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The Cadomian unconformity in the Saxo-Thuringian Zone, Germany: Palaeogeographic affinities of Ediacaran (terminal Neoproterozoic) and Cambrian strata

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Abstract

The most complete Ediacaran (terminal Neoproterozoic) to Early Cambrian record in the Saxo-Thuringian Zone is provided by the Cadomian-deformed Ediacaran Rothstein Formation and the unconformably overlying Early Cambrian Zwethau Formation in the Torgau–Doberlug Syncline (TDS). Conglomerates and greywackes of the marine Rothstein Formation are of continental magmatic arc provenance and record detrital zircon SHRIMP ages that indicate a Late Cryogenian to Early Ediacaran (700–580 Ma) age for the arc source and its emplacement into Palaeoproterozoic (2000 Ma) crust. Tuffaceous intercalations record extrabasinal eruptions of evolved calc-alkaline lavas that point to ongoing Cadomian continental arc magmatism. SHRIMP zircon ages from a tuffaceous layer date this volcanic activity and the formation's deposition as Late Ediacaran (566 ± 10 Ma). Close correlation in provenance and age to other Ediacaran units of the Saxo-Thuringian Zone points to a common palaeogeographic setting in the Avalonian–Cadomian belt. Detrital and inherited zircon ages, and Nd-isotopic ratios from these Ediacaran siliciclastic rocks suggest a position on the active margin of Gondwana near the West African craton.

The Early Cambrian Zwethau Formation records the erosion of the underlying Ediacaran rocks followed by the successive evolution of: (i) a carbonate-dominated subtidal ramp with calcimicrobial–archaeocyathan buildups, (ii) a shallow-subtidal to intertidal mixed ramp with peritidal sediments, and oolite shoal complexes, and (iii) a more siliciclastic depositional environment. Calcimicrobial–archaeocyathan buildups, oolite shoals, and sulfate nodules in intertidal sediments indicate warm, arid to semi-arid climatic conditions and a palaeogeographic setting in equatorial to sub-equatorial latitudes. Archaeocyaths, the trilobite taxon *Dolerolichia*, and the sedimentary facies assemblages compare closely to those of the "Mediterranean" Early Cambrian, constraining the palaeogeographic setting to the European, sub-equatorial, western Gondwana shelf realm. Archaeocyaths record a mid-Early Cambrian (Middle Issendalenian/Ovetian) age, making these the oldest Cambrian sediments in both the Saxo-Thuringian Zone and the Bohemian Massif. The Middle Cambrian lithological and palaeontological records of the TDS closely resemble those of the Frankenwald area of the Saxo-Thuringian Zone as well as those of other fragments of the western Gondwana shelf in Spain, Morocco, and Bohemia.

Archaeocyaths, Early Cambrian trilobites, and correlations with Morocco suggest Cambrian deposition commenced at ca. 520 Ma, such that the Cadomian unconformity represents a time gap of about 35–55 Ma (latest Ediacaran to Early Lower Cambrian). This gap, which is related to the Cadomian orogeny and so common to all areas of the Cadomian belt, obscures some of palaeobiological, palaeogeographic, and climatic change that marks the Precambrian–Cambrian transition.

Keywords: Neoproterozoic; Ediacaran; Cambrian; Saxo-Thuringian Zone; Cadomian orogeny; Palaeogeography

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1. Introduction

Ediacaran (terminal Neoproterozoic)[1] rock complexes are widespread in the Saxo-Thuringian Zone of the Bohemian Massif (Fig. 1) (Linnemann and Romer, 2002, and references therein). These complexes record sedimentary and volcanic processes in marginal basin and continental arc environments of the Cadomian orogenic belt, and subsequent granitoid emplacement that continued until the earliest Cambrian. Owing to the Cadomian orogenic overprint, these complexes constitute the basement to Early to Middle Palaeozoic sedimentary and igneous events preceding the Variscan orogeny. The close palaeogeographic affinities of Ediacaran and Early to Middle Palaeozoic units in the Saxo-Thuringian Zone suggest derivation from a common palaeogeographic precursor, termed 'Saxo-Thuringia', that is considered to represent part of the western Gondwana margin situated near the West African craton (e.g., Linnemann et al., 2000, 2004b).

In contrast to the widespread occurrence of Ordovician units in the Saxo-Thuringian Zone, Cambrian rocks postdating the Cadomian orogeny are only locally preserved and usually tectonically detached from the Cadomian basement (Elicki, 1997; Linnemann et al., 2004a,b). An intact stratigraphic relationship between the basement and unconformably overlying Cambrian strata is only known from the Torgau–Doberlug Syncline (TDS) in the northeastern part of the zone (Fig. 1) (Buschmann et al., 1995). Here, unmetamorphosed Early Cambrian shallow marine deposits that have been dated by archaeocyaths (Elicki and Debrenne, 1993) represent the oldest Cambrian strata in the entire Bohemian Massif.

The only other area in the Bohemian Massif with an exposed Cadomian unconformity at the base of Early or Middle Cambrian strata is in the Teplá–Barrandian Zone (Fig. 1) (Chlupáč, 1993; Kříbek et al., 2000; Drost et al., 2004). However, probable Early Cambrian strata in this region are predominantly terrestrial siliciclastic deposits with rare endemic fauna (Havlíček, 1971; Kukal, 1971; Chlupáč, 1995). Hence, the geological importance of the Cadomian unconformity in the TDS for the Bohemian Massif is comparable to that of the Cadomian unconformity in northern Normandy (France) for the Armorican Massif (Fig. 1), where the term 'Cadomian' was first introduced (Bertrand, 1921). This paper provides a brief description of the palaeogeographic affinities, fauna, and climatic record of both the Ediacaran units constituting the Cadomian basement and the unconformably overlying Cambrian strata in the TDS.

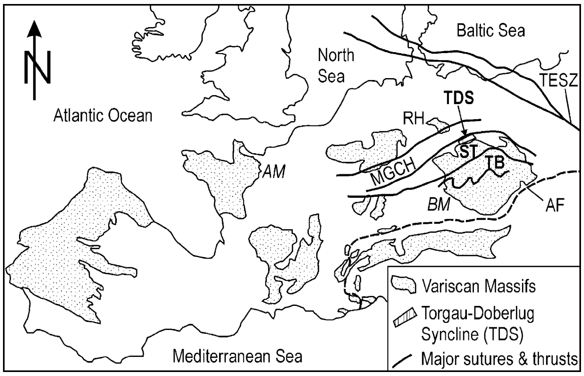

Fig. 1. Distribution of Variscan Massifs and selected structural units in the western European mainland, modified after Franke (1989). AF: Alpine front; AM: Armorican Massif; BM: Bohemian Massif; MGCH: mid-German Crystalline High; RH: Rheno-Hercynian Zone; ST: Saxo-Thuringian Zone; TB: Teplá–Barrandian Zone; TDS: Torgau–Doberlug Syncline; TESZ: Trans-European Suture Zone.

2. Geology of the Torgau–Doberlug Syncline

The TDS is a subsurface structural unit of the Saxo-Thuringian Zone covered by up to 200 m of Cenozoic strata that has been explored by drill holes reaching depths of up to 1200 m. The recovered pre-Cenozoic succession comprises Ediacaran, Lower and Middle Cambrian, and, in central parts of the TDS Viséan strata (Fig. 2) (Buschmann et al., 1995). The Viséan sediments overlie the Cambrian strata with angular disconformity (Brause, 1969; Nöldeke, 1976). Viséan plutonic complexes and Late Carboniferous to Early Permian Variscan molasse deposits occur along the northern and western flanks of the TDS. The very low grade Ediacaran rocks are more intensely folded and cleaved than the Cambrian strata which do not record a regional metamorphic overprint (Buschmann, 1995). Ediacaran and Cambrian strata comparable to the succession in the TDS are known only from core profiles around a Variscan plutonite complex in the buried Delitzsch Syncline to the east (Elicki, 1992; Buschmann, 1995). Owing to a contact metamorphic overprint, these profiles have been less studied and are not considered in this paper. Relations between the Ediacaran of the TDS and adjoining units to the south are unclear because contacts between the structural units are buried.

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[1] In the most recent version of the International Stratigraphic Chart recommended by the International Commission on Stratigraphy of the IUGS, the terminal Neoproterozoic stage is replaced by the Ediacaran stage (600–542 Ma) (Knoll et al., 2004).

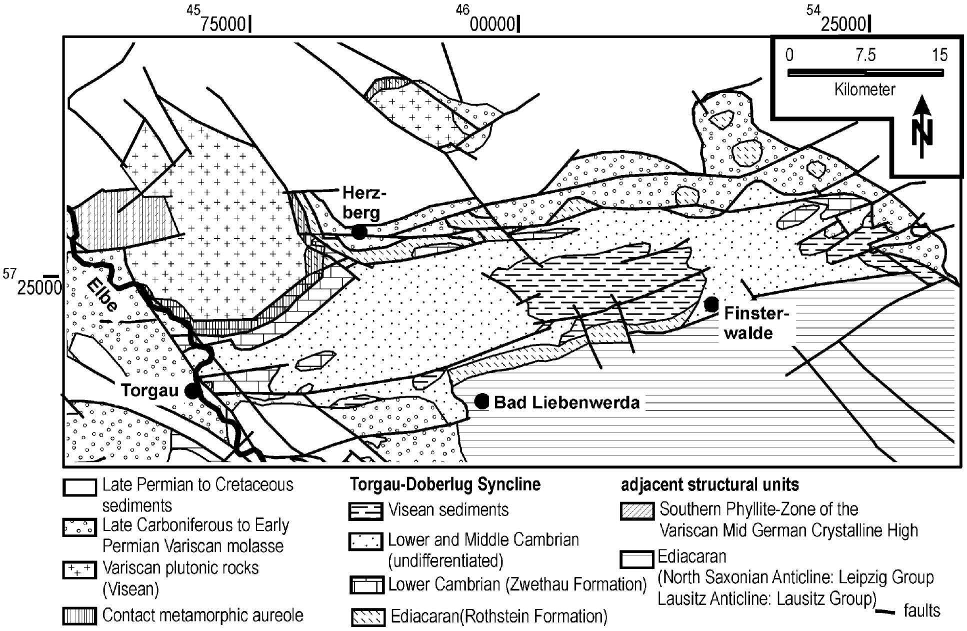


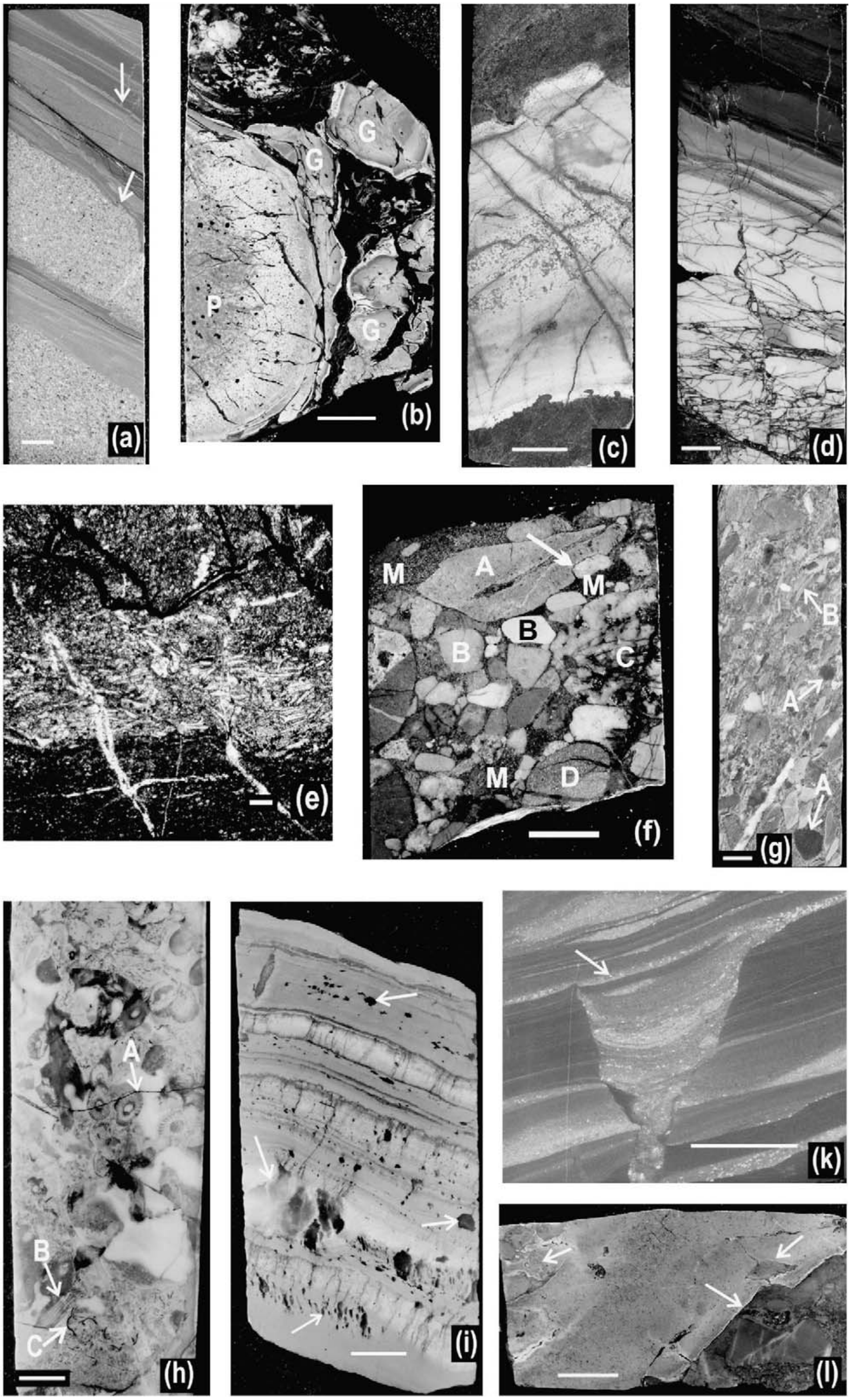
Fig. 2. Geological map of the TDS showing distribution of rock complexes at the pre-Cenozoic surface deduced from geophysical mapping and drilling. The extent of the TDS is defined by the presence of the Ediacaran Rothstein Formation, Cambrian units, and Viséan sediments.

3. Ediacaran of the TDS: Rothstein Formation

Lithostratigraphy: The Ediacaran rocks of the TDS stratigraphically comprise the Rothstein Formation (Buschmann, 1995, 2001; Buschmann et al., 1995). This unit is represented by two outcrops of chert and by some 50 boreholes from which approximately 10 km of core profiles have been recovered. In order of abundance, the lithological inventory of the Rothstein Formation comprises greywacke–siltstone–shale successions, pillow basalts, basaltic to andesitic sills emplaced in siliciclastic rocks, cherts, pyritic black shales, and rare intercalations of conglomerate and tuff (Plate 1(a–f)). Pillow basalts are intercalated with siliciclastic rocks, and cherts are associated with both siliciclastic rocks and pillow basalts. The lack of key horizons and a data gap between the southern and northern flanks of the TDS hinders distinction of stratigraphic members. The base of the Rothstein Formation has not been reached by boreholes and its thickness is estimated to be in excess of 1000 m. Cores that sample the contact with overlying Cambrian sediments show the contact to be sheared. However, the presence of highly immature sedimentary breccias and conglomerates at the base of the Early Cambrian succession that are composed of debris of the underlying Rothstein Formation (Plate 1(g)) demonstrates an unconformable relationship.

Absolute age data: Magmatic zircons from a tuffaceous layer in the Rothstein Formation yielded a concordant SHRIMP U/Pb age of 566 ± 10 Ma (Buschmann et al., 2001). This assigns both deposition of the Rothstein Formation and volcanic activity in the source area to the Late Ediacaran. A polygenetic detrital zircon grain from a greywacke sample revealed: (i) a discordant Archaean Pb/Pb age for the inner core, (ii) a concordia intercept age for the outer core of ca. 2000 Ma, and (iii) a concordant Ediacaran age of ca. 600 Ma for the rim (Buschmann et al., 2001). Single spot SHRIMP measurements on six other detrital zircon grains from the same sample yielded concordant Neoproterozoic U/Pb ages between 700 and 580 Ma for four grains, and slightly discordant Palaeoproterozoic Pb/Pb ages of ca. 2000 Ma for two grains. These data suggest the presence of Palaeoproterozoic and Ediacaran crustal components as well as Ediacaran magmatic reworking of Palaeoproterozoic crust in the source area of the greywackes.

Fossil content: Macrofossils and trace fossils were not observed in the Rothstein Formation, and micropalaeontological investigations yielded only a poor assemblage of pyritized spherical and filamentous microforms (Buschmann, 1990). Thin sections of chert from surface samples with naturally oxidized pyrite display organic walled microbiota. However, the imprint of pyrite growth on the organic matter precludes taxonomic assignment. Organic walled microbiota with processes at the surface (Acanthomorphs) were not observed. The observed microfossil assemblage is considered broadly compara-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ble to Proterozoic shale facies microbiota (e.g., Hofmann and Jackson, 1994).

3.1. Provenance of tuffaceous shales and terrigenous siliciclastic debris

Provenance assessment of the tuffaceous layers and their siliciclastic host rocks are considered the best palaeogeographic correlation tool for the Ediacaran, because of the availability of zircon age data and the absence of palaeobiogeographically useful fossils. However, a detailed provenance analysis of the Rothstein Formation is beyond the scope of this paper (Buschmann, 1995, unpublished data). The following is therefore a condensed interpretation of key data.

The tuffaceous layers are conspicuous, light coloured, less than 10 cm thick intercalations in successions of shales to siltstones (Plate 1(d)), and comprise very fine grained phyllosilicate minerals. One sample also contained tiny grains of embayed volcanic quartz, broken phenocrysts of feldspar, and zircons, suggesting a felsic igneous component. Laminae containing minute light coloured volcanic glass shards that also suggest a felsic volcanic source were rarely observed in chert beds (Plate 1(e)). The layers are silicified to varying degrees, but are best characterized on the basis of major and trace element data.

The least silica-rich of several samples from tuffaceous layers and a sample of associated dark shale show PAAS-normalized rare earth element (REE) patterns that display a distinct depletion of light REE compared to the average shale value (Fig. 3). The depletion is more pronounced in the tuffaceous sample, where its shape closely matches that of sandstones of oceanic arc provenance. This suggests the prevalence of a very fine grained, juvenile igneous component in the tuffaceous sample and its admixture in the shale sample.

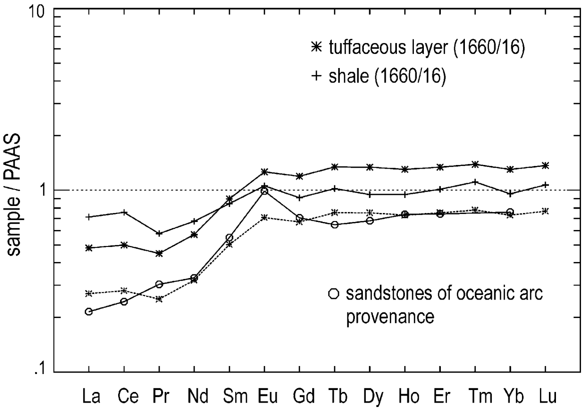

Fig. 3. REE patterns for a tuffaceous layer and an associated shale of the Ediacaran Rothstein Formation normalized to Post-Archaean Average Australian Shale (PAAS; Taylor and McLennan, 1985). Stippled pattern shows position of tuffaceous spectrum at ca. 2.5-fold lower normalized values, where it displays a close affinity to the REE pattern for sandstones of oceanic arc provenance (after Bhatia, 1985). See Table 1 for analytical data.

Three samples from tuffaceous layers considered to be rich in volcanic ash according to their REE patterns were selected for characterization of the igneous component (Fig. 4). The multielement patterns show a general enrichment of incompatible elements, a positive K anomaly, and pronounced negative anomalies for Nb, Ta, Sr, P, and Ti compared to N-MORB. This pattern is characteristic of evolved calc-alkaline igneous rocks. According to the ratios of the largely immobile elements Nb/Y and Zr/Ti, the samples classify as andesites to rhyodacites/dacites (Winchester and Floyd, 1977). By contrast, intraformational volcanic rocks of the Rothstein Formation are represented by seafloor extrusives and sills composed of alkaline and tholeiitic basalts, and tholeiitic andesites (authors' unpublished data). This suggests the volcanic ash in the tuffaceous layers was derived from

Plate 1. Slabbed core and thin section images from: (a–f) the Ediacaran Rothstein Formation and (g–l) the Early Cambrian Zwethau Formation. Scale bar corresponds to 1 cm, in (e) 10 μm. (a) Alternations of greywacke, siltstone, and mudstone. Arrows mark flame-like structures on top of internally liquified greywacke. Borehole 1634/80, 641.5 m. Sample 1634/61-2. (b) Small basaltic pillow (P) surrounded by chloritized glass (G) in dark matrix of chlorite and quartz. Borehole 1650/80A, 218.5 m. Sample 1650A/5. (c) Subvolcanic basaltic andesite sill with variolitic centre and chilled margins against dark silty greywacke. Borehole 1654/81, 315 m. Sample 1654/19. (d) Light coloured tuffaceous layer overlain by dark silicified shale. Borehole 1634/80, 496 m. Sample 1634/123. (e) Thin section of lamina containing fragments of disintegrated vesicular volcanic glass (shards). Plane polarized light. Borehole 1200/78, 304.5 m. Sample 1200/10′. (f) Polymict conglomeratic layer containing well-rounded clasts of mafic (A), and felsic (B) volcanic rocks, quartz-bearing granitoid (C), and silty greywacke (D) supported by greywacke-matrix (M). Arrow marks pressure solution on clast margin. Borehole 1707/81, 305 m. Sample 1707/24. (g) Highly immature conglomerate of reworked Ediacaran Rothstein Formation containing particularly greywacke and rare mafic volcanic rock (A) fragments. Note chip-like size of shale fragments (B) indicating low degree of sedimentary reworking. Borehole 1614/79, 296.0 m. Sample 1614/8. (h) Limestone with cross (A) and perpendicular (B) sections of archaeocyaths and trilobite fragments (C). Borehole 1612/79, 264.5 m. Sample 1612/173. (i) Laminated marly dolostone from tidal environment with sulfate nodules (arrows). Borehole 1612/79, 397 m. Sample 1612/19. (k) Bedded siliciclastic sediment from tidal environment with perpendicular section of mud crack. Note independent fill of crack and seal by silty layer (arrow). Borehole 1612/79, 376.5 m. Sample 1612/146. (l) Subvolcanic basalt with chilled margins (arrows) emplaced into conglomerate. Note lava partly fills space between sedimentary clasts indicating emplacement prior to complete lithification of sediment. Borehole 1603/79, 321.5 m. Sample 1603/30.

Table 1
Major, trace and rare earth element concentrations of samples from the Ediacaran Rothstein Formation used for graphs in Figs. 3–5. Major elements were determined by XRF (Freiberg), trace and rare earth elements by research-grade ICP-MS analyses at ACTLABS (Activation Laboratories Ltd., Ancaster, Ont., Canada)

Sample Rock type		1660/15 Shale	1660/16 Tuffaceous shale	1634/46 Tuffaceous shale	1634/51 Tuffaceous shale	Mean Greywacke[c]
	% Detection limits					
SiO_2	1	63.54	66.26	71.56	79.02	
TiO_2	5	0.64	0.59	0.51	0.11	
Al_2O_3	1	14.76	15.67	14.94	10.54	
Fe_2O_3[a]	5	7.43	3.42	3.41	2.96	
MnO	1	0.32	0.17	0.08	0.11	
MgO	1	1.63	1.54	0.96	1.18	
CaO	5	0.49	1.71	0.43	0.61	
Na_2O	1	1.77	0.92	0.14	0.24	
K_2O	1	3.10	3.83	3.44	1.76	
P_2O_5	1	0.10	0.10	0.13	b.d.l.[b]	
LOI		6.38	5.93	4.38	3.38	
Sum		100.14	100.13	99.99	99.92	
	ppm					
Pb	5	7	b.d.l.[b]	b.d.l.[b]	b.d.l.[b]	
Rb	1	115	127	122	62	
Cs	1	11.74	11.60	4.29	3.58	
Ba	1	512	915	932	496	
Sr	1	68	48	33	37	
Ta	1	0.69	0.48	0.90	0.81	
Nb	5	10.0	5.7	14.0	6.4	
Hf	1	4.31	5.09	6.94	3.50	
Zr	1	121	153	224	89	
Y	1	27	37	41	22	
Th	5	6.68	5.94	8.37	12.50	
U	5	1.60	2.82	4.46	4.14	
La	1	27.26	18.40	12.03	19.24	26.63
Ce	1	60.26	39.75	28.80	38.40	53.00
Pr	5	5.10	3.97	2.80	3.57	6.03
Nd	1	22.90	19.38	13.87	15.76	23.19
Sm	1	4.69	4.98	4.19	3.96	4.46
Eu	5	1.14	1.36	1.14	0.57	0.95
Gd	1	4.24	5.57	4.36	3.42	3.77
Tb	1	0.79	1.04	1.11	0.63	0.59
Dy	1	4.43	6.28	6.75	3.49	3.34
Ho	1	0.94	1.29	1.38	0.69	0.66
Er	1	2.89	3.82	4.31	2.16	1.98
Tm	5	0.45	0.56	0.63	0.33	0.28
Yb	1	2.70	3.68	4.15	2.08	1.90
Lu	2	0.46	0.59	0.67	0.32	0.31

[a] Fe_2O_3 is total iron.

[b] b.d.l. – below detection limit.

[c] Arithmetic mean of REE concentrations of 11 greywacke samples.

an extrabasinal, calc-alkaline andesitic to felsic volcanic source. In view of the very fine grained composition of the tuffaceous material, this source is likely to have been a distal one.

Rare coarse-grained intercalations of turbiditic greywacke–siltstone are highly immature, comprising angular or flattened fragments of reworked intraformational rocks and well-rounded clasts of extraformational derivation (Plate 1(f)). Of the well-rounded clasts, more than 75% comprise rocks of igneous origin (Buschmann, 1995). These include roughly equal proportions of mafic and felsic volcanic rocks, subordinate quartz-bearing

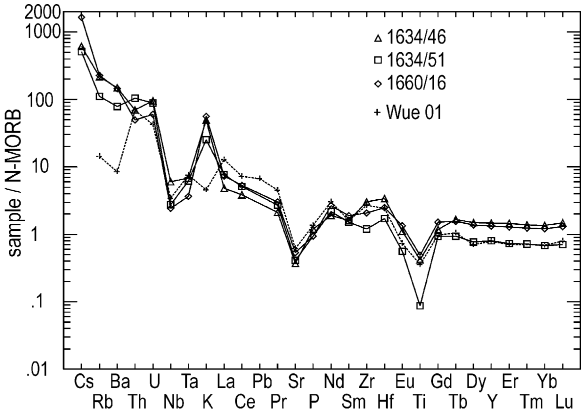

Fig. 4. Multielement patterns for tuffaceous samples from Ediacaran units of the Saxo-Thuringian Zone normalized to N-MORB (Hofmann, 1988). Patterns are characteristic of evolved calc-alkaline volcanic rocks. See Table 1 for analytical data. Sample Wue 01 from Linnemann and Romer (2002).

plutonic rocks, and varying proportions of volcanoclastic or volcanogenic sedimentary rocks some of which contain volcanic quartz grains. Argillaceous rocks make up the second most abundant clasts, followed by quartz pebbles and metamorphic rock clasts. The composition of the extraformational clast population suggests a source area dominated by igneous rocks with plutonic complexes at the surface. The diameter of the well-rounded clasts only once exceeded the core diameter of 4.2 cm, suggesting a relatively distal depositional setting.

Quantitative modal compositions were determined for 28 samples of greywacke using the point counting method of Dickinson (1985). The proportions of grains composed of monocrystalline quartz, feldspar, and rock fragments correspond to a transitional to dissected magmatic arc provenance (Buschmann et al., 1995). Hot cathodoluminescence analyses (operator J. Götze, Freiberg) showed a distinct predominance of igneous quartz grains (Buschmann, 1995).

REE concentrations in the greywackes serve to distinguish between continental and oceanic affinity for the magmatic arc source (Fig. 5). The arithmetic mean REE concentration of 11 greywacke samples most closely resembles the discriminatory pattern for sandstones derived from a continental magmatic source, favouring a continental magmatic arc provenance of the greywackes. In view of the greywacke detrital zircon age data, the siliciclastic debris was derived from a Late Neoproterozoic magmatic arc floored by Palaeoproterozoic continental crust in the source area of the greywackes (Buschmann et al., 2001).

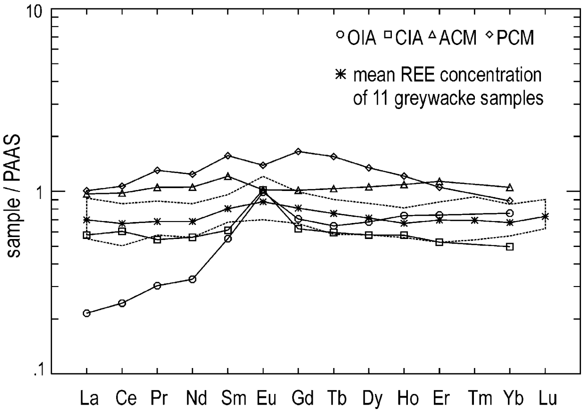

Fig. 5. Average PAAS-normalized REE pattern for greywacke from Ediacaran Rothstein Formation compared to those for sandstones from different provenances (after Bhatia, 1985). OIA: oceanic island arc; CIA: continental island arc; ACM: active continental margin; PCM: passive continental margin. Average greywacke pattern represents arithmetic mean REE concentration of 11 greywacke samples (Table 1). Hatched field shows the range of REE patterns. Normalization values from Taylor and McLennan (1985).

3.2. Regional correlation and palaeogeographic affinity

Major and trace element data for Ediacaran siliciclastic rocks from other areas of the Saxo-Thuringian Zone are indicative of an active continental margin (continental arc) source (Kemnitz, 1994; Linnemann and Romer, 2002). Zircons from a tuffaceous layer in the Ediacaran Lausitz Group yielded a concordant SHRIMP U/Pb age of 574 ± 8 Ma that is identical within errors to the tuffaceous layer SHRIMP age (566 ± 10 Ma) obtained from the Rothstein Formation (Buschmann et al., 2001). Although the tuffaceous layer of the Lausitz Group has been metamorphosed to a calc-silicate rock (Linnemann and Romer, 2002), the concentrations of minor and trace elements are similar to those of the volcanic ash layers of the Rothstein Formation (Fig. 4).

The detrital zircon SHRIMP ages from the Rothstein Formation are similar to those of detrital and inherited zircons from Ediacaran to Early Palaeozoic rocks of the Saxo-Thuringian Zone. The latter record source areas of Archaean© (3400–2500 Ma), Palaeoproterozoic© (2200–1800 Ma), and Neoproterozoic to earliest Cambrian (750–540 Ma) age (Linnemann et al., 2004b). The continental arc source of the debris that accumulated within the Ediacaran sedimentary basins likely formed between 700 and 600 Ma. The Nd-isotopic record of the Ediacaran sediments is considered to reflect the average age (ca. 2000 Ma) of the pre-Neoproterozoic crustal sources (Linnemann and

Romer, 2002; Linnemann et al., 2004b). These provenance data and the presence of Cadomian deformation place the sites of the Ediacaran sedimentary accumulation on the active continental margin portion of the Avalonian–Cadomian orogenic belt bordering the West African craton at the periphery of Gondwana and display palaeogeographic affinities to France (Armorican Massif) and southwest Iberia (Ossa-Morena Zone) (Nance and Murphy, 1994; Linnemann and Romer, 2002; Fernández-Suárez et al., 2002; Gutiérrez-Alonso et al., 2003; Linnemann et al., 2004b).

The Nd-isotopic ratios of the greywacke samples from the Rothstein Formation display a distinct detrital contribution from young volcanic material when compared to greywackes from other Ediacaran units of the Saxo-Thuringian Zone (Linnemann and Romer, 2002). Hence, the Rothstein Formation was probably deposited in a position more proximal to the 700–580 Ma continental magmatic arc source and/or received more volcanic material from the synsedimentary extrabasinal volcanic source.

The palaeoclimatic record of the Rothstein Formation is ambiguous. The highly immature character of the siliciclastic sediments suggests a rapid erosion and/or limited chemical weathering in the continental arc source. Glaciomarine quartzites like those recorded in other Ediacaran units of the Saxo-Thuringian Zone, and unambiguous dropstones are not present in the Rothstein Formation. The absence of carbonate sediments may reflect the proposed deep marine depositional setting of the Rothstein Formation and/or the existence of unfavourable climatic conditions. Elsewhere in the Saxo-Thuringian Zone, Ediacaran fossil remains are likewise restricted to poor assemblages of organic walled microbiota that have been tentatively correlated to the Ediacaran sediments of Bohemia and France (e.g., Burmann, 1972; Chauvel and Mansuy, 1981; Konzalová, 1981, 2000; Weber et al., 1990; Heuse et al., 1994).

4. Cambrian strata of the TDS

Cambrian strata of the TDS comprise the Lower Cambrian Zwethau Formation and the Middle Cambrian Tröbitz and Delitzsch formations (Fig. 6) (Freyer and Suhr, 1987; Brause and Elicki, 1997; Elicki, 1999a). These units are only known from boreholes and it is not clear, whether the stratigraphic gap between the Lower and Middle Cambrian units shown in Fig. 6 represents an exposure gap or a hiatus, since either Lower or Middle Cambrian strata were recovered in any of the studied core profiles. The gaps between the Middle Cambrian units are likely exposure gaps since each continuous

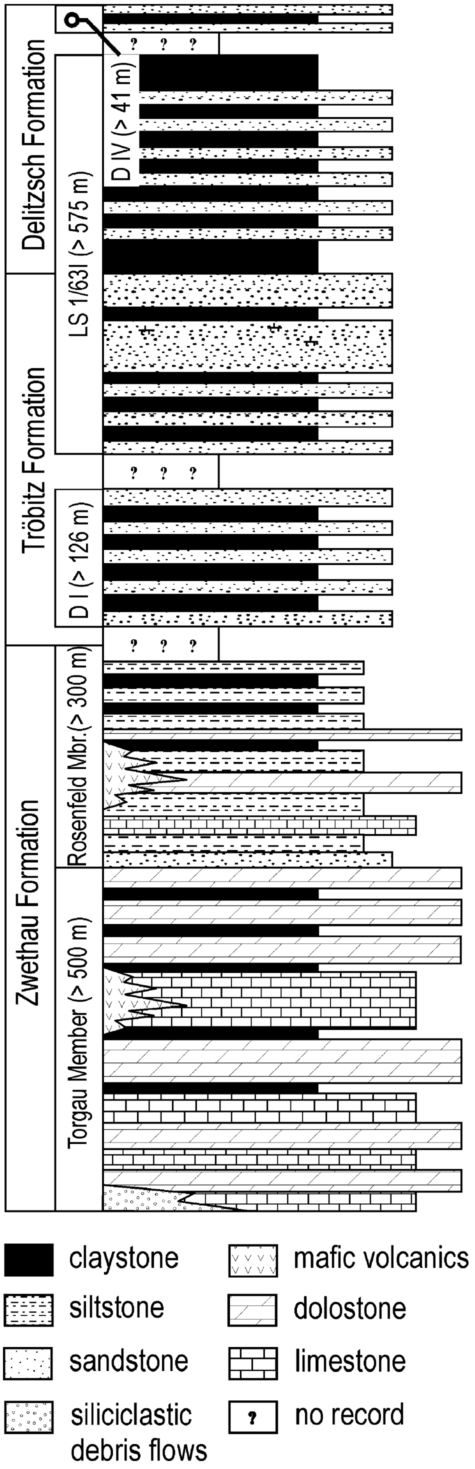

Fig. 6. Generalized lithological columns for the Cambrian succession of the TDS. Gaps are not drawn to scale (cf. Fig. 7). The Lower Cambrian column is based on numerous core profiles, whereas the Middle Cambrian column is derived from reference profiles (boreholes D I, LS 1/63, D IV).

stratigraphic column represents one reference borehole profile. The total thickness of Cambrian strata in the TDS is estimated to be in excess 1500 m.

4.1. Early Cambrian: Zwethau Formation

Sampled by numerous boreholes, the Zwethau Formation is more than 700 m thick and comprises a lower portion dominated by carbonates (Torgau Member) and an upper portion of alternating carbonate–siliciclastic and pure siliciclastic sediment (Rosenfeld Member) (Fig. 6). Coarse grained basal sediment composed of reworked debris from the underlying Ediacaran Rothstein Formation grades upwards either into carbonatic successions or intertidal siliciclastic mudstones.

The Torgau Member consists of fossiliferous oolitic and intraclastic limestones and dolostones, with claystone and siltstone intercalations in the upper part. Common sedimentary structures include small scale ripples, cross bedding, bioturbation, and mudcracks, as well as local sulfate nodules (Plate 1(i and k)) and record shallow subtidal to intertidal conditions and the existence of migrating oolite shoals and partly restricted lagoons (Elicki, 1992, 1999b; Buschmann et al., 1995).

Open-marine fauna are mainly represented by widespread archaeocyaths (e.g., *Dictyocathus*, *Protopharetra*, and *Erismacoscinus*) and cyanobacteria (*Epiphyton*, *Renalcis*, *Girvanella*, *Proaulopora*, *Kordephyton*, *Botomaella*, and *Subtifloria*) that often form calcimicrobial–archaeocyathan carpets and reef-mounds (Plate 1(h)) (Freyer and Suhr, 1987, 1992; Elicki and Debrenne, 1993; Elicki, 1999b; Wotte, 2004). But trilobites (*Dolerolichia*), chancelloriids (*Allonnia*, *Archiasterella*, and *Chancelloria*), and phosphatic small shelly fossils (e.g., *Halkieria*, *Torellella*, and *Cambroclavus*) have also been described (Sdzuy, 1962; Elicki, 1994). The biota are dominated by photosynthetic organisms and passive filter-feeders with an epifaunal mode of life possibly under oligotrophic conditions. Infaunal elements and deposit- and suspension-feeders are of minor significance (Elicki, 1994, 2003).

The depositional environment of the Torgau Member is interpreted as that of a carbonate-dominated subtidal ramp with calcimicrobial–archaeocyathan buildups succeeded by a shallow-subtidal to intertidal mixed ramp with peritidal sediments, oolite shoal complexes, and partly restricted areas (Elicki, 1999b). The archaeocyaths correlate with Lower Ovetian archaeocyathan zones of the Ossa-Morena Zone (SW Iberia), that are correlated by trilobites with the Middle Issendalenian of Morocco in turn, indicating a mid-Early Cambrian age of the Torgau Member (Elicki and Debrenne, 1993; Perejón, 1994; Elicki, 1997; Geyer and Landing, 1995, 2004).

The Rosenfeld Member consists mainly of alternations of limestone, dolostone, and siliciclastic sediments. In contrast with the Torgau Member, the amount of siliciclastic sediment is distinctly higher, and redeposition features such as slump structures and fining upward cycles within the carbonates are often present (Freyer and Suhr, 1987). Fossils include cyanobacteria, shelly remains, and poorly investigated redeposited archaeocyaths. The depositional environment is poorly constrained and was assigned to a deeper basinal area by Freyer and Suhr (1987), although the occurrence of coarser siliciclastic sediments might equally reflect climatic and related run-off changes under neritic conditions and/or a palaeogeographic dislocation (Elicki, 2003).

Core profiles in the Zwethau Formation locally contain sills and dikes of tholeiitic basalts and basaltic andesites and calc-alkaline andesites emplaced into incompletely lithified sediment (Plate 1(l)) (Jonas et al., 2000; Jonas and Buschmann, 2001). This, and the lack of these volcanic rocks in Middle Cambrian core profiles, suggests a late Early Cambrian age for the volcanic activity. The major and trace element geochemistry of these volcanic rocks is interpreted to record partial melting of the upper mantle beneath thinned continental crust (Jonas et al., 2000).

4.2. Middle Cambrian

The Middle Cambrian sediments of the TDS are overwhelmingly siliciclastic and carbonatic intercalations are very rare (Fig. 6) (Brause, 1970; Elicki, 1997). The succession has been poorly investigated in terms of sedimentology and palaeontology, with the exception of the trilobites (Sdzuy, 1957a,b, 1958, 1970). The latter assign the Tröbitz Formation to the Lower Middle Cambrian “*Paradoxides*” *insularis* biozone, which corresponds to the Middle Agdzian (Celtiberian) of western Gondwana (Geyer and Landing, 2004), or broadly the Lower Leonian of the Iberian scale (Fig. 7). Trilobites in the overlying Delitzsch Formation belong to the Middle Cambrian “*Paradoxides*” *insularis* to lowest *Paradoxides paradoxissimus* biozones (sensu Sdzuy, 1957a,b, 1958, 1970), which correspond to the late Agdzian to Early Caesaraugustian (Celtiberian) of western Gondwana (Geyer and Landing, 2004), and the late Leonian to Early Caesaraugustian of the Iberian scale (Fig. 7).

The Tröbitz Formation is dominated by alternating quartzitic sandstones and dark grey micaceous claystones. Several thin calcareous layers occur near to the transition to the overlying Delitzsch Formation (Brause,

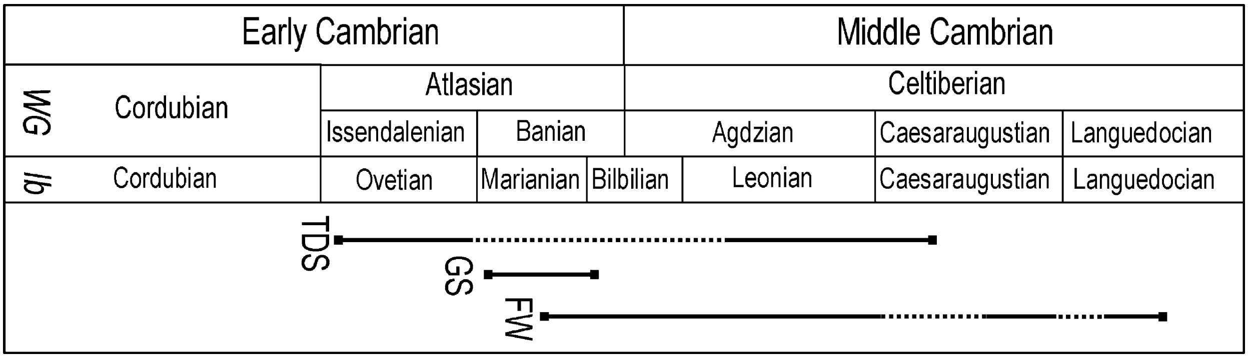

Fig. 7. Stratigraphic position of biostratigraphically well constrained Cambrian deposits of the Saxo-Thuringian Zone. WG: western Gondwana standard (sensu Geyer and Landing, 2004); Ib: Iberian scale; TDS: Torgau–Doberlug Syncline; GS: Görlitz Syncline; FW: Frankenwald area. Assignment of lower part of Frankenwald section to the late Early Cambrian is based on lithostratigraphy.

1970). Fossils include hyoliths and brachiopods (Sdzuy, 1970). The overlying Delitzsch Formation also consists of alternating quartzitic sandstones and micaceous claystones with decreasing sandstone intercalations towards the top. In contrast to that of the Tröbitz Formation, the claystones are mostly greenish and more micaceous. Small-scale sedimentary cycles of up to 10 cm thick were observed by Brause (1970), in the upper parts of which cross bedding and abundant trace fossils occur. Several thin calcareous horizons occur in the middle part of the Delitzsch Formation. Fossils include hyoliths, brachiopods, echinoderms, and helcionellids (Sdzuy, 1970). The sedimentary environment of both formations is thought to be that of a quite siliciclastic shelf area, with occasional higher energy conditions recorded in the Delitzsch Formation.

4.3. Palaeogeography, climate, and regional correlation

The facies signatures of the Early Cambrian Zwethau Formation, in particular the presence of calcimicrobial–archaeocyathan buildups, oolite shoals, and sulfate nodules in intertidal sediments, point to the presence of arid to semi-arid conditions and an equatorial to sub-equatorial depositional setting (Elicki, 1992, 1999b; Buschmann et al., 1995). This correlates well with contemporaneous sedimentary patterns in peri-Gondwanan regions such as Morocco, Spain and France (Álvaro et al., 2000b, 2003; Gubanov, 2002), and Sardinia (Bechstädt and Boni, 1989; Cocozza and Gandin, 1990; Elicki et al., 2003). A clear palaeobiogeographic relationship to Spain and Morocco is recorded by the archaeocyaths (Elicki and Debrenne, 1993), and the trilobite *Dolerolichia* is typical of the "Mediterranean" Early Cambrian (Sdzuy, 1962). Hence, the Early Cambrian strata of the TDS are considered to represent a fragment of the "Mediterranean" or European, sub-equatorial, western Gondwana shelf realm (Fig. 8).

Active Early Cambrian faunal migration, not only over the whole European shelf portion of Gondwana, but also into the northerly situated Asiatic shelf, and possibly to Kazakhstan, can be assumed from the distribution of cambroclaves (phosphatic micro-problematica) and other microfossils (Elicki, 1998; Gubanov, 1998, 2002; Vidal et al., 1999; Elicki and Wotte, 2003). In fact, the

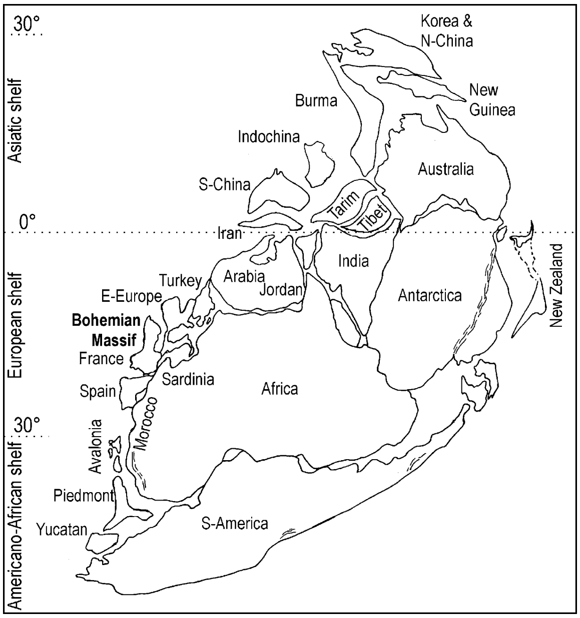

Fig. 8. Early Cambrian palaeogeography of Gondwana after Courjault-Radé et al. (1992), showing assumed positions of European shelf fragments preserved in Variscan Massifs. Saxo-Thuringian Zone is part of the Bohemian Massif.

presence of the bradoriid *Hipponicharion* in Early Cambrian deposits of the TDS may indicate intercontinental palaeobiogeographic linkages since this taxon is not only typical of Avalonia, but also of Baltica (Gozalo and Hinz-Schallreuter, 2002).

Additional palaeogeographic constraints are provided by the Early Cambrian volcanism. Alkaline basalts and rhyolites are absent in the Zwethau Formation, in contrast to the Early Cambrian volcanism recorded in Bohemia, southwestern Spain, and France (Le Gall and Cabanis, 1985; Giese and Bühn, 1993; Patočka et al., 1993; Colchen and Poncet, 1994; Doré, 1994). This atypical composition of the Early Cambrian volcanism recorded in the TDS is considered to reflect the presence of thinned continental crust in a more external setting of the western Gondwana margin (Jonas, 1999; Jonas et al., 2000).

Along the western Gondwana margin, a switch from carbonate platforms to siliciclastic deposition, and the disappearance of indicators of higher salinities occur near to the transition to the Middle Cambrian (Courjault-Radé et al., 1992; Álvaro et al., 2000a). This is attributed to southward drift into higher latitudes and related climatic changes. The lithological and trilobite record of the Middle Cambrian in the TDS correlates well with other fragments of the western Gondwana shelf, like Spain and Morocco, assumed to have experienced this drift, but also correlates with the Teplá–Barrandian, where non-marine deposits of presumed Early Cambrian age do not record arid climatic conditions (Sdzuy, 1957b; Chlupáč, 1995; Fatka and Konzalová, 1995; Kukal, 1995; Mikulás, 1995).

Other biostratigraphically dated Early and Middle Cambrian strata in the Saxo-Thuringian Zone are represented only by tectonically isolated units in the Görlitz Syncline (Charlottenhof Formation) and the Frankenwald area of Bavaria (Fig. 7) (e.g., Sdzuy, 1972; Elicki, 1997, 2003). The late Early Cambrian Charlottenhof Formation postdates the Zwethau Formation and records an evolution from carbonate ramp with open marine and restricted lagoonal environments to a predominantly siliciclastic deeper marine setting (Elicki and Schneider, 1992; Geyer and Elicki, 1995). The trilobite and microfaunal assemblages compare closely with those of Morocco, Spain, and southern France, again indicating a provenance within the European, sub-equatorial shelf realm of western Gondwana (Geyer and Elicki, 1995; Elicki, 2000). The trilobites correspond to the upper Banian stage of western Gondwana (Geyer and Elicki, 1995; Geyer and Landing, 2004). The Banian upper *Antatlasia guttapluvia* Zone of Morocco is dated at 517 ± 1.5 Ma and the upper part of the sub-trilobitic (pre-Issendalenian) Lower Cambrian of Morocco is dated at 522 ± 1 Ma (Landing et al., 1998; Geyer and Landing, 2004). This constrains the deposition of the trilobite-bearing Middle Issendalenian Zwethau Formation to ca. 520 Ma.

The Middle Cambrian strata of the Frankenwald area represent a discontinuous succession of siliciclastic sediments containing trilobites of Early to late Middle Cambrian age that are palaeobiogeographically comparable to those of the TDS (Sdzuy, 1964, 1972; Ludwig, 1969). Unambiguous Upper Cambrian deposits are not known from the Saxo-Thuringian Zone (Elicki, 1997; Linnemann et al., 2004a).

5. Discussion

Deposition of the Ediacaran rocks in the TDS is dated at 566 ± 10 Ma, whereas deposition of fossiliferous Early Cambrian rocks is estimated to have taken place at ca. 520 Ma. This suggests a gap in the record across the unconformity surface of ca. 35–55 Ma. Corresponding to onset of the Cambrian at 542 Ma, between two-thirds and one-half of the gap correspond to the late Ediacaran. The remainder corresponds to the sub-trilobitic and earliest trilobitic Early Cambrian time period. How much of this gap comprises the period of Cadomian deformation is unknown. In other parts of the Saxo-Thuringian Zone, granodioritic to granitic complexes were emplaced in folded, greywacke-dominated Ediacaran units between ca. 550 and ca. 520 Ma, but contemporaneous sediments are not preserved (Linnemann et al., 2000, 2004a,b).

Despite the incomplete Early and Middle Cambrian record in the Saxo-Thuringian Zone, both faunal assemblages and sedimentary patterns clearly show a palaeogeographic provenance in the European portion of the western Gondwana margin. The local preservation of Cambrian strata contrasts with the widespread occurrence of Early Ordovician siliciclastic sediments (Linnemann et al., 2000, 2004a,b), which show a higher degree of modal and geochemical maturity (Linnemann and Romer, 2002). This is likely related to an inversion of tectonic regime from subsidence to uplift on the western margin of Gondwana and accompanying widespread erosion under the humid climatic conditions of the Upper Cambrian (Linnemann et al., 2000, 2004a,b; Linnemann and Romer, 2002).

The geotectonic regime recorded by the Early and Middle Cambrian of the Saxo-Thuringian Zone is difficult to constrain. The character of the sedimentary and volcanic rocks suggests a subsidence and crustal extension in a passive continental margin setting. However, the proposed anticlockwise rotation of the western Gondwanan margin from equatorial to higher southerly latitudes during the Cambrian implies the likelihood of a transform regime on this continental margin (Courjault-Radé et al., 1992; Álvaro et al., 2000a). A transform margin setting has also been proposed to account for the Early Cambrian cessation of Cadomian subduction in the Avalonian–Cadomian belt (Nance et al., 1991).

In contrast to other Early Cambrian fragments of the European margin of Gondwana, like those of Bohemia, France, and southwestern Spain, the late Early Cambrian volcanism in the TDS does not include alkaline basalts and rhyolites (e.g., Le Gall and Cabanis, 1985; Giese and Bühn, 1993; Patočka et al., 1993; Doré, 1994). This is interpreted to reflect enhanced crustal extension in a transtensional and/or a more external shelf domain (Jonas, 1999; Jonas et al., 2000). It remains unclear, however, whether relics of the Early and Middle Cambrian shelf succession of western Gondwana in the Saxo-Thuringian Zone represent pull-apart depocentres with enhanced subsidence rates, which would have favoured their preservation during Late Cambrian erosion. Cambro-Ordovician pull-apart basins on the Gondwana shelf are described from the western Avalonian margin (Keppie and Murphy, 1988). The high degree of regional faunal exchange recorded by the Early and Middle Cambrian fossil assemblages of the European margin suggests a persistent shelf regime that was not dissected into isolated transtensional basins. This agrees with records from the western Avalonian margin showing successive flooding and faunal connections to a larger ocean during the Early Cambrian transgression (e.g., Keppie and Murphy, 1988; Tanoli and Pickerill, 1990).

6. Conclusions

The fundamental palaeobiological, palaeogeographic, and climatic changes of the Precambrian–Cambrian transition are not recorded in the sedimentary strata in the Saxo-Thuringian Zone, because of the latest Ediacaran to earliest Cambrian Cadomian orogenic overprint. Nevertheless, the most constrained record of these changes is provided in the TDS by the unconformable relationship between the Late Ediacaran Rothstein Formation and the mid-Early Cambrian Zwethau Formation. This Cadomian unconformity is estimated to represent a time gap of less than 55 Ma.

The palaeogeographic signature of the Ediacaran Rothstein Formation reveals affinity with the West African portion of the Avalonian–Cadomian belt in common with other Ediacaran units of the Saxo-Thuringian and Teplá–Barrandian zones as well as the northern Armorican Massif and southwest Iberia (Gutiérrez-Alonso et al., 2003; Linnemann et al., 2004b, and references therein). The palaeogeographic affinity of the overlying Early Cambrian Zwethau Formation likewise links it to the European portion of the western Gondwana margin, in particular to southwest Iberia and Morocco. It is therefore unlikely that the Ediacaran rocks experienced significant geographic displacement along this margin during the Late Ediacaran and Early Lower Cambrian.

The abrupt change in sedimentary regime between the Ediacaran and Early Cambrian in the TDS is related to a switch from an active continental margin setting and a likely cold and humid climate in the Ediacaran to a marine transform margin under warm and arid conditions in the Early Cambrian. This suggests northward drift of the West African margin of Gondwana into subequatorial southerly latitudes in the Early Cambrian. The striking changes in the faunal complexity and organization between the Ediacaran and the Early Cambrian are the result of the "Cambrian radiation". Consistent with contemporary global evolutionary patterns, the Early Cambrian strata in the TDS record a complex photosynthetic and filter-feeder dominated trophic ecosystem that additionally included suspension- and deposit-feeders, scavengers, and probable predators represented by a highly diverse shelly fauna and intensely bioturbated siliciclastic horizons.

Q&A section

Nance: To what extent might the composition of the sills and dykes in the Early Cambrian strata reflect the nature of the basement rather than the tectonic setting of the volcanism?

Answer by Buschmann et al.:

Our knowledge of composition of sills and dykes in Early Cambrian strata of the Torgau–Doberlug Syncline is based on petrographic studies and major and trace element analyses of whole rock samples showing the presence of tholeiitic basalts and basaltic andesites and calc-alkaline andesites (Jonas, 1999; Jonas et al., 2000; Jonas and Buschmann, 2001). The tholeiitic basalts that are to be considered as derivates of partial mantle melts. Their geochemical signatures indicate that the influence of basement on composition appears to be largely restricted to the thickness of the lithospheric cap. Trace element patterns normalized to N-MORB are most similar to the within plate tholeiitic basalt pattern after Pearce (1996) although elements with higher incompatibility such as Th, U, Nb, Ta, and Zr are less enriched.

Concentrations of Ytterbium and heavy rare earth elements (REE) are at or slightly above the N-MORB value after Pearce (e.g., 1996) or Sun and McDonough (1989) and Ti/Y ratios are comparable to those of N-MORB. Samples of tholeiitic basaltic andesite composition are considered as fractionation derivates of tholeiitic basaltic melts.

Samples of calc-alkaline andesites display N-MORB-normalized patterns with concentrations of Y and heavy REE at or slightly above the N-MORB value, but pronounced negative Nb, Ta, and Eu anomalies, as well as distinct enrichments in Ba, Th, and U compared to samples of tholeiitic basalts. It is not clear, whether the calc-alkaline andesites record crustal contamination of tholeiitic basaltic melts or tapping of mantle that trapped metasomatic domains derived from late Cadomian subduction processes. However, the high N-MORB-normalized abundances of Y and heavy REE in sills and dykes of different geochemical compositions suggest shallow mantle melting above the garnet lherzolite stability field, whereas incompatible element concentrations in tholeiitic basalt samples indicate minor source enrichment. In context with the geological framework, this points to an attenuated continental lithosphere setting of the late Early Cambrian volcanism.

Murphy: You describe a 35–55 million year gap in the record across the unconformity surface. Your data and reconstructions imply linkages with France (Armorica) and Spain during much of this time period. Do these successions fill in any of the 'gap' and if so, what do they reveal?

Answer by Buschmann et al.:

Sedimentary deposition from Late Ediacaran to trilobitic Early Cambrian time is recorded by stratigraphic patterns and fossils in the Central Iberian Zone (e.g., Valladares et al., 2002; Linan et al., 2002). Successions display marine to terrestrial sedimentation patterns with slump horizons, erosional disconformities and local volcanism attributed to an immature passive margin or pull-apart basin regime (Rodríguez-Alonso et al., 2004). The sub-trilobitic Early Cambrian (Cordubian) profiles display predominantly siliciclastic deposition with transition to carbonatic shelf environment in the Issendalenian suggesting climatic warming up during the Early Cambrian. This applies to successions elsewhere in Iberia, where Cordubian sediments rest unconformably on metamorphosed Cadomian complexes. However, provenance data of Neoproterozoic and Cambrian sediments suggest contrasting sources and palaeogeographic affinities for central and northwest Iberia (recycled orogen source, Avalonian affinity) and southwest Iberia (Ossa-Morena Zone, magmatic arc source, Cadomian affinity) (Valladares et al., 2000; Gutiérrez-Alonso et al., 2003). The latter correlate with the North Armorican domain of France (Fernández-Suárez et al., 2002).

In France, Cordubian sediments resting unconformably on Cadomian basement are apparently present in the southern Massif Central and the northern domain of the Armorican Massif (e.g., Keppie, 1994, and references therein). The first probably correlate with complexes of NW Iberia. In the Armorican Massif, sedimentary deposition in Cordubian time is indicated by predominantly siliciclastic littoral sediments containing trace fossils followed higher in section by small shelly fossils and overlapping shallow marine strata with carbonates containing 'old' archaeocyaths and the trilobite *Bigotina* (Doré, 1994). The succession commences with conglomerates covering unconformably Cadomian batholite rocks or conformably ignimbritic rhyolites with absolute ages not excluding commencement of post-Cadomian siliciclastic sedimentation in the latest Ediacaran (Chantraine et al., 1994; Doré, 1994, and references therein).

Hence, the latest Ediacaran to Early Cambrian record of France and Iberia corresponding to the 'gap' in the Saxo-Thuringian Zone shows erosion of the Cadomian belt and local, terrestrial volcanism followed by marine transgression dominated by siliciclastic deposition and transition to shallow neritic carbonate environment. The earlier onset of transgression in the record of NW Iberia might point to earlier closure of orogeny in parts of the Avalonian province of the Avalonian–Cadomian belt.

Late Cadomian orogenic processes recorded by folding of Cadomian flysch and subsequent emplacement of anatectic plutons in the latest Ediacaran to early Lower Cambrian of the North Armorican domain and the Ossa-Morena Zone correlate closely to the record of the Saxo-Thuringian Zone (Keppie, 1994, and references therein; Eguíluz et al., 2000; Linnemann and Romer, 2002). However, late Neoproterozoic unconformities between Cadomian successions such as in Spain and France are not recognized in the Saxo-Thuringian Zone.

Linnemann: Cadomian unconformity is a local name. Why don't you use Pan African orogeny?

Answer by Buschmann et al.:

The Pan African or Pan African–Brasiliano orogeny (720–550 Ma) shaped Neoproterozoic Gondwanaland supercontinent accretion and is recorded by Neoproterozoic mobile belts suturing Archaean–Palaeoproterozoic cratons particularly in the interior of West Gondwanaland (e.g., Unrug, 1996). Although Cadomian and Avalonian terranes record contemporary orogenic events (700–540 Ma), collisional orogenesis is not evident and palaeogeographic features indicate peripheral setting with respect to the African–South American margin of Gondwanaland from Late Neoproterozoic to Early Palaeozoic time (Murphy and Nance, 1989, 1991; Nance et al., 1991; Keppie et al., 2003). By following the concept of Murphy, Nance and co-workers, we favour a nominal distinction between 'Avalonian–Cadomian' and 'Pan African' in view of contrasting orogenic styles and palaeogeographic settings displayed by interior collisional Pan African–Brasiliano belts and the peripheral Avalonian–Cadomian province of Gondwanaland. The double-barrelled name 'Avalonian–Cadomian' necessitates maintenance since it reflects contrasting basement isotopic signatures and different palaeobiogeographic affinities of fauna in Early Cambrian overstep successions between Avalonian and Cadomian terranes (Nance and Murphy, 1994; Linnemann et al., 2004).

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