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 osolite shoal complexes, and (iii) a more siliciclastic depositional environment. Calcimicrobial–archaeocyathan buildups, osolite 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 palaeontological, palaeogeographic, and climatic change that marks the Precambrian–Cambrian transition.

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1. Introduction

Ediacaran (terminal Neoproterozoic) 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 sediments 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 the Teplá–Barrandian Zone (Fig. 1) (Chlupaˇc, 1993; Kˇr´ıbek et al., 2000; Drost et al., 2004). However, probable Early Cambrian strata in this region are predominantly terrestrial siliciclastic deposits with rare endemic fauna (Havl´ıˇcek, 1971; Kukal, 1971; Chlupaˇc, 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.

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; Nölkeke, 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 plutonic complex in the buried Delitzscht 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.

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 microbacteria. However, the imprint of pyrite growth on the organic matter precludes taxonomic assignment. Organic walled microbacteria with processes at the surface (Acanthomorphs) were not observed. The observed microfossil assemblage is considered broadly compara-
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 palaeobiotically 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.

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 anodesites to ryhodacites/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 anodesites (authors’ unpublished data). This suggests the volcanic ash in the tuffaceous layers was derived from basaltic andesite to andesite in the Ediacaran Rothstein Formation and g–l the Early Cambrian Zwethau Formation.

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 cm. (a) Alternations of greywacke, siltstone, and mudstone. Arrows mark flame-like structures on top of internally liquidated greywacke. Borehole 1634/80, 641.5 m. Sample 1634/61-2. (b) Small basaltic pillow (P) surrounded by chloritized glass (G)/H9262. (c) Subvolcanic basaltic andesite sill with variolitic centre and chilled margins against dark silty greywacke. 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.

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, 1983). See Table 1 for analytical data.

Fig. 4. Multielement patterns for three samples from tuffaceous layers considered to be rich in volcanic ash. The samples have negative Nb and Ti anomalies compared to N-MORB but are consistent with intraformational volcanic rocks of the Rothstein Formation.

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Table 1

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| 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      | 905    | 932    | 496    |        |      |
| Sr 1  | 68       | 48     | 33     | 37     |        |      |
| Ta 1  | 0.69     | 0.48   | 0.90   | 0.81   |        |      |
| Nb 5  | 10.5     | 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  | 5.16     | 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   | 1.80   |      |
| Lu 2  | 0.46     | 0.59   | 0.67   | 0.32   | 0.31   |      |

^a Fe₂O₃ 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 extrabasinal 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...
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. Götz, 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 (Buschmann et al., 2001). 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
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 Trobitz 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...
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 carbonate successions or intertidal siliciclastic mudstones.

The Torgau Member consists of fossiliferous oolitic and intraclastic limestones and dolostones, with claystone and silstone 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. 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(i)) (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, which 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 (Sdany, 1957a,b, 1958, 1970), which correspond to the late Agdzian to Early Caesaraugustian (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” 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 (Senus Sdany, 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).
Fossils include hyoliths and brachiopods (Sdzuy, 1970). The overlying Delitzsch Formation also consists of alternating quartitic 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 micaeous. 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 (Alvaro et al., 2000b, 2003; Gubanov, 2002), and Sardinia (Bechstäd and Boni, 1989; Ciccuza and Gandin, 1990; Elicki et al., 2003). A clear palaeobiogeographic relationship to Spain and Morocco is recorded by the archaeocyaths (Elicki and Debrène, 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
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 palaeobiogeographic 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. How-
ever, 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-Rade et al., 1992; Alvaro 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; Grese and Bühn, 1993; Patocka et al., 1993; Dott, 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; Limennan 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 sub-equatorial 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 siliceous 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 derivatives 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 basaltic 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 unconformities 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 northern Europe, the Iberian Peninsula, 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.:

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...
Palaeozoic time (Murphy and Nance, 1989, 1991; Nance of Gondwanaland from Late Neoproterozoic to Early 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–Braziliano belts and the peripheral Avalonian–Cadomian province of Gondwanaland. The double-barreled 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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References

Brook Formation), Saint John area, southern New Brunswick.