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Vendian glaciations and their relation to the dispersal of Rodinia: Paleomagnetic constraints

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ABSTRACT

Paleomagnetic data from the interglacial Nyborg Formation (653 ± 7 Ma), northern Norway, compare with data from the Egersund dikes (ca. 650 Ma), southwest Norway, and demonstrate that tillite formations associated with the Varanger Ice Age in Baltica accumulated at latitudes greater than 30 S. Vendian glaciations are associated with reorganization of the Rodinia supercontinent, but they are controlled by latitude. The breakup of Rodinia and opening of the proto-Pacific imposed clockwise rotation and southward movement of Laurentia-Baltica. On their combined approach toward the south pole, Baltica and northeast Laurentia were first glaciated during the Varanger Ice Age (ca. 650 Ma) and then by the Ice Brook glacial events (625–580 Ma) when Laurentia had reached intermediate southern latitudes. During the 625–580 Ma period Laurentia and Baltica drifted apart, resulting in the opening of the Iapetus ocean, but both continents remained in high southern latitudes during most of the Vendian.

INTRODUCTION

Paleolatitudes are most accurately quantified by paleomagnetic data, and paleomagnetic latitude estimates for the Phanerozoic are generally consistent with biological and lithological climate indicators. Late Riphean and Vendian paleolatitudes, however, have bewildered geoscientists for decades, given the various postulates of glaciation events (ca. 750–550 Ma) at low and even at equatorial latitudes. Hypotheses of low-latitude glaciation derive mainly from paleomagnetic data, and there are several explanations for this apparent paradox (Chumakov and Elston, 1989; Williams, 1993; Meert and Van der Voo, 1994, and references therein).

Late Precambrian paleogeography has been the subject of renewed attention arising from the postulate of a supercontinent, Rodinia (McMenamin and Schulte McMenamin, 1990), which is hypothesized to have formed ca. 1100 Ma and to have started to break up ca. 750–725 Ma (Moores, 1991; Dalziel, 1991; Hoffman, 1991; Powell et al., 1993; Dalziel et al., 1994). In this paper we (1) report new paleomagnetic data from lower Vendian interglacial sedimentary rocks (Varanger Ice Age) in northern Norway, (2) develop a model for late Precambrian paleolatitudinal drift for Baltica, and (3) discuss the possibility that the Rodinia breakup and subsequent rift events on remnants of Rodinia during late Precambrian time (ca. 650–580 Ma) were coeval with the Vendian glacial events (Young, 1995).

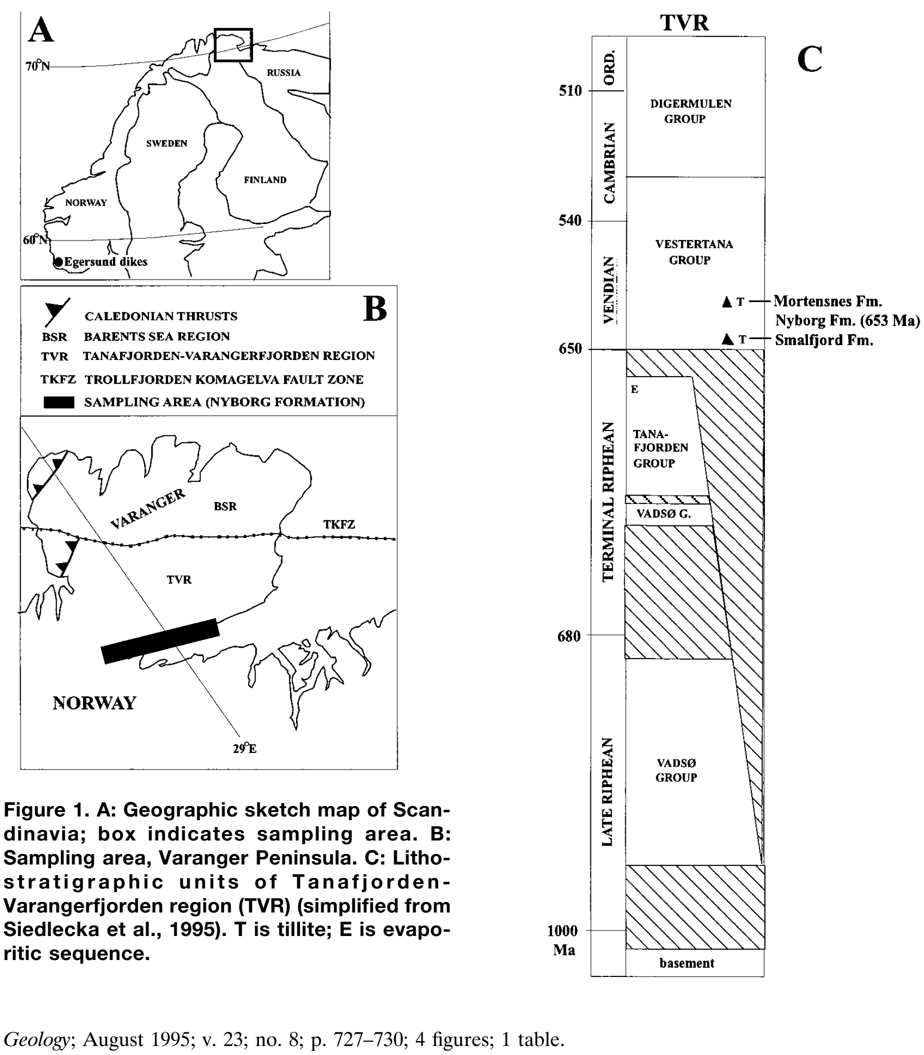

Figure 1. A: Geographic sketch map of Scandinavia; box indicates sampling area. B: Sampling area, Varanger Peninsula. C: Lithostratigraphic units of Tanafjorden-Varangerfjorden region (TVR) (simplified from Siedlecka et al., 1995). T is tillite; E is evaporitic sequence.

PALEOMAGNETIC SAMPLING

Glaciogenic deposits are generally poor paleomagnetic recorders. Therefore, we avoided the Vendian tillites (Smalfjord and Mortensnes Formations) in favor of interglacial basinal turbidites and shallow-water deposits (Nyborg Formation). All three formations are in the lowest part of the Vendian–Early Cambrian Vestertana Group (Siedlecka et al., 1995; Fig. 1C). The Nyborg Formation has been dated to 653 ± 7 Ma (Rb/Sr; recalculated from Pringle, 1973); this is considered to represent isotopic homogenization during diagenesis and therefore to be a minimum age. Pringle (1973) produced parallel isochrons from red and green shale bands giving identical ages but different initial $^{87}Sr/^{86}Sr$ ratios, considered to be related to provenance. $^{40}Ar/^{39}Ar$ study on illite fractions from the Nyborg Formation indicated that the pelites had been affected by a "diagenetically related geologic disturbance at ~635 Ma" (Dallmeyer and Reuter, 1989).

In the sampling region (Fig. 1B), the lower tillite (Smalfjord Formation) varies in thickness from 2 to 100 m and is interpreted

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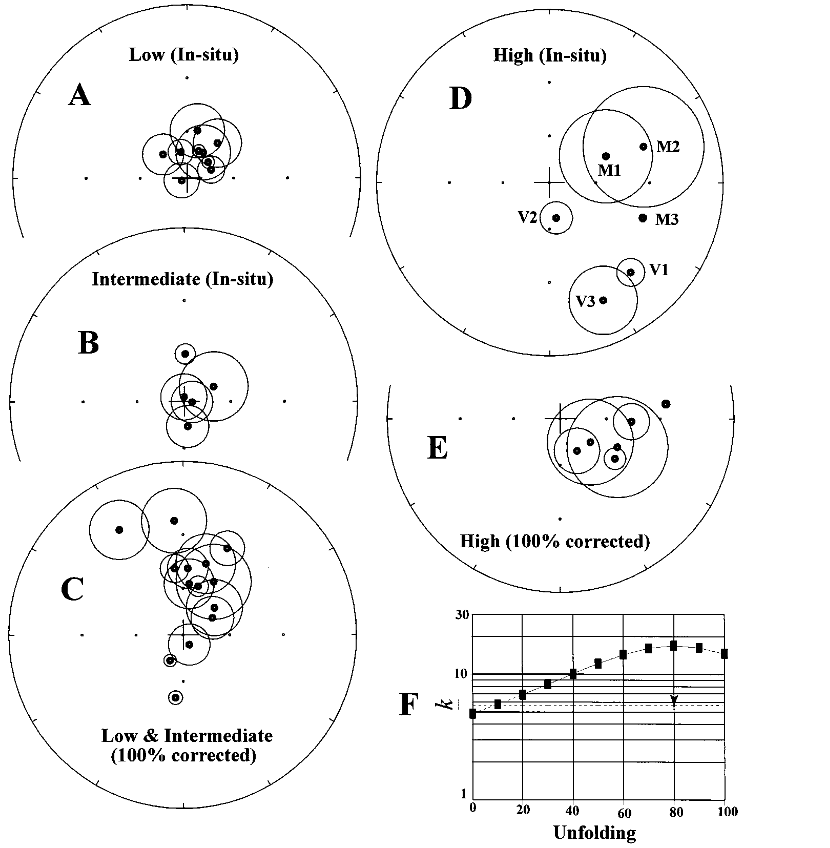

Figure 2. In situ and tectonically corrected site-mean directions with α_{95} confidence circles for low (A and C), intermediate (B and C), and high unblocking components (D and E; sites V1-V3 and M1-M3 were sampled from Varangerbotn and Mortensnes, respectively). F: Variation in precision parameter (*k*) during stepwise unfolding for high unblocking components. In stereoplots, closed circles represent downward-pointing (positive) inclinations. Note that α_{95} confidence circle for site M3 is below size of plotting symbol.

as both continental and offshore deposits (Edwards, 1984). The overlying Nyborg Formation comprises red-brown and gray-green sandstone, siltstone, and mudstone, and basal dolomitic beds, up to 400 m thick. The upper tillite (10–60 m), the Mortensnes Formation, is separated from the underlying sedimentary rocks by an erosional contact, and has been interpreted as continental and offshore glacial deposits (Føyn, 1985, and references therein). In this area (Fig. 1B), part of the authothonous Caledonides, the Nyborg Formation represents a comparatively incompetent unit between massive tillites and is folded along east-northeast–west-southwest axes. A weakly developed cleavage is observed in fold hinges. In this study we address the paleomagnetic signatures of noncleaved reddish-gray sandstones and siltstones, which were sampled across mesoscopic fold structures from five different locations within the area indicated in Figure 1B.

TABLE 1. SITE-MEAN DIRECTIONS FROM NYBORG FORMATION, 70.1°N AND 28.7°E

Component	Dec. (°)	Inc. (°)	*N*	R	α_{95}	*k*	Lat (°)	Long (°)	dp	dm	Stat. sig.*
Low											
In situ	020.8	73.9	9	8.7	9.3	31.5	N76.8	E157.9	15.1	16.8	1
100% unfolded	002.1	57.3	9	7.2	27.9	4.4					
Intermediate											
In situ	047.3	82.3	5	4.8	18.0	19.1	N75.5	E078.5	34.2	35.1	2
100% unfolded	029.3	66.3	5	4.8	18.4	18.2					
High											
In situ	117.1	41.8	6	4.9	33.8	4.9					
100% unfolded	110.3	52.3	6	5.7	18.1	14.6	N24.3	E088.5	17.1	24.9	3

Note: Dec = mean declination; Inc = mean inclination; *N* = number of sites; R = total vector; α_{95} = 95% confidence circle; *k* = precision parameter; Lat = pole latitude; Long = pole longitude; dp/dm = semi-axis of the 95% confidence ovals.

*Statistical significance: 1 = negative fold test at 95% significance level; 2 = insignificant at 95% confidence level; 3 = positive fold-test at 95% significance level.

PALEOMAGNETIC RESULTS

Natural remanent magnetization (NRM) was measured with a cryogenic magnetometer at the University of Michigan, and 185 samples were subjected to stepwise thermal demagnetization and, to a lesser extent, alternating field demagnetization. Characteristic remanence components were calculated with a least square algorithm.

Most samples are dominated by low (L) or intermediate (I) unblocking components with northward or northeastward declinations and steeply downward dipping inclinations that in many cases plot near the present Earth's field direction (Fig. 2, A and B). Demagnetization behavior is commonly complex, and from many sites the high (H) temperature component could not be determined (Fig. 3A), owing to onset of viscous behavior (>600 °C). Component L (20–300 °C; Fig. 3) and I (ca. 350–600 °C) may coexist in a single sample (Fig. 3A), but in many cases only component L was identified before the onset of irregular demagnetization behavior.

From two sampling areas (55 samples from sites V1-V3 and M1-M3), however, we could identify high-temperature components (Fig. 3, B–D) that clearly converge toward the origin of the orthogonal vector plots. Maximum unblocking temperatures up to 680 °C demonstrate hematite as the chief remanence carrier (Fig. 3, B and C), but in some instances magnetite seems to be the chief remanence carrier (Fig. 3D). In the examples shown in Figure 3, B and D, low-temperature and high-temperature components were readily separated, whereas in Figure 3C, the low-temperature component is comparably small and difficult to estimate; thus the NRM is almost single component from this site (V2).

In situ site-mean directions for components L and I are similar (Fig. 2, A and B) and their 95% confidence ovals overlap (Fig. 2, A and B, Table 1). Component L fails a fold test at the 95% confidence level (Table 1), and component I shows insignificant changes during stepwise unfolding. Both components, however, are interpreted as secondary overprints. Component L probably represents a recent viscous magnetization. Conversely, a fold test for the H component (Table 1, Fig. 2, D–F) is positive at the 95% confidence level. We note a minor peak in the precision parameter (Fig. 2F). This peak, however, is insignificant when compared with a 100% unfolding

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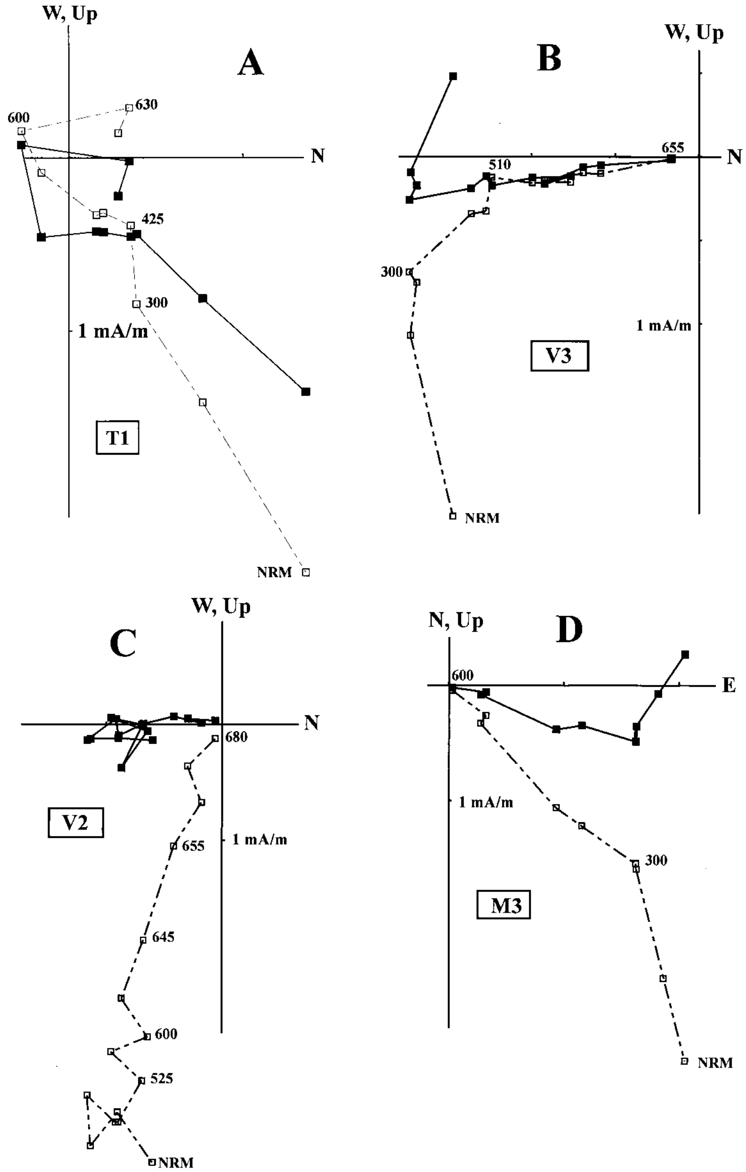

Figure 3. Typical examples of thermal demagnetization behavior for samples from Tanafjord (A, site T1), Varangerbotn (B, sites V3 and V2), and Mortensnes (D, site M3). In orthogonal vector diagrams, solid squares represent points in vertical plane, and open squares represent points in horizontal plane.

state, and it could result from minor component contamination. We conclude that component H is of primary or early diagenetic origin.

DISCUSSION

The Varangerian tillites and the interglacial Nyborg Formation are widely held to be of Vendian age and are correlated with tillite sequences in Spitsbergen, Greenland, southern Norway, and western Scotland (Harland et al., 1993). Recent isotopic data (Sm-Nd and Rb/Sr) from the west-northwest–east-southeast–orientated Egersund dike swarm in southwest Norway suggest a Vendian age (650 Ma; mean of four preliminary dates; Sundvoll, 1987; B. Sundvoll, personal commun). The paleomagnetic pole for the prefold H component from the Nyborg Formation plots near two paleomagnetic poles reported from the Egersund dikes (Fig. 4A), fitting well with the 653 ± 7 Ma age obtained by Pringle (1973) from the Nyborg Formation. The Nyborg pole is also significantly different from (older than) poles derived from dikes in northern Norway and Russia dated between 580 and 546 Ma (cf. Torsvik et al., 1995).

Paleomagnetic data from the interglacial Nyborg Formation indicate a local paleolatitude of 33°S (Fig. 4B), or 41°S (Fig. 4C) if we use an integrated paleolatitude estimate based on a mean of the Egersund dikes and the Nyborg Formation (650 and 653 Ma). These data indicate that the Varangerian tillites and assumed coeval tillites in southern Scandinavia were deposited at intermediate latitudes, probably from 30° (Smalfjord Formation) to 40° (Mortensnes Formation) south, when Baltica was moving southward. These intermediate paleolatitude estimates seeming to conform with lithologic indicators, because tidal flat dolomites in the basal Nyborg Formation suggest a warm rather than a high-latitude climate (Edwards and Føyn, 1981).

The time of initial breakup of Rodinia is estimated as ca. 750–725 Ma (Dalziel, 1992; Powell et al., 1993), when Australia-Antarctica (east Gondwana) rifted off the western margin of Laurentia. Major intercontinental crustal rupture at this time is also indicated along the Baltic margin (Kumpulainen and Nystuen, 1985). The 650 Ma Egersund diabase dike swarm probably indicates the initiation of rifting prior to the opening of the Iapetus ocean. In north Norway, dolerite dikes in a Caledonian nappe unit have been Sm/Nd dated to 582 ± 30 Ma (Zwaan and van Roermund, 1990); these latter dikes are of transitional mid-ocean ridge basalt character and are considered to have intruded immediately prior to the start of Iapetus sea-floor spreading (Roberts, 1990). Iapetus opening probably began at 600–570 Ma, which accords with paleomagnetic data from Baltica and Laurentia which indicate that the two paleocontinents were in contact until at least 620–630 Ma (Torsvik and Meert, 1995).

Although Vendian glaciations in the North Atlantic region are coeval with the reorganization of Rodinia (Young, 1995), which was originally nucleated around Laurentia at low latitudes in late Riphean time (Fig. 4B), our analysis suggests that the glaciations are to a first approximation latitudinally (climatically) controlled. During the opening of the paleo-Pacific between Laurentia and Australia-Antarctica (Dalziel, 1992) ca. 750–725 Ma, Laurentia and Baltica (and probably other remnants of Rodinia; e.g., Amazonia) were rotating clockwise and also moving southward. Consequently, by early Vendian time (ca. 650 Ma), Baltica and the northeast margin of Laurentia occupied southern latitudes >30° while central parts of Laurentia were still within temperate latitudes (Fig. 4C). Continued south pole–directed movement brought all of Laurentia (Fig. 4D) into paleolatitudes >30°S (cf. Meert and Van der Voo, 1994) during the Ice Brook glaciations (ca. 625–580 Ma), which occurred at ≥45°S. Paleomagnetic data show that Laurentia and Baltica had already rifted apart at 580 Ma (Fig. 4C), and that a rift-to-drift transition probably occurred ca. 600 Ma, following the Varanger Ice Age, although details in their breakup history are difficult to assess from

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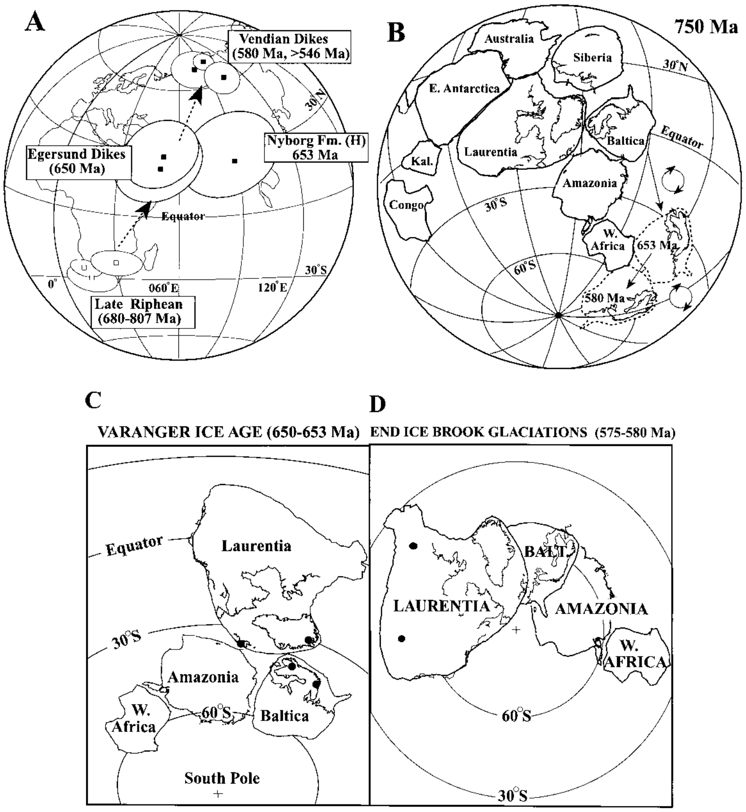

Figure 4. A: Comparison of Nyborg Formation pole (H component) with two existing poles from Egersund dikes (650 Ma) along with late Riphean (680–807 Ma) and Vendian poles from northern Norway and Russia (cf. Torsvik et al., 1995, for details). B: Rodinia configuration at ca. 750 Ma, simplified from Dalziel (1991) but Laurentia-Baltica (Euler lat = 72°N; long = 43°E; rotation angle = −50°) and Laurentia-Siberia (Euler lat = 29.3°; long = 341.2°; rotation angle = 19.6°) fits are modified; mean paleomagnetic pole: lat = 17.5°S, long = 329.8°E (North American coordinates; spline fitted with no errors provided; data of Torsvik et al.). Subsequent latitudinal drift history of Baltica, Nyborg Formation pole, and average (pole: 68.6°N and 093.2°E, α_{95} = 10.8°) for Vendian (ca. 580 Ma) dikes from Northern Baltica were used. Note southward-directed and clockwise rotation of Baltica during Vendian time. C: Reconstruction of Laurentia, Baltica, Amazonia, and West Africa during Varanger Ice Age. Large black dots indicate Varangerian tillites. Same Laurentia–Baltica–Amazonia–West Africa fit as (B), but pole is 26°N, 63.6°E and α_{95} = 30° (European coordinates; average of Egersund dikes and Nyborg Formation) were used). D: Reconstruction at end of Ice Brook glaciations (ca. 575–580 Ma). Baltica was positioned with mean pole of 68.6°N, 93.2°E, α_{95} = 10.8° (European coordinates), whereas Laurentia was positioned with mean pole of 44.4°N, 308.4°E, α_{95} = 7.9° (North American coordinates). Large black dots indicate Ice Brook glaciations. See text for discussion.

existing paleomagnetic data (Torsvik and Meert, 1995). Opening of the Iapetus ocean involved asymmetric rifting and large relative rotations between Laurentia (counterclockwise) and Baltica (clockwise), although they remained in high polar latitudes (Fig. 4D); these polar latitudes, however, pose an apparent space problem. If the Laurentia-Amazonia fit at 750 Ma was valid until latest Vendian–Early Cambrian time (Dalziel et al., 1994), we note that no space is available for Baltica (Fig. 4D) between these plates. This suggests inaccuracy in the existing paleomagnetic or isotopic data, an incorrect fit between Laurentia-Amazonia, or that Amazonia (west Gondwana) rifted off east Laurentia prior to 580 Ma. However, the space problem can be removed by adjusting the continental positions within the palaeomagnetic pole uncertainties.

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