Precambrian Research 267 (2015) 94–105

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Baltica during the Ediacaran and Cambrian: A paleomagnetic study of Hailuoto sediments in Finland

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ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form 29 May 2015
Accepted 3 June 2015
Available online 12 June 2015

Keywords:
Ediacaran
Paleomagnetism
Paleogeography
Baltica
Laurentia
Hailuoto sediments

ABSTRACT

We present a new Late Neoproterozoic paleomagnetic pole for Baltica from an inclined 272 m deep oriented sedimentary drill core in Hailuoto, Western Finland. The depositional age of the Hailuoto sediments is poorly constrained at 570–600 Ma. Three components of magnetization were isolated with thermal and alternating field (AF) demagnetization treatments. The ChRM (characteristic remanence magnetization) component is a high coercivity/unblocking temperature dual polarity component that passes a reversal test. The combined observed ChRM component of the Hailuoto sediments ($D = 334.2^\circ$; $I = 44.4^\circ$; $\alpha_{95} = 7.2^\circ$; $k = 16.5$) yields a paleomagnetic pole of Plat = 48.7° N and Plon = 241.1° E with A95 = 8.1°. The inclination corrected direction ($f = 0.6$) of $D = 334.4^\circ$; $I = 57.7^\circ$; $\alpha_{95} = 5.8^\circ$; $k = 25.2$ yields a paleomagnetic pole of Plat = 60.5° N and Plon = 247.9° E with A95 = 7.6°. As it is a dual-polarity ChRM carried by both magnetite and hematite, with no resemblance to younger events, we interpret it as a primary component. A paleolatitude for Hailuoto of 38.3° was calculated from the ChRM. Two secondary components were identified. The first is a low coercivity/blocking temperature component with a remanent magnetization of $D = 239.0^\circ$; $I = 67.3^\circ$; $\alpha_{95} = 8.7^\circ$ ($N = 13$ samples), which we interpret as drilling-induced remanent magnetization (DIRM). The second secondary component has a remanent magnetization of $D = 49.4^\circ$; $I = 34.9^\circ$; $\alpha_{95} = 8.6^\circ$ ($N = 5$ samples) and is commonly seen in Fennoscandian formations.

The ChRM Hailuoto pole adds to the scattered Ediacaran paleomagnetic data of Baltica and indicate large distances between other late Neoproterozoic and early Cambrian paleomagnetic poles. We present reconstructions of Baltica and Laurentia between 616 and 550 Ma which move Baltica from high latitudes (615 Ma), over the polar region, to low latitudes (550 Ma), and Laurentia from low latitudes (615 Ma) to a polar position (570 Ma) and back to an equatorial position (550 Ma). A low to mid latitude position of Baltica determined by the Hailuoto paleomagnetic pole, and the lack of glaciogenic sediments determined in an earlier study of Hailuoto sediments indicate a warm deposition environment.

1. Introduction

The Late Neoproterozoic to Early Cambrian is a fascinating time interval in Earth's history. It includes global scale glaciations (Kirschvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002), the diversification of early life (Knoll, 1992), and the break-up of the supercontinent Rodinia (e.g. Hoffman, 1991; Dalziel, 1997; Bingen et al., 1998; Evans, 2009). Laurentia and Baltica occupied central positions at the core of Rodinia. They became more isolated from other continents as rifting along Rodinia's margins occurred during the mid to late Neoproterozoic. By the start of the Ediacaran (ca. 635 Ma) the break-up of Rodinia was near completion. With the exception of Baltica and Siberia, all continents were separated from Laurentia (Li et al., 2013). Li et al. (2013) further show that by ca. 580 Ma the break-up of Rodinia was complete, Gondwana was in its early stages of assembly, and Baltica and Siberia had separated from Laurentia.

The role of paleomagnetism in reconstructing lithospheric blocks in their ancient paleopositions is vital. Paleomagnetism is the only quantitative tool for providing ancient latitudes and azimuthal orientations of continents and it also reveals information of the geomagnetic field in the past. A reliable paleomagnetic pole generally fulfils at least three of the seven quality criteria of Van der Voo (1990). If two of these include adequate geochronology and a positive paleomagnetic field test, the obtained paleomagnetic pole can be considered a "key" pole (Buchan et al., 2000; Buchan,

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http://dx.doi.org/10.1016/j.precamres.2015.06.005
0301-9268/

2013). The paleogeography for the Ediacaran–Cambrian is the subject of significant controversy and it has puzzled researchers for the past two decades (Meert et al., 1993, 1994; Kirschvink et al., 1997; Meert, 1999; Popov et al., 2002; Meert et al., 2003; Nawrocki et al., 2004; Iglesia Llanos et al., 2005; McCausland et al., 2007; Meert et al., 2007; Pisarevsky et al., 2008; Abrajevitch and Van der Voo, 2010; McCausland et al., 2011). Ediacaran paleomagnetic data is complex since contradictory paleomagnetic results from coeval rocks have been obtained from both Baltica and Laurentia. McCausland et al. (2011) show how Laurentia has unclear paleogeographic relations during the Precambrian–Cambrian transition. Published paleomagnetic results from the Ediacaran period positions Laurentia at low paleolatitudes at 615 Ma, shortly after that at high southern latitudes during 590–570 Ma, and then again at low latitudes from 565 to 550 Ma.

A similar phenomenon is observed in high quality paleomagnetic data from Baltica. Higher quality paleomagnetic data for Baltica exist for only three time intervals during the Ediacaran–Ordovician (Meert, 2014). The 616 ± 3 Ma pole from Egersund dykes (Walderhaug et al., 2007) positions Baltica at high latitudes. Between 570 Ma and 550 Ma, poles from Zigan formation (547.6 ± 3.8 Ma; Levashova et al., 2013), Verkhotina sediments (550.2 ± 4.6 Ma; 550 ± 5.3 Ma; Popov et al., 2005), Winter coast sediments (555 ± 3 Ma; Popov et al., 2002), Zolotitca sediments (550.2 ± 4.6 Ma, 550 ± 5.3 Ma; Iglesia Llanos et al., 2005), Chernokamenskay group sediments (557 ± 13 Ma, Fedorova et al., 2014), Basu formation (ca. 560 Ma, Levashova et al., 2014), and recent poles from 560 to 570 Ma Kurgashlya, Bakeevo and Krivava Luka formations (Lubnina et al., 2014) positions Baltica at low to equatorial latitudes. The Late Cambrian–Middle Ordovician poles from Narva Limestones (Khramov and Iosifidi, 2009) and St. Petersburg Limestones (Smethurst et al., 1998) positions Baltica at high latitudes again. Based on these high quality data Baltica swayed by ca. 90°, from high latitudes at 616 Ma to low latitudes at 570–550 Ma and again to high latitudes from 550 to 500 Ma.

The other Late Neoproterozoic poles presented in Table 2 are too questionable or unreliable to include in the APWP. The two poles – equatorial and high latitude – from the 584 ± 7 Ma (^{39}Ar–^{40}Ar) Alnö carbonatite complex dikes were artificially derived from a wide spread in magnetic declinations and inclinations (Meert et al., 2007). The 583 ± 15 Ma (^{39}Ar–^{40}Ar) pole from the Fen Carbonatite Complex lacks stability tests and is likely a Permo-Triassic overprint (Meert, 2014). The Cambrian Andarum-alum limestone and Tornetrask group poles are questionable. The Tornetrask results (Torsvik and Rehnström, 2001) come from samples taken close to tectonically disturbed regions of Caledonian front, which can cause complications in interpreting those results (Meert, 2014). The pole for Andarum-alum is calculated from only 11 samples, therefore yielding only virtual geomagnetic pole, which cannot be used in the APWP. Both the Tornetrask and Andarum-alum (Torsvik and Rehnström, 2001) have a dual-polarity magnetization, but they fall close to the remagnetized Fen Complex pole.

Explanations for the two almost coeval magnetization components (high and low latitude) include fast continental motions (Meert and Tamrat, 2004), rapid true polar wander (TPW) (Mitchell et al., 2011), or a non-actualistic geodynamo where the geomagnetic field alternated between axial and equatorial configurations during the Ediacaran (Abrajevitch and Van der Voo, 2010). In a recent paper by Halls et al. (2015) it is suggested that the rapid oscillatory motion of paleomagnetic poles is related to the polarity reversal that involves an equatorial dipole field as an intermediate step during the reversal of the axial dipole. Abrajevitch and Van der Voo (2010) argued that high plate velocities and true polar wander are implausible explanations for such rapid changes in the positions of continents, as both TPW and plate tectonics are speed-limited phenomena. However, as Meert (2014) pointed out, the analysis of Abrajevitch and Van der Voo (2010) relied on problematic poles for Baltica, implying apparent polar wander (APW) rates exceeding 70 cm/yr (Meert et al., 2007). By taking into account reliable poles only, rapid plate motions can explain individual segments of the apparent polar wander path (APWP).

The Neoproterozoic is also characterized by global scale glaciations. Two major glaciation events occurred during the Ediacaran, namely the Marinoan (ca. 635 Ma) and the Gaskiers (ca. 580 Ma) (e.g. Hoffman and Li, 2009). The Marinoan glaciation extended from >70° palaeolatitude to the equator (e.g. Hoffman and Li, 2009), implying global glaciation and has been interpreted to represent a Snowball Earth event (Kirschvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002). Marinoan glacial deposits have been found on all major continental blocks except for the North China block (Li et al., 2013). Gaskiers glacial deposits are found on Baltica, Laurentia, North China, Australia, Tarim, Avalonia, Congo-São Francisco and Amazonia (Li et al., 2013), however, feeble evidence of low latitude glaciation (e.g. Hoffman and Li, 2009) suggests that the Gaskiers was not as widespread as the Marinoan. Li et al. (2013) point out that on the Avalon Peninsula, Newfoundland, precise TIMS U–Pb zircon dates appear to constrain the duration of the Gaskiers glaciation to ≤2.6 m.y. (Condon and Bowring, 2011). The short duration has commonly been regarded as evidence that it was not a Snowball glaciation (e.g., Halverson, 2006).

The aim of the present work is: (1) to obtain a new paleomagnetic pole for Baltica; (2) to test the Late Neoproterozoic paleogeographic positions of Baltica; and (3) to better understand the environmental conditions during that time. With a new Late Neoproterozoic pole, we further aim to explore if the large sways in the Ediacaran APWP can be explained by high plate velocities alone.

2. Geological background

The assembly of the Baltica began at 2.0 Ga when Sarmatia and Volgo-Uralia joined each other to form the Volgo-Sarmatian protocraton, which existed as a separate unit until ca. 1.8–1.7 Ga when it docked with Fennoscandia and a unified Baltica was created (Bogdanova et al., 2008). After the movements of the Svecofennian orogeny in Baltica and Trans-Hudson orogeny in Laurentia ended at ca. 1750 Ma (Bogdanova et al., 2008) Baltica and Laurentia formed a joint NENA continent (Gower et al., 1990). This was followed by a geologically passive time of about 150 Ma when no significant deformation occurred and when the crust eroded to a peneplain. The quiet time ended with the intrusion of rapakivi granites and associated bimodal magmas at 1650–1500 Ma (Rämö and Haapala, 2005; Bogdanova et al., 2008). This caused instability of the crust and led to the development of intracratonic rift basins between ca. 1600 and 1300 Ma when thick fluvial layers started to fill the basins (Kohonen and Rämö, 2005). The crust was thinned by about 20 km at the Gulf of Finland and about 10 km at Lake Ladoga in Russia and at the Bay of Bothnia (Fig. 1; Korja et al., 1993).

Due to the Sveconorwegian orogeny, the southwestern parts of the Fennoscandian shield were uplifted. This resulted in the formation of thick and hundreds of kilometres long foreland sedimentary deposits east of the Sveconorwegian orogeny (Larson et al., 1999). During the Neoproterozoic a vast area of the crystalline bedrock was exposed when about 500–2000 m of sediments were eroded away (Puura et al., 1996). Due to marine transgression, a new sedimentary event began in Baltica at the end of the Neoproterozoic (Puura et al., 1996). Fluvial and shallow marine deposition prevailed in the slowly submerging northwestern part of Baltica