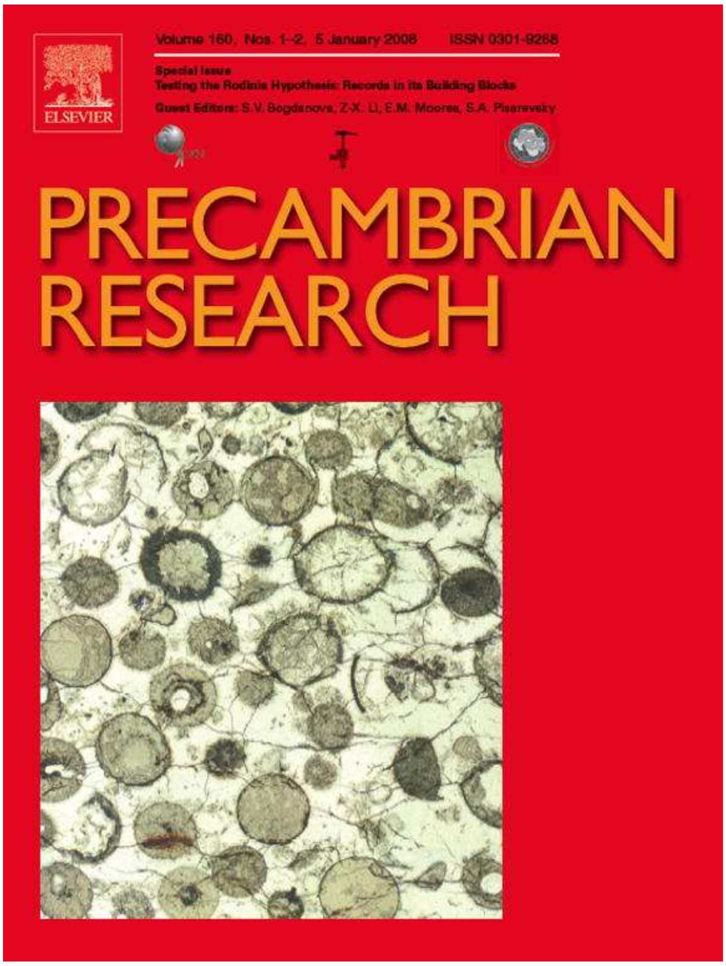
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Baltica in the Cryogenian, 850–630 Ma

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Abstract

This new tectonic synthesis provides a framework for understanding the dynamic evolution of Baltica and for constraining tectonic correlations within the context of the Neoproterozoic break-up of Rodinia–Pannotia. Cryogenian Baltica is described with respect to five geographic regions: the northwest, northeast, east, south, and southwest (modern coordinates). These geographic regions define three principal Cryogenian tectonic margins: a rifting northwestern margin, a passive northeastern margin, and a poorly understood southern margin.

The northwest region is characterized by Neoproterozoic to lower Ordovician sedimentary successions deposited on Archean to late Mesoproterozoic crystalline complexes, reworked during Caledonian orogenesis. Lare Neoproterozoic to lower Ordovician sedimentary strata record the change from an alluvial setting to a marine environment, and eventually to a partially starved (?) turbidite basin. They document rifting from the Rodinian-Pannotian supercontinent, which was unsuccessful until ca. 620–550 Ma when voluminous dikes and mafic/ultramafic complexes were intruded.

Baltica's northeastern and eastern regions document episodic intracratonic rifting throughout the Mesoproterozoic, followed by pericontinental passive margin deposition throughout the Cryogenian. In the northeast platformal and deeper-water basin deposits are preserved, whereas the eastern region was later affected by Paleozoic rifting and preserves only shelf deposits. The northeastern and eastern regions define Baltica's Cryogenian northeastern tectonic margin, which was an ocean-facing passive margin of the Rodinia–Pannotia supercontinent. It remained a passive margin until the onset of Timanian orogenesis at ca. 615 Ma, approximately synchronous with the time of Rodinia–Pannotia rifting.

Baltica's southern and southwestern regions remain enigmatic and controversial. Precambrian basement is generally hidden beneath thick successions of Ediacaran and younger platform sediments. Similarities between these regions exist, however, and suggest that they may share a similar tectonic evolution in the Cryogenian and therefore define the southern tectonic margin of Baltica at this time. Paleo- to Mesoproterozic basement was affected by Neoproterozoic and younger tectonism, including Cryogenian (?) and Ediacaran rifting. This was followed by Ediacaran (ca. 550 Ma) passive margin sediment deposition at the time of Rodinia–Pannotia break-up, until Early Paleozoic accretion of allochthonous terranes record the transition from rifting to a compressional regime.

Paleomagnetic and paleontological data are consistent with Baltica and Laurentia drifting together between ca. 750 and 550 Ma, when they had similar apparent polar wander paths. Microfossil assemblages along the eastern margin of Laurentia and the western margin of Baltica (modern coordinates), suggest proximity between these two margins at this time. At ca. 550 Ma, Laurentia and Baltica separated, consistent with paleomagnetic, paleontological, and geological data, and a late break-up for Rodinia–Pannotia.

Keywords: Baltica; Rodinia; Neoproterozoic; Orogeny; Paleogeography

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1. Introduction

This tectonic synthesis of Baltica's geology, conducted under the auspices of IGCP 440 "Assembly and break-up of Rodinia", was initially compiled by the Nordic Working Group which included over 15 persons from Norway, Sweden, Finland, and Russia. It is derived from the digital databases for the geological map of the Fennoscandian Shield (1:1,000,000; Koistinen et al., 2001), the International Tectonic Map of Europe (1:5,000,000; Khain and Leonov, 1998), and the International Tectonic Map of Europe and Adjacent Areas (1:5,000,000; Khain and Leonov, 1996).

'Baltica' is used here to denote the continent which is thought to have existed since the break-up of Rodinia in the Neoproterozoic and through most of the Paleozoic, e.g. Torsvik et al. (1996). In a 'Rodinia' context, it is Baltica's Cryogenian (850–630 Ma, timescale of Gradstein et al., 2004) margins which form the basis for tectonic correlation to other fragments of the supercontinent during break-up. For descriptive purposes, Baltica is divided into five geographic environments: a northwestern region, a northeastern region, an eastern region, a southern region, and a southwestern region (modern day coordinates; Fig. 1). Each of these regions is described below. It is concluded that Baltica possessed three distinct tectonic margins in the Cryogenian, a rifting northwestern margin, a passive northeastern margin, and a poorly understood southern margin.

This synthesis has two principal limitations:

(1) As with all such efforts, it is limited by the state of knowledge at the time of its compilation. Undoubtedly, as lesser known regions are better mapped, as new age data is generated, etc., this synthesis will necessarily need to be revised.
(2) It represents an *interpretation* of the geologic record. Though every effort has been made to present a balanced viewpoint, e.g. to clearly state where alternative interpretations exist, this synthesis necessarily reflects the bias of the author(s). However, building strongly on published literature and providing extensive references, this synthesis permits full access to the primary material on which the interpretations are based.

Though the revised Precambrian timescale of the International Commission of Stratigraphy (Gradstein et al., 2004) has been used throughout, there are several other timescales in routine use in the scientific community at present. These include the IUGS International Stratigraphic Chart (2000), the older International Stratigraphic Chart of Plumb (1991), as well as the Russian timescale (Semikhatov et al., 1991) in which Riphean and Vendian subdivide parts of the Precambrian. For the convenience of the reader, the various timescales are summarized (Fig. 2).

2. The northwestern region of Baltica: pre-Caledonian

The break-up of Rodinia–Pannotia (e.g. Dalziel, 1997; Powell, 1995) has been described by studying deposits of Neoproterozoic sedimentary systems ('basins'), and the chemistry and age of the igneous activity along the Baltoscandian margin of Baltica. Before the time of the rift–drift transition at ca. 600–550 Ma (Paulsson and Andréasson, 2002; Siedlecka et al.,

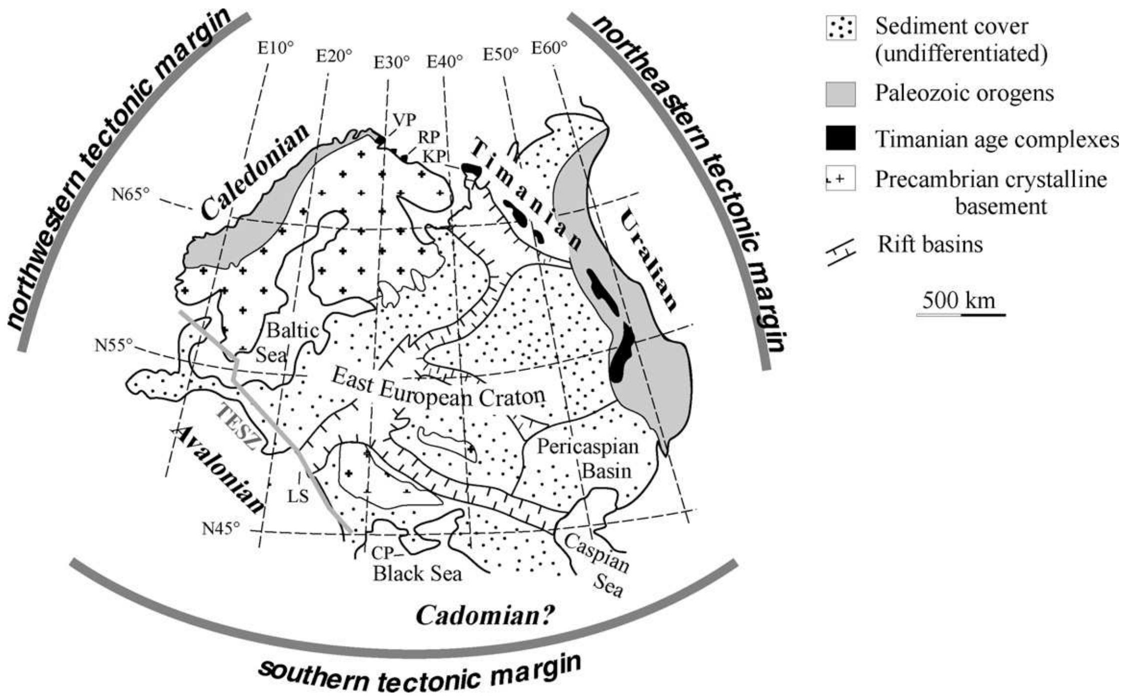

Fig. 1. Simplified geology of Baltica showing the five geographic regions described in the text (Caledonian, Timanian, Uralian, Cadomian (?) and Avalonian), as well as the three tectonic margins existing in the Cryogenian (bold grey lines). CP, Crimea Peninsula; KP, Kanin Peninsula; LS, Lublin Slope; RP, Rybachi Peninsula; TESZ, Trans-European Suture Zone (light grey line); VP, Varanger Peninsula.

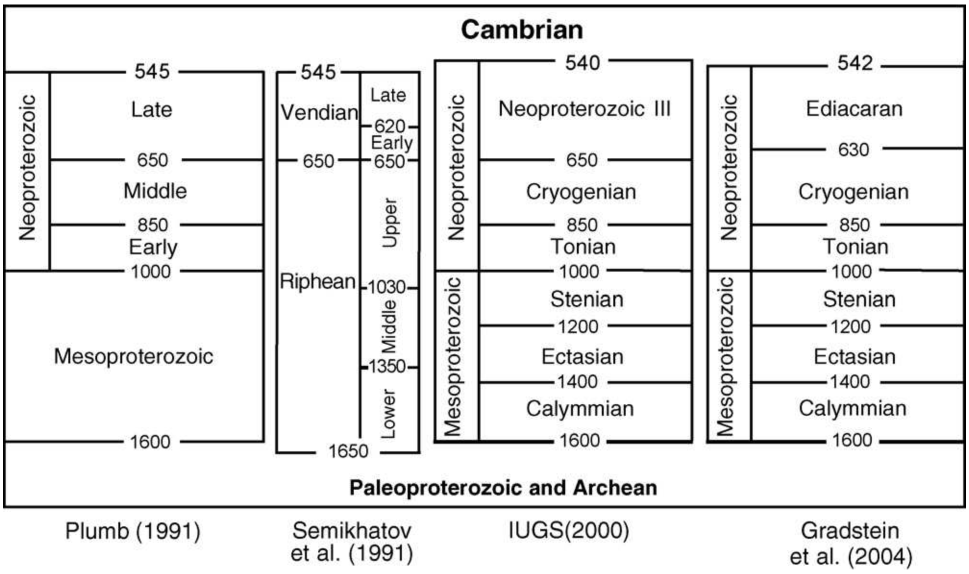

Fig. 2. Comparison of Meso- and Neoproterozoic timescales. Note that in early 2006, changes were suggested in the third edition of the Stratigraphic Code of Russia for the base of the Upper Riphean (1030 ± 30 Ma) and base of the Vendian (650 ± 20 Ma) to 1000 and 600 Ma. In the first case the boundary change is within the indicated error, however, in the second case the age of the base of the Vendian is poorly constrained by either geological or geochronological data.

2004), this margin was inferred to have faced either Laurentia (e.g. Roberts and Gale, 1978; Gower et al., 1990; Gorbatschev and Bogdanova, 1993), an unknown continent (Soper, 1994), or Siberia (Torsvik et al., 1995).

The Scandinavian Caledonides hosts a number of Neoproterozoic to Lower Ordovician sedimentary successions with affinity to Baltica (Fig. 3). The Caledonian allochthon is composed of two major Baltica-related nappe complexes, the lower thrust sheets and the Seve-Kalak Superterrane and two overlying exotic nappe complexes (Andréasson et al., 1998); the latter two are beyond the scope of this paper. The various nappe complexes are composed of a sequence of nappe units (thrust sheets) stacked onto northwest Baltica and are traceble across most of the thrust belt (e.g. Gee, 1977; Björklund, 1985). The Baltica-related sed-

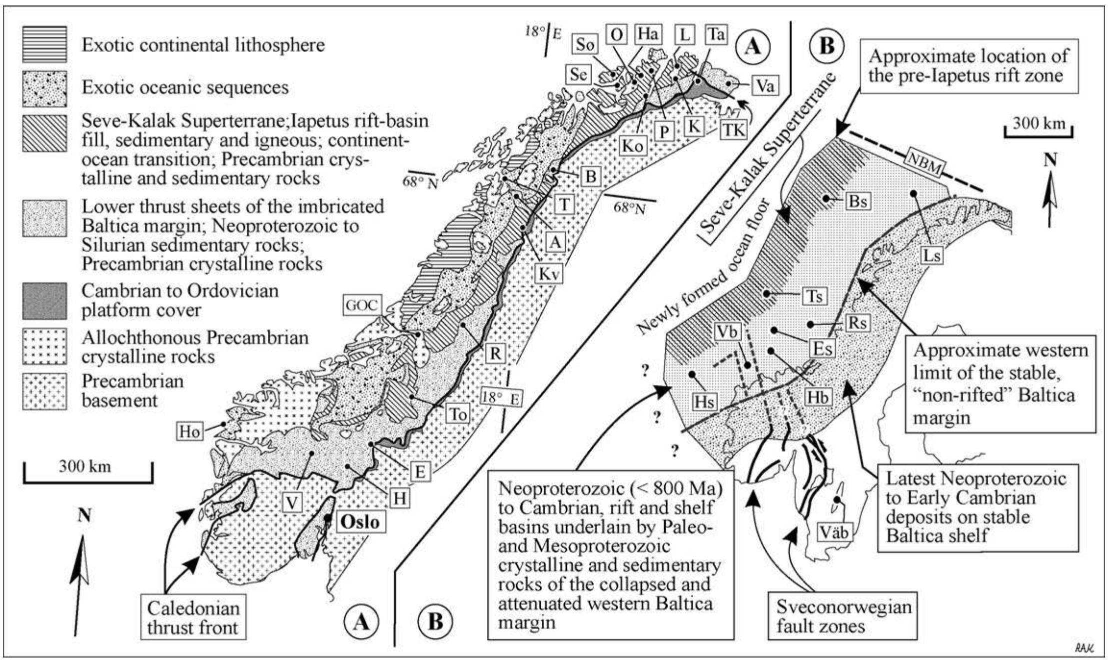

Fig. 3. (A) Simplified tectonostratigraphic map of the Scandinavian Caledonides (modified after Andréasson et al., 1998). Abbreviations: A, Akkajaure; B, Belggesgorsajohka; E, Engerdal; GOC, Grong-Olden Culmination; H, Hedmark; Ha, Havvattnet; Hø, Høyvik; K, Kalak; Ko, Kolvik; Kv, Kvikkjokk; L, Laksefjord; O, Olderfjord; P, Porsangerhalvøya; R, Risbäck; Se, Seiland; Sø, Sørøya; Ta, Tanafjord; To, Tossåsfjället; V, Valdres; Va, Varangerhalvøya. (B) Inferred original sites of formation of the various sedimentary successions, segments or basins. The present Norwegian coastline is indicated for reference. Abbreviations: Bs, Balggesgorsajohka segment; Es, Engerdalen segment; Hb, Hedmark basin; Hs, Høyvik segment; Ls, Laksefjord segment; NBM, Northern Baltica Margin; Rs, Risbäck segment; Ts, Tossåsfjället segment; Vb, Valdres basin; Väb, Vättern basin.

imentary successions are deformed by one or more cleavages, folds (polyphase in the Seve-Kalak Superterrane) and faults. The metamorphic grade varies from sub-greenschist facies in the Autochthon and lower thrust sheets via upper greenschist facies to amphibolite, granulite and eclogite facies in the Seve-Kalak Superterrane. Further details of the structural and metamorphic geology and tectonostratigraphy are summarized by Andréasson (1994), Andréasson et al. (1998), and Siedlecka et al. (2004).

Interpretations of the restored pre-Caledonian Baltoscandian margin (e.g. Kumpulainen and Nystuen, 1985; Gayer et al., 1987; Gayer and Greiling, 1989; Andréasson, 1994; Andréasson et al., 1998; Siedlecka et al., 2004) indicate that margin-parallel deposition occurred over 2000 km along western Baltoscandia, while the distance across this region to the continent–ocean transition is estimated at 300–600 km. The westernmost 100–200 km of this area hosts most of the Baltoscandian mafic dike swarms and related igneous rocks.

The Sveconorwegian (1200–900 Ma) orogen represents a small segment of the global Grenvillian belt, but comprises a significant part of the pre-rift crystalline basement in the southern Baltoscandian region. Using the terminology of Bingen et al. (2005b), it represents the polyphase imbrication of 1.80–1.64 Ga parautochthonous crust at the margin of Fennoscandia (the Eastern segment) during collision involving 1.66–1.52 Ga arc material (Idefjorden terrane), a 1.52–1.48 Ga continental fragment (Telemarkia) and an unknown craton between 1.13 and 0.97 Ga (Bingen et al., 2005b; Bogdanova et al., this volume and references therein). The Sveconorwegian orogen is manifest by a series of steep NW/SE-trending fault zones (Fig. 3) which project beneath the Caledonian nappes to the northwest and were cut by the Iapetus rift zone (Kumpulainen and Nystuen, 1985).

Further north, from mid-Norway/Sweden, the Svecofennian domain (1.9–1.8 Ga) forms the crystalline basement to the Caledonian nappes, while Archean and Paleoproterozoic rocks occupy most of the shield areas of northern Fennoscandia (Andréasson, 1994). New geochronology from the Kalak Nappe Complex (KNC) in Finnmark has revealed granitic magmatism of Sveconorwegian age (980 Ma), as well as structural evidence of pre-980 Ma deformation (Kirkland et al., 2005, 2006). It is uncertain, however, whether this event affected the Baltoscandian margin because the rocks involved are allochthonous and their time of arrival in Baltica is uncertain.

Daly et al. (1991) first demonstrated the existence of a Precambrian orogenic event within the KNC, assumed to represent part of the Baltoscandian passive margin of Iapetus. Deformation predating granitic magmatism was attributed to the Porsanger Orogeny, which was assumed to affect the entire nappe complex (Daly et al., 1991). New geochronology (Kirkland et al., 2006, 2007), however, demonstrates a series of Precambrian events between 980 and 1030 Ma, 840 and 910 Ma, and at ca. 710, 670, 560, and 520 Ma. Granitic magmatism or migmatization ranging in age from 980 to 710 Ma decreases in age upwards and westwards within the KNC. Tectonic slices of Sveconorwegian granites are found in the east at the lowest structural levels, within the Kolvik and Olderfjord nappes on both sides of Porsangerfjord. Cross-bedding in arkoses at these structural levels indicates sediment derivation from the S-SE (D. Roberts, unpublished data).

Metasedimentary rocks within the overlying Havvatnet Nappe are cut by ca. 840–820 Ma old granites and pegmatites, while ca. 710 Ma migmatites occur within the Sørøy-Seiland Nappe at still higher structural levels. Importantly, juxtaposition of the higher nappes with their lower neighbours was episodic and preceded granitic magmatism. Thus, a series of accretionary tectonic events started before 980 Ma and continued until at least 710 Ma.

The geographical extent and ultimate origin of these accreted terranes is the subject of ongoing research. While Kirkland et al. (2006) provide minimum ages for the metasediments within the KNC, Kirkland et al. (2007) combine these with U–Pb detrital zircon ages to place maximum age constraints. Thus the KNC has now been shown to comprise two distinct successions—a newly defined Sørøy Succession within the upper nappes (Havvatnet and Sørøy-Seiland), deposited between 840 and 910 Ma, and an older, Svaerholt Succession deposited between 980 and 1030 Ma, occupying the lower (Kolvik and Olderfjord) nappes. While the Sørøy Succession is definitely Neoproterozoic, it is possible that the Svaerholt Succession is latest Mesoproterozoic in age. Kirkland et al. (2007) further suggest that the two successions were deposited well away from Baltica as successor basins developed upon successively accreted portions of the Grenville orogen within the easterly Rodinia embayment. Kirkland et al. (2007) discuss possible correlations between the KNC and the Seve rocks within the proposed Seve-Kalak Superterrane of Paulsson and Andréasson (2002). In contrast to the conclusions of Kirkland et al. (2007), Paulsson and Andréasson (2002) considered that the protoliths of the Seve-Kalak Superterrane were formed on the Baltica margin and attributed the 840 Ma old Vistas Granite to the break-up of Rodinia. If the Seve rocks are correctly correlated with the KNC and if the KNC is allochthonous as suggested by Kirkland et al. (2005, 2006, 2007), then the relevance of the Vistas Granite to rifting remains to be proven.

Along the incipient Iapetus rift zone (Fig. 3), the Baltican crustal segment probably developed initially as attenuated rift shoulders and subsequently into the continent–ocean transition. The intracratonic Vättern Basin subsequently formed in this fault system. The Neoproterozoic sediments, i.e., in the Seve-Kalak Superterrane (Roberts, 1974; Kathol, 1987; Andréasson and Albrecht, 1995; Andréasson et al., 1998; Svenningsen, 1993), were mostly arkoses and semi-pelites, with some limestones, dolomites, evaporites, bituminous shales and turbidites which document the change from an alluvial setting to a marine environment and eventually to a possibly starved (?) turbidite basin. Voluminous rift-related igneous activity, including large ultramafic/mafic magmatism (e.g. the Seiland Igneous Province) and extensive, margin-parallel dike swarms, intrudes the Seve-Kalak Superterrane (Andréasson, 1994; Bingen et al., 1998; Roberts et al., 2006). Polyphase deformation and partial migmatisation precludes reliable observations of possible lateral facies changes, particularly within the Seve Nappe Complex.

Neoproterozoic to early Cambrian sediments were also deposited off the initial rift axis on top of the crystalline platform in smaller, restricted rift basins; these later developed into marine shelf basins along the Baltoscandian margin. Some of the local successions have been referred to previously using 'basin' or 'sub-basin' nomenclature. However, many of the successions represent only a segment of a basin and where applicable, this term is used. The Neoproterozoic Baltoscandian successions (Kumpulainen and Nystuen, 1985; Siedlecka et al., 2004) contain tillites of the Varanger (Varangerian) Ice Age (≤620 Ma, Bingen et al., 2005a) which conveniently divides them into three informal units: (1) pre-glacial, (2) glacial and (3) post-glacial. The pre-glacial successions on the Baltoscandian shelf include laterally continuous facies up to 4 km thick (e.g. the Tossåsfjället segment—Kumpulainen, 1980; the Engerdalen segment—Nystuen, 1980; the Laksefjord segment of northern Norway—Føyn et al., 1983; the Høyvik (Group) segment of Southwest Norway—Brekke and Solberg, 1987). These successions, including the Bálggesgorsajohka segment (of the Seve Complex—Kumpulainen and Nystuen, 1994), are intruded by mafic intrusions and dike swarms (Andréasson, 1994). The Hedmark basin is a typical rift basin with rapid lateral facies changes from alluvial to shallow-marine, deep-water fans and bituminous shales, and a transgressive limestone (Bjørlykke et al., 1976; Nystuen, 1987; Siedlecka et al., 2004). Benthic cyanobacteria of ca. 800–700 Ma are documented from the Hedmark and Tanafjorden groups (southern and northern Norway, respectively), and the Visingsö Group (central Sweden) (Vidal and Moczydłowska, 1995; Vidal and Moczydłowska-Vidal, 1997). Alluvial conglomerates and arkoses dominate the Valdres rift basin (Nickelsen et al., 1985). The geometry and infill of these two basins may have been controlled by the reactivated Sveconorwegian fault zone and the dissecting rift-parallel fault system (Fig. 3). The Risbäck segment of central Scandinavia (Kumpulainen and Nystuen, 1985) displays a lateral facies change from an alluvial setting to shallow-marine conditions. Farther north in the Kvikkjokk area, the corresponding units comprise turbidites (Greiling and Kumpulainen, 1989). In Finnmark, a pericratonic fluvial to shallow-marine clastic succession of southern derivation extends eastwards via the Tanafjord area to the Varanger Peninsula. The long-lived and partly syn-depositional Trollfjorden-Komagelva strike-slip fault separates this succession from a very thick, deep-water to shallow-water basinal succession in the north. In most of the Scandinavian successions the uppermost pre-glacial unit is a sabhka-type, evaporitic transgressive dolomite, which in the Porsanger area of northern Norway also contains stromatolites (Bertrand-Sarfati and Siedlecka, 1980; Raaben et al., 1995).

The Varangerian tillites occur in many of the successions in the southern and central Scandinavian Caledonides (Kumpulainen and Nystuen, 1985). In Finnmark, northern Norway, the late Neoproterozoic succession hosts two tillites. The available age data suggest that the upper Mortensnes tillite correlates with the tillites in other parts of Scandinavia (Siedlecka et al., 2004).

The post-glacial units in the southern and central Scandinavian Caledonides and in Finnmark are almost exclusively shallow-marine sandstones and shales. They increase in thickness from a few metres in the Autochthon to ca. 200–300 m in the Lower Allochthon, almost 600 m in Finnmark, and ca. 2 km in the Tossåsfjället and Engerdalen segments of the Middle Allochthon (Kumpulainen and Nystuen, 1985). The generally more or less uniform thickness of the post-glacial successions and available age data of the Baltoscandian mafic dike swarms (Andréasson, 1994; Svenningsen, 2001) indicate that Ediacaran (Vendian) rifting was well advanced and the passive Baltica margin was stabilized. The rift-to-drift transition then followed as Baltica separated from its conjugate Rodinian–Pannotian counterpart and ocean floor began to form between these diverging continental units in latest Ediacaran to Early Cambrian time.

2.1. Summary

Early Neoproterzoic siliciclastic and carbonate sediments contain benthic cyanobacteria of ca. 800–700 Ma. When rifting began after Grenvillian (Sveconorwegian) orogeny is unknown, however, late Neoproterozoic to lower Ordovician sediments record the transition from an alluvial setting to a marine environment, and eventually to a possibly starved (?) turbidite basin. They document rifting of the Rodinian–Pannotian supercontinent, which was unsuccessful until ca. 620–550 Ma when voluminous intrusion of dikes and mafic/ultramafic complexes (e.g. Seiland Igneous Province) occurred marking the rift–drift transition and formation of the incipient Iapetus Ocean.

3. The northeastern region of Baltica: pre-Timanian

Following a period of episodic rifting that started early in the Mesoproterozoic, the northeastern margin of Baltica developed passively during Cryogenian time in a continuing extensional regime. Controlled by an array of major, deep-seated, NW–SE trending faults, this margin became the foreland to the Timanide Orogen during the Ediacaran (Roberts and Siedlecka, 2002; Gee and Pease, 2004 and references therein). The Timanides are traceable as a ca. 2000 km linear belt extending northwestwards from the southern Urals to the Varanger Peninsula of northern Norway (Fig. 1). Underlain by Archean and Paleoproterozoic crystalline terranes, the Meso- and Neoproterozoic rock complexes of the Timan Range disappear northeastwards beneath thick, Phanerozoic successions of the Pechora Basin, but equivalents reappear in the Uralian hinterland (Puchkov, 1997a,b).

During the Cryogenian, the Timanian passive margin was characterized by a system of longitudinal border faults which effectively separated a southwestern pericratonic or *platformal domain* from a deeper-water, *basinal domain* farther away from the craton (Siedlecka and Roberts, 1995; Olovyanishnikov et al., 2000). A variety of microfossils and columnar stromatolites indicate that the oldest parts of some successions are of late Mesoproterozoic (Stenian- to Tonian) age, but they are predominantly Neoproterozoic in age (Getsen and Pykhova, 1977; Bertrand-Sarfati and Siedlecka, 1980; Lyubtsov et al., 1989; Raaben et al., 1995). Microfauna in some of the youngest platformal sequences suggest that deposition continued into late Neoproterozoic (Cryogenian) time.

In the *platformal domain*, which also encompasses the extensive intra- to pericratonic Mezen Basin (Grazhdankin, 2004;

Maslov, 2004) southwest of the central Timan Range, successions of Cryogenian age are characterized by diverse fluvial to shallow-marine, siliciclastic rocks of very low metamorphic grade. Although dominated by arenites derived largely from southwesterly source regions, successions also include shales, marls, dolostones and some limestones. Carbonate rocks are generally more common towards the southern Urals. Sporadic tuffs and rare basalt layers have been reported in the Mezen Basin and there is an increase in volcanic rocks farther southeast in the southern Urals (Maslov, 2004). In contrast, no volcanic rocks have been documented from the Cryogenian successions in the northwest (Varanger and Sredni areas). This may be partly fortuitous, however, as the older parts of the Cryogenian stratigraphic record are absent in the far northwest.

Sedimentation in the *basinal domain* of the exposed Timanides shows marked contrasts in facies and lithology to that characterising the adjacent pericratonic shelf areas. Although there are facies differences along strike, partly arising from transverse faulting and basin segmentation (Roberts and Siedlecka, 2002; Roberts et al., 2004), this basinal slope-and-rise domain is dominated by thick, mainly pelitic, turbidite successions of low to intermediate metamorphic grade. In the northwest (Varanger-Rybachi region), relatively deep-marine turbidite-fan systems prevail (up to 9 km thick), grading upwards into prodelta and delta-front deposits, and topped by shallow-marine strata (Siedlecka, 1972; Pickering, 1983; Siedlecka et al., 1995). The nature of the substrate is unknown. On Varanger, the platformal succession lies unconformably upon turbiditic rocks of the basinal domain (Rice, 1994). On Rybachi Peninsula, a distinctive olistostrome occurs at the base of the turbiditic succession, adjacent to the major shelf-edge fault, attesting to the presence of a steep slope with fast subsidence and rapid sedimentation. Many of the metre-size olistoliths are of older Precambrian crystalline rocks—local basement evidently exposed to erosion at the time of deposition. In the Timan–Kanin region, the deep-water, turbiditic systems reach up to 10 km in thickness. In the central Timan Range, a mud-rich, slope-to-basin succession reflects accumulation on a fairly gentle, stable slope, whereas on Kanin Peninsula Cryogenian deposition was interrupted by repeated faulting and volcanism (Roberts et al., 2004). In many parts of the Timan–Kanin region the successions are intruded by abundant, undated mafic dikes which are affected by Timanian deformation and suspected to be of latest Cryogenian (early Vendian) age.

Northeast of the Timan Range and west of the Urals, the turbiditic assemblages disappear beneath Ordovician through Mesozoic cover rocks of the Pechora Basin. A combination of geophysical data and several dozen deep drillholes across the Pechora Basin defines the character of the Cryogenian bedrock at depth (Beliakova and Stepanenko, 1991; Olovyanishnikov et al., 1995; Dovshikova et al., 2004). Three principal zones are recognized, each delimited by major faults: (a) the *Izhma Zone*, adjacent to the Timan Range, consists largely of turbiditic successions with intercalated volcanic rocks; (b) the *Pechora Zone*, comprising diverse oceanic and magmatic-arc, bimodal volcanic and plutonic rocks; and (c) the outermost *Bolshezemel Zone*, a complex interplay of magmatic rocks and inferred microcontinental blocks (Beliakova and Stepanenko, 1991; Olovyanishnikov et al., 1995, 2000). Calc-alkaline granites and diorites with U–Pb ages of ca. 560–550 Ma (Gee et al., 2000; Dovshikova et al., 2004) cut the deformed Cryogenian rocks of the Pechora and Izhma zones and thus appear to date the termination of Timanian orogeny in these zones. The Bolshezemel Zone passes eastwards via a poorly defined zone of volcanic rocks and reef carbonates (known as the Varandey-Adzhva Zone or Neoproterozoic accretionary terranes) into the foothills of the Polar Urals where the 670 Ma Enganepe ophiolite occurs (Puchkov, 1997a,b; Scarrow et al., 2001).

These various Cryogenian associations occurring beneath the Pechora Basin are traced northwestwards into the southern Barents Sea on the basis of geophysical data (Gafarov, 1963; Zhuravlev, 1972; Fig. 4). The principal NW–SE trending faults are also distinguishable. Immediately offshore from the northwestern Kola Peninsula, deep seismic profiling, aided by drillcore material, has shown that a 4–8 km thick sequence of Izhma zone turbidites is present (Simonov et al., 1998). The original northwestward extent of these rocks offshore of Varanger Peninsula is unknown, as they are hidden beneath the frontal allochthon of the Norwegian Caledonides.

3.1. Summary

The northeastern region of Baltica evolved as a passive margin throughout much of Cryogenian time, with distinctive platformal and deeper-water basin domains. These give way progressively to accreted oceanic and magmatic-arc rocks and microcontinental slivers associated with the latest Neoproterozoic Timanian orogeny. A subduction system is thus inferred to have developed within a pre-Timanian ocean.

4. The eastern region of Baltica: pre-Timanian

Archean (?) and Paleoproterozoic crystalline basement of the East European Craton (EEC) (see reviews by Maslov et al., 1997; Scarrow et al., 2002; Maslov, 2004; Bogdanova et al., this volume and references therein) is overlain unconformably by a thick (12–15 km in places), predominantly Mesoproterozoic through Neoproterozoic (Upper Riphean and Vendian) sedimentary succession, best exposed in the region of the Bashkirian anticlinorium (Fig. 4). This rather long period of sedimentation gave way to late Neoproterozoic Timanian (ca. 615–550 Ma) orogeny, followed by initiation of rifting in the Late Cambrian to Early Ordovician associated with the beginning of the Uralian orogenic cycle. Comparatively little sedimentation occurred during this early Paleozoic rifting episode. Late Ordovician-Silurian to Devonian passive margin sediments (mainly siliciclastics and limestones) were deposited unconformably above the Mesoproterozoic through Neoproterozoic succession prior to the onset of later Devonian–Carboniferous Uralian convergence (see reviews by Savelieva and Nesbitt, 1996; Maslov et al., 1997; Puchkov, 1997a,b; Maslov, 2004).

Tectonic processes related to both late Neoproterozoic Timanian orogeny and Devonian–Carboniferous Uralian orogeny have determined the structural architecture of the region. The

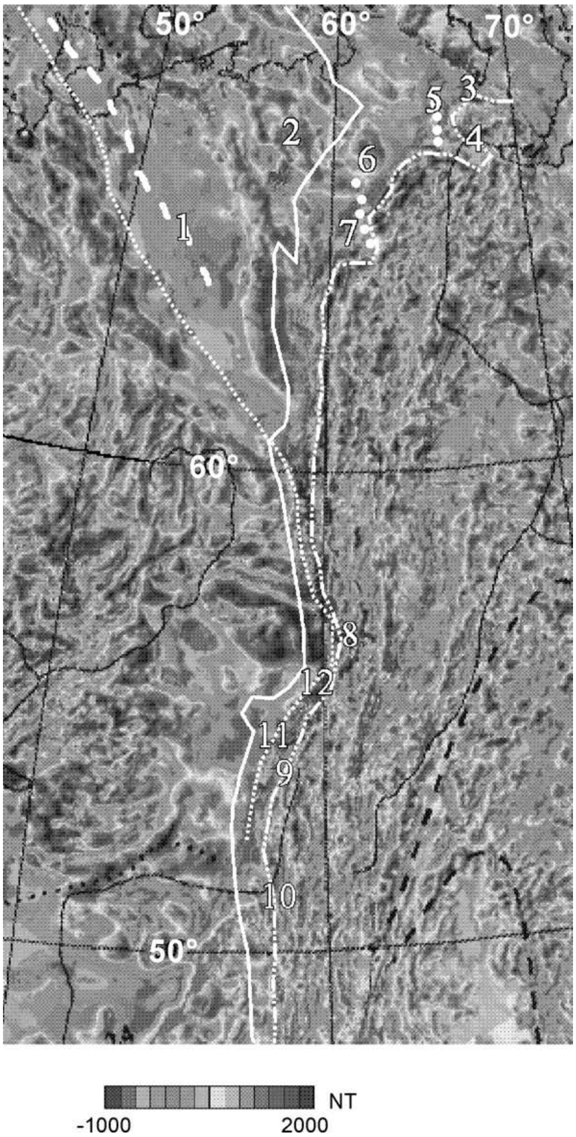

Fig. 4. Magnetic anomalies of eastern Baltica (after Jorgensen et al., 1995, with data processed by CONOCO Inc., USA). White dotted line, Timanian deformation front; white solid line, Uralide deformation front; white dot-and-dash line, the Main Uralian Fault. (1) Timan and Izhma depression (former passive continental margin); (2) Pechora-Ilych Chiksha and Bolshezemel zones (former oceanic, island arc, microcontinental and probably active margin areas); (3) Marun-Keu uplift; (4) Kharbey uplift; (5) Maniuku-Yu (Engane-Pe) suture; (6) Dzela-Parus-Shor suture; (7) Rhobe-Iz uplift; (8) Sysert-Ilmenogorsk uplift; (9) Maksyutovo complex; (10) Ebeta zone; (11) Bashkirian anticlinorium (with Beloretsk metamorphic complex); (12) Taratash uplift (metamorphic complex).

angular unconformity between the strikes of the Timanian and Uralian fold-and-thrust belts in the central Urals define magnetic anomalies which can be traced to the northeastern part of the East European platform (EEP) (Fig. 4; Gafarov, 1963; Zhuravlev, 1972; Puchkov, 1975). Timanian and Uralian tectonism exposed Paleoproterozoic to Mesoproterozoic, as well as Timanian-age, metamorphic complexes mainly as nappes. These are our only access to the pre-Uralian regional crystalline basement of Eastern Baltica.

Windows to pre- and syn-Timanian processes, partly formed during Timanian tectonism, include basement complexes of the Sysert-Ilmenogorsk uplift, Taratash uplift, Marun-Keu uplift, Kharbey uplift, Enganepe suture, Dzela-Parus-Shor suture, Rhobe-Iz uplift, Ebeta zone, and the Beloretsk complex (Fig. 4). In the Sysert-Ilmenogorsk dome, metabasalts and plagiogneisses with Timanian ages of 543 ± 46 and 590 ± 20 Ma (U–Pb zircon, isotope dilution) alternate with the Paleoproterozoic Selyankino formation (2083 ± 54 Ma, U–Pb zircon, isotope dilution; Krasnobaev et al., 1998; Institute of Geology and Geochemistry, 2002). The Archean to Paleoproterozoic Taratash complex preserves granulite facies metamorphic conditions, granite genesis associated with retrograde amphibolite facies metamorphism at ca. 2344 and 2044 Ma, later granitic intrusion at ca. 1848 Ma, and greenschist facies metamorphism from ca. 1848 to 1350 Ma (Sindern et al., 2005). The Yumaguzino suite rhyolites of the Maksyutov complexes are mid-Mesoproterozoic in age (Krasnobaev et al., 1996). Recent studies, however, suggest that some of these tectonic window complexes represent juvenile Neoproterozoic igneous protolith, without any pre-Neoproterozoic components (e.g. Glodny et al., 2004).

Unconformably overlying sediments were deposited in alluvial and shallow-marine environments in intra- and pericratonic basins (see reviews of Maslov et al., 1997; Puchkov, 1997a,b; Maslov, 2004). The early Mesoproterozoic sequence represents subalkaline magmatism synchronous with conglomerate deposition, suggesting a rift event. Mid-Mesoproterozoic strata unconformably overlie early Mesoproterozoic sequences; basal strata include voluminous bimodal volcanism and terrigenous clastic sediments, including conglomerates (*cf.* Bogdanova et al., this volume). These give way to fluviatile (braided river), littoral (black shale) and shallow-marine deposits up-section. These mid-Mesoproterozoic strata are unconformably overlain by early Neoproterozoic (Tonian) sediments that include oxidized clastic deposits with minor conglomerates, giving way to unoxidized siltstones and shales, carbonates, sandstones, laminated siltstones and shale; in the uppermost part of the section these in turn give way to predominantly stromatolitic and microphytolitic dolostones and limestones. The Tonian and Cryogenian sediments were mainly derived *from the west* and document a transition to marine facies eastward (Maslov et al., 1997 and references therein).

An important change in tectonic environment is associated with sedimentation along this margin in the late Neoproterozoic (Cryogenian) and is thought to reflect an increase in submarine relief prior to the onset of Timanian orogenesis. The conformably overlying early Ediacaran (Vendian) successions comprising sandstone and siltstone of shallow-marine and terrigenous origin, are sourced *from the southeast* and deposited into a shallow-marine basin(s) on the eastern margin of Baltica (Maslov et al., 1997). The late Ediacaran sediments preserve thick, repeating packages of monotonous subgreywackes and proximal grainflow deposits.

Neoproterozoic subalkaline volcanic rocks occur in both the Kvarkush and Bashkirian anticlines. In the Kvarkush region, which represents the shelf region of the Neoproterozoic EEP, volcanic and intrusive rocks have a fragmentary distribution, a more alkaline trend, and are Cryogenian to Ediacaran in age, i.e., isotopic ages between ca. 672 and 608 Ma. The volcanogenic series includes basalt, trachybasalt, trachyte, trachyrhyolite, trachyandesite-basalt, augitite, limburgite, essexite- and picrite-diabase (Ablizin et al., 1982; Smirnov et al., 1977; Stratigraphic schemes of the Urals, 1993; Zoloev et al., 2001; Petrov et al., 2004). They are accompanied by alkaline gabbro, picrite, and ferrugineous ultramafic intrusions. Late Cryogenian–Ediacaran volcanism concludes with carbonatites and non-diamondiferous kimberlites associated with the alkaline basaltic rocks (Zilberman et al., 1980). Subalkaline volcanic rocks in the eastern limb of the Bashkirian anticlinorium include subalkaline basalts, trachybasalts and rare trachyandesites and trachydacites. Their association with tillite-like conglomerates suggests a late Cryogenian–Ediacaran age.

From the northernmost Urals to the southern Urals, fragmentary evidence for Neoproterozoic oceanic crust and subduction along the eastern edge of Cryogenian–Ediacaran Baltica exists. In the north, the 670 Ma Enganepe ophiolite documents oceanic spreading, subsequent intra-oceanic subduction, and ultimately later accretion during Timanian orogeny (Dushin, 1997; Khain et al., 1999; Scarrow et al., 2001). South of Enganepe in the southernmost Polar Urals, the age of the Parus-shor meta-ophiolite complex is unknown, but the lack of geological relationships with Paleozoic strata (Puchkov, 1993) does not exclude a Neoproterozoic age. Situated nearby, the ca. 580 Ma Dzela complex represents residual oceanic lithospheric mantle, partial melt derived from it and seafloor basalt (Remizov and Pease, 2004). A Neoproterozoic suture zone may be located immediately to the south, where granites and related volcanic and intrusive rocks are described (Goldin et al., 1999). Recently, the granites have been recognized as comprising both I- and A-type, with the former attributed to a 695–510 Ma suprasubduction-collisional volcano–plutonic series (Kuznetsov et al., 2005). Still further south in the Kvarkush anticline, Timanian tectonism culminated with blueschist facies metamorphism at ca. 540 Ma (Beckholmen and Glodny, 2004).

These data indicate that a dramatic change in the tectonic evolution of the eastern region of Baltica took place, from extension in the Cryogenian–early Ediacaran to convergence in the Ediacaran (Vendian) (Puchkov, 1997a,b, 2000; Giese et al., 1999; Scarrow et al., 2001). Eastern Baltica's passive margin platform was converted to an active ocean–continent convergent margin in the late Neoproterozoic, i.e., the onset of Timanian orogeny. While Timanian orogeny is well documented in the Timan region to the north (see Gee and Pease, 2004 and references therein), it has been a subject of debate further south (e.g. Ivanov and Rusin, 2000; Rusin, 2004). That said, this change from an extensional to convergent regime is recorded across Baltica's eastern region: (i) fold and thrust tectonics are well documented by a pre-Paleozoic unconformity traced along the entire western slope of the Urals, and it is evident that the structural trends of the Timanian and Uralian fold belts do not coincide (Fig. 4); (ii) Cambrian strata are almost absent in the Urals (Stratigraphic schemes of the Urals, 1993); (iii) Ediacaran (Early Vendian) sediments, in contrast to the older Neoproterozoic sediments, are represented by polymict molasse (Ablizin et al., 1982; Willner et al., 2001, 2003, 2004); (iv) Orogeny was accompanied by regional greenschist metamorphism which is traced continuously along the deformation front of the Timanides, with amphibolite and even lower-eclogite facies metamorphism recorded locally (Getsen et al., 1987; Rusin et al., 1989; Glasmacher et al., 2001; Alexeev et al., 2002; Rusin, 2004; Lorenz et al., 2004).

After Timanian orogeny a new period of uplift took place, which explains the almost complete absence of Cambrian sediments in the Urals. At the beginning of the Uralian orogenic cycle, Late Cambrian to Early Ordovician rifting across the eastern edge of the EEC was roughly parallel to the regional trend of Timanian orogeny (Puchkov, 1997a,b; Pease and Gee, 2003). This may explain why deeper marine facies of the Cryogenian EEP (e.g. slope turbidites) in the southern Urals are absent, whereas they are well preserved to the northeast in the Timan–Pechora region. The Late Cambrian to Early Ordovician rifted margin predetermined the 'Uralian' trend of subsequent collisional deformation.

During Uralian orogenesis, subduction of the EEC resulted in eclogite facies metamorphism of both platform sediments (e.g. Maksyutov complex; Schulte and Sindern, 2002 and references therein) and Timanian-age igneous complexes (Marun-Keu; Glodny et al., 2004). The Maksyutov metamorphic complex is predominantly metasediment derived from the detritus of Baltica's crystalline basement. Most isotopic dates record Uralian subduction-exhumation at ca. 380–370 Ma (Glodny et al., 2002; Schulte and Sindern, 2002). Metamorphosed ultramafic rocks and metacherts, eclogites with E-MORB characteristics (Volkova et al., 2004), as well as the presence of metamorphosed melange (Lennykh and Valizer, 1999), suggest imbrication of the pre-Uralian passive margin with some ocean floor material and upper plate mantle slices during subduction for some Maksyutov rocks.

4.1. Summary

Throughout the Mesoproterozoic, coarse terrigenous sediment deposition associated with subalkaline volcanism occurred mostly within an intracratonic-type basin in the eastern part of the EEC, documenting an episodic pre-Rodinian (unsuccessful?) rift history. A change in tectonic regime occurred in the early Neoproterozoic (Tonian, late Riphean): alluvial and shallow-marine sediment deposition in a pericratonic basin environment (accompanied by subalkaline intrusions of broadly Neoproterozoic age) was followed by deposition of near-shore, semi-mature clastic sediments and shallow-marine carbonate sediments. Thus, in the Cryogenian when Baltica was part of the Rodinia–Pannotia supercontinent, its eastern region was an ocean-facing volcanic passive margin. It remained a passive margin during Rodinia–Pannotia break-up until the onset of Timanian orogenesis at ca. 615 Ma. Collision and island arc accretion document the change from an extensional to a compressional regime in the Ediacaran.

5. The southern region of Baltica: pre-Cadomian (?)

The southern region of the eastern European continental landmass consists mainly of a thick platform of Ediacaran (Vendian) and younger sedimentary rocks overlying Precambrian base-

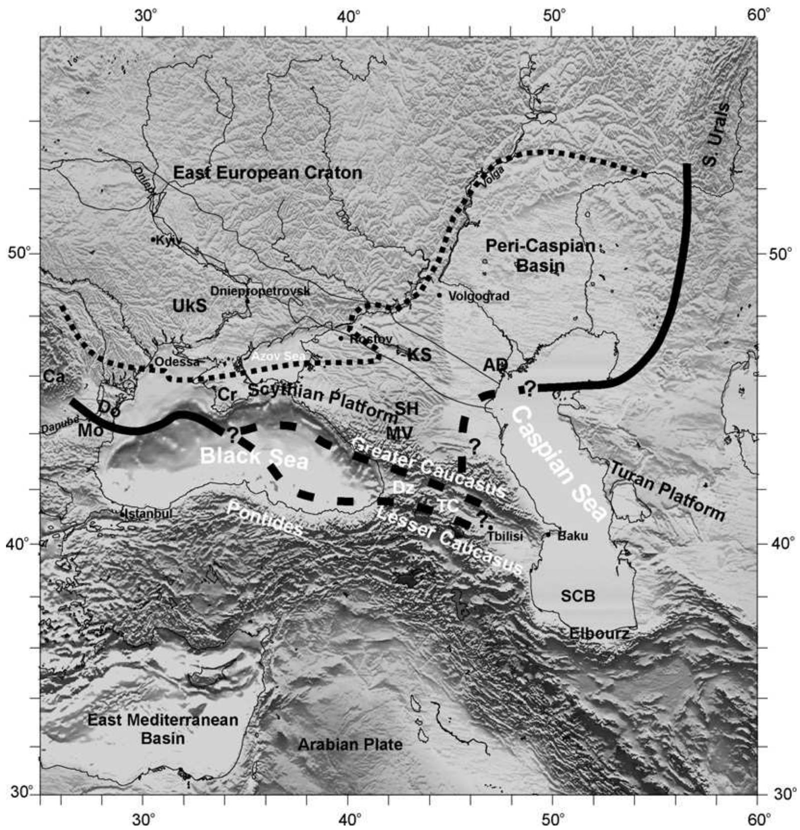

Fig. 5. The southern margin of Baltica. Black dotted line, southern limit of the East European Craton (northeast of the Karpinsky Swell) (after Nikishin et al., 1996); thicker black solid and dashed line, possible southern limit of Cryogenian Baltica as discussed in the text. AD, Astrakhan Dome; Ca, Carpathian Belt; Cr, Crimea; Do, Dobrogea; Dz, Dzirula Massif; KS, Karpinsky Swell; Mo, Moesia; MV, Mineralnie Vody Dome; SCB, South Caspian Basin; SH, Stavropol High; TC, Transcaucasus; UkS, Ukrainian Shield.

ment. In part, this defines the EEP, where the sedimentary successions overlie the crystalline crust of the EEC. Fringing the EEP to the south, in southwestern Ukraine, Crimea, and in the North Caucasus, is a related physiographic platform called the Scythian Platform (SP) (Fig. 5). The sedimentary successions overlying the SP are generally thicker than those of the EEP and contain more post-Paleozoic units. For this reason the crust underlying the SP has traditionally been thought to be younger than that of the EEP. The SP is a key zone for understanding the evolution of the southern region of Baltica. Its basement, however, is buried beneath 5–12 km of Paleozoic to Quaternary sedimentary cover, resulting in a significant lack of data on the nature, structure, and evolution of the SP (*cf.* Stephenson et al., 2004). Accordingly, the SP basement (and the adjacent southern EEP) is poorly known and hence the southern margin of Baltica is poorly investigated compared to its other margins. There are few available subsurface data characterising the Paleozoic and Mesozoic successions in the area and even fewer for the basement underlying the EEP and SP and adjacent North Dobrogea-Crimea-Greater Caucasus (-Pontides) deformed belt.

The SP is classically considered to be a wide Variscan belt between the EEC and the Alpine-Cimmerian folded belts on its southern border, referred to as the 'Scythian Orogen' (Milanovsky, 1987; Zonenshain et al., 1990 and others). Active orogenesis supposedly occurred from Early Carboniferous to Permian times (Stampfli and Borel, 2002; Nikishin et al., 1996, 2001), with a platform stage of development in the Mesozoic (Muratov, 1979). As such, it has often been considered to be the link between the Variscan orogenic system of western and central Europe and the Uralian belt at the eastern edge of Baltica. According to this model, the southernmost EEP was the passive margin of Baltica from the Cambrian until collision and accretion of SP crust in the Late Paleozoic. Natalín and Şengör (2005), while retaining the stance that an active Late Paleozoic orogenic belt resided south of the EEC in the area of the present Black Sea northern margin, consider that it was initially quite narrow, broadening later (Permian–Jurassic) as other narrow continental fragments were stitched onto it in a gigantic zone of dextral transpression. While it is not possible to reject such a model, the evidence that the basement crust of the SP comprises even a narrow Late Paleozoic (Variscan) accretionary orogenic belt is poor (Stephenson et al., 2004; Saintot et al., 2006). Indeed, if the basement of the SP was consolidated during the Late Paleozoic, this basement and overlying pre-Early Carboniferous sedimentary strata should display intense and penetrative deformation (and concomitant metamorphism) of this Paleozoic age but there is no observed evidence for this at all. What is reported as Variscan metamorphism in the SP is low-grade, not higher than greenschist facies, with sedimentary layering intact (Khain, 1975; Adamia et al., 1981). It is most easily interpreted in terms of simple sedimentary burial. Furthermore, the geophysical structure of SP lithosphere and crust has a greater affinity with the

EEC than with the Variscan belt of western Europe. Both crust and lithosphere are thicker than Phanerozoic terranes in western Europe (e.g. Yegorova and Starostenko, 2002; Stephenson et al., 2004). Accordingly, the nature and evolution of the SP needs to be placed in the context of Neoproterozoic–Early Paleozoic (pre-Variscan) tectonic events affecting Baltica. Indeed, many previous authors have considered the SP to be a part of Baltica, reworked by Late Proterozoic and younger tectonism (*cf.* Kruglov and Cypko, 1988; Gerasimov, 1994; Yudin, 1995; Milanovsky, 1996; Shnyukov et al., 1997; Stephenson, 2004).

The tectonic unit north of North Dobrogea (the Pre-Dobrogean Depression) is generally referred to as part of the SP (e.g. Sandulescu, 1990), though its basement could be older. Granites, diorites and gabbros are reported that apparently yield Cryogenian and Ediacaran K–Ar ages (790 and 640–620 Ma; Belov et al., 1987), perhaps part of a widespread magmatic event throughout the EEC around this time related to intracratonic rifting (e.g. Bogdanova et al., 1996). The crystalline basement is overlain by what appear to be Ediacaran passive margin and younger sedimentary rocks, thickening to the southwest. Obviously, what is called the SP north of North Dobrogea is a remnant of the latest Precambrian–Early Paleozoic passive margin of Baltica. Baltican crust, however, probably extends further south to somewhere in the northern Moesian Platform, south of North Dobrogea. The paleogeography and crustal affinity of the Moesian Platform is a matter of debate (e.g. Winchester et al., 2006). The basement of its northern part (referred to as Central Dobrogea) and North Dobrogea display lower grades of Neoproterozoic metamorphism than the Moesian basement cropping out in the Carpathian belt, along strike with the southern Dobrogean segment of the Moesian Platform (Haydoutov and Yanev, 1997; Seghedi, 1998 and references therein; Crowley et al., 2000; Seghedi et al., 2000, 2003). The latter segment is thought to be derived from the Cadomian arc (e.g. developed along the Gondwanan margin) and, as such, it follows that the northern part of Moesia (Central and Northern Dobrogean basement) likely formed a part of Baltica's Late Proterozoic passive margin, whereas the southern part of Moesia consists of a subsequently accreted Gondwana-derived terrane (*cf.* Saintot et al., 2006). The suture lies perhaps in the vicinity of the Capidava-Ovidiu Fault Zone (Romania), which marks a significant lateral change in crustal–upper mantle velocity structure according to recent refraction seismic data (Hauser et al., 2001). The likely affinity of crust of the Istanbul Zone (western Pontides) in western Turkey with that of the southern part of the Moesian Platform (e.g. Ustaömer, 1999; Chen et al., 2002) indicates that the eastern prolongation of this part of the Cryogenian Baltica margin lay somewhere within the present-day western Black Sea Basin or its northern shelf.

The Crimean segment of the SP has a heterogeneous basement consisting of metamorphic late Precambrian and some Paleozoic rocks overprinted by Mesozoic deformation (Garetsky, 1972; Kruglov and Cypko, 1988; Nikishin et al., 2001). The metamorphic complex has been sampled in wells that penetrate overlying Mesozoic–Cenozoic sediments on structural highs (Muratov, 1969; Shnyukov et al., 1997; Kruglov and Cypko, 1988). These 'North Crimean' Precambrian highs developed during Cryogenian rifting, thus implying that crustal consolidation occurred as early as the Mesoproterozoic (Chekunov, 1994; Milanovsky, 1996). Greenschist metamorphism is thought to be Neoproterozoic in age (Khain, 1985, 1994; Milanovsky, 1996). The basement of the (Mesozoic–Cenozoic) Crimean Foldbelt, adjoining the SP to the south on the Crimean Peninsula, is unknown; although very speculative, this crust may comprise a Paleozoic–Triassic accretionary complex (Stephenson et al., 2004). It is underthrust by thinned continental crust of the Mid-Black Sea Rise that is typically correlated (as a conjugate margin of the eastern Black Sea Basin; Stephenson et al., 2004) with the offshore prolongation of the western Georgian Transcaucasus, discussed below.

The SP basement of the central north Greater Caucasus is uplifted as the Stavropol High (SH) and exposed on the Mineralnie Vody Dome, as well as further to the south in the main range of the Greater Caucasus. Precambrian and Early Cambrian metamorphism and magmatism (Letavin, 1980; Milanovsky, 1987) is related to the so-called 'Baikalian' orogeny (Khain, 1975, 1994), though strictly speaking we prefer to restrict this terminology to events associated with southern Siberia. In the northern Greater Caucasus belt itself, isotopic (Rb–Sr) dates suggest a Neoproterozoic age for metamorphism (790 Ma; Belov, 1981) and mantle/subduction-type granitoid magmatism (700–600 Ma; Khain and Leonov, 1998). This crust is correlatable with the basement of the SH on the basis of potential field data (in particular, magnetic anomalies; *cf.* Kostyuchenko et al., 2004).

Little can be said about the crustal affinity of the basement of the Peri-Caspian Basin. It is generally considered to be Precambrian although Zonenshain et al. (1990) hypothesised that it comprised Devonian oceanic crust (*cf.* Stephenson et al., 2006). The basement of the Astrakhan Dome, a structural high in the southern Peri-Caspian Basin, is consistently interpreted as Precambrian in age from numerous integrated seismic and potential field studies (e.g. Kostyuchenko et al., 2004; Yegorova et al., 2004), though it is not known whether it is Neoproterozoic or older. A 10 km-thick, anomalously high-velocity, lower crustal body lies beneath the Peri-Caspian Basin (e.g. Brunet et al., 1999; Volozh et al., 2003 and references therein). Rejecting earlier models in which it was generated by rifting (e.g. Lobkovsky et al., 1996), Volozh et al. (2003) interpreted it as an eclogitic lens emplaced during Baikalian-age Proto-Urals subduction/orogenesis. This implies that the basement of the Peri-Caspian Basin would be Neoproterozoic in age.

The basement of the Dzirula terrane of the western Georgian Transcaucasus, south of the Greater Caucasus belt, can be correlated with the Mid-Black Sea Rise to the south of Crimea. It is characterized by high-grade metamorphism and significant magmatism. It is interpreted as a Neoproterozoic Arc Accretion Complex (Zakariadze et al., 2001), with Sm–Nd ages ranging from 810 ± 100 to 657 ± 78 Ma (Zakariadze et al., 1998). It can be either a Gondwana/Cadomian-derived terrane as shown in recent plate reconstructions (*cf.* Golonka, 2000; Stampfli and Borel, 2002) or a Baikalian-age terrane as described in the Russian literature (Khain, 1985, 1994; Milanovsky, 1987, 1996). Thus, its precise Neoproterozoic affinity is at best speculative.

The similarities between the Late Proterozoic of the Greater Caucasus (described above) and the Transcaucasus imply that the latter could be Baikalian-age, i.e., accreted to Baltica in the Neoproterozoic. Alternatively, as a Cadomian terrane, it could be the eastern prolongation of a Moesia–Istanbul Zone lithospheric block, implying the presence of a Paleozoic suture zone somewhere between the Greater Caucasus and the Transcaucasus. In either case, it remains problematic to link the boundary from this area north to the eastern edge of the Peri-Caspian Basin and southern Urals. The kinematic model of Natalín and Şengör (2005) assumes that the Turan and Scythian plates are contiguous, although it is also commonly implied that they are distinct (*cf.* Brunet et al., 1999; Volozh et al., 2003), with some kind of suture presumably between them in the area of the present Caspian Sea. Garzanti and Gaetani (2002), based on stratigraphic, sedimentological, and petrographic studies on the Turan Platform in western Turkmenistan, envisaged a model in which the Turan basement was contiguous with only the easternmost part of the North Caucasus SP and this is what is tentatively shown here (Fig. 5). There is also the suggestion of a change of crustal structure in the North Caucasus SP (considerably thinner to the east) along a roughly N–S boundary (Kostyuchenko et al., 2004) coinciding with the line shown in Fig. 5.

5.1. Summary

Southern Baltica in the Cryogenian included all of the crust that is referred to as the Scythian Platform (SP) in southern Ukraine and Russia, and very likely underlies most of what is now the Peri-Caspian Basin. To the southwest it likely extended beyond North Dobrogea to include the northern part of the Moesian platform crust, on a margin that was subsequently developed during Rodinia–Pannotia break-up. The eastern extension of Baltica's Cryogenian margin lay somewhere within the present-day western Black Sea Basin or its northern shelf. Although the nature of the basement of the Crimean Foldbelt is unclear, the thinned crust of the Mid-Black Sea Rise may have been contiguous with Baltica since at least the time of Baikalian-age orogenesis, given its correlation with the Dzirula terrane of the western Georgian Transcaucasus, and assuming that the latter is indeed a Baikalian-age terrane. Alternatively, if the Dzirula has Cadomian affinity, the southern Cryogenian margin of Baltica may coincide with a Paleozoic suture somewhere between the Greater Caucasus and the Transcaucasus and, westwards, along the northern margin of the eastern Black Sea. The link between the Caucasus and the eastern boundary of Cryogenian Baltica in the Peri-Caspian Basin-southern Urals area is problematic. The possibility that a fragment of southeastern Cryogenian Baltica separated during late Paleozoic rifting and now lies in an unknown location cannot be excluded.

6. The southwestern region of Baltica: pre-Avalonian

The southwestern region of Baltica (e.g. the southwest EEC) has been the subject of many investigations, which over the past 15 years have focused on the Trans-European Suture Zone, TESZ (Fig. 1). Recent overviews of the nature, age and geometry of this structure(s) are provided by Pharaoh et al. (2006), Winchester et al. (2006), and Lyngsie and Thybo (2007). The TESZ defines the SW margin of the EEC, where the edge of the thicker and colder lithosphere of the Precambrian Baltic Shield meets the Paleozoic accretionary complexes of the central European mobile belts (e.g., Avalonian and Variscide terranes). The nature of this margin has been constrained, despite being buried beneath thick sedimentary cover of predominantly Permian to Cenozoic age, using geophysical techniques such as deep seismic reflection and refraction, teleseismic tomography, magnetotellurics, and gravity and magnetic potential field modeling, combined with borehole data.

The TESZ, a 400 km wide WNW-ESE trending tectonic boundary over 2000 km long stretching from the Black Sea to the North Sea coast (Gee and Zeyen, 1996; Pharaoh, 1999), comprises several major lineaments (e.g., the Sorgenfrei-Tornquist, Teisseyre-Tornquist, and Elbe lineaments). The 3D continuation of these lineaments can be traced beneath the surface and define planar structures which dip more steeply than the tectonic boundaries associated with Paleozoic accretionary complexes. Consequently, the TESZ likely records Paleozoic (and younger) reactivation(s) of an older structure(s).

Crystalline basement of the EEC near the TESZ is known from exposures in the Scandinavian part of the Baltic Shield and in the southeast from drillcores in Poland (Fig. 1). Paleo- to Mesoproterozoic basement (e.g. Bingen et al., 1998; Valverde-Vaquero et al., 2000; Mansfeld, 2001; Krzeminska et al., 2005) of the EEC is overprinted by later orogeny at ca. 1.5–1.4 Ga (the Gothian or Danopolonian orogeny) and/or at ca. 1.2–0.9 Ga (the Sveconorwegian orogeny, the Grenvillian time-equivalent) (*cf.* Bogdanova et al., this volume). These episodes of Proterozoic amalgamation, overprinted by late Precambrian extension, presumably reactivated Sveconorwegian basement shear zones (Lassen et al., 2001; Lassen and Thybo, 2004). The seismic character of this crust is well constrained from samples. In addition, offshore boreholes south of the TESZ reach crystalline basement with K–Ar ages of 880–825 Ma (Larsen, 1971; Frost et al., 1981; MONA LISA Working Group, 1997), which probably represent post-Sveconorwegian thermal cooling ages. Geophysical data suggest that the basement of southwestern Baltica extends ca. 150–400 km southwest of the TESZ as a tapering wedge beneath Paleozoic accretionary terranes (e.g., East Avalonia; Pharaoh et al., 2006; Lyngsie and Thybo, 2007). Extensional horst and graben structures are also well-imaged within the basement southwest of the TESZ (Lassen et al., 2001; Grad et al., 2002; Sroda et al., 2002; Lyngsie and Thybo, 2007) (Fig. 6).

Sediments of the EEP, flat-lying and essentially unmetamorphosed, are known from drillcores in the Lublin Slope region of Poland (Fig. 1). In this area, Paleoproterozoic crystalline basement is overlain by probably continental conglomerates and hematitic arkosic sandstones of the Polesie Formation (Moczydlowska, 1995 and references therein). The Polesie Formation, initially regarded as Neoproterozoic, has also been correlated with the Mesoproterozoic Jotnian sandstones on the Baltic Shield (Moczydlowska, 1995). Consequently its age is not confidently known.

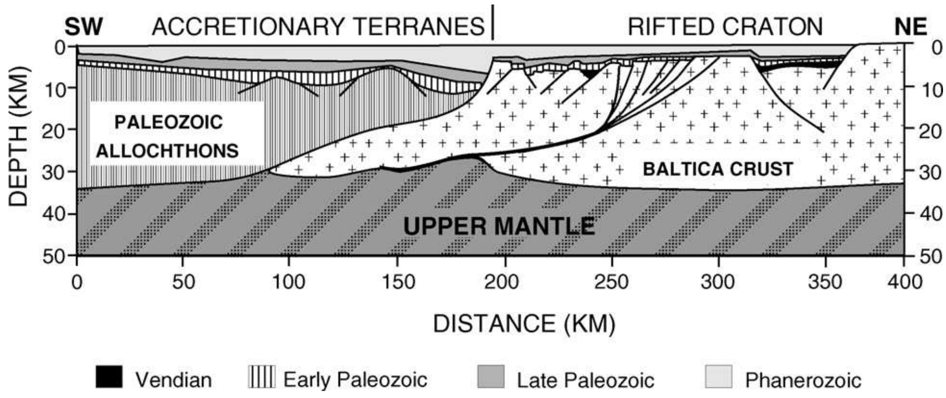

Fig. 6. Schematic profile across the southwestern tectonic margin of Baltica (after Pharaoh et al., 2006; Lyngsie and Thybo, 2007). Note the inferred depth and extent of Baltica's Precambrian basement, as well as the superimposed late Precambrian (Vendian) extensional deformation preceding Paleozoic accretion.

Ediacaran (predominantly Vendian) sedimentation followed a depositional hiatus (Vidal and Moczydłowska, 1995). The Cryogenian of southwest Baltica records a period of uplift and erosion, with no known rocks or sediments of this age. Basalts, tuffs, agglomerates, sandstones, and polymict conglomerates of the terrigenous Sławatycze Formation unconformably overlie the Polesie Formation *or* lie directly upon crystalline basement (Moczydłowska, 1995; Vidal and Moczydłowska, 1995). The lower Sławatycze Formation represents fluvial conglomerate and debris flow deposition in a braided delta environment. Lavas and tuffs of the upper Sławatycze Formation are ca. 550 Ma (^{206}Pb/^{238}U age; Compston et al., 1995) and the thick basalt flows comprising a major part of the section are probably correlative with Volynian trap magmatism of Ukraine (Vidal and Moczydłowska, 1995; Elming et al., 2007). Volynian-related magmatism is interpreted to reflect aborted intracratonic rifting along the Paleoproterozoic suture between the Ukrainian and Baltic shields (Compston et al., 1995). Mudstones of the upper Sławatycze Formation are transitional to arkoses and sandstones (Siemiatycze Formation), and shallow-marine sandstones, siltstones and shales (Bilopole Formation). In some locations, the Siemiatycze Formation lies directly upon basement.

The Sławatycze, Siemiatycze, and Bilopole Formations reflect sedimentation on an epicontinental shelf; these grade upward into alternating silty and argillaceous rocks of the Lublin Formation, which in turn grade into the poorly sorted sandstones (with minor mudstone and argillite) of the Włodawa Formation (Vidal and Moczydłowska, 1995, and references therein). The Włodawa Formation of Poland, as well as several formations in Ukraine (Moczydlowska, 1991 and unpublished data), preserves siliciclastic deposits which contain late Neoproterozoic (ca. 600–545 Ma) fossils of cyanobacteria, acritarchs, and vendotaenids. Consequently, the Ediacaran southwestern Baltica succession was initially deposited in a continental environment which gradually changed to the shallow-marine environment of Baltica's shelf region during the Ediacaran to Middle Cambrian.

Of the lineaments comprising the TESZ, only the Teisseyre-Tornquist in Poland might actually represent part of the original Neoproterozoic passive margin architecture of the EEC (Pharaoh et al., 2006). If true, this older structure (the 'proto-TESZ') extended from Denmark to Poland. This ancestral structure may be an Edicaran-aged rift and the evidence for this is as follows:

(i) Rifting of Baltica from Rodina-Pannotia occurred before Cambrian time as indicated by the truncation of Sveconorwegian age (and older) structures and deposition of Cambrian deposits on the passive margin elsewhere in the EEC (Poprawa et al., 1999; Šliaupa et al., 2006).
(ii) Cryogenian–Ediacaran rifting of Baltica (at least its Fennoscandian part) from Rodinia-Pannotia is supported by sparagmite basins (Kumpulainen and Nystuen, 1985) and tholeiitic dike intrusion throughout the inferred paired rift margins of Baltica and Laurentia (Andréasson et al., 1998).
(iii) Similar age rift basins are present in the EEC, e.g. basins of eastern Poland (Compston et al., 1995; Oaie, 1998) and Ukraine which contain the Volyn trap magmatism (Vidal and Moczydłowska, 1995).
(iv) Anomalously low velocity (P-wave velocity ca. 5.8 km/s) material at mid-crustal levels beneath strata not older than latest Carboniferous or Permian age (Grad et al., 2002) may represent Neoproterozoic rift-related fill. Alternatively, it could represent thick earlier Paleozoic basins as young as Devonian–Carboniferous age.
(v) From the depositional history of sedimentary basins, Ediacaran (Vendian) continental break-up/rifting progressed from the south to the northwest (Šliaupa et al., 2006).

Rifting of Baltica's Cryogenian southwest margin in the late Neoproterozoic resulted in deposition of Ediacaran passive margin sediments, possibly on basement within half-graben structures (Fig. 6). However, it is also possible that late Paleozoic (post-Avalonian) rifting may have resulted in brittle, extensional reactivation of pre-existing shear zones (Scheck et al., 2002; Pharaoh et al., 2006) and that sediment in these half-graben structures represent thick Paleozoic deposits. By the end of the Cambrian, the Paleozoic accretionary terranes of the southern EEC had begun to amalgamate (Winchester et al., 2006).

6.1. Summary

The southwestern region of Baltica comprises Paleo- to Mesoproterozoic crystalline basement reworked during Mesoproterozoic and early Neoproterozoic orogenic events. Geophysical data suggests it extends 165–400 km southwest of the TESZ beneath the allochthonous terranes accreted in the Paleozoic. The Cryogenian, i.e., post-820 Ma, geologic record is poor. The correlation and age of the Polesie Formation, resting conformably on Paleo-to-Mesoproterozoic basement, is critically important for determining whether southwest Baltica records a period of Cryogenian uplift and erosion. Following a depositional hiatus, Ediacaran shelf sediments were deposited on southwest Baltica's passive margin. Subsequently, the amalgamation of accretionary terraines along this margin occurred in the Paleozoic.

7. Paleogeography of Baltica in the Cryogenian

Paleomagnetism is useful for the study of past movements of continental blocks and plates, and for the assembly of supercontinents. Paleomagnetic data, however, can generally only be used to define latitudinal position and orientation, and other constraints are needed for the reconstruction of configuration and break-up of supercontinents. Paleontological data is an example of such a constraint. Paleomagnetic and paleontological data are combined below to constrain the position of Baltica within a Rodinia framework.

7.1. Paleomagnetic constraints

For tectonic reconstructions of the Rodinia Supercontinent in Neoproterozoic time, paleomagnetic poles for Baltica are still sparse. From 750 to ca. 500 Ma the apparent pole positions for Baltica can be restricted to nine more or less well-defined poles (Elming et al., 2007). A Neoproterozoic (750 Ma) mean pole has been calculated by Torsvik et al. (1996) and with decreasing age this is followed by the Egersund pole (616 Ma; Poorter, 1972; Storetvedt, 1966; Bingen et al., 1998), the A- and B-poles of Ukrainian trap magmatism (ca. 580, 580–561, and 582–545 Ma, respectively; Elming et al., 2007; Nawrocki et al., 2004), the Fen pole (583 Ma; Piper, 1981; Meert et al., 1998), the Z-pole of the Winter Coast (555 Ma; Popov et al., 2002), the Zolotica 2 and Stappogiedde poles (550 Ma; Llanos et al., 2005), the pole of the Dividal Group (535 Ma; Rehnström and Torsvik, 2003), and the pole of the Andarum limestone (ca. 500 Ma; Torsvik and Rehnström, 2001). The A-poles of the Ukrainian traps and the pole of the Fen Complex are coeval but have very different positions. The age of the Fen Complex seems very well defined, while the similarity in the position of its pole with the Permian pole for Baltica may suggest a Permian overprint. The ca. 555 Ma Z-pole, and Zolotica and Stappogiedde poles are similar to a pole that Elming et al. (C-pole; 2007) interpreted as secondary, of Late Ediacaran or Devonian age. Popov et al. (2002) and Llanos et al. (2005) suggested an apparent polar wander path for Baltica with a different selection of poles, and polarities of the 550–555 Ma poles opposite to poles of similar age, as presented in Elming et al. (2007). Here for Baltica the A-poles of the Ukrainian traps, which are located on the northern hemisphere not far from the Egersund pole, are chosen to represent a magnetization of ca. 580 and 580–561 Ma, followed by the 580–545 Ma B-poles of the traps, the 535 Ma Dividalen and 500 Ma Andarum poles.

In modeling Rodinia break-up, the 750–535 Ma poles chosen for Baltica can be compared with Laurentian poles of corresponding age. For this comparison, the North American reference poles (Meert and Torsvik, 2003) have been rotated into the reference frame of Baltica using the Bullard et al. (1965) fit. The pole positions at 750 and ca. 580 Ma are similar for the two continents, suggesting that Baltica and Laurentia drifted together from 750 to ca. 580 Ma. In this paleomagnetic reconstruction (Fig. 7; Elming et al., 2007), Baltica and Laurentia were joined in a similar relative position during the whole time period, but ca. 180° from that suggested in earlier reconstructions (e.g. Torsvik et al., 1996; Cocks and Torsvik, 2005). The two continents drifted from an equatorial position at 750 Ma to a high southern latitude at ca. 580 Ma and then back to shallower southern latitudes. Tillites overlain by late Neoproterozoic (early Vendian) sediments have been identified in drillcores from western Ukraine (Maknach and Veretennikov, 1976) and a global glaciation is suggested to have occurred at ca. 600 Ma on the basis of tillite studies from Belarus, western Ukraine, and western and central Russia (Veretennikov, 1998). The tectonic reconstruction of Elming et al. (2007) suggests that Baltica and Laurentia occupied high (60°–70° S) latitudinal positions during this Ediacaran glaciation, which has implications for hypotheses on the origin of global glaciation. A high obliquity elliptic for the Earth has been suggested to explain low latitude Neoproterozoic glaciation (Williams, 1975, 1993). In this model, however, glaciation is not expected at high latitudes. Consequently, the paleomagnetic results of Elming et al. (2007) do not support a high obliquity Earth model.

Volcanic trap formation in Ukraine marks initiation of rifting between southwestern Baltica and an unknown continent that may have been Amazonia, apparently requiring r-r-r rifting (Bingen et al., 1998). This rifting is suggested to have started in the south, as indicated by Ediacaran (essentially Vendian) dikes younging northward along the eastern margin of Laurentia, and resulted in the northward opening of the Iapetus Ocean by 570 Ma (Cawood et al., 2001). Rifting continued until ca. 550 Ma and the final opening is related to a large clockwise rotation of Baltica (Elming et al., 2007).

7.2. Paleontological constraints

Several rift basins (intracratonic and epicontinental shelves) developed on Baltica and Laurentia during the time interval of ca. 800–550 Ma. Siliciclastic and carbonate deposits filled these basins and preserve records of organic-walled microfossils of prokaryotic (bacterial) and protoctistic (unicellular eukaryotic) origins. These microbiota were benthic cyanobacteria, such as *Palaeolyngbya*, *Siphonophycus*, *Tortunema* and *Eoentophysalis*, and planktonic green algae (informally called acritarchs; *Leiosphaeridia*, *Chuaria*, *Octoedryxium*, *Trachyhys-*

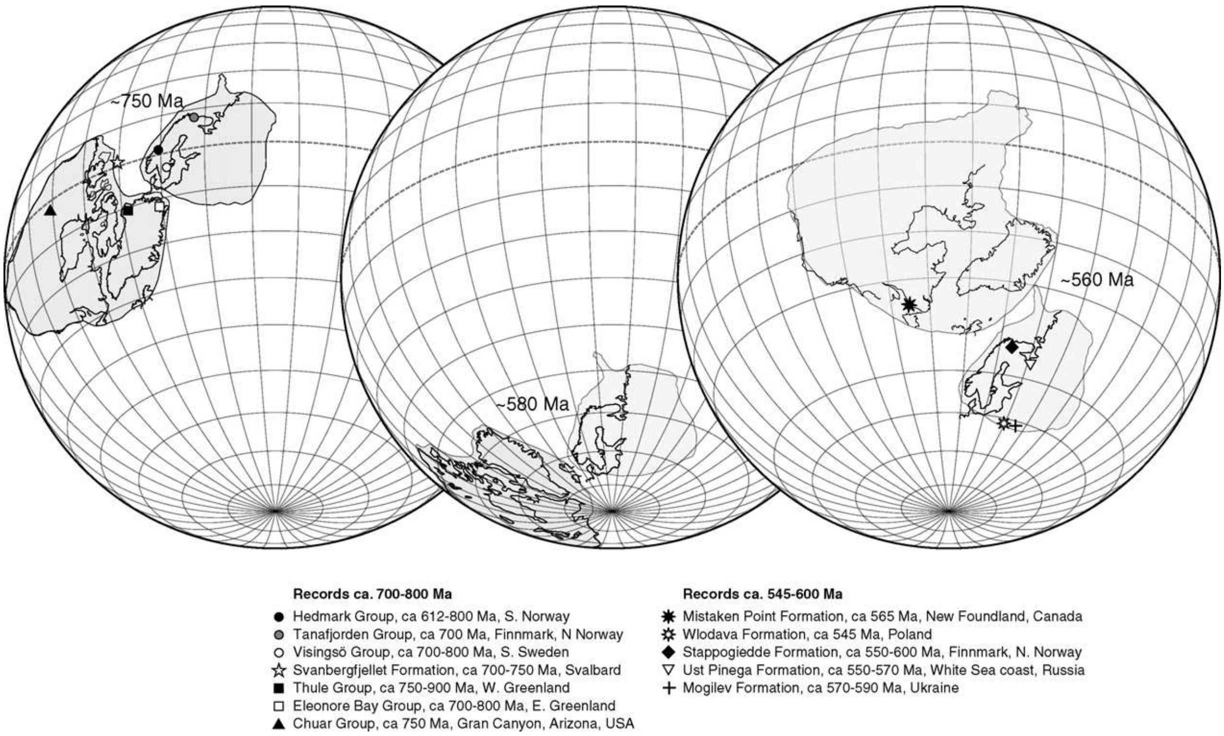

Fig. 7. The drift of Baltica and Laurentia from 750 to ca. 550 Ma based on paleomagnetic data in Elming et al. (2007) and Torsvik et al. (1996). The symbols show the occurrence of microbiotic assemblages in sedimentary successions of ca. 700–800 Ma and the location of microbiotic assemblages and the Ediacara-type metazoans in the successions of ca. 600–545 Ma (compiled from various sources and unpublished data by Moczydlowska).

trichosphaera) and thecoamoebans (vase-shaped microfossils; *Mellanocyrillium*). Some incerte sedis taxa represent also tallophytic organisms, i.e. *Valkyria*. Planktonic biota has limited significance for paleobiogeographic reconstructions, but benthic cyanobacteria are useful in deciphering the paleogeographic relationships between presently dismembered crustal blocks with respect to their original proximity and shelfal interconnections.

The records of microbiota in Baltica in the interval of ca. 800–700 Ma are from the Visingsö Group (central Sweden), and Hedmark and Tanafjorden groups (southern and northern Norway, respectively) (Vidal and Moczydłowska, 1995; Vidal and Moczydłowska-Vidal, 1997). Several taxa in these assemblages are common to those known from the Laurentian paleocontinent in the Chuar Group (Grand Canyon, Arizona, U.S.A.), Thule and Eleonore Bay groups (Northwest and central West Greenland, respectively), as well as from the Svanbergfjellet Formation (Svalbard) (Vidal, 1979; Vidal and Ford, 1985; Butterfield et al., 1994). Taxonomically comparable assemblages of microfossils, including cyanobacteria, acritarchs and vendotaenids in the time period of ca. 600–545 Ma are recorded in the Stappogiedde Formation (northern Norway), Wlodawa Formation (Poland), and in several formations in Ukraine and Podolia (Moczydlowska, 1991 and unpublished data).

These microfossils indicate a close proximity between Baltica and Laurentia during ca. 750–545 Ma and the existence of contiguous marine shelves along them, thus allowing free migration of benthic microbiota and dispersal of phytoplankton comprising cosmopolitan species, which otherwise could not cross the deep basins or oceans. The persistence of certain taxa throughout 200 Ma of geological history in shallow-marine habitats along the margins of Baltica and Laurentia supports the interpretation based on paleomagnetic data, in which close proximity and parallel drift of these continents is inferred (Elming et al., 2007; Fig. 7). The new record of the benthic multicellular microfossil *Valkyria* in the subsurface sediments of the ca. 545 Ma Wlodawa Formation in Poland (Moczydłowska unpublished data), together with several taxa of cyanobacteria, provides evidence that shelves of Baltica and Laurentia were continuously adjacent between ca. 750 and 545 Ma (Fig. 7). The existence of close proximity between shelves of Baltica and Laurentia until the terminal Neoproterozoic (Ediacaran Period) is also supported by the occurrence of some benthic species of the Ediacara-type metazoans at ca. 565–550 Ma. They are well known in the Stappogiedde Formation, Ust Pinega Formation (White Sea coast, Russia), Mogilev Formation (Ukraine), and in the Mistaken Point Formation (Newfoundland, Canada) (Sokolov and Iwanowski, 1990; Farmer et al., 1992) (Fig. 7).

7.3. Summary

Paleomagnetic data indicate that in the time interval of 750 to ca. 580 Ma, Baltica moved from an equatorial position to a high southern latitude position at ca. 580 Ma, and then moved northward to an intermediate high latitude at ca. 560 Ma. When comparing the paleomagnetic poles of Baltica with those of Laurentia, a close plate tectonic link is indicated for this time period, suggesting that the two continents drifted together in a similar relative position. This interpretation is supported by paleontological data, which show fossils of similar affinity in Baltica and Laurentia at two time periods (800–700 and 600–542 Ma) when these shields are suggested to be joined. The Baltica and Laurentia assembly then split up at ca. 550 Ma. These results suggest a late break-up for parts of Rodinia–Pannotia.

8. Conclusions

Baltica in the Cryogenian had distinct *northwestern*, *northeastern*, and *southern* tectonic margins with distinct evolutionary histories.

- The northwestern tectonic margin is characterized by Neoproterozoic to lower Cambrian sedimentary successions deposited on crystalline rocks of Archean to Mesoproterozoic age, which were remobilized during the amalgamation of Rodinia (e.g. during the Sveconorwegian) and reworked during Caledonian orogenesis. The sediments record a change from an alluvial setting to a marine environment, and eventually to a partially starved (?) turbidite basin. They document rifting from the Rodinian–Pannotian supercontinent at ca. 620–550 Ma, when the voluminous intrusion of dikes and mafic/ultramafic complexes (e.g. Seiland Igneous Province) occurred.
- The northeastern tectonic margin evolved as a passive margin throughout much of Cryogenian time, with distinctive platformal and deeper-water basin deposits. In the Timan–Pechora region, Meso- to Neoproterozoic turbidites are well preserved. In the western part of the Ural Mountains, similar age shelf deposits are exposed in the westernmost Kvarkush and Bashkirian anticlines. The shelf/basin transition along most of the eastern margin of Baltica is either concealed at depth in the footwall to the main Uralian fault or was removed from Baltica during later Ordovician rifting (associated with the formation of the Paleouralian Ocean). There is little difference between the northeastern and eastern regions of Baltica in the Cryogenian, consequently these regions together define the ocean-facing northeastern tectonic margin of Baltica. A subduction system is inferred to have developed outboard of this margin, within a pre-Timanian ocean. Baltica's Cryogenian passive margin stratigraphy gives way to accreted oceanic and magmatic-arc rocks and microcontinental slivers (?) associated with latest Neoproterozoic Timanian orogeny along the entire length of the northeastern tectonic margin.
- The southern tectonic margin of Cryogenian Baltica, predominantly buried beneath Paleozoic and younger sediments, is the most controversial. Important aspects of the southern and the southwestern regions, however, suggest a similar tectonic development in the Cryogenian. The crystalline basement of the EEC in both regions share similar geophysical features, i.e., a thicker crust and lithosphere (than adjacent Paleozoic accretionary terranes) is defined and thought to extend at depth to the south/southwest in both regions. Possible Cryogenian rifting in both regions implies crustal consolidation as early as the Mesoproterozoic, which was affected by later Proterozoic and younger tectonism. The overlying late Neoproterozoic passive margin sediments of both regions exhibit minor or low-grades of metamorphism and have intact sedimentary layering. Both regions experienced significant Paleozoic and younger accretion of allochthonous terranes.
- Paleomagnetic data from the Baltic Shield indicates that in the time interval ca. 750–580 Ma Baltica moved from an equatorial position to a high southern latitude, and then moved northward to an intermediate high latitude at ca. 560 Ma. When comparing the APWP of Baltica with that of Laurentia, a close tectonic link is indicated for this time period, suggesting that the two continents drifted together in a similar relative position. This interpretation is supported by paleontological data in which microfossils of similar affinity existed in Baltica and Laurentia at 800–700 and 600–545 Ma, time intervals when these continents are suggested to have been joined. The Baltica and Laurentia assembly then split up at ca. 550 Ma. These results suggest a late break-up for these parts of the Rodinia-Pannotia supercontinent.

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