporeliefs (e.g. Bromley, 1996). It represents passive infilling of open-dwelling burrows of unknown organisms (probably worms), feeding on organic-rich sediments (Fillion & Pickerill, 1990). Detailed interpretations are provided by Seilacher (1955), Osgood (1970), Fillion & Pickerill (1990) and Seilacher (2000).

Phycodes cf. *palmatus* (Hall, 1852)

Figure 5c, d

Material. One specimen as convex hyporeliefs within the Purpurberg Quartzite; the eastern side of the Bahre River valley.

https://doi.org/10.1017/S0016756825000032 Published online by Cambridge University Press

Description. Horizontal bundled burrows, having a central branch, which distally diverge into 3–5 smooth, cylindrical branches. The common branch is ~35 mm wide; the diverging branches are 10–15 mm wide and 10–15 cm long.

Remarks. Compared to *Phycodes circinatus* (Richter, 1853), *P. palmatus* has a smaller number of branches and larger width and palmate arrangement. *P. palmatus* has been found in marine strata from the Cambrian to Palaeogene (e.g. Jensen & Grant, 1998; Miller, 2001).

Bilobate burrows

Ichnogenus *Rusophycus* Hall, 1852

Rusophycus? isp.

Figure 6e

Material. A probable, poorly preserved specimen at a lower bedding plane within the Purpurberg Quartzite; the eastern side of the Bahre River valley.

Description. The trace is a convex hyporelief with a maximum length and width of 10 cm and 4.5 cm respectively, resembling *Rusophycus* in outline. A cover of fine-grained sediment is the likely cause that no clear bilobate structure is visible.

Remarks. Although the single specimen preserves neither scratch marks nor the characteristic bilobation of *Rusophycus*, a tentative attribution to this ichnogenus is based on the broadly tear-drop-shaped outline. *Rusophycus* are commonly assumed to be trace fossils of bilaterally symmetrical organisms, most probably arthropods such as trilobites (e.g. Osgood, 1970). *Rusophycus* traces are known from the Cambrian to Permian (e.g. Brandt, 2007), but some were also found in freshwater deposits of Triassic age (Bromley & Asgaard, 1979).

Resting trace (cubichnia)

Ichnogenus *Lockeia* James, 1879

Type ichnospecies. Lockeia siliquaria James, 1879; Upper Ordovician Cincinnati Group, Ohio State, USA.

Lockeia siliquaria James, 1879

Figure 6f

Material. A single, large specimen as convex hyporelief within the Purpurberg Quartzite; the eastern side of the Bahre River valley.

Description. The trace consists of an elongated, seed-shaped body, tapered at both ends. Length and width of the trace are approximately 6.5 cm and 2 cm, respectively.

Remarks. Lockeia has been interpreted as a resting trace (cubichnion), produced by bivalves (Seilacher, 1953; Häntzschel, 1975; Bromley, 1996; Cónsole-Gonella *et al.* 2017). Some specimens of *Lockeia*, however, representing the lower end of relatively deep structures, may be regarded as semi-permanent domiciles (domichnia) (Mángano *et al.* 2002). *Lockeia* is known from fluvial to deep marine deposits from the late Cambrian/early Ordovician to the Pleistocene (e.g. Seilacher, 1953; Pemberton & Jones, 1988; Fillion & Pickerill, 1990; Mángano *et al.* 2002; Kim & Kim, 2008). Specimens reported as *Lockeia* isp. from Upper Ediacaran sedimentary rocks, for example by McMenamin (1996), do not display the characteristic morphology of this ichnogenus (Mángano *et al.* 2002). Most *Lockeia* are rather small in size, less than 2 cm. However, exceptions are known such as *Lockeia* isp. of up to 6 cm in length from the Middle Ordovician of southern Spain (Rodríguez-Tovar *et al.* 2014), *Lockeia siliquaria* of up to 2.7 cm in length from the Upper Ordovician of central Wales (Pickerill, 1977), up to 4.5 cm in length from the Lower Devonian of the southern Rhenish Slate Mountains (Schlirf *et al.* 2002) and the Upper Carboniferous of Eastern Kansas (Mángano *et al.* 1998), up to 4 cm in length from the Middle Jurassic of Rajasthan (Paranjape *et al.* 2013) as well as specimens of *Lockeia gigantus* of up to 7 cm in length from the Lower Cretaceous of South Korea (Kim & Kim, 2008). *Lockeia gigantus*, however, is characterized by a prominent longitudinal furrow, and marginal rims laterally developed at both sides. Particularly large specimens of *Lockeia* may occur singly or in patches, forming groups of three or more (Mángano *et al.* 2002). The report of *Lockeia* from the Purpurberg Quartzite is to the authors' knowledge the first from the pre-Permian of Saxo-Thuringia.

5. Discussion

First, we discuss in detail the stratigraphic implications of the trace fossil findings for the Seidewitz Formation, followed by a brief discussion on how this impacts the age of the Müglitz Formation, i.e. the Weesenstein diamictite and the proposed Ediacaran Weesenstein glaciation.

5.a. Implications for the Seidewitz Formation

The trace fossils from the Weesenstein Group in the Elbtalschiefergebirge occur in distinct horizons at the lower bedding planes of the thickly-bedded quartzite succession making up the prominent Purpurberg Quartzite. The trace fossil assemblage (Figure 7a) is dominated by the presence (in places with high density) of simple (sub)horizontal burrows assigned to *Palaeophycus* isp. and *Palaeophycus tubularis* and rare *Phycodes* cf. *palmatus* (Figure 5). The horizons richest in trace fossils are between 4.10 and 4.40 m above the base of the Purpurberg Quartzite. A single specimen of *Lockeia siliquaria* and possible *Rusophycus* were also found. Especially for *Palaeophycus* the burrowing seems to have occurred occasionally within intercalated siltstone beds. Later, the burrows were filled by the host (sandy) sediment. *Skolithos* isp. may also be present (see Alder, 1987) but was not found during fieldwork. Overall, the sedimentary facies including the trace fossil assemblage are indicative for a shallow to marginal marine, sand-dominated depositional environment. A proximal lower to middle shoreface is suggested following Pemberton *et al.* (2012) (Figure 7b). However, the low diversity of monospecific trace fossil assemblages may point toward a brackish-water environment, like an estuary (e.g. Buatois *et al.* 2005). The basal conglomerate indicates a very energetic environment during the onset of the deposition of the thick sandy (today quartzite) succession.

Although we deem the trace fossil interpretation unquestionable, alternative interpretations may be considered, especially because of their stratigraphical implications. Scour marks and flow rolls can generate structures similar to cylindrical trace fossils and produce curved and hook-like structures also seen in the here described material (e.g. Dżułyński & Walton, 1965). However, the highly variable orientations, uniform widths along the structures and their interweawing rule out this interpretation. It should also be noted that such sedimentary structures form in a different depositional setting than that envisaged for the Purpurberg Quartzite.

In Saxo-Thuringia, quartz-rich sedimentary rocks (sandstones, quartzites, metapelites, and minor conglomerates) are known from distinct stratigraphic positions within the Lower Ordovician (e.g. Falk & Wiefel, 2003; Mingram, 1996; Falk *et al.,* 2000; Linnemann *et al.* 2007, 2008, 2010b). Prominent exposures are known from the Schwarzburg Anticline (Frauenbach and Phycodes groups), Berga Anticline (Weißelster and Phycodes groups), NW Saxony (Collmberg Formation including the

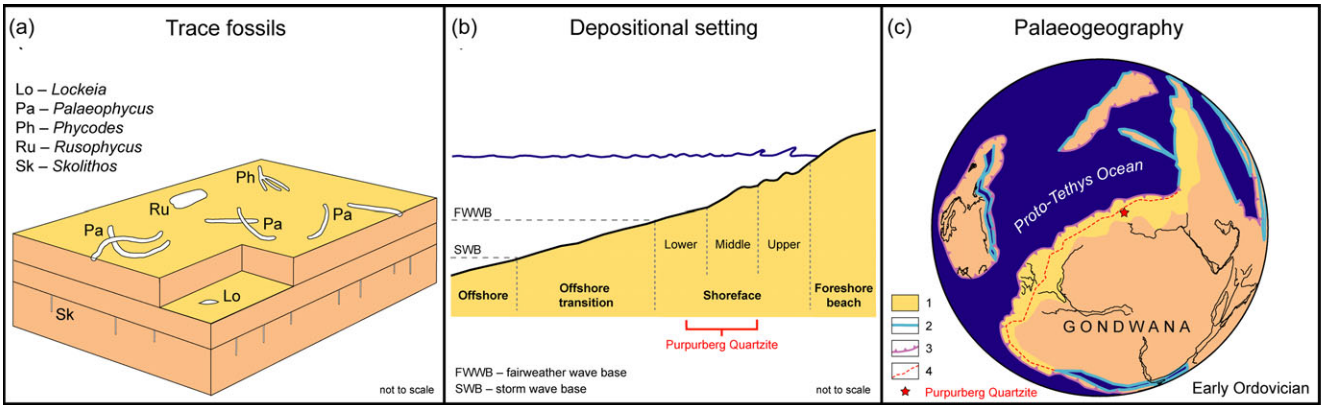

Figure 7. **(a)** Summary of the trace fossil findings of the Purpurberg Quartzite. See Section 4 for details. **(b)** The suggested depositional environment of the Purpurberg Quartzite. **(c)** Early Ordovician global palaeogeographic reconstruction (modified from Stampfli *et al.* 2013), illustrating the proposed depositional position of the Purpurberg Quartzite. 1 – Peri-Gondwana units, 2 – Passive margin, 3 – Active margin, 4 – Future opening of the Rheic Ocean.

localities of Hainichen, Otterwisch near Borna, Deditzhöhe near Grimma, and Collmberg near Oschatz) and Lausitz Anticline (Dubrauquarzit Formation; formerly known as Dubrau Quartzite) (e.g. Falk & Wiefel, 2003; Linnemann & Buschmann, 1995a, b; Linnemann *et al.* 2007, 2008) (Figure 1b). Depending on the depositional facies, these mineralogically mature, quartz-rich sedimentary rocks may contain diverse trace fossil assemblages.

Trace fossil findings are rare from the Frauenbach Group. *Arenicolites*-like (Volk, 1964) and *Skolithos*-like traces may be found (Benton, 1982). The Frauenbach Group is of early to middle Tremadocian age (Kemnitz *et al.* 2018).

The overlying Phycodes Group consists of the Phycodenschiefer Formation and the Phycodenquarzit Formation. The Phycodes Group comprises the name-giving trace fossil *Phycodes*, mainly represented by *Phycodes circinatum* Richter (von Freyberg, 1923; Volk, 1964; Falk & Wiefel, 2003). This trace is rare in the Phycodenschiefer Formation but prominent in the overlying Phycodenquarzit Formation. In the Phycodenschiefer Formation, traces resembling *Arthrophycus* or *Palaeophycus* may be found (Volk, 1964). Seidolt (2023) mentioned (in text form only) *Palaeophycus* bioturbation structures from the upper part of the Phycodenschiefer Formation of the Schwarzburg Anticline. Also, in the upper part of this formation, close to the onset of the Phycodenquarzit Formation the characteristic vertically oriented spreite *Daedalus* is commonly observed (Hundt, 1941; Volk, 1964). The Phycodenquarzit Formation shows a higher diversity of traces (Volk, 1964; Benton, 1982). The most prominent traces are *Phycodes circinatum* and *Daedalus*. In addition, *Arenicolites*-like, *Skolithos*-like and *Balanoglossites* trace fossils, and tube systems similar to those produced by the polychaete *Lanice* may be found (Volk, 1964) as well as arthropod trackways, assigned to *Petalichnus* (Lützner & Mann 1988; Falk & Wiefel, 2003). The Phycodes Group is of late Tremadocian age (Kemnitz *et al.* 2018).

The Collmberg Formation yields *Cruziana* (Pietzsch, 1910; Gläsel, 1955; Freyer 1981), *Monocraterion* isp. (L. Bartsch, unpub. Diploma thesis, Univ. Greifswald, 1956), and *Skolithos*-like traces (Gläsel, 1955; L. Bartsch, unpub. Diploma thesis, Univ. Greifswald, 1956). Its stratigraphic age is broadly given as Tremadocian (Linnemann *et al.* 2008).

The Dubrauquarzit Formation yields a diverse trace fossil assemblage comprising mainly *Skolithos linearis* and *Skolithos* isp. and minor *Monocraterion* isp., *Diplocraterion* isp., *Arenicolites* isp., *Diplichnites* isp., *Rusophycus* isp., *Bergaueria* isp., and *Palaeophycus* isp. (Abdelkader & Elicki, 2018, and references therein). Its stratigraphic age is late Tremadocian (Abdelkader & Elicki, 2018).

Although biostratigraphic constraints are lacking from the meta-siliciclastic succession above the Purpurberg Quartzite up to the NW–SE striking southern branch of the West Lausitz Fault in the SW (corresponding to the Weesenstein Fault of Alexowsky *et al.* 1997), this low-grade metamorphosed sedimentary succession is likely also Ordovician (or younger) in age and does not belong to the Ediacaran part of the Weesenstein Group (see also Kühnemann *et al.*, 2025). This is founded on comparisons with similar strata of Saxo-Thuringia, following Alder (1987), and on detrital zircon U–Pb ages from a quartzitic sample adjacent to the SW of the thick quartzite unit of the Purpurberg Quartzite exposed along the Seidewitz River valley, with the youngest zircon grains being ~505–495 Ma old (V. Kühnemann, unpubl.). In the absence of fossil and other stratigraphic data, the youngest detrital grains such as zircon in a sedimentary rock can indicate a maximum depositional age (e.g. Fedo *et al.*, 2003; Meinhold & Frei, 2008). Often the depositional age is younger by several millions of years than the youngest dated grains, especially in mineralogically mature siliciclastic strata (e.g. Meinhold *et al.* 2011).

Considering all the above, the mineralogical maturity of the studied low-grade metamorphosed sedimentary rocks and the trace fossil findings point toward a Phanerozoic age of the Purpurberg Quartzite. A Lower Ordovician, likely upper Tremadocian or Floian age, is suggested. A younger stratigraphic age cannot be excluded. The Variscan tectonothermal overprint defines the upper time limit of deposition. Similar mineralogically mature quartz-rich, shallow marine strata of the Armorican Quartzite facies are known from southwestern Europe (e.g. Sá *et al.* 2011). Sedimentation occurred along the peri-Gondwanan shelf south of the Rheic Ocean during the Early Ordovician (Figure 7c).

An Ediacaran age for the entire Weesenstein Group is not valid anymore, and palaeoenvironmental models for the deposition of the Purpurberg Quartzite need to be revised. Furthermore, the contact metamorphic overprint recorded in the metasedimentary succession of the Seidewitz Formation cannot be a result of late Neoproterozoic–early Cambrian intrusions but is rather caused by Variscan thermal processes.

5.b. Implications for the Müglitz Formation

The findings of the present study also have implications for the stratigraphic age of the Müglitz Formation. Depending on the contact between the Seidewitz Formation and the Müglitz Formation, two hypotheses are put forward for discussion (Figure 2b).

Hypothesis 1 is based on the assumption of a gradual transition from the Seidewitz Formation to the Müglitz Formation, following Linnemann *et al.* (2018). However, as shown in the present study, the Seidewitz Formation is younger than Ediacaran and overlies the Müglitz Formation. Accepting (i) a Lower Ordovician age for the Seidewitz Formation and (ii) a gradual transition between both formations makes it difficult to continue accepting an Ediacaran age for the Müglitz Formation because an unconformity is developed between Neoproterozoic and lower Palaeozoic strata throughout Saxo-Thuringia, i.e. the Cadomian unconformity as defined by Linnemann & Buschmann (1995a, b). If true, the Müglitz Formation containing the Weesenstein diamictite cannot be of Ediacaran age but must be of Cambrian or Lower Ordovician age. Accepting such a revised age makes it unlikely that the contact metamorphic overprint recorded in the metasedimentary succession of the Müglitz Formation was caused by the ~538 Ma-old Dohna granodiorite.

Hypothesis 2 is based on the assumption that the transition between the Müglitz Formation and the overlying Seidewitz Formation is not gradual but rather marked by a hiatus in sedimentation. If true, the Müglitz Formation containing the Weesenstein diamictite could be of Ediacaran (or slightly younger) age. However, whether the Weesenstein diamictite is of glacial origin needs to be proved by stronger evidence.

6. Conclusions

The Purpurberg Quartzite, part of the Weesenstein Group traditionally regarded as Ediacaran, contains a low diversity trace fossil assemblage of mainly *Palaeophycus* isp., *Palaeophycus tubularis* and rare *Phycodes* cf. *palmatus*. *Lockeia siliquaria* and probably *Rusophycus* also occur. This and the sediment's high maturity point toward a Lower Ordovician (upper Tremadocian or Floian) stratigraphic age and a facies correlation with Lower Ordovician quartz-rich sequences of southwestern Europe. Palaeoenvironmental models of glacio-eustatic controlled deposition of the Purpurberg Quartzite due to sea-level fall during the ~565 Ma-old Weesenstein–Orellana glaciation need to be abandoned. The term Weesenstein Group requires a revision adjusting for the new stratigraphic concept of the area.

Acknowledgements. This work was partially supported by the Saxon State Office for Environment, Agriculture and Geology. Victoria Kühnemann acknowledges a Saxon State Scholarship for the promotion of doctoral students. Sören Jensen acknowledges current funding from PID2021-125585NB-I00 of the Spanish Ministry of Science and Innovation. We warmly thank Ulrich Henk and Jochen Thum for some joint field trips and for pointing out the existence of the rock slab shown in Figure 5c. We thank Sebastian Weber for discussions about the Neoproterozoic of Saxony, Mike Krause for the transportation of a rock slab and Cornelia Feldmann for providing some of the older literature. Supportive reviews by Olev Vinn and Alfred Uchman are greatly appreciated. Open Access funding enabled and organized by Projekt DEAL.

Competing interests. None.

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https://doi.org/10.1017/S0016756825000032 Published online by Cambridge University Press