Ediacaran rocks from the Cadomian basement of the Saxo-Thuringian Zone (NE Bohemian Massif, Germany): age constraints, geotectonic setting and basin development

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Ediacaran rocks from the Cadomian basement of the Saxo-Thuringian Zone (NE Bohemian Massif, Germany): age constraints, geotectonic setting and basin development

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Abstract: This paper is focused on a compilation of known data from the low-grade metamorphosed rocks of the Ediacaran period in the German part of the Saxo-Thuringian Zone at the northeastern margin of the Bohemian Massif. The geotectonic setting during the formation of Ediacaran rock units is characterized by Cadomian orogenic processes from *c.* 650–540 Ma at the periphery of the West African Craton. The basin development during that time is characterized by the formation of a Cadomian backarc basin with a passive margin, and the outboard sitting Cadomian magmatic arc originated at *c.* 570–560 Ma. This arc-marginal basin system was formed on stretched continental crust in a strike-slip regime and reflects an active-margin setting in a style similar to the recent West Pacific. The backarc basin was closed between *c.* 560–540 Ma by the collision of the Cadomian magmatic arc with the cratonic hinterland: this resulted in the closure of the backarc basin and the formation of a Cadomian retroarc basin. Collision of an oceanic ridge with the Cadomian Orogenic Belt led to a slab break-off of the subducted oceanic plate resulting in an extreme heat flow, and a magmatic and anatectic event culminating at *c.* 540 Ma that was responsible for the intrusion of voluminous granitoid plutons.

Ediacaran rock complexes in Germany are restricted to the Saxo-Thuringian Zone in the Bohemian Massif, which represents the largest and most important basement inlier of the Central European Variscides (Fig. 1). Low-grade Ediacaran metamorphic rocks occur mainly in the Saxo-Thuringian Zone (Germany) and the Tepla-Barrandian Unit (Czech Republic) (Fig. 2). This paper presents a review on the weakly metamorphosed Ediacaran to Early Cambrian rocks of the Saxo-Thuringian Zone. These rocks units are affected by the tectonometamorphic overprint of the Late Neoproterozoic–Early Cambrian Cadomian and the Late Devonian–Early Carboniferous orogenies. In some areas of the Saxo-Thuringian Zone, such as the Erzgebirge Mountains, some of the rocks display a high-grade metamorphic overprint. These rocks are not discussed in this paper.

Cadomian orogenic processes comprise a series of complex sedimentary, magmatic, and tectonometamorphic events that spanned the period from the mid-Neoproterozoic (*c.* 650 Ma) to the earliest Cambrian (*c.* 540 Ma) (e.g. Linnemann *et al.* 2000; Nance *et al.* 2002). Rock units formed by the Cadomian orogeny are generally referred to as 'Cadomian basement'. Due to very similar contemporaneous orogenic processes in the Avalonian microplate, the collective term 'Avalonian-Cadomian' orogeny has often been used in the modern literature (e.g. Dörr *et al.* 2004). Peri-Gondwanan terranes, microcontinents and crustal units in Europe and in North Africa are affected by the Cadomian orogeny (e.g. Murphy *et al.* 2004). Related orogenic events, such as the Avalonian orogeny, are known in the Appalachians (eastern US and Atlantic Canada), and from the non-Laurentian part of Ireland and the British Isles (e.g. Nance & Murphy 1996). Baltica escaped the Avalonian-Cadomian orogenic activity, although the 'Cadomian affinity' of the late Precambrian orogenic events in the Urals and in the Timanides on the periphery of Baltica was recognized (Roberts & Siedlecka 2002; Glasmacher *et al.* 2004).

The Cadomian orogeny was first defined in the North Armorican Massif in France on the basis of the unconformity that separates deformed Precambrian rock units from their Early Palaeozoic (Cambro-Ordovician) overstep sequence (Bunel 1835; Dufrenoy 1838; Barrois 1899; Kerforne 1901). 'Cadomus' is an old Latin term for the modern city of Caen and is the source of the name of the orogeny. The term 'discordance cadomienne' was first used by Bertrand (1921). The best illustration of the unconformity in Rocreux (Normandy) was published by Graindor (1957). In Central and Western Europe the unconformity is commonly referred to as the 'Cadomian unconformity'. It is possible that the youngest metasedimentary rocks

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affected by the Cadomian deformation are earliest Cambrian in age. Many geologists assume that the final stages of Cadomian orogenesis were spatially diachronous, lasting from the latest Neoproterozoic to the earliest Cambrian. From this viewpoint the term 'Cadomian basement' includes Neoproterozoic (Ediacaran) to Early Cambrian sedimentary, igneous and metamorphic complexes. The stratigraphic range of the involved rock complexes changes from region to region.

In some publications, the term 'Pan-African orogeny' is used in the same sense as Cadomian orogeny, because both events were related to the Gondwana supercontinent in the late Precambrian and occurred more or less in the same time interval. The main difference between the Cadomian and Pan-African orogenic events is their position within the configuration of the Gondwana supercontinent in Neoproterozoic time. The crustal units affected by the Pan-African orogeny are located between the cratons assembling Gondwana and reflect continent–continent collision, at least in most cases (e.g. compilation of Windley 1996). In contrast, the Cadomian orogen or, alternatively, the Avalonian-Cadomian orogenic belt is a peripheral orogen at the edge of the Gondwanan supercontinent and was characterized by orogenic processes similar to those presently observable in the Andes and the Cordilleran chains of the American continents and in the West Pacific Region (Murphy & Nance 1991; Nance & Murphy 1994; Buschmann 1995; Linnemann *et al.* 2000; Nance *et al.* 2002; Linnemann *et al.* 2004).

Provenance studies including: (1) U/Pb-ages of detrital zircon grains from sedimentary rocks and inherited zircons from igneous rocks; (2) Nd–Sr–Pb isotope; and (3) palaeomagnetic and palaeobiogeographic data, suggest that the origin of the Cadomian basement of Central and Western Europe was at the periphery of the West African craton of Gondwana (e.g. Linnemann *et al.* 2004; Murphy *et al.* 2004).

Remnants of the old cratonic basement derived from the cratonic source areas are represented by the Icartian basement (2.01–2.06 Ga) in the Armorican massif, and the Svetlik gneiss (2.05–2.1 Ga) and the Dobra gneiss (1.38 Ga) in the Bohemian Massif. In view of the occurrence of these rock complexes, and many Archaean and Palaeoproterozoic detrital zircons in Neoproterozoic sedimentary rocks, it seems that most of the Cadomian basement had developed on a stretched and thinned old cratonic crust, from which cratonic material was available for erosion and deposition into basins and also for the incorporation of large blocks from the basement into the Cadomian orogen.

Nance *et al.* (2002) proposed a Cordilleran model for the evolution of the Neoproterozoic to Cambro-Ordovician rock complexes in Avalonia that was a part of the 'Avalonian-Cadomian orogenic belt' on the periphery of the Gondwana supercontinent during the Neoproterozoic and the Early Palaeozoic. This model uses the North American plate at Baja California as a modern analogue to explain the plate-tectonic setting, including terrane accretion, subduction-related processes, ridge-trench collision and rifting.

The impact of the Variscan orogeny during the closure of the Rheic Ocean in Devonian and Carboniferous times resulted in a penetrative overprinting and recrystallization of the Cadomian basement rocks and of their structures in many areas during Pangea amalgamation. Therefore, this compilation is focused on the Saxo-Thuringian Zone at the periphery of the Bohemian Massif, which is less affected by younger orogenies. This zone contains a number of the best-preserved and most representative Ediacaran rock complexes in the Cadomian basement of Central Europe.

The Precambrian of the Bohemian Massif

The Bohemian Massif is bounded to the north and the NE by the Mid-German Crystalline zone, which most likely represents the suture formed during the closure of the Rheic Ocean in the Late Devonian to Early Carboniferous period. To the south and SE the Bohemian Massif is covered by the Meso-Cenozoic orocline of the Alps and the Carpathians. Steeply dipping faults in the SW, such as the Franconian Line and the Danube Fault, divide the basement rocks from Mesozoic platform sediments and the Alpine molasses (Fig. 1).

The Bohemian Massif represents the most prominent inlier of basement rocks in Central Europe that underwent a long geological history from Cadomian orogenic processes to the core of the Variscan Orogen in the Central European Variscides. Some of the marginal units and inliers contain very weak metamorphosed and deformed Ediacaran to Palaeozoic rock complexes. Good examples are the western and northern parts of the Saxo-Thuringian Zone and the Tepla-Barrandian Unit (Fig. 1).

The Bohemian Massif is generally interpreted as a part of Armorica (Van der Voo 1979). Tait *et al.* (1997, 2000) suggested that Armorica drifted across the Rheic Ocean during Ordovician to Devonian times. In contrast, the interpretation of palaeobiogeographical, geochronological, geochemical and sedimentological data led to the conclusion that Armorica never left Gondwana mainland in pre-Pangean time (Robardet 2002; Linnemann *et al.* 2004). The Cadomian basement of the Armorican Massif, the French Central

Massif and the Bohemian Massif, excepting the Brunovistulian in the Moravo-Silesian Zone, is summarized as 'Cadomia' (Nance & Murphy 1996; Murphy *et al.* 2004). Studies of U/Pb-ages from detrital zircon grains have suggested that the Saxo-Thuringian Zone, the Tepla-Barrandian Unit and the Moldanubian Zone of the Bohemian Massif show a West African provenance (Linnemann *et al.* 2000, 2004; Gehmlich 2003; Tichomirowa 2003; Drost *et al.* 2004). These units are believed to be a part of Cadomia *sensu* Murphy *et al.* (2004). One old basement sliver from the Cadomia part of the Bohemian Massif is represented by the *c.* 2.1 Ma old Svetlik gneiss (Wendt *et al.* 1993), which probably was a part of the West African Craton.

According to Finger *et al.* (2000) the Brunovistulian in the Moravo-Silesian Zone may represent a part of Avalonia. For that part in the Bohemian Massif, an Amazonian provenance is suggested at the base of the age cluster of magmatic and inherited zircon grains (Friedl *et al.* 2000). A cratonic inlier related to Avalonia is represented by the 1.38 Ma old Dobra gneiss (Gebauer & Friedl 1994; Friedl *et al.* 2004).

Ediacaran rock units of the Saxo-Thuringian Zone

The Saxo-Thuringian Zone was defined by Kossmat (1927) and is situated in the northeast region of the Bohemian Massif (Fig. 1). To the north, the Saxo-Thuringian Zone is separated by the Mid-German Crystalline Zone from the Rheno-Hercynian Zone (Fig. 2). The bounding element to the SW is the Franconian Line, which is a relatively young fault system originated during Mesozoic to Cenozoic reactivation of the crust. A continuation of the Saxo-Thuringian Zone to the west, up into the northern parts of the Black Forest and the Vosges, is suggested by many authors. To the south, the fault system representing the boundary to the Moldanubian zone is mostly hidden by Tertiary sediments of the Ohre Graben. In its eastern part the Saxo-Thuringian Zone continues into the eastern part of the Sudetes (Fig. 2).

Important and dominant structures of the Saxo-Thuringian Zone are represented by the Schwarzburg, North Saxon, Berga and Lausitz Antiforms, the Torgau-Doberlug and the Ziegenrück-Teuschnitz Synclines and the Elbe Zone (Fig. 2).

Zircon dating has shown that Ediacaran rocks in the Cadomian Basement of the Saxo-Thuringian Zone are generally not older than *c.* 570 Ma (Linnemann *et al.* 2000, 2004). The sections are rootless in the lower part and fault-bounded. Older Precambrian basement rocks are not known. In the upper part, Ediacaran rocks, except for the Schwarzburg antiform, are unconformably overlain by Cambro-Ordovician sedimentary rocks. This unconformity in the Saxo-Thuringian Zone is interpreted as the Cadomian unconformity, and was first recognized in the drill core of the deep drilling 5507/77 near Gera (Linnemann & Buschmann 1995*a*, *b*). In that core, steeply dipping Ediacaran rocks of the Leipzig Formation are overlain by sub-horizontal Early Ordovician quartzites (Linnemann & Buschmann 1995*a*). Later, the unconformity between Late Ediacaran sediments of the Rothstein Formation and Lower Cambrian sedimentary rocks is described from the drill core 1614/79 from the Torgau-Doberlug Syncline (Buschmann *et al.* 2006).

The Ediacaran rocks and the rest of the Cadomian basement are divided into an internal and an external domain (Figs 2 & 3). The external zone is composed of Ediacaran volcano-sedimentary units (Rothstein Formation in the Torgau-Doberlug Syncline and Altenfeld Formation in the NW part of the Schwarzburg Antiform). Both are characterized by massive black chert units (Figs 3, 5a), and are assumed to be originated in a backarc setting (Buschmann 1995; Linnemann *et al.* 2000). The sediments include dark-grey to black distal turbidites, with greywacke and mudstone bedsets. The Rothstein Formation is overlain by Lower to Middle Cambrian sediments, whereas the Altenfeld Formation is covered by Lower Ordovician siliciclastics. In contrast to the internal domain, no extensive plutonism is known at *c.* 540 Ma in the external domain. Only one very small granitoid body of uncertain age, represented by the Milchberg Granite, was intruded into the Altenfeld Formation. Another important part of the external domain is the Vesser complex, which is Middle to Upper Cambrian in age. This unique complex is characterized by mid-ocean ridge-related rocks (Bankwitz *et al.* 1992).

The boundary between the external and the internal domains is represented by the Blumenau Shear Zone, dividing the Schwarzburg Antiform into a NW and a SE region (Fig. 2). In this paper, the Blumenau Shear Zone is interpreted as a structural feature that most probably formed during the Cadomian Orogeny, during the transition between backarc basin and retroarc basin (Fig. 10). During Variscan orogenic processes, the Blumenau Shear Zone was reactivated into a sinistral shear zone (Heuse *et al.* 2001).

The internal domain of the Saxo-Thuringian Zone contains sedimentary units from two different Ediacaran basin types. It is characterized by voluminous Cadomian plutons intruded at *c.* 540–530 Ma, and a very thick and widespread Ordovician overstep sequence. Cambrian deposits are very rare

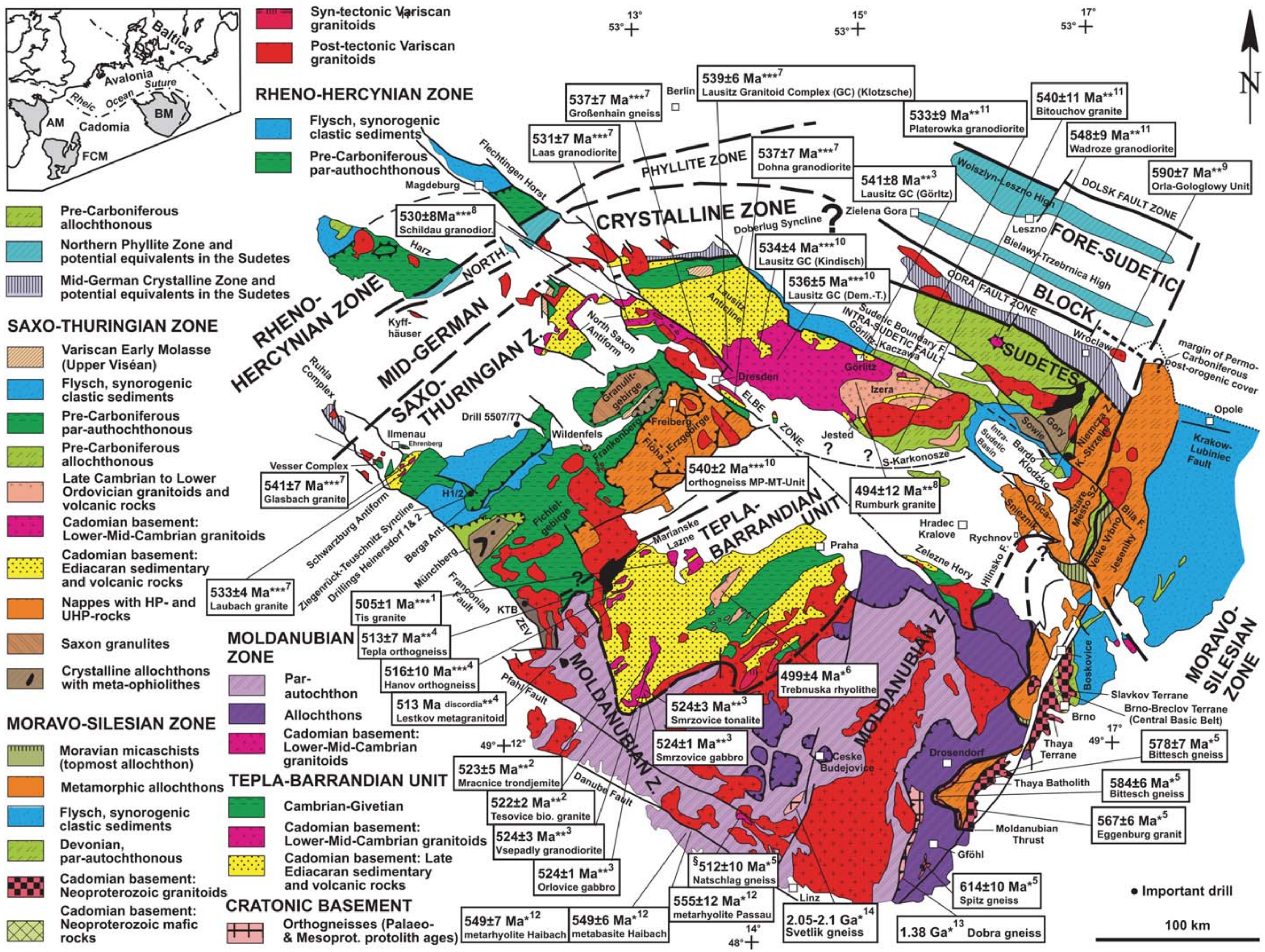

Fig. 1. Geological map of the Bohemian Massif showing the Cadomian orogenic imprints and cratonic slivers in the Variscan basement, the published ages of plutons and volcanic rocks related to pre-Cadomian, Cadomian and Cambro-Ordovician geotectonic processes and the opening of the Rheic Ocean (modified after Linnemann & Schauer 1999; Kozdrój *et al.* 2001; Franke & Żelaźniewicz 2002). Sources of geochronological data: 1, Venera *et al.* 2000; 2, Zulauf *et al.* 1997; 3, Dörr *et al.* 2002; 4, Dörr *et al.* 1998; 5, Friedl *et al.* 2004; 6, Drost *et al.* 2004; 7, Linnemann *et al.* 2000; 8, Hammer *et al.* 1999; 9, Mazur *et al.* 2004; 10, Tichomirowa 2003; 11, Żelaźniewicz *et al.* 2004; 12, Teipel *et al.* 2004; 13, Gebauer and Friedl 1994; 14, Wendt *et al.* 1993. (*, U/Pb-SHRIMP; **, U/Pb TIMS; ***, Pb/Pb TIMS; §, age of the youngest concordant zircon of the Natschlag gneiss; Lausitz GC, Lausitz Granitoid Complex). Inset: Location of the prominent massifs of Cadomia containing Ediacaran rocks: BM, Bohemian Massif; AM, Armorican Massif; FCM, French Central Massif.

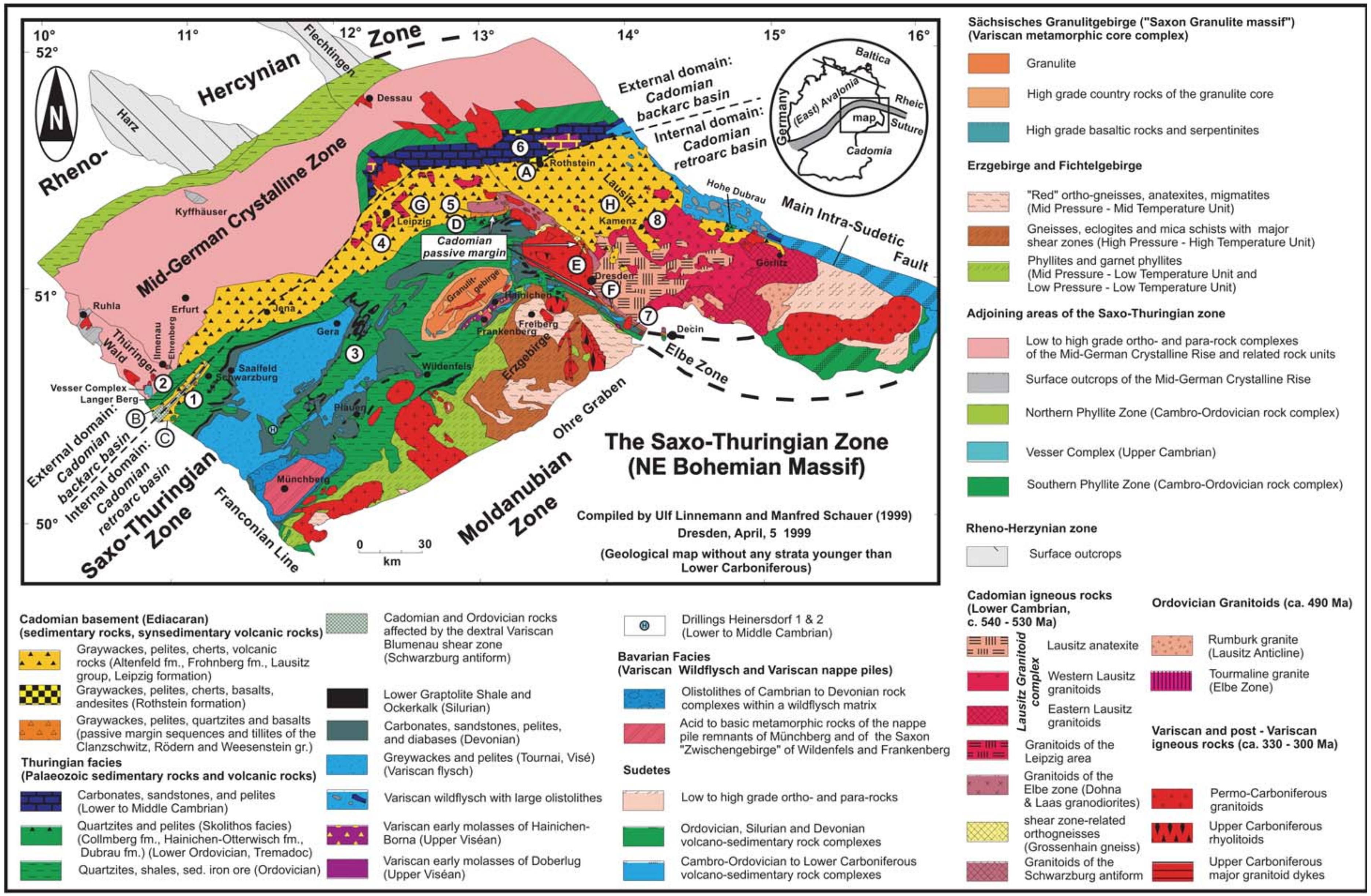

Fig. 2. Geological map of the Saxo-Thuringian Zone in the NE part of the Bohemian Massif, showing Lower Carboniferous and older strata only, and the principal distribution of fragments from different stages of Cadomian basin development (modified from Linnemann & Schauer 1999; Linnemann & Romer 2002). Tectonostratigraphic units: 1, Schwarzburg Antiform (SE-part); 2, Schwarzburg Antiform (NW-part); 3, Berga Antiform; 4, North Saxon Antiform (Leipzig area); 5, North Saxon Antiform (Clanzschwitz area); 6, Torgau-Doberlug Syncline; 7, Elbe Zone; 8, Lausitz Antiform. Neoproterozoic volcano-sedimentary complexes: (**A**) Rothstein formation; (**B**) Altenfeld formation; (**C**) Frohnberg formation; (**D**) Clanzschwitz group; (**E**) Rödern group; (**F**) Weesenstein group; (**G**) Leipzig formation; (**H**) Lausitz group.

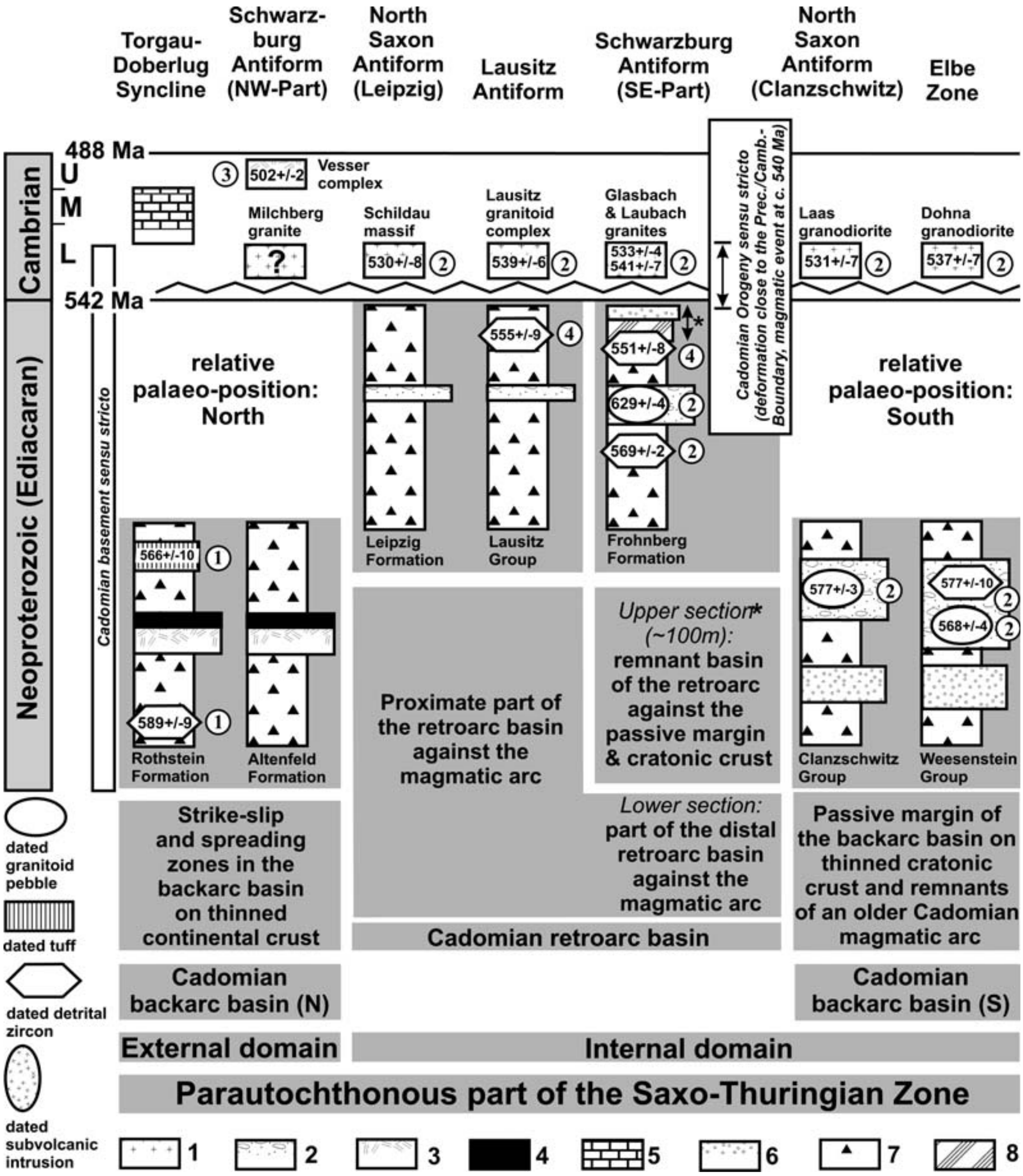

Fig. 3. Generalized lithosections, geotectonic setting and published geochronological data of the Cadomian basement and parts of its Cambrian overstep sequence in the Saxo-Thuringian Zone. Legend: 1, Cadomian granitoids of the magmatic event at *c.* 540 Ma; 2, Ediacaran diamictites; 3, igneous rocks and meta-sediments of the Upper Cambrian Vesser complex (predominatly mafic rocks); 4, Ediacaran hydrothermal cherts; 5, Lower to Middle Cambrian sediments; 6, conglomerates, quartzites and quartzitic shales of the Purpurberg Quartzite in the Weesenstein Group, and its equivalent in the Clanzschwitz group; 7, greywackes and mudstones; 8, predominantly mudstones. Sources of geochronological data (encircled numerals): 1, SHRIMP U/Pb (Buschmann *et al.* 2001); 2, TIMS Pb/Pb (Linnemann *et al.* 2000); 3, TIMS U/Pb (Kemnitz *et al.* 2002); 4, SHRIMP U/Pb (Linnemann *et al.* 2004).

and restricted to the drillings Heinersdorf 1 and 2 in the Berga Antiform. In addition, Cambrian rocks became known from large olistoliths in a Lower Carboniferous flysch matrix in the Görlitz Synform.

One basin type in the internal domain is represented by passive margin sequences characterized by high mature quartzites, sandstones and quartz-rich shales deposited in a shallow marine environment (Figs 2 & 10). The most prominent deposit of this type is represented by the Purpurberg Quartzite in the lower part of the Weesenstein Group (Fig. 4). A facies analysis of the Purpurberg Quartzite has shown that this deposit displays a fan shape, an upward increase in bed thickness, and sedimentary structures typical of shallow water deposits, such as cross-bedding and ripple-marks

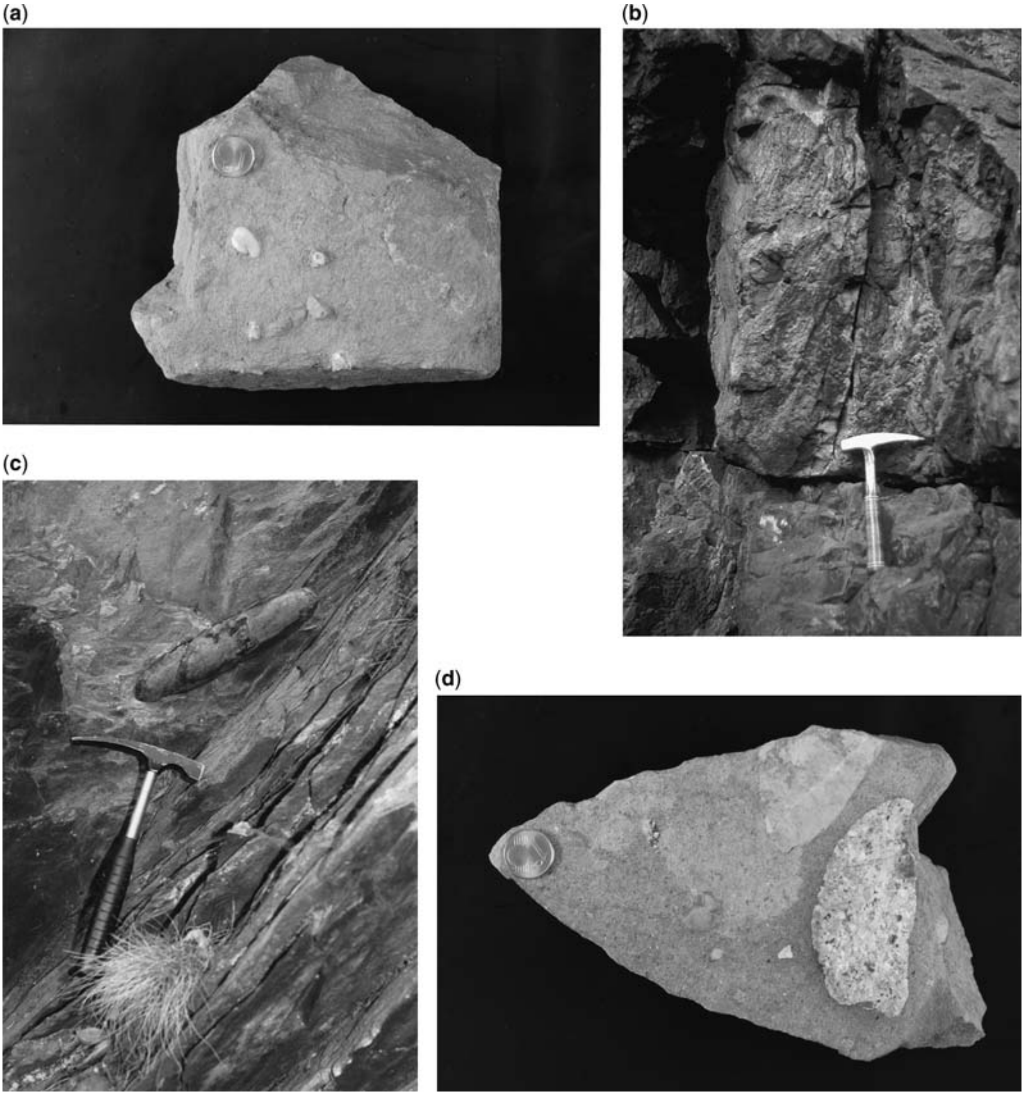

Fig. 4. Photographs of Ediacaran rocks in the Cadomian backarc basin (Saxo-Thuringian Zone, Bohemian Massif): (**a**) Hand specimen of a diamictite of possible glaciomarine origin with out-weathered fragments from the upper Weesenstein Group (Ediacaran, *c.* 570 Ma, Weesenstein Group, 100 m to the east of the Weesenstein Railway Station, Cadomian basement of the Elbe zone); (**b**), Steeply dipping bed of the Purpurberg quartzite with internal cross bedding and ripple marks. The quartzite occurs in the lower part of the Weesenstein Group, which represents the passive margin of the Cadomian backarc basin (Ediacaran, *c.* 570 Ma, Weesenstein Group, Purpurberg near Niederseidewitz, Cadomian basement of the Elbe zone); (**c**) Stretched granitoid pebble from a diamictite in the upper part of the Weesenstein Group. The pebbly mudstone facies of the Weesenstein Group is interpreted to be in part glaciomarine (Ediacaran, *c.* 570 Ma, Weesenstein group, 100 m to the east of the Weesenstein Railway Station, Cadomian basement of the Elbe zone); (**d**) Polished handspecimen of a diamictite of possible glaciomarine origin from the upper Weesenstein Group (Ediacaran, *c.* 570 Ma, Weesenstein Group, 100 m to the east of the Weesenstein Railway Station, Cadomian basement of the Elbe zone).

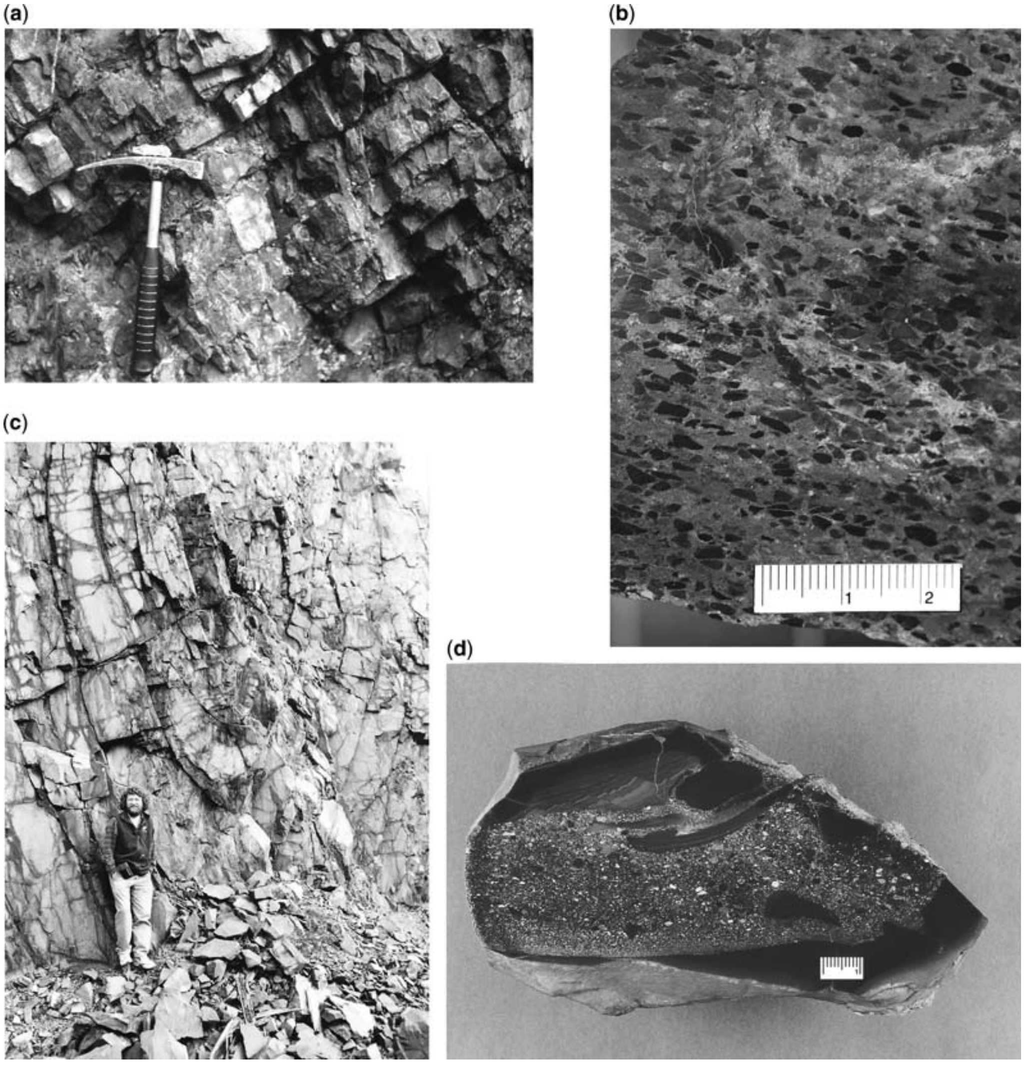

Fig. 5. Photographs of Ediacaran rocks in the Cadomian retroarc basin (Saxo-Thuringian Zone, Bohemian Massif): (**a**) Black cherts at the Rothstein Rock originated close to spreading zones in the Cadomian backarc basin (Ediacaran, *c.* 566 Ma, Rothstein Formation, Cadomian basement of the Torgau-Doberlug Syncline); (**b**) Microconglomerate with clasts of cherts and felsic rocks of the Lausitz Group, demonstrating the re-deposition of the black cherts and arc volcanics during the formation of the Cadomian retroarc basin (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Petershain near Kamenz, Cadomian basement of the Lausitz Antiform); (**c**) Isoclinally folded greywacke turbidites of the Lausitz Group (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Butterberg Quarry near Bernsdorf, Cadomian basement of the Lausitz Antiform); (**d**) Specimen from a seismically induced debris flow. The conglomeratic matrix includes fragments of seismites (upper left), mudclasts and black chert fragments (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Wetterberg Quarry near Ebersbach, Cadomian basement of the Lausitz Antiform).

(Fig. 4) (Linnemann 1991). In this paper, the depositional environment is interpreted as a deltaic deposit resulting from a drop in sea level. A stratigraphic equivalent of the Purpurberg Quartzite occurs in the Clanzschwitz Group (North Saxon Antiform). Other parts of the Weesenstein and Clanzschwitz Groups are also related to passive margin deposits, with quartz-rich mud- and siltstones.

In the upper part of the Weesenstein and the Clanzschwitz Groups, diamictites and layers with isolated pebbles occur that could be glaciomarine in origin (Fig. 5) (Linnemann & Romer 2002).

This is yet to be confirmed as tectonometamorphic overprinting may have obscured diagnostic criteria, such as dropstones or striated pebbles. The main argument for a glaciomarine origin of the diamictites of the Weesenstein and the Clanzschwitz Groups is based on the drastic sea level fall in the lower part of the section, which is represented by the deposition of the Purpurberg Quartzite. Further, the diamictites are distributed over long distances, and not interfingered with turbidites. It is, therefore, unlikely that the diamictites are debris flows, which are commonly intercalated with turbidites.

The second basin type in the internal domain is represented by the Lausitz Group (Lausitz Antiform), the Leipzig Formation (Northsaxon Antiform) and the Frohnberg Formation (SE region of the Schwarzburg Antiform). All three units are characterized by monotonous and flysch-like sections of proximal to distal, dark-grey to black turbidites, composed of greywacke and mudstone units (Figs 5 & 6). The presence of seismites indicates an active tectonic setting during basin formation (Fig. 5). Further, intercalations of conglomerates containing fragments of black chert and other debris from older Neoproterozoic sediments and igneous rocks occur (Fig. 5). Especially, the abundant occurrence of black chert fragments in the greywackes and conglomerates (Fig. 5) suggests that deposits from the Cadomian backarc basin of the external zone became eroded, recycled and redeposited in a Cadomian retroarc basin, from which the remnants are represented by the Lausitz Group, and the Leipzig and the Frohnberg Formations (Fig. 10).

The turbidites of the Lausitz Group often show typical groove and tool marks at their base (Fig. 6). In some layers, scours and remnants of microbial mats (‘elephant skin’) can be observed (Fig. 6). The latter is sometimes deformed by chevron marks caused by passing tools or slumps (Fig. 6). Early diagenetic concretions of calc-silica rock occur in places (Fig. 7). These often contain a fragment of mudstone in the centre, suggesting that the activity of microorganisms in the mudstone fragment may be responsible for the formation of the concretions. In one case, hemispherical bodies on the surface of a mudstone bed were found, and interpreted to be of organic origin (Fig. 8). Similar organic structures have been described in the Ediacaran sediments of the Longmyndian Supergroup in Shropshire (UK) (McIlroy *et al.* 2005).

SHRIMP-U/Pb dating of detrital zircon grains has shown that the Lausitz Group and the Frohnberg Formation are younger than 555 ± 9 Ma and 551 ± 8 Ma, respectively (Fig. 3) (Linnemann *et al.* 2004). In general, all Ediacaran sections in the Cadomian basement of the Saxo-Thuringian Zone seem to be rootless. An underlying cratonic basement is not known. But all Nd-model ages of Late Neoproterozoic sediments in the Cadomian basement are very old and range between 1.3–1.9 Ga (Linnemann & Romer 2002). These data show clearly that the source area of the Neoproterozoic sediments was dominated by old cratonic crust.

All the Ediacaran sedimentary sequences of the Cadomian basement in the Saxo-Thuringian Zone were intruded by Early Cambrian post-kinematic granitoid plutons in a time interval of *c.* 540–530 Ma (Tichomirowa 2003; Gehmlich 2003; Linnemann *et al.* 2000). These plutonic rocks are composed of granites, syeno- and monzogranites, granodiorites and tonalites (Hammer 1996). Most of the plutons are granodiorites.

Ediacaran sedimentary rocks in the Cadomian basement of the Saxo-Thuringian Zone are overlain unconformably by Lower Palaeozoic sediments (Cadomian Unconformity), except in the SE part of the Schwarzburg Antiform (see below). Transgression and the development of Lower to Middle Cambrian overstep sequences, including the deposition of conglomerates, carbonates, siliciclastics, and red beds, with a depositional gap during the lowermost Cambrian (*c.* 540–530 Ma), represent the first post-Cadomian sedimentary sequence (Buschmann *et al.* 2006). A second remarkable and widespread gap in sedimentation occurred during the Upper Cambrian (*c.* 500–490 Ma). Exceptionally, the Vesser Complex is composed predominantly of Mid- to Upper Cambrian MOR-related magmatic rocks and metasediments (Bankwitz *et al.* 1992; Kemnitz *et al.* 2002).

Ediacaran rocks of the Cadomian backarc basin

There are a number of key features in the Saxo-Thuringian Zone and adjoining crustal units of the Bohemian Massif, relating to the origin of Ediacaran rocks and the modelling of the Cadomian Orogeny. Firstly, the recycling of old cratonic crust is documented by: (1) the occurrence of large quantities of Archaean and Palaeoproterozoic zircons (Linnemann *et al.* 2000, 2004; Drost *et al.* 2004), and (2) the Nd-model ages of Late Neoproterozoic to Cambro-Ordovician sediments ranging from *c.* 1.5–2.1 Ga (Linnemann & Romer 2002; Drost *et al.* 2004). Secondly, large sedimentary basins opened up during Ediacaran time at *c.* 570 Ma with simultaneous magmatic arc activity (Linnemann *et al.* 2000). Thirdly, the deformation of most of the sedimentary basins, close to the magmatic event at *c.* 540 Ma, is documented in the

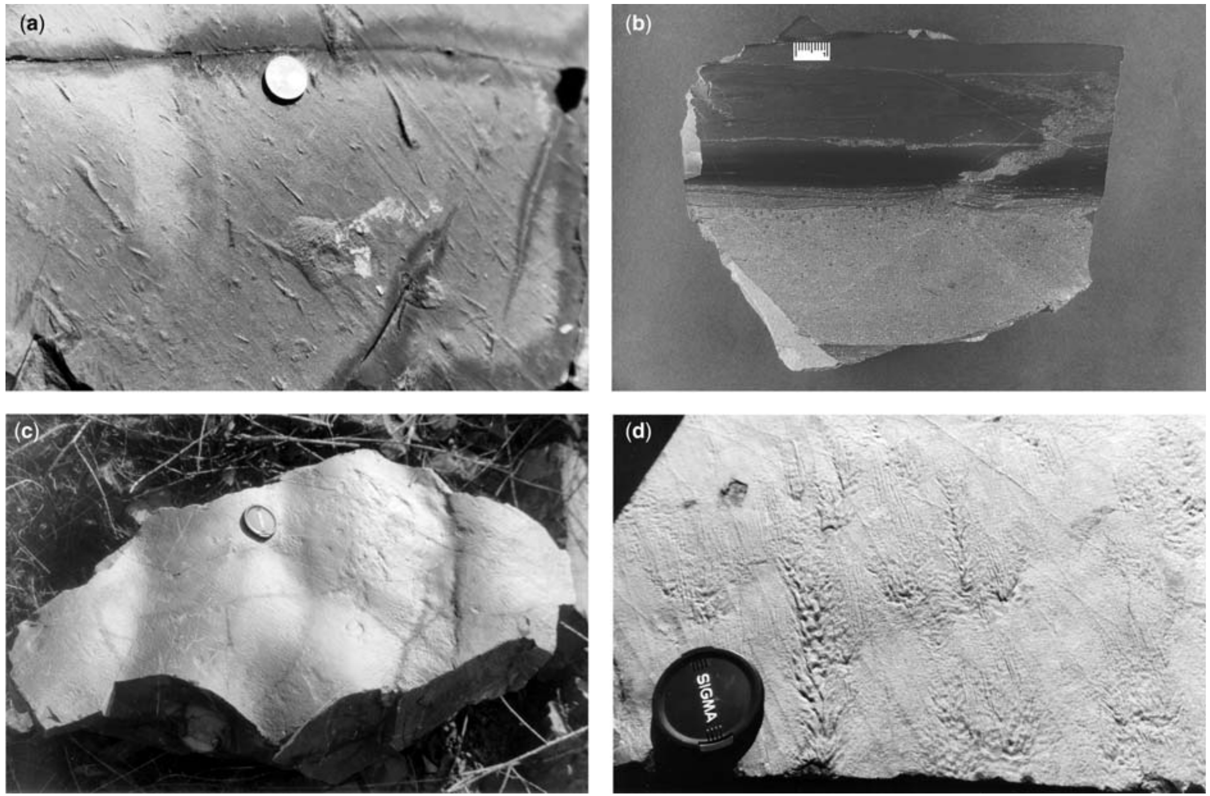

Fig. 6. Photographs of bed surfaces from Ediacaran sediments in the Cadomian retroarc basin (Saxo-Thuringian zone, Bohemian Massif): (**a**) Tool and groove marks at the base of a slab from a greywacke turbidite of the Lausitz Group (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Butterberg Quarry near Bernsdorf, Cadomian basement of the Lausitz Antiform); (**b**) Water escape structure at the top of the a-interval of a greywacke turbidite of the Lausitz Group demonstrating rapid sedimentation in the Cadomian retroarc basin (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Wetterberg Quarry near Ebersbach, Cadomian basement of the Lausitz Antiform); (**c**) Rough surface on a wavy greywacke bed interpreted as microbial mat ('elephant skin') (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Butterberg Quarry near Bernsdorf, Cadomian basement of the Lausitz Antiform); (**d**) Structures on a greywacke bed interpreted as microbial mat deformed by slumping or a passing tool (chevron mark) (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Butterberg Quarry near Bernsdorf, Cadomian basement of the Lausitz Antiform).

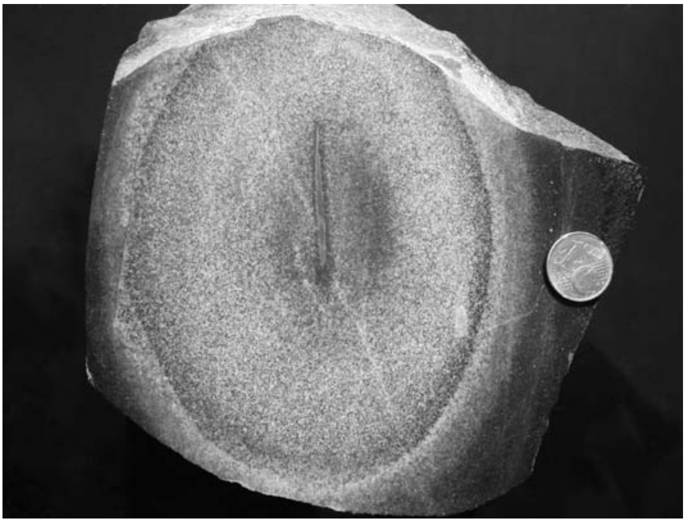

Fig. 7. Polished hand specimen of an early-diagenetic concretion with a mud clast in the centre. The concretion consists of calc-silicate rock and is developed in the greywacke layer of a turbidite (Ediacaran, *c.* 555–540 Ma, Lausitz Group, Butterberg Quarry near Bernsdorf, Cadomian basement of the Lausitz Antiform).

Fig. 8. Hemispherical bodies on the surface of a mudstone bed interpreted to be of organic origin (Ediacaran, *c.* 555–540 Ma, Lausitz Group, quarry Butterberg near Bernsdorf, Cadomian basement of the Lausitz Antiform).

intrusion of voluminous granitoid plutons. There is no noticeable tectonic thickening of the crust (Linnemann *et al.* 2000). Cadomian orogenic processes in the Saxo-Thuringian Zone are bracketed between *c.* 570–540 Ma (Linnemann *et al.* 2000). But there are also numerous detrital zircons from Ediacaran sediments in the range of *c.* 600–650 Ma, which most probably were also related to Cadomian orogenic processes (Linnemann *et al.* 2004). Lastly the record of detrital and inherited zircons points to a West African provenance for the Saxo-Thuringian Zone (Fig. 11) (Drost *et al.* 2004; Linnemann *et al.* 2004).

The oldest rocks in the Saxo-Thuringian Zone are sediments aged at *c.* 570 Ma (Linnemann *et al.* 2000). The general setting of these Late Neoproterozoic deposits in the Saxo-Thuringian Zone is interpreted in terms of a backarc basin generated on thinned continental crust, and flanked by a magmatic arc and a cratonic source (Fig. 9) (Linnemann *et al.* 2000; Buschmann *et al.* 2001). The existence of the latter is represented by: (1) Nd-model ages of Late Neoproterozoic to Cambro-Ordovician sediments in the range of *c.* 1.5–2.1 Ga (Linnemann & Romer 2002); (2) pre-Neoproterozoic detrital and inherited zircons, most of which are Palaeoproterozoic (Linnemann *et al.* 2004); and (3) passive margin sequences like the Weesenstein and Clanzschwitz Groups are extremely enriched in cratonic detrital zircons and characterized by the occurrence of highly mature sediments like the Purpurberg Quartzite (Linnemann 1991; Linnemann *et al.* 2004). Significant traces of the magmatic

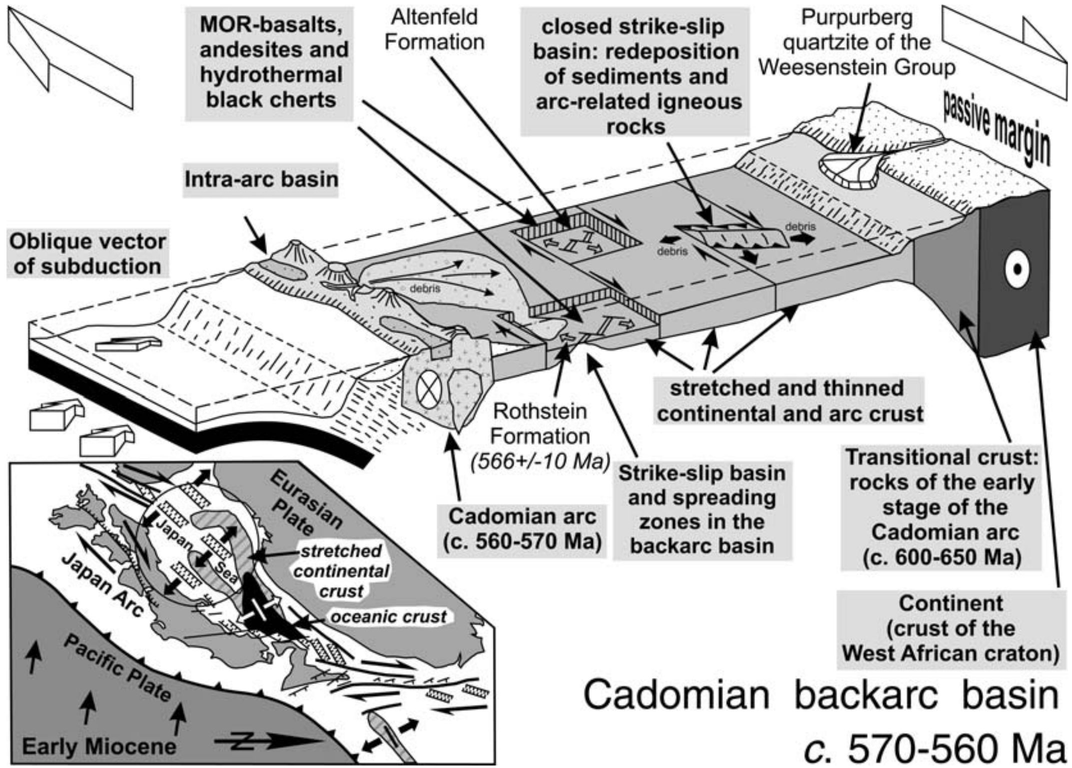

Fig. 9. Model of the geotectonic setting of Ediacaran rocks and development of the Cadomian backarc basin at *c.* 570–560 Ma derived from data of the Saxo-Thuringian Zone (Bohemian Massif). Not to scale. Please note: The basin consists of a continentward passive margin characterized by a stretched continental crust, accumulation of predominantly arc-derived debris, spreading zones with MORB-related rocks and the formation of hydrothermal black cherts (examples: Altenfeld Formation in the NW part of the Schwarzburg Antiform and the Rothstein Formation). Inset shows the sketch of an analogue plate tectonic configuration from the opening of the Japan Sea in the Western Pacific region during the Early Miocene (after Jolivet *et al.* 1992). Please note: The backarc basin of the Japan Sea is developed in large parts on stretched continental crust.

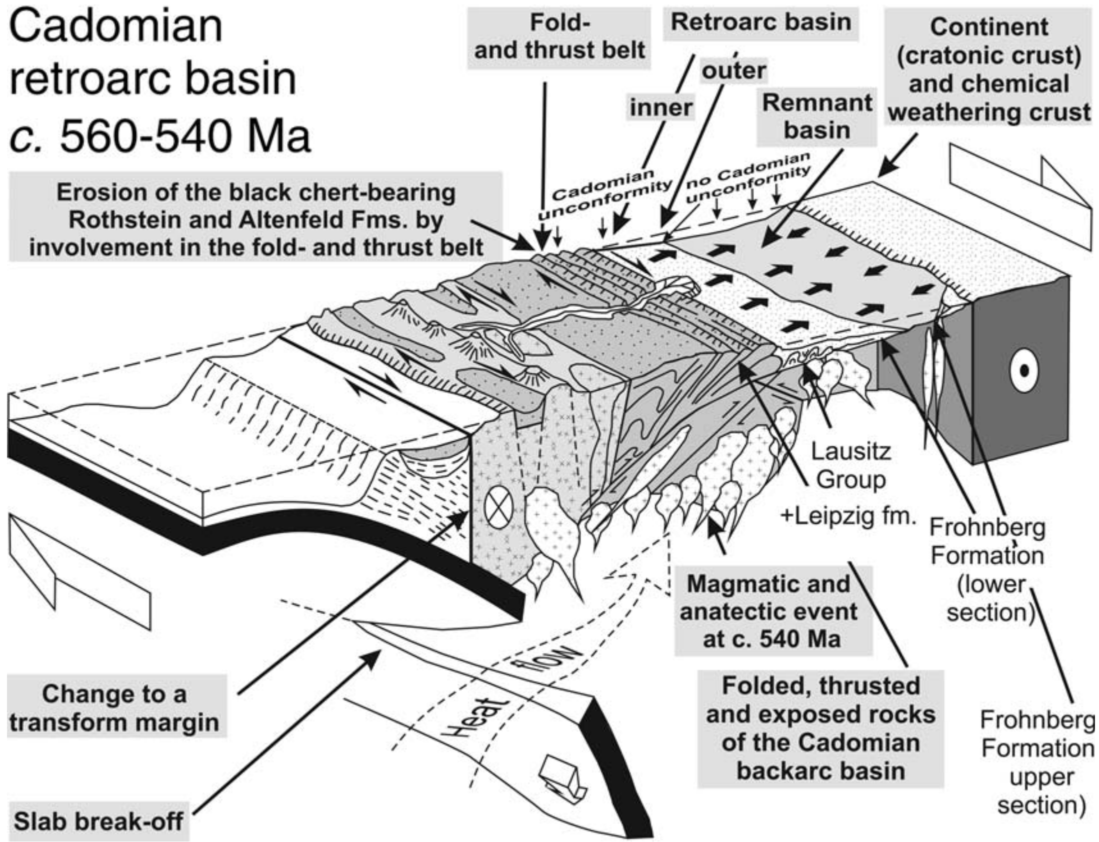

Fig. 10. Model of the geotectonic setting of Ediacaran rocks and the Cadomian retroarc basin at *c.* 560–540 Ma derived from data of the Saxo-Thuringian Zone (Bohemian Massif). Not to scale. Please note: There is no Cadomian unconformity in the continent-directed outer margin of the retroarc basin, because the Ediacaran sediments are not affected by any deformation (example: upper section of the Frohnberg Formation in the SE part of the Schwarzburg Antiform). In contrast, closer to the fold and thrust belt in the inner part of the retroarc basin, the sediments are deformed and, consequently, there is an unconformity observable between Neoproterozoic retroarc sediments and overstepping Cambro-Ordovician strata (example: Cadomian unconformities at the top of the Lausitz Group and the Leipzig Formation).

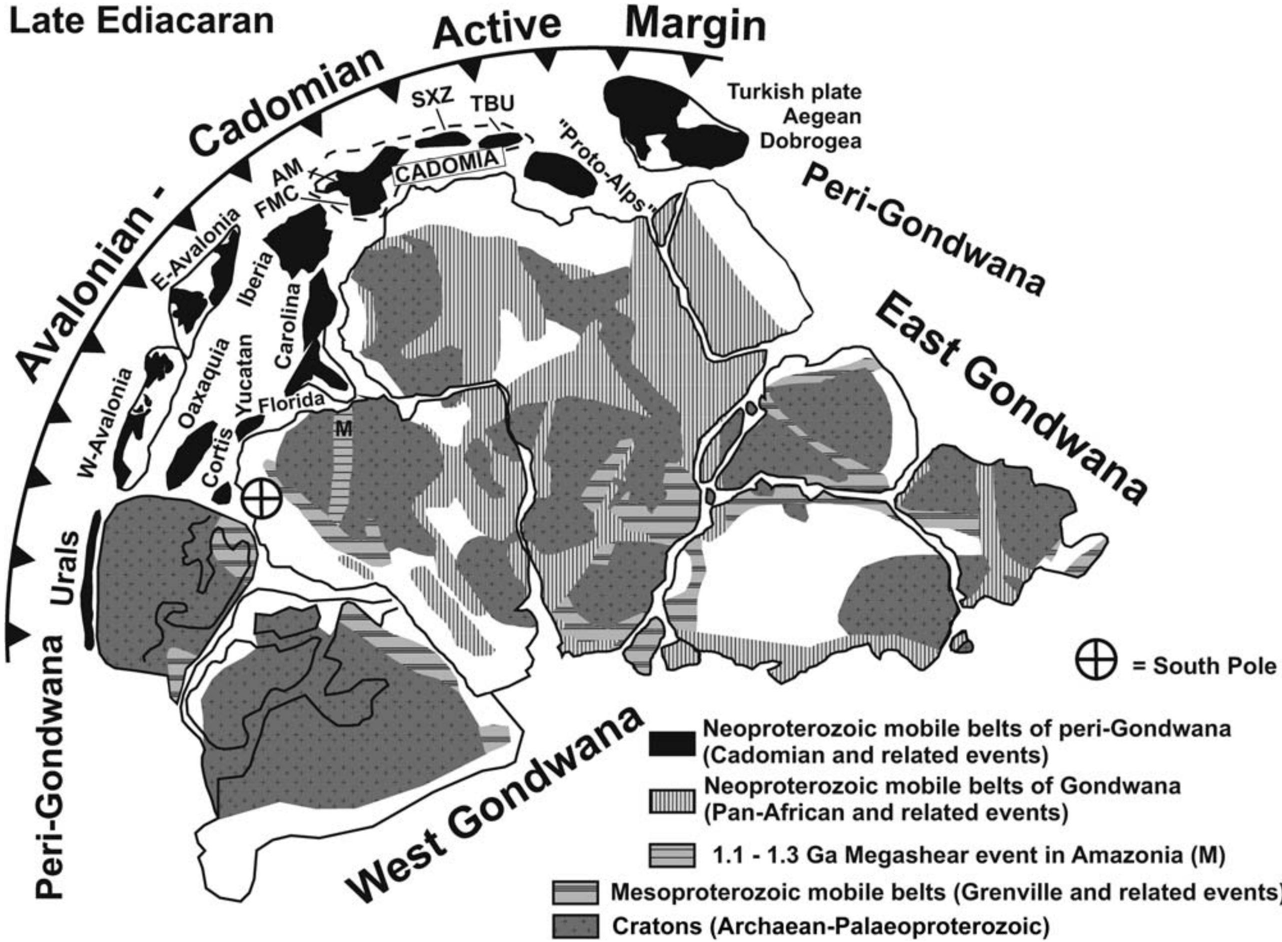

Fig. 11. Palaeogeography of the Cadomian—Avalonian active margin and related prominent peri-Gondwanan terranes at *c.* 580–560 Ma (modified after Nance & Murphy 1994, 1996; Linnemann *et al.* 2000; Murphy *et al.* 2004; Linnemann & Romer 2002; Nance *et al.* 2004; Linnemann *et al.* 2004); palaeogeography of the Gondwanan continental plates after Unrug (1996). AM, Armorican Massif; FMC, French Central Massif; SXZ, Saxo-Thuringian zone (Bohemian Massif); TBU, Tepla-Barrandian unit (Bohemian Massif).

arc are represented by geochemical signatures of Late Neoproterozoic sediments, pointing to deposition in a continental arc setting (Buschmann 1995; Linnemann & Romer 2002; Drost *et al.* 2004). These sedimentary rocks show a felsic provenance, suggesting that the Cadomian arc was developed on a relatively thick arc root.

The main activity of the arc magmatism must be placed at *c.* 560–580 Ma. This is the age of the majority of detrital zircons in Ediacaran sediments (Linnemann *et al.* 2004).

Backarc spreading is best documented in the magmatism and hydrothermal activity of the Rothstein Formation (Fig. 9) (Buschmann 1995). The geochemistry of the volcanic rocks is diverse, comprising a suite of E-type MOR metabasalts to metaandesites, calc-alkaline metabasalts, and subordinate alkaline metabasalts. Effusive alkaline metabasalts form mini-pillow sequences, E-type MOR metabasalts pillow sequences, calc-alkaline metabasalts and metaandesites sills and dykes. The eruption modes, characterized by the formation of pillow sequences and sill emplacements in unconsolidated sediments, point to seafloor-spreading processes in thinned continental crust. Further, the presence of seafloor-spreading processes is supported by relics of hydrothermal activity in volcanic and sediment-hosted submarine environments (e.g. black cherts). The cherts reflect discharges of silica-rich hydrothermal fluids. The basin formation of the Rothstein Formation is attributed to submarine pull-apart processes in a strike-slip dominated active continental margin environment. Strike-slip motions resulted in resedimentation of unconsolidated sediments (Buschmann 1995). Seafloor spreading and hydrothermal activity point to the development of an oceanic substratum in a continental-margin back-arc facies. The sedimentation age of the Rothstein Formation was determined by SHRIMP U/Pb dating of zircons from a submarine tuff, and gave an age of 566 $\pm$ 10 Ma (Buschmann *et al.* 2001). The Altenfeld Formation, in the NW part of the Schwarzburg antiform, is characterized by the occurrence of black chert deposits and mafic igneous rocks. Therefore, the Altenfeld Formation is interpreted in this study to be an equivalent of the Rothstein Formation, indicating the same geotectonic setting.

The passive margin sequences of the Weesenstein and Clanzschwitz Groups were most probably deposited at approximately the same time as the Rothstein and the Altenfeld Formations. A model for the Cadomian backarc basin in the Saxo-Thuringian Zone can be reconstructed, based on the isochronous origin of passive margin sequences (Weesenstein and Clanzschwitz Groups) and the inner parts of the backarc basin (Rothstein and Altenfeld Formations) (Fig. 9). The passive margin sequences of the Weesenstein and Clanzschwitz Groups occur in the southern flank of that area in the Saxo-Thuringian Zone, in which only weakly metamorphosed Late Ediacaran rock units are present (Fig. 2). On the opposite side of this area, in the external domain of the Saxo-Thuringian Zone, the Rothstein and Altenfeld Formations are located. This geographical situation is interpreted to be a result of the palaeoposition of the rock units in their original setting during Ediacaran time. There is strong evidence that the inner part of the Cadomian backarc basin in the Saxo-Thuringian zone is preserved in the external zone to the north, and its passive margin sequences are positioned to the south (Fig. 2).

Dating of granitoid pebbles from the Weesenstein and Clanzschwitz Groups, with ages at 577 $\pm$ 3 Ma and 568 $\pm$ 4 Ma (Linnemann *et al.* 2000), demonstrates the rapid exhumation of these granitoids in the source area. The rapid exhumation of *c.* 570 Ma old granitoid pebbles (Linnemann *et al.* 2000) and their deposition together with intraformational sediments in Ediacaran sediments (Linnemann 1991), and the style of the magmatism in the Rothstein Formation (Buschmann 1995) suggest that intense strike-slip processes took place during the history of the backarc basin. Local subbasins, which opened in the backarc basin in a strike-slip-regime, may also have contributed sediments, including material derived from the underlying stretched crust. Comparing this with a similar situation in Avalonia, Nance and Murphy (1994) proposed a model assuming the oblique vector of subduction beneath the arc leading to strike-slip motions in the backarc basin. The model of backarc spreading, oblique running subduction, and resulting effects is shown in Figure 9. The geotectonic setting is comparable to a modern equivalent in the Western Pacific (inset, in Fig. 9).

Ediacaran rocks of the Cadomian retroarc basin

Most of the well-preserved Ediacaran sedimentary rocks in the Saxo-Thuringian Zone belong to the Lausitz Group (Lausitz Antiform), Leipzig Formation (North Saxon Antiform) and Frohnberg Formation (SE part of the Schwarzburg Antiform). These units are characterized by monotonous series of dark-grey greywacke turbidites, with intercalation of conglomerates and microconglomerates. The latter often show fragments of granitoids, metasediments and black cherts. The flysch-like character and abundant chert fragments, both in the conglomerates and in the sandy grain fraction, show that these sedimentary complexes differ very much from backarc basin deposits.

The primary and massive deposits of black cherts are a distinct feature of the Rothstein and Altenfeld Formations from the Cadomian backarc basin. Because of the frequent occurrence of black chert fragments, it is suggested in this paper that the Lausitz Group and the Leipzig and Frohnberg Formations consist mostly of debris derived from reworked parts of the backarc basin.

In view of their spatial distribution, the Lausitz Group, and the Leipzig and Frohnberg Formations are positioned between the deposits from the inner backarc basin in the north (Rothstein and Altenfeld Formations) and the passive margin deposits to the south (Weesenstein and Clanzschwitz Groups).

Because of the occurrence of chert fragments in the monotonous turbidites and conglomerates, there is strong evidence that: (1) the Lausitz Group and the Leipzig/Frohnberg Formations are significantly younger than the deposits of the Cadomian backarc basin; and (2) that these sedimentary units are composed mostly of the eroded material derived from the deposits of the backarc basin. SHRIMP-U/Pb dating of detrital zircon grains in the Lausitz Group and the Frohnberg Formation has shown that these deposits are younger than 555 ± 9 Ma and 551 ± 8 Ma, respectively (Fig. 3) (Linnemann *et al.* 2004). Further, in these sequences, primary sedimentary structures occur such as water escape structures, soft pebbles and seismites: these are typical of rapid sedimentation and seismic vibrancies (Figs 5, 6) (Linnemann 2003). Because of age constraints and basin history, the Lausitz Group and the Leipzig/Frohnberg Formations are interpreted as parts of a Cadomian retroarc basin or foreland basin, respectively (Fig. 10). The retroarc basin was formed during the collision of the Cadomian magmatic arc with the West African Craton, and the closure of the backarc basin. The inner part of the retroarc basin was folded and thrusted, whereas the outer part was not deformed. Consequently, the more northern Lausitz Group and Leipzig Formation were deformed before the magmatic event at *c.* 540 Ma occurred (Linnemann *et al.* 2000). An angular Cadomian Unconformity between Ediacaran rocks and Cambro-Ordovician deposits can be observed (Linnemann & Buschmann 1995*a*, *b*). In contrast, there is no evidence for of a Cadomian deformation of the Frohnberg Formation in the SE part of the Schwarzburg Antiform. Therefore, in our interpretation, the Frohnberg Formation was originated more distally from the fold and thrust belt that was feeding the assumed Cadomian retroarc basin. This part of the sedimentary system escaped the Cadomian deformation (Fig. 10). The palaeogeographic position of the Frohnberg Formation is proximal to the cratonic hinterland, whereas the folded and thrusted sediments of the Lausitz Group and the Leipzig Formation are more distal to the craton, and more proximal to the colliding arc (Fig. 10).

The lower part of the Frohnberg Formation is composed of thick-bedded greywacke turbidites and some conglomeratic layers of a deeper marine basin. In contrast the *c.* 100 m thick upper part of the Frohnberg Formation displays features of deposition in a shallower basin: this is documented by: (1) rare findings of hummocky cross-stratification in sandstones; (2) the occurrence of laminated mudstones reflecting a muddy coast; and (3) a topmost upward-thickening bed set of quartzite layers (former sandstone bed sets). The latter show a much higher maturity than the greywackes from the lower part of the section (Linnemann 2003). These characteristics of the Frohnberg Formation show that the retroarc basin ended at the top of the lower part of the Frohnberg formation. The deposition of sediments in the upper part of the Frohnberg formation was probably controlled by shallower sedimentation in a remnant basin, which was placed in front of the outer retroarc deposits (Fig. 10). The uppermost quartzite bed of the section is often referred to as ‘Basisquarzit’ (=basal quartzite) in the traditional German literature. This quartzite layer represents the youngest Ediacaran sediment in the pile of sediments, because it is the final bed of a continuous thickening-upward section in the remnant basin. The traditional German name ‘Basisquarzit’ is confusing, because in former time the quartzite was believed to be the base of the Cambrian. This interpretation was done without any palaeontological or geochronological data.

The Cadomian retroarc basin and the related remnant basin were short-lived depositional systems. The age of these sediments is bracketed between *c.* 555–540 Ma. The Precambrian-Cambrian boundary dated at 542 Ma (Bowring *et al.* 2003) has not been observed in the Saxo-Thuringian Zone.

The deposits of the backarc and retroarc basins were both intruded by voluminous granitoid plutons (e.g. the Lausitz Granitoid Complex (539 ± 6 Ma), the Glasbach Granite (533 ± 4 Ma), the Laubach granite (541 ± 7 Ma), the Schildau Massif (530 ± 8 Ma), the Laas Granodiorite (531 ± 7 Ma) and the Dohna Granodiorite (537 ± 7 Ma) (Linnemann *et al.* 2000)). These granitoids are anatectic, and show a large amount of inherited zircons with the same ages as the zircon populations from the Late Neoproterozoic sediments (Linnemann *et al.* 2000, 2004; Gehmlich 2003; Tichomirowa 2003). Most of these granitoids were derived from molten Ediacaran sedimentary rocks. This interpretation is supported by geochemical data and greywacke xenoliths in the granitoids, which range from granites and granodiorites to rare tonalites (Hammer 1996). The magmatic and anatectic event at *c.* 540 Ma is expressed by the intrusion of granodiorites (Linnemann *et al.* 2000). The intense heat flow and the lack of evidence of a much-thickened crust, allows only two explanations: (1) slab break-off; or (2) delamination of the crust. The latter is restricted to orogens resulting from continent-continent collision and the formation of a thick orogenic root. The slab break-off of the subducted oceanic plate is typical of active margin settings: in view of the known data, this is a more likely case for the Cadomian orogenic processes (Fig. 10).

All the processes resulting from the activity of the Cadomian magmatic arc (the opening of the Cadomian backarc basin (*c.* 560–570 Ma), its closure by the arc-continent collision resulting in the formation of a retroarc basin (>*c.* 560 Ma and <*c.* 540 Ma) and the magmatic/anatectic event at *c.* 540 Ma) can be attributed to Cadomian orogenic processes, which formed a part of the Cadomian orogen at the margin of the West African Craton (Fig. 11). This is the geotectonic framework within which the Ediacaran rock units of the Saxo-Thuringian Zone originated.

Conclusions

Available data and field observations allow the reconstruction the geotectonic setting during the Ediacaran period and Early Cambrian in the Saxo-Thuringian Zone (NE Bohemian Massif, Germany):

- Ediacaran rocks of the Saxo-Thuringian Zone were formed in an active margin setting during Cadomian orogenic processes on the periphery of the West African Craton (peri-Gondwana).
- Ediacaran rocks of the Saxo-Thuringian Zone are younger than *c.* 570 Ma.
- Activity of the Cadomian magmatic arc starts in a Cordilleran-type margin setting at *c.* 600–650 Ma, as shown by detrital and inherited zircons in younger Ediacaran rocks.
- A Cadomian backarc basin with a passive margin and the outboard sitting Cadomian magmatic arc commenced at *c.* 570–560 Ma on stretched continental crust in a strike-slip regime.
- There is some evidence, but no certain proof, for a local glaciation during the deposition of the passive margin sequence in the backarc basin.
- The Cadomian magmatic arc collided with the cratonic hinterland, resulting in the closure of the backarc basin and the formation of a Cadomian retroarc basin between *c.* 555 Ma and *c.* 540 Ma.
- Mat grounds (‘elephant skin’) and hemispherical bodies, interpreted to be of organic origin, were observed in the retroarc basin.
- Slab break-off of the subducted oceanic plate caused a magmatic/anatectic event culminating in the earliest Cambrian at *c.* 540 Ma.

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