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RESEARCH ARTICLE

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Was Baltica part of Rodinia?

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Abstract

Late Ediacaran opening of the Iapetus Ocean is typically considered to reflect separation of Baltica and Laurentia during final breakup of the Rodinia supercontinent, with subsequent closure during the Caledonian Orogeny. However, evidence of the pre-opening juxtaposition of Baltica and Laurentia is limited to purportedly similar apparent polar wander paths and correlation of Rodinia-forming orogenic events. We show that a range of existing data do not unequivocally support correlation of these orogens, and that geologic and palaeomagnetic data instead favour separation of Baltica and Laurentia as early as 1.1–1.2 Ga. Furthermore, new detrital zircon U–Pb age and Ar–Ar thermochronological data from Norway point towards an active western Baltican margin throughout most of the Neoproterozoic and early Palaeozoic. These findings are inconsistent with the majority of palaeogeographic reconstructions that place Baltica near the core of the Rodinia supercontinent.

1 | INTRODUCTION

The idea that a proto-Atlantic Ocean (later named the Iapetus Ocean; Harland & Gayer, 1972) opened sometime in the past, in essentially the same manner and location as the Atlantic Ocean (Wilson, 1966), proved pivotal to interpretations of the evolution of the present North Atlantic region. This interpretation had major ramifications for Precambrian palaeogeography in general, and reconstructions of the Rodinia supercontinent in the early Neoproterozoic in particular (Hartz & Torsvik, 2002; Hoffmann, 1991), and indeed the inferred behaviour of North Atlantic oceanic crust and plate margins throughout the Neoproterozoic (Cawood et al., 2010; McCausland et al., 2007). However, while both faunal and other geologic evidence (e.g. ophiolites and thrust sheets with high-pressure metamorphic assemblages) support the closure of this northern segment of the Iapetus Ocean at ca. 450 Ma during the Caledonian Orogeny (e.g. Bruton & Bockelie, 1980), evidence for contiguity of Laurentia and Baltica prior to 600 Ma is sparse (Robert et al., 2020). Here, we review the widely cited evidence of proximity for Baltica and Laurentia prior to late Neoproterozoic Iapetus opening and provide new data implying separation of Baltica and Laurentia from ca. 1.1–1.2 Ga until Caledonian collision.

2 | WHAT IS THE EVIDENCE FOR BALTICA–LAURENTIA PROXIMITY DURING THE NEOPROTEROZOIC?

The most cited geological argument for Baltica–Laurentia proximity during the Neoproterozoic is based on the correlation of the late Mesoproterozoic Grenvillian and Sveconorwegian orogens, with Baltica located at the nexus of Amazonia and Laurentia, sutured along the Sveconorwegian–Sunsás–Grenville orogens (Li et al., 2008). A Geological Association of Canada Special Publication edited by

Gower et al. (1990), presented a series of papers documenting a similar Palaeo- and Mesoproterozoic evolution of the SW Baltican and SE Laurentian margins, culminating in late Mesoproterozoic orogeny interpreted to reflect collision with Amazonia. More recent work on the Sveconorwegian Orogen has, however, shown that this orogeny was characterized by a lack of crustal thickening and near-continuous heating by mantle-derived magma, refertilizing the crust on time scales of 150–250 Myr (Bingen et al., 2021; Slagstad et al., 2018). These tectonic features are very different from the Grenvillian Orogeny, characterized by crustal thickening and radiogenic self-heating (Jamieson et al., 2007; Rivers, 2015), and inconsistent with late Mesoproterozoic continent-continent collision at the SW Baltican margin (Slagstad et al., 2020). The Neoproterozoic evolution of western Baltica is poorly constrained but was dominated by widespread deposition of clastic sediments and intermittent, rift-related magmatism (Siedlecka et al., 2004; Nystuen et al., 2008; see also Figure 1).

Palaeomagnetic reconstructions of Rodinia are inherently poorly constrained given later metamorphic overprinting (Meert & Torsvik, 2003; Torsvik, 2003). Historically, the late Mesoproterozoic–early Neoproterozoic proximity of Baltica and Laurentia was accepted based on a rather vague similarity of the Grenvillian and Sveconorwegian segments of the respective apparent polar wander paths (APWPs) (e.g. McWilliams & Dunlop, 1978; Piper, 1980; Piper, 2009). More recent analyses of available palaeomagnetic data, however, indicate that direct comparison of the APWPs for Baltica and Laurentia is problematic at best because the relevant polar tracks are only partly coeval and, with the exception of a ca. 30 Myr period, represented by the Laurentian Keweenawan track, are characterized by relatively poor data resolution with gaps in the palaeomagnetic record that in some cases exceed 100 Myr (Evans et al., 2021; Kulakov et al., 2022). Whilst detailed analysis of the relevant APWPs is beyond the scope of this paper a detailed review of APWPs for Baltica and Laurentia are given by Kulakov et al. (2022). Palaeomagnetic data imply that Baltica and Laurentia were rather distant at the peak of the Grenville–Sveconorwegian orogeny at ca. 1100–1050 Ma (Figure 2a; Li et al., 2008; Kulakov et al., 2022). Thus, an ocean must have existed at that time, separating Baltica and Laurentia.

Given sparse and highly equivocal palaeomagnetic constraints on the Baltica–Laurentia relationship through the Neoproterozoic, widely different orientations of the two continents have been proposed, even with Baltica inverted in some reconstructions (Hartz & Torsvik, 2002; McCausland et al., 2007). Figure 2b shows that Laurentia appears to have resided at low southern latitudes for a significant time interval, at least between ca. 830 and 720 Ma (Eyster et al., 2020; Maloof et al., 2006). In contrast, Baltica occupied polar latitudes at 848 ± 27 Ma (Walderhaug et al., 1999). The precise latitudinal position of Baltica between ca. 850 and 615 Ma is difficult to assess due to a lack of well-dated, high-quality palaeomagnetic data, however, the palaeomagnetic pole from the Katav formation (Pavlov & Gallet, 2009) reconstructs Baltica at low latitudes at ca. 800 Ma. However, the age of the Katav formation as well as the age of magnetic remanence is ill-defined and can fall anywhere between ca. 860 and 700 Ma (Ovchinnikova et al., 1998; Ovchinnikova et al., 2000; Pavlov & Gallet, 2009).

Significance Statement

The manuscript presents arguments against the widely held hypothesis that Baltica formed part of the core of the Rodinia supercontinent, and that the Iapetus Ocean opened at ca. 600 Ma during separation of Baltica and Laurentia. The manuscript points out obvious weaknesses in the sparse data used to argue for such a configuration and opening history, and reviews recently published and presents new data that support the presence of an active Baltican margin where Laurentia is located in most Neoproterozoic reconstructions. The alternative views presented are innovative and will almost certainly be provocative. We do, however, believe they are well founded and of broad interest to anyone working with supercontinent reconstructions and the Mesoproterozoic through Palaeozoic evolution of the North Atlantic region.

Thus, although an orientation like modern-day Baltica is by far the most favoured reconstruction, this interpretation stems largely from the poorly established correlation of the Grenville and Sveconorwegian orogens and equally poorly constrained APWPs. Thus, there is no unique geologic or palaeomagnetic support for such an interpretation. Here, we present new geochronologic data that do not require the assumption of Baltica–Laurentia proximity and, instead, appear incompatible with such a configuration.

3 | THE WESTERN BALTICAN MARGIN IN THE NEOPROTEROZOIC

3.1 | Detrital zircon geochronology

New detrital zircon data presented here (see Data Supplements S1–S3), along with earlier work in SW Norway (Sláma & Pedersen, 2015), show that late Cambrian through Middle Ordovician (par)autochthonous metasedimentary units deposited on Baltica (Figure 2) are dominated by Palaeo- through Mesoproterozoic detrital zircon grains (Figure 3a). Detrital zircon of this age is ubiquitous in metasedimentary sequences around the North Atlantic region and typically interpreted to reflect erosion from the Grenville–Sveconorwegian orogen (e.g. Kirkland et al., 2007; Krabbendam et al., 2022). In addition, Cambrian to Middle Ordovician sedimentary successions in SW Norway contain sparse 850 to 700 Ma and abundant 700 to 500 Ma zircon grains (Sláma & Pedersen, 2015; this study). εHf_t values for the Neoproterozoic grains range widely, from −27 to +13 (Sláma & Pedersen, 2015), indicating both juvenile and evolved crustal sources. Sedimentary sequences of similar

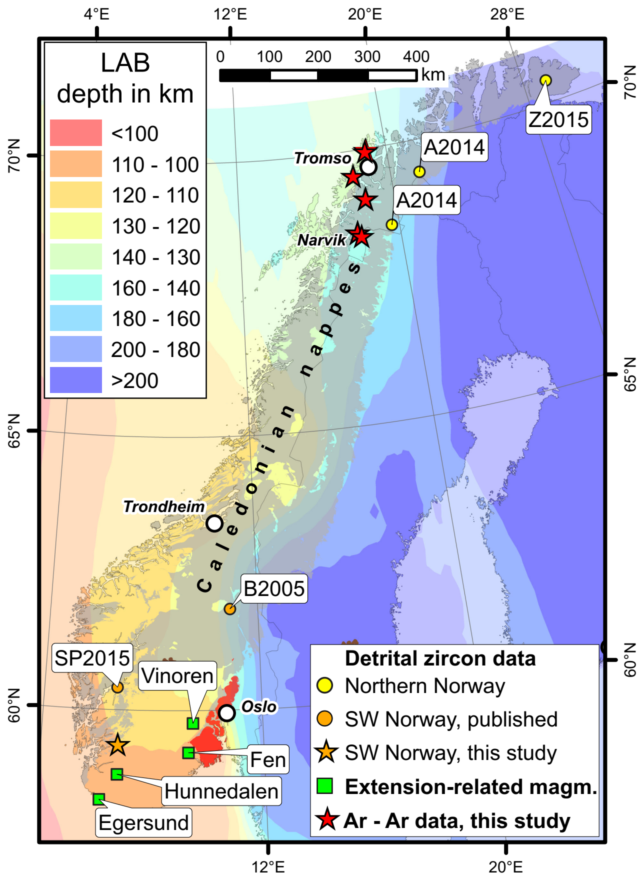

FIGURE 1 Map of Scandinavia showing Caledonian nappes in grey, overlying Precambrian basement. The coloured underlay shows depth to the lithosphere–asthenosphere boundary (LAB), based on data from Gradmann et al. (2013) and Plomerová and Babuška (2010). The locations discussed in the text are indicated. Detrital zircon locations include Varanger peninsula (Z2015, Zhang et al., 2015), Divial group (A2014, Andresen et al., 2014), SW Norway (SP2015, Sláma & Pedersen, 2015), Rendalen formation (B2005, Bingen et al., 2005) and data presented in this study. Extension-related magmatism includes the 850 Ma Hunnedalen mafic dikes (Walderhaug et al., 1999), the 686 Ma Vinoren ailikite dike, the 616 Ma Egersund dikes (Bingen et al., 1998) and the 583 Ma Fen carbonatite (Meert et al., 1998).

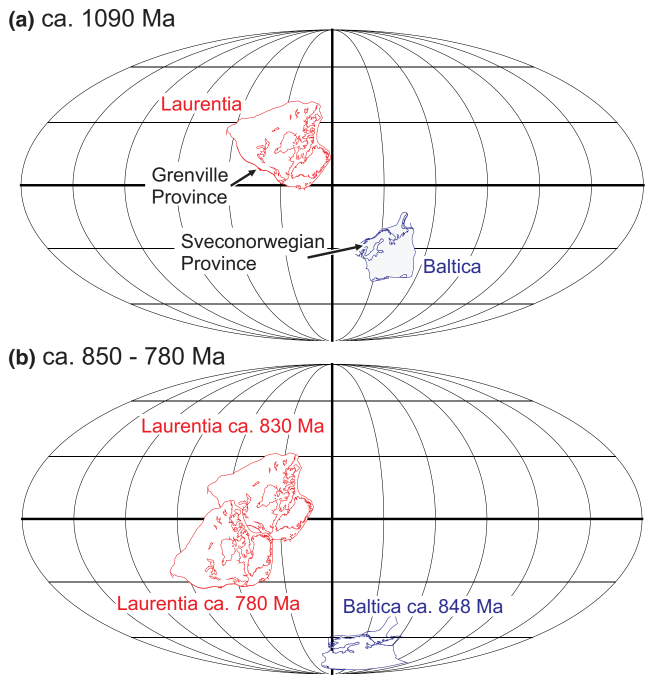

FIGURE 2 Palaeomagnetic reconstructions of Baltica and Laurentia. (a) At ca. 1090 Ma with the Sveconorwegian and Grenvillian orogenies indicated. Data from Kulakov et al. (2013) and (2022). See Kulakov et al. (2022) for details. (b) At ca. 850–830 Ma, and ca. 780 Ma based on data from Maloof et al. (2006), Walderhaug et al. (1999) and Eyster et al. (2020). Note that the 830 Ma palaeomagnetic pole of Maloof et al. (2006) was rotated to North American coordinates using rotation parameters from Torsvik et al. (2012). In addition, this pole may reflect an episode of true polar wander and needs to be treated with caution.

age in N Norway (Figure 1) yield generally fewer Neoproterozoic zircon grains with a narrower peak, ranging from 680 to 540 Ma (Figure 3b; Andresen et al., 2014; Zhang et al., 2015), with largely superchondritic εHf_t values.

Abundant 700 to 500 Ma detrital zircon grains with subchondritic to superchondritic Hf isotopic compositions in late Cambrian/Ordovician (par)autochthonous units in SW Norway suggest derivation from an active continental margin with both new mantle input and recycling of pre-existing ancient continental crust. Such an isotopic evolution pathway is consistent with the relatively short duration from zircon crystallization to deposition (Cawood et al., 2012). Earlier work discussing these Neoproterozoic detrital zircon data have argued for their derivation from the Ediacaran Timanian Orogen at the E and NE margin of Baltica (Andresen et al., 2014; Sláma & Pedersen, 2015; Zhang et al., 2015). While the Timanides record calc-alkaline magmatism as old as ca. 700 Ma, it appears that the orogenic evolution took place outboard of Baltica, with oceanic subduction away from the Baltican passive margin, driving arc magmatism at the active margin of a hypothesized Arctida microcontinent (Kuznetsov et al., 2007). According to these authors, accretion of the active margin of Arctida onto Baltica was marked by intrusion of a suite of 560 Ma syn-collisional granites. Whilst the Timanian Orogen is purported to have continued north of the Varanger Peninsula into N Norway (Figure 2), evidence of such a westward arm is lacking. We also note that the type area of Timanian Orogeny and the Varanger Peninsula are located ca. 2,200 and 1,500 km, respectively, from the study area in SW Norway. Hence, we stress that comparatively few 'Timanian'-age grains are found in N Norway parautochthonous sedimentary rocks, close to their assumed source, whereas such grains abound in sedimentary rocks in SW Norway, likely indicating a different, non-'Timanian' source for the latter. Finally, the presence of late Cryogenian–early Ediacaran grains (Figure 3a) in the Rendalen Formation underlying the pre-Squantum–Gaskiers (ca. 580 Ma; Bingen et al., 2005; Adamson, 2016) Moelv tillite (Figure 1), suggests that

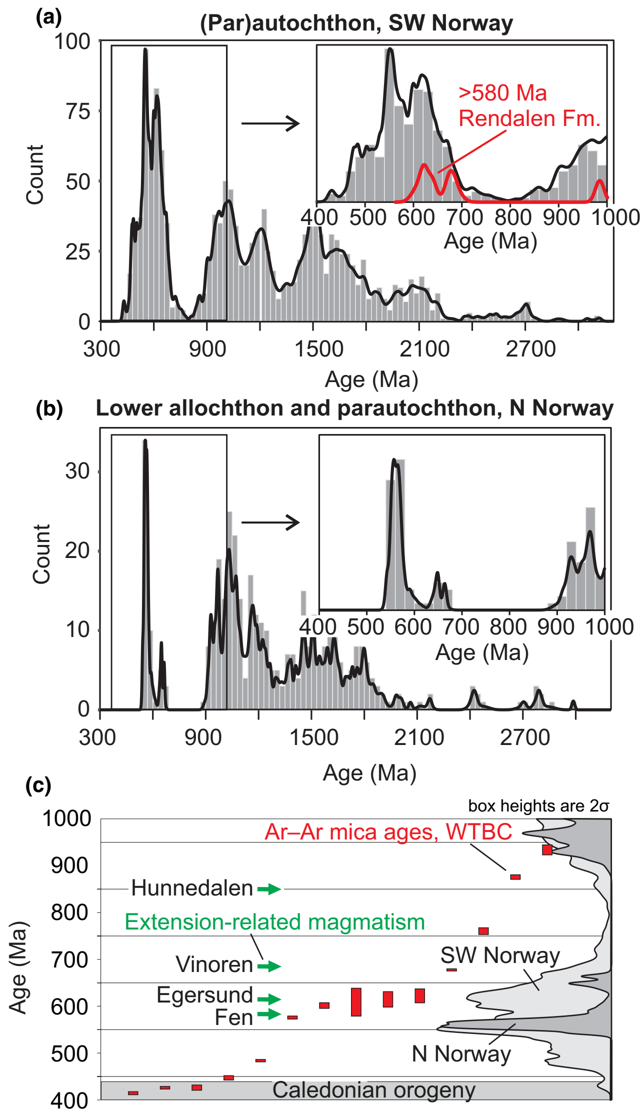

FIGURE 3 (a) Detrital zircon probability density plot from (par) autochthonous metasedimentary units in SW Norway (Sláma & Pedersen, 2015; this study). Data for the Rendalen formation from Bingen et al. (2005). (b) Detrital zircon age data from lower allochthonous and parautochthonous rocks in N Norway (Andresen et al., 2014; Zhang et al., 2015). (c) Ar–Ar biotite ages from this study, plotted with detrital zircon probability density plots from SW and N Norway and ages of extension-related magmatism in SW Norway (see Figure 1 for references).

an alternative source of detritus must have existed, since accretion of Timanian rocks took place 20 Myr later.

A southerly, Avalonian source has also been proposed for these Neoproterozoic detrital zircon grains (Andresen, 2021); however, considering that Avalonia and Baltica collided in the latest Ordovician to earliest Silurian (Domeier, 2016) and the general lack of grains younger than early Middle Ordovician, we consider this interpretation unlikely.

Hence, a more likely derivation of these Neoproterozoic detrital zircon grains is from a source region west of the present western Baltican margin. Available detrital zircon data from (par)autochtonous sedimentary rocks in Norway are, therefore, indicative of a long-lived, active margin west of present-day Baltica (Figure 4), which rules out most pre-Iapetus reconstructions of Baltica and Laurentia in which the western Baltican margin is placed adjacent to the eastern Laurentian margin.

3.2 | Ar–Ar ages of Neoproterozoic thermal events

New Ar–Ar biotite data from autochthonous basement in the West Troms Basement Complex (WTBC) and the Narvik area (Figure 3, Data Supplements S4 and S5) yield a range of ages from 950 to 400 Ma, with most between 620 and 580 Ma. While ages younger than 440 Ma can be ascribed to Caledonian continent-continent collision, older ages cannot and are interpreted to correspond to Neoproterozoic through Ordovician thermal events. Although the tectonic significance of these thermal events is unconstrained, a clear overlap in Neoproterozoic ages with detrital zircon ages in northern and southwestern Norway and extension-related magmatism in south Norway is evident (Figure 3c), implying magmatism and tectonometamorphism at this time. Hence, the Ar–Ar data from the WTBC are consistent with an active margin west of the present western margin of Baltica, rather than to its north or south (Figure 4).

A 700 to 450 Ma active margin corresponds to extension-related magmatic events in Baltican basement in S Norway starting at ca. 850 Ma and lasting until at least 580 Ma (Figure 4c). Evidence of long-lived extension is restricted to S Norway, which is characterized by comparatively thin and weak lithosphere (Figure 1). Divergent settings generally produce little magma that crystallizes zircon (Cawood et al., 2012), and it is, therefore, unlikely that these rift events reflect continental rifting, as generally assumed, but rather extensional basins formed behind, and filled by erosion of, an active continental margin. The geographic distribution of Neoproterozoic detrital zircon and thermal events constrained by the Ar–Ar data suggest the presence of an active margin outboard of the present western margin of Baltica.

4 | WHEN DID BALTICA AND LAURENTIA SEPARATE?

The timing of Baltica–Laurentia separation and Iapetus opening remains unknown, but we speculate that widespread rifting around 1.2 Ga, recorded on both continents (Bingen et al., 2002 and references therein), marks this event, consistent with a very similar tectonic evolution up until this point and a rather more dissimilar evolution thereafter (Karlstrom et al., 2001; Slagstad et al., 2019; Spencer et al., 2019). Available palaeomagnetic data indicate latitudinal separation of at least 20° between the two continents as early as ca. 1090 Ma (Figure 4a, adopting the classic right-way-up position of Baltica; Kulakov et al., 2022), consistent with contrasting styles of Grenvillian–Sveconorwegian orogeny (Slagstad et al., 2019). We

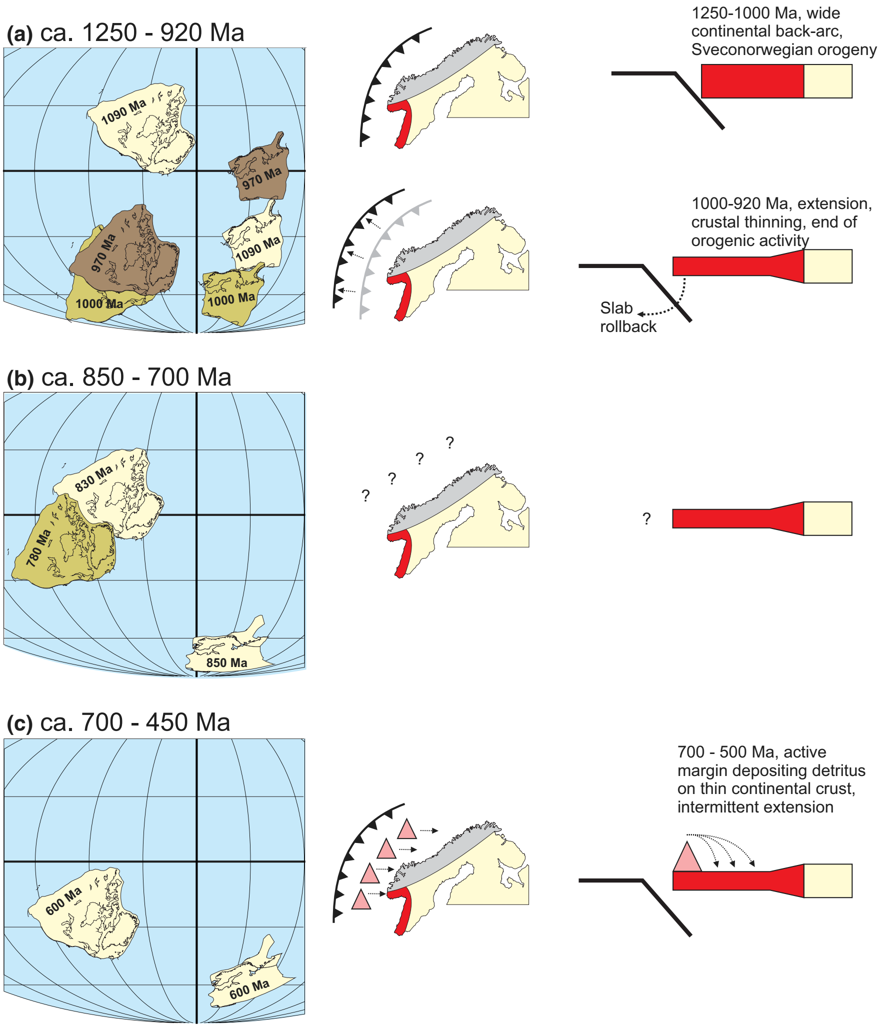

FIGURE 4 Palaeogeographic reconstructions and interpreted tectonic setting along the western Baltican margin at different, critical time periods. (a) the period between 1,250 and 920 Ma was dominated by the Sveconorwegian Orogeny, which in recent studies have been interpreted to represent an active margin geographically separated from Laurentia (Kulakov et al., 2022; Slagstad et al., 2019, 2020) (b) palaeomagnetic and geologic data are sparse between 850 and 700 Ma, and neither support nor reject contiguity of Baltica and Laurentia. (c) between 700 and 500 Ma, that is, leading up to the Caledonian Orogeny, palaeomagnetic data are inconclusive with respect to separation of Baltica and Laurentia, however, if separation of Baltica and Laurentia during Sveconorwegian–Grenvillian orogeny is accepted, a hitherto unknown, Neoproterozoic collision must have brought them together prior to separation at 600 Ma.

posit that these continents remained separated until Caledonian continent–continent collision commenced at ca. 440 Ma (e.g. Slagstad & Kirkland, 2018), following a period of accretionary tectonics along both margins (Barnes et al., 2019; Gasser et al., 2021; Majka et al., 2014; Zagorevski et al., 2006), and argue that the commonly held interpretation of Baltica being located adjacent to Laurentia in the supercontinent Rodinia and during most of the Neoproterozoic is founded on incomplete information and is inconsistent with presently available geologic and palaeomagnetic data.

5 | CONCLUSIONS

The available geologic and palaeomagnetic data are best explained by separation of Baltica and Laurentia well before assembly of Rodinia. In contrast, the available age and thermal history information suggest that the western Baltican margin was active throughout much of the Neoproterozoic and located some unconstrained distance from Laurentia, as suggested by palaeomagnetic data. This margin remained active until the onset of Caledonian continent-continent collision. It is unlikely that Baltica formed an integral component of the Rodinia supercontinent, and the ocean separating Baltica from Laurentia must have existed well before the generally accepted separation at 600 Ma, perhaps as early as ca. 1,200 Ma.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. Sample coordinates and descriptions.

Data S2. Detrital zircon U-Pb data.

Data S3. Methods.

Data S4. Ar-Ar spectra.

Data S5. Ar-Ar data.

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