Geoscience Canada
Journal of the Geological Association of Canada
Journal de l’Association Géologique du Canada

Ediacaran–Middle Paleozoic Oceanic Voyage of Avalonia from Baltica via Gondwana to Laurentia

Paleomagnetic, Faunal and Geological Constraints

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Volume 41, Number 1, 2014

URI: https://id.erudit.org/iderudit/1023627ar

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Keppie, J. D. & Keppie, D. F. (2014). Ediacaran–Middle Paleozoic Oceanic Voyage of Avalonia from Baltica via Gondwana to Laurentia: Paleomagnetic, Faunal and Geological Constraints. *Geoscience Canada*, *41*(1), 5–18.

Article abstract

Current Ediacaran–Cambrian, paleogeographic reconstructions place Avalonia, Carolinia and Ganderia (Greater Avalonia) at high paleolatitudes off northwestern Gondwana (NW Africa and/or Amazonia), and locate NW Gondwana at either high or low paleolatitudes. All of these reconstructions are incompatible with 550 Ma Avalonian paleomagnetic data, which indicate a paleolatitude of 20–30ºS for Greater Avalonia and oriented with the present-day southeast margin on the northwest side. Ediacaran, Cambrian and Early Ordovician fauna in Avalonia are mainly endemic, which suggests that Greater Avalonia was an island microcontinent. Except for the degree of Ediacaran deformation, the Neoproterozoic geological records of mildly deformed Greater Avalonia and the intensely deformed Bolshezemel block in the Timanian orogen into eastern Baltica raise the possibility that they were originally along strike from one another, passing from an island microcontinent to an arc-continent collisional zone, respectively. Such a location and orientation is consistent with: (i) Ediacaran (580–550 Ma) ridge-trench collision leading to transform motion along the backarc basin; (ii) the reversed, ocean-to-continent polarity of the Ediacaran cratonic island arc recorded in Greater Avalonia; (iii) derivation of 1–2 Ga and 760–590 Ma detrital zircon grains in Greater Avalonia from Baltica and the Bolshezemel block (NE Timanides); and (iv) the similarity of 840–1760 Ma TDM model ages from detrital zircon in pre- Uralian–Timanian and Nd model ages from Greater Avalonia. During the Cambrian, Greater Avalonia rotated 150º counterclockwise ending up off northwestern Gondwana by the beginning of the Ordovician, after which it migrated orthogonally across Iapetus to amalgamate with eastern Laurentia by the Late Ordovician–Early Silurian.

HAROLD WILLIAMS SERIES

Ediacaran–Middle Paleozoic Oceanic Voyage of Avalonia from Baltica *via* Gondwana to Laurentia: Paleomagnetic, Faunal and Geological Constraints

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SUMMARY
Current Ediacaran–Cambrian, paleogeographic reconstructions place Avalonia, Carolinia and Ganderia (Greater Avalonia) at high paleolatitudes off northwestern Gondwana (NW Africa and/or Amazonia), and locate NW Gondwana at either high or low paleolatitudes. All of these reconstructions are incompatible with 550 Ma Avalonian paleomagnetic data, which indicate a paleolatitude of 20–30ºS for Greater Avalonia and oriented with the present-day southeast margin on the northwest side. Ediacaran, Cambrian and Early Ordovician fauna in Avalonia are mainly endemic, which suggests that Greater Avalonia was an island microcontinent. Except for the degree of Ediacaran deformation, the Neoproterozoic geological records of mildly deformed Greater Avalonia and the intensely deformed Bolshezemel block in the Timanian orogen into eastern Baltica raise the possibility that they were originally along strike from one another, passing from an island microcontinent to an arc-continent collisional zone, respectively. Such a location and orientation is consistent with: (i) Ediacaran (580–550 Ma) ridge-trench collision leading to transform motion along the backarc basin; (ii) the reversed, ocean-to-continent polarity of the Ediacaran cratonic island arc recorded in Greater Avalonia; (iii) derivation of 1–2 Ga and 760–590 Ma detrital zircon grains in Greater Avalonia from Baltica and the Bolshezemel block (NE Timanides); and (iv) the similarity of 840–1760 Ma T_{DM} model ages from detrital zircon in pre-Uralian–Timanian and Nd model ages from Greater Avalonia. During the Cambrian, Greater Avalonia rotated 150º counterclockwise ending up off northwestern Gondwana by the beginning of the Ordovician, after which it migrated orthogonally across Iapetus to amalgamate with eastern Laurentia by the Late Ordovician–Early Silurian.

SOMMAIRE
Les reconstitutions paléogéographiques courantes de l'Édiacarien–Cambrien placent l'Avalonie, la Carolinia et la Ganderia (Grande Avalonie) à de hautes paléolatitudes au nord-ouest du Gondwana (N-O de l'Afrique et/ou de l'Amazonie), et placent le N-O du Gondwana à de hautes ou de basses paléolatitudes. Toutes ces reconstitutions sont incompatibles avec des données avaloniennes de 550 Ma, lesquelles indiquent une paléolatitude de 20–30ºS pour la Grande Avalonie et orientée à la marge sud-est d'aujourd'hui sur le côté nord-ouest. Les faunes édicacariennes, cambriennes et de l'Ordovicien précoce dans l'Avalonie sont principalement endémiques, ce qui permet de penser que la Grande Avalonie était une île de microcontinent. Sauf pour le degré de déformation édiacarienne, les registres géologiques néoprotérozoïques d'une Grande Avalonie légèrement déformée et ceux du bloc intensément déformé de Bolshezemel dans l'orogène Timanian dans l'est de la Baltica soulèvent la possibilité qu'ils aient été à l'origine de même direction, passant d'une île de microcontinent à une zone de collision d'arc continental, respectivement. Un tel emplacement et une telle orientation sont compatibles avec: (i) un contexte de collision crête-fosse à l'Édiacarien (580–550 Ma) se changeant en un mouvement de transformation le long du bassin d'arrière-arc; (ii) l'inversion de polarité de marine à continentale, de l'arc insulaire cratonique édicarien observé dans la Grande Avalonie; (iii) la présence de grains de zircons détritiques de 1 à 2 Ga et 760–590 Ma de la Grande Avalonie issus de la Balti-

Geoscience Canada, v. 41, http://dx.doi.org/10.12789/geocanj.2014.41.039

ca et du bloc Bolshezemel (N-E des Timanides); et (iv) la similarité des âges modèles de 840–1760 Ma T_{DM} de zircons détritiques pré-ourallien-timanien, et des âges modèles Nd de la Grande Avalonie. Durant le Cambrien, la Grande Avalonie a pivoté de 150° dans le sens antihoraire pour se retrouver au nord-ouest du Gondwana au début de l'Ordovicien, après quoi elle a migré orthogonalement à travers l'océan Iapetus pour s'amalgamer à la bordure est de la Laurentie à la fin de l'Ordovicien–début du Silurien.

INTRODUCTION

Current models for the transfer of Avalonia, Ganderia and Carolinia (collectively grouped as Greater Avalonia throughout this paper) from Gondwana to Laurentia mainly favour orthogonal transport across the Iapetus Ocean (Fig. 1) (e.g. Keppie et al. 1996; Golonka 2000; Scotese 2001 and references therein; Stampfli et al. 2002, 2011; Murphy et al. 2006; Pollock et al. 2012). Orthogonal models generally assume Greater Avalonia originated on the northern margin of Gondwana (Amazonia–NW Africa) in the Ediacaran, passed through a transtensional rift stage in the Cambrian, drifted in the Ordovician, docked softly with Baltica at the Ordovician–Silurian boundary, and accreted to the eastern margin of Laurentia in the mid-Silurian (Fig. 1a; Murphy et al. 2006). Mechanisms for the transfer of Avalonia are inferred to have started by slab pull towards a subduction zone on the margin of Laurentia, however once the Rheic mid-ocean ridge had formed, ridge push could have become a factor (Fig. 1a; Murphy et al. 2006), with slab rollback on the Gondwanan margin-induced opening of a backarc basin that became the Rheic Ocean behind Greater Avalonia as it departed (Fig. 1b; Stampfli et al. 2002, 2011).

A lateral transfer model was developed to explain the present SE to NW, ocean to continent polarity in the Precambrian basement across Avalonia and Ganderia observed in the Nd isotopic signature (Keppie et al. 2003, 2012). This lateral transfer model involved collision of an Ediacaran mid-ocean ridge with Avalonia followed by penetration of the ridge into the peri-Gondwanan margin, leading to

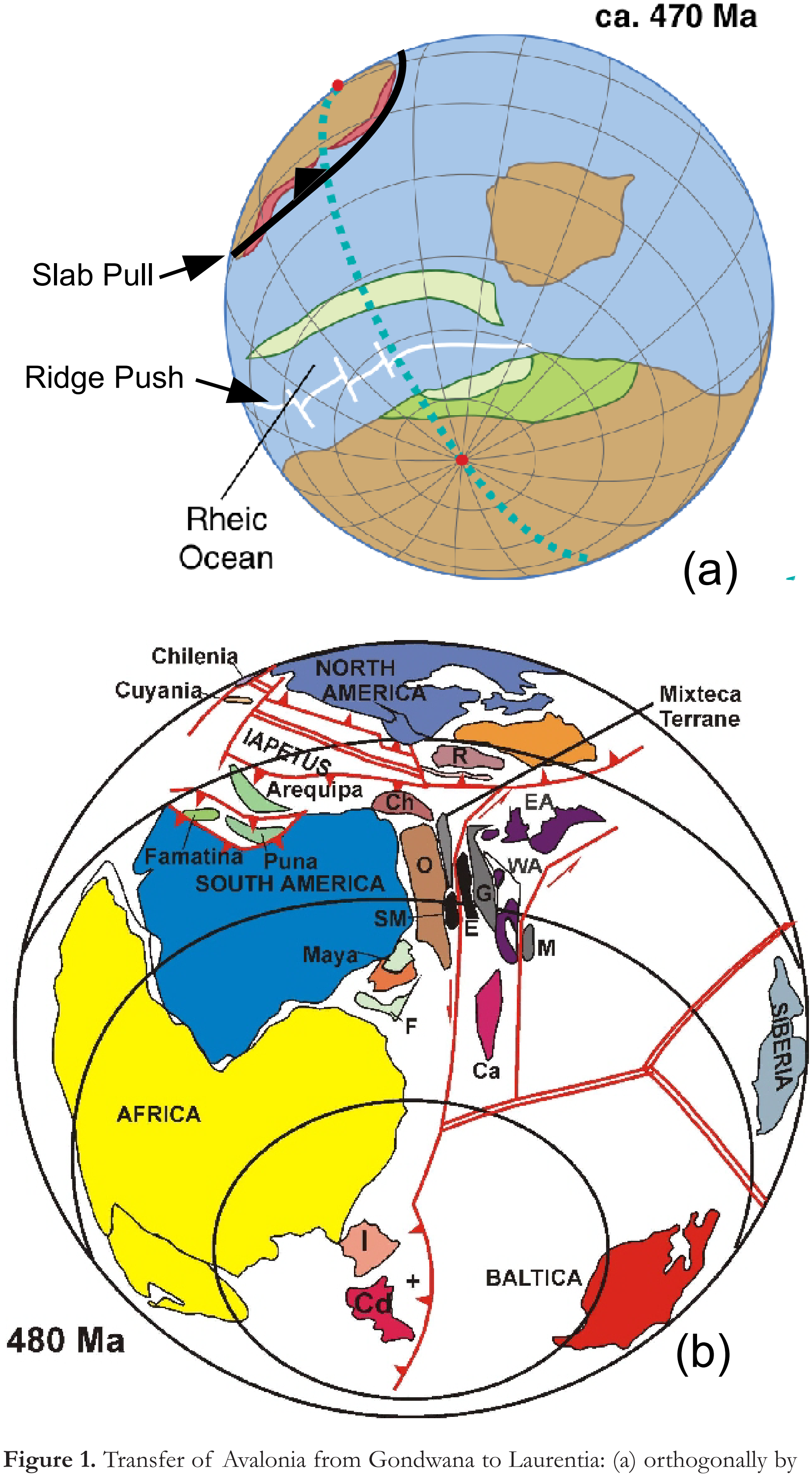

Figure 1. Transfer of Avalonia from Gondwana to Laurentia: (a) orthogonally by slab pull (Murphy et al. 2006); and (b) laterally by ridge-trench collision followed by lateral intrusion and slab pull (Keppie 2004): Abbreviations: Ca = Carolina; Cd = Cadomia; Ch = Chortis; E = Exploits; EA = East Avalonia; F = Florida; G = Gander; I = Iberia; M = Meguma; Mx = Mixteca; O = Oaxaquia; R = Rockall; SM = Sierra Madre; WA = West Avalonia; Y = Yucatan.

transtensional rifting of Avalonia from Gondwana, with clockwise rotation of Greater Avalonia followed by reversal of subduction polarity that ultimately culminated in accretion to Laurentia (Keppie et al. 1996, 2003; Keppie and Dostal 1998; Keppie and Ramos 1999; Keppie 2004).

The geological records of Iapetus and Avalonia have been extensively reviewed recently (Hibbard et al. 2002, 2007; Keppie et al. 2003; Landing 1996a; Nance et al. 2008; van Staal et al. 2009; Murphy et al. 2010; Pollock et al. 2012; Landing et al. 2013a, b), and so only data bearing on the origin of Avalonia and its transfer to Laurentia, such as paleolatitude, faunal provinciality, rifting, drifting and accretion, are described in this paper. Avalonia, Ganderia, and Carolinia are generally regarded as either separate terranes with large bounding faults derived from different locations on the margin of Gondwana (e.g. van Staal et al. 1998; van Staal and Hatcher 2010), or as part of one 'superterrane' where the Avalonia–Carolinia microcontinent is bounded on either side by the Gander and Meguma zones/terranes (Keppie et al. 2003, 2012; Murphy et al. 2004, 2008). Paleomagnetic data for Carolinia are limited to the Late Ordovician and suggest that it docked with eastern Laurentia at ca. 460 Ma (Vick et al. 1987; Hibbard 2000): earlier paleomagnetic data are lacking making it impossible to tell if Carolinia had a distinct polar wander path prior to 450 Ma. Post-accretion dispersion tends to mask pre-docking configurations. So Avalonia, Ganderia and Carolinia are collectively designated Greater Avalonia to distinguish them from Avalonia *sensu stricto*.

PALEOMAGNETIC DATA

Paleomagnetic data determine the paleolatitude by using inclination data and paleo-orientation is given by relative declination data, but provides no constraints on absolute paleolongitude. Evans (2003) and Mitchell et al. (2011) have identified an episode of True Polar Wander (TPW) in the Laurentian Apparent Polar Wander (APW) path between 615 and 565 Ma when the magnetic pole rotated through 90º and back. A similar TPW excursion appears to be recorded in both Baltica (one of the alternative apparent polar wander paths of Cocks and Torsvik 2005) and in Avalonia, which only shows a ca. 45º excursion (Pisarevsky et al. 2012). This renders the use of paleomagnetic data for reconstruction during the 615–565 Ma interval very difficult, so only post 565 Ma paleomagnetic data are used herein.

The paleomagnetism and paleogeography of the major continental blocks have recently been extensively reviewed by a number of authors, including Cocks and Torsvik (2002, 2005, 2006, 2007, 2011), Meert and Torsvik (2003), Torsvik and Cocks (2004, 2013), Torsvik et al. (2012), and Meert (2013), who combined paleomagnetic, faunal and geological constraints. Here, we use paleomagnetic apparent polar wander paths (APWPs) for major blocks provided by Torsvik et al. (2012) back to 530 Ma for Baltica and Laurentia and to 550 Ma for East Gondwana.

For Baltica at 550 Ma, we use the inclination-corrected pole provided by Meert (2013, f-corrected pole using uncorrected pole of Popov et al. 2005), who oriented Baltica 50º counterclockwise of its present orientation. Previously, Hartz and Torsvik (2002) proposed that Baltica lay 'upside-down' (i.e. rotated 180º about a vertical axis) at 550 Ma based on paleomagnetic data at 750 and 500 Ma. More recently, Walderhaug et al. (2007) acquired paleomagnetic data from the 616 Ma Egersund dykes in Baltica, which suggest Baltica lay 50º clockwise from its present orientation at that time.

For Laurentia at 550 Ma, we used the pole provided for the Skinner Cove volcanic rocks by McCausland and Hodych (1998), but note that the Skinner Cove pole is ambiguous for both paleo-orientation and absolute longitude relative to the Laurentian craton (McCausland and Hodych 1998; Hodych et al. 2004). Use of the Skinner Cove pole therefore permits diverse implementations including: (i) the assumption that Laurentia spun about a vertical axis between ca. 550 Ma and ca. 530 Ma, (ii) the assumption that the Skinner Cove tectonic slice spun about a vertical axis after ca. 550 Ma, and/or (iii) the possibility that Laurentia lay to the north of the equator (a paleolatitude of 15°N) rather than to the south as is generally implemented (e.g. McCausland and Hodych 1998). Here, we adopt the third possibility listed, principally for convenience, because it allows the direct use of the published pole without speculating about components of vertical axis rotations for Laurentia or the Skinner Cove tectonic slice. Validation of this choice requires further consideration, but it allows us to include Laurentia in our model in a reproducible way back to 550 Ma. The eastern margin of Laurentia lay at 15–30ºS between 535–430 Ma paleolatitudes (Fig. 2; Cocks and Torsvik 2011). In contrast, Amazonia/São Francisco is constrained by very few paleomagnetic data from poorly dated rocks (Fig. 2; Trindade et al. 2004, 2006). Baltica appears to have lain between 30º and 60ºS from 550 to 460 Ma (Cocks and Torsvik 2006; Meert 2013).

For Greater Avalonia, we supplement the paleomagnetic poles given by Torsvik et al. (2012) with those in Table 1. In general, paleomagnetic data show that Avalonia migrated from ca. 15–25ºS through 60ºS and back to 25ºS between 550 and 430 Ma, but are insufficient to independently locate different parts of Avalonia (Fig. 2). We assume East Avalonia traveled with West Avalonia prior to 420 Ma (e.g. Landing 1996a, 2004) and with Baltica/Europe after 320 Ma. Paleolatitudes for Avalonia in Canada and New England are estimated to be (Fig. 2): (i) 49 ± 11°S in the Middle Cambrian (Johnson and Van der Voo 1985), (ii) 65 ± 12°S at 490 Ma (Thompson et al. 2010a), and (iii) ca. 42°S at 460 ± 3 Ma (Van der Voo and Johnson 1985). Accretion to Laurentia is estimated to have occurred at 430–422 Ma (van Staal et al. 2008). We assume Avalonia traveled with Laurentia after 420 Ma.

Paleomagnetic data for Carolinia indicate a paleolatitude of ca. 22°S at 450–455 Ma (Vick et al. 1987; Noel et al. 1988). Hibbard (2000) has proposed initial docking of Carolinia to eastern Laurentia occurred at 460 Ma followed by sinistral transpression. We assume Carolinia traveled with Avalonia prior to 490 Ma and with Avalonia–Laurentia after 420 Ma.

FAUNAL PROVINCIALITY

Faunal provinciality has been used to

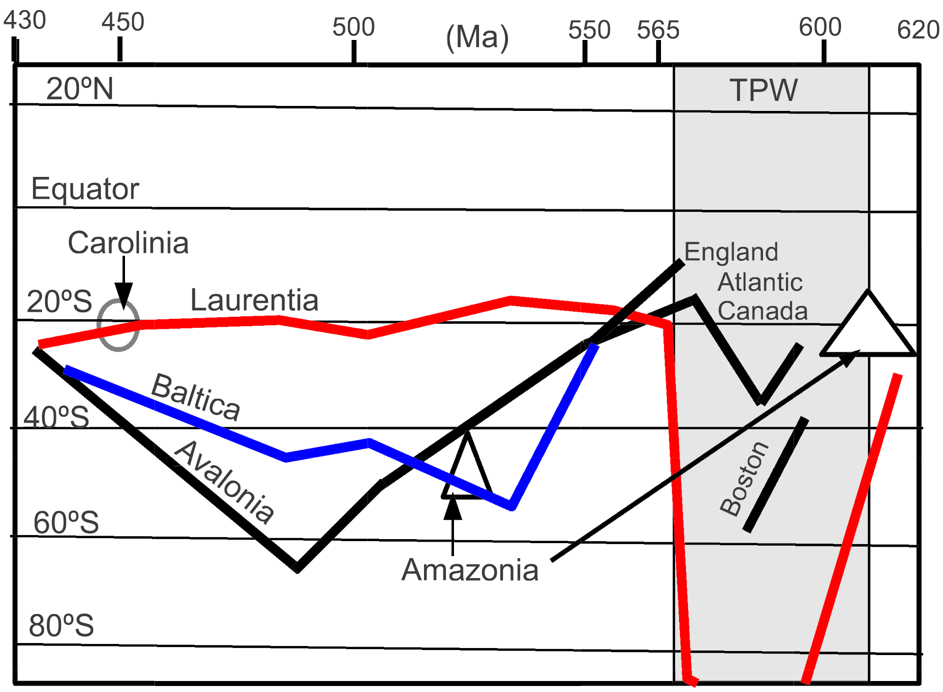

Figure 2. Paleolatitudes of Laurentia, Baltica, Avalonia, Carolinia, and Amazonia based on paleomagnetic data (see text for sources).

help determine the paleoposition of Avalonia, however the analyses commonly focus on the faunal affinities with major continents, such as Laurentia, Baltica and Gondwana. In this paper, faunal endemism and its implications for paleogeography, are more closely examined using papers published by paleontologists.

The similarity of the Ediacaran–Early Ordovician platformal successions throughout Avalonia suggests they form an overstep sequence (Keppie 1985), and they are dominated by marine siliciclastic rocks, with minor limestone, that were deposited in a series of pull-apart basins (Woodcock 1984; Landing and Benus 1988; Landing 1996a; Landing et al. 2013a, b). The stratigraphic record progresses upwards from: (a) Ediacaran–lower Lower Cambrian red bed units and marine sandstone, through (b) platformal middle Lower Cambrian units, (c) shoaling upward, shelf to peri-tidal, shale-carbonate sequences, (d) an upper Lower Cambrian sandstone-mudstone sequence, (e) Middle Cambrian mudstone-ash-limestone-sandstone sequence, to (f) an upper Middle Cambrian–lowest Ordovician (Tremadocian) shale-siltstone-sandstone sequence (Landing 1996b).

The Ediacaran and benthic Lower Cambrian ‘Avalonian’ fauna is predominantly endemic and distinct from that of Gondwana (Theokritoff 1985; Landing 1996a; Wagonner 2003; Álvaro et al. 2003; Landing et al. 2013a). Parsimony analysis of endemism in Ediacaran biota shows the Avalonian assemblage to be a distinctive, endemic assemblage (Waggoner 2003). In the Middle Cambrian, 21% of the British Avalonian trilobite fauna (excluding agnostid genera) are mainly endemic, with the rest showing connections with many regions, principally Baltica and Gondwana (Fig. 3a: Cocks and Fortey 2009). Two Middle Cambrian trilobite species and three or four genera are comparable with Baltic fauna, and three species show affinities with the Ossa Moreno zone in Iberia (marginal Gondwana) (Álvaro et al. 2003). The hundred Upper Cambrian trilobite taxa recorded in British Avalonia contrasts with the rare trilobite fauna in Morocco (lacking common genera) (Álvaro et al. 2003), which may be related to facies: dysoxic mudstones in Avalonia versus oxygenated sandstone in Morocco (Landing et al. 2013a). Trilobite and brachiopod endemism in Avalonia decreased during the Ordovician from 44% through 29% and 20% to 12%, which was concurrent with an increasing share of genera between Avalonia and Baltica (8 to 10.5 to 25 to 33.5%), and Avalonia and Laurentia (6 to 12 to 20 to 29%) (Fig. 4). On the other hand, genera shared between Avalonia and West Gondwana are relatively constant throughout the Ordovician (Fig. 3b). Together, the biota, trilobites and brachiopods indicate a progression from mainly endemic Ediacaran–Cambrian forms in Avalonia to increasing genera shared with Baltica and Laurentia through the Ordovician, which has been interpreted in terms of the approach of Avalonia to both Baltica

Table 1. Virtual Geomagnetic Poles (VGPs) used to reconstruct various blocks at different times that supplement the APWPs provided for Laurentia, Baltica and Gondwana in Torsvik et al. (2012). The opposite pole to the VGP directly reported in the associated source is indicated in brackets where used. Listed absolute ages either correspond to radiometric geochronology or our estimates of a corresponding absolute age from the relative age descriptions given in the associated sources.

Block	Age (Ma)	Latitude	Longitude	95%	Source
Baltica	550	40.3	296	5.7	Meert (2013) f-corrected pole
Laurentia	550	15 (-15)	157 (337)	9	McCausland and Hodych (1998)
Avalonia	460	-2 (2)	136 (316)	4.1	Van der Voo and Johnson (1985)
	490	34	320	7.2	Thompson et al. (2012)
	505	-21 (21)	160 (340)	12	Johnson and Van der Voo (1985)
	550	55.8	183.8	17.7	Pisarevsky et al. (2012)
Carolinia	450	29.6 (-29.6)	122.1 (302.1)	5.0	Vick et al. (1987)

and Laurentia. Conodont and ostracod fauna show similar trends (Landing et al. 2013a, c). Amalgamation of Avalonia to Baltica and Laurentia has been estimated to have occurred at ca. 443 Ma and 425 Ma, respectively (Torsvik and Rehnström 2003; Cocks and Torsvik 2005, 2011; Cocks and Fortey 2009). In conclusion, the faunal data suggest that Avalonia was an island microcontinent from the Ediacaran to the Late Ordovician, when combined Baltic+Laurentian fauna in Avalonia exceeded the combined endemic+ Gondwanan fauna (Fig. 3b).

DETRITAL ZIRCON AND T_{DM} MODEL AGES

Provenance of detrital zircon has also been used in paleogeographic reconstructions assuming local sources, however, long distance transport of zircon by ancient and modern large rivers, such as the Mississippi and Amazon, renders this method difficult to assess (e.g. Rainbird et al. 1992; Meinhold et al. 2013). Nd isotopic data in igneous rocks may allow the nature of the basement to be compared, but has to be used judiciously due to the potential of mixing magma sources.

Detrital zircon ages in Greater Avalonia were used in the 1990s to suggest an Amazonian provenance (Keppie and Krogh 1990; Keppie et al. 1998). Thompson et al. (2012) have proposed SW Baltica (Sveconorwegian orogen) as an alternative source for 900–2200 Ma detrital zircon grains in Neoproterozoic rocks of Greater Avalonia, however, they retained the location for Greater Avalonia adjacent to NW Gondwana, which allows Amazonia to be a potential source. Although it is very difficult to discriminate between Baltic and Amazonian sources, the 800–900 Ma Goiás arc in Amazonia appears to be unique (Keppie et al. 2008). As 800–900 Ma detrital zircon grains are absent or rare from Avalonia (Willner et al. 2013 and references therein), a Baltic source is favoured, although a river system that does not pass through the Goiás arc is still possible. A source for Ediacaran detrital zircon in Greater Avalonia may be found in the 620–550/500 Ma, Timanian orogen located along the northeastern and eastern margins of Baltica (Fig. 4b) (Maslov and Isherskaya 2002; Siedlecka et al. 2004; Kuznetsov et al. 2010).

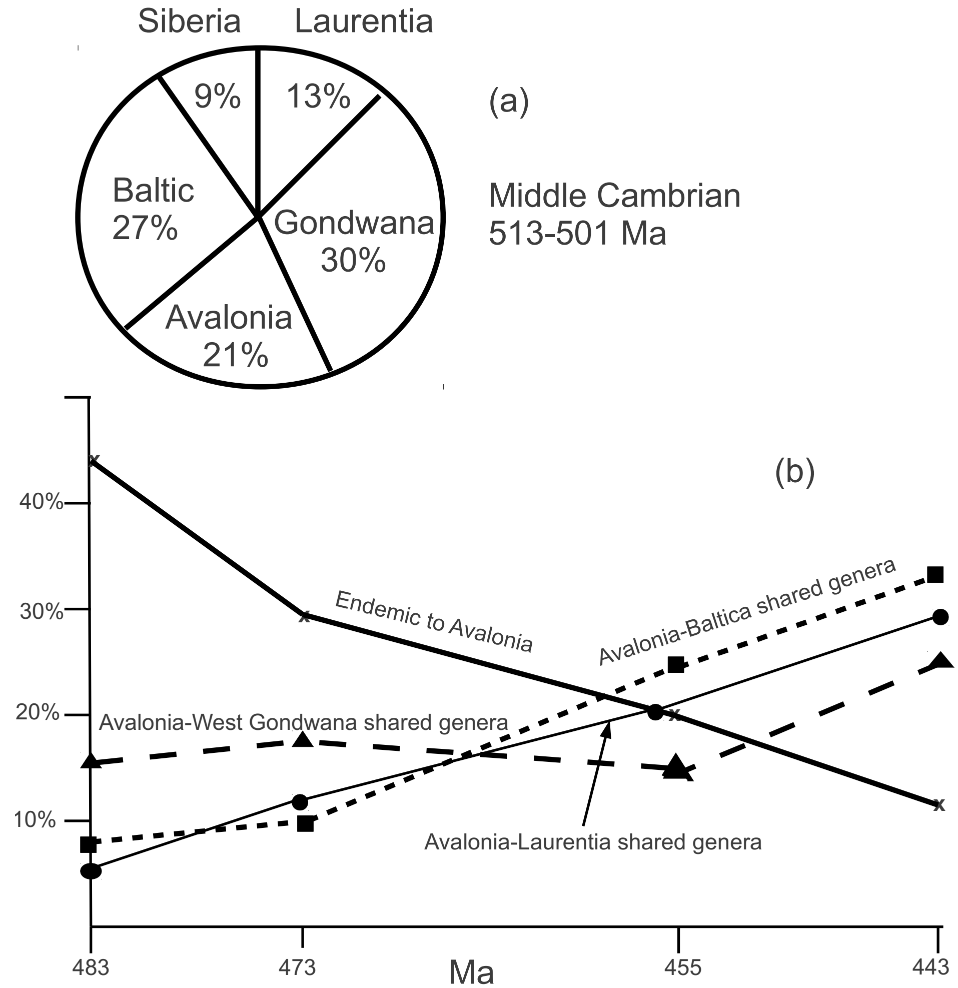

Figure 3. Analysis of trilobite affinities of Avalonian Lower Paleozoic fauna: (a) distribution of closest relatives of Welsh, Avalonian, Middle Cambrian, non-agnostid trilobite species in other terranes (modified from Cocks and Fortey 2009); (b) statistical analysis of Ordovician trilobite and brachiopod affinities (data from Lees et al. 2002).

The Neoproterozoic Timanian orogen has been divided along the N–S collisional, Baltica–Bolshezemel suture (Gee and Pease 2004; Moczydlowska et al. 2004). The western part of the Timanian orogen (SW Timanides) record Mesoproterozoic rifting followed by deposition of latest Mesoproterozoic to early Neoproterozoic passive margin rocks that were deformed by the 630–535 Ma Timanian orogeny (Roberts and Siedlecka 2002). The eastern part consists of subduction-related igneous rocks of the Bolshezemel block that have yielded many detrital zircon grains with ages of 590–760 Ma and a single detrital zircon grain of 1143 Ma (Kuznetsov et al. 2010). Within the Bolshezemel block, the Manyukuyakha serpentinitic mélange has been interpreted as a forearc basin (Scarrow et al. 2001). The Timanian orogeny has been interpreted as the result of accretion of an island arc complex (Bolshezemel block) to the northeastern Baltic margin (Fig. 4; Dovzhikova et al. 2004).

The Nd isotopic data in Neoproterozoic rocks across Avalonia in Newfoundland have T_{DM} ages of 0.745–1.12 Ga in the east to 0.74–1.65 Ga in the west (Keppie et al. 2012). These ages are similar to those from Avalonia in the United Kingdom: T_{DM} ages of 1.0–1.3 Ga in the southeast and 1.25–1.53 Ga in the northwest (Keppie et al. 2012). Nd isotopic data from Ganderia have generally yielded similar T_{DM} ages, whereas those from Carolinia range from 0.75 to 1.1 Ga

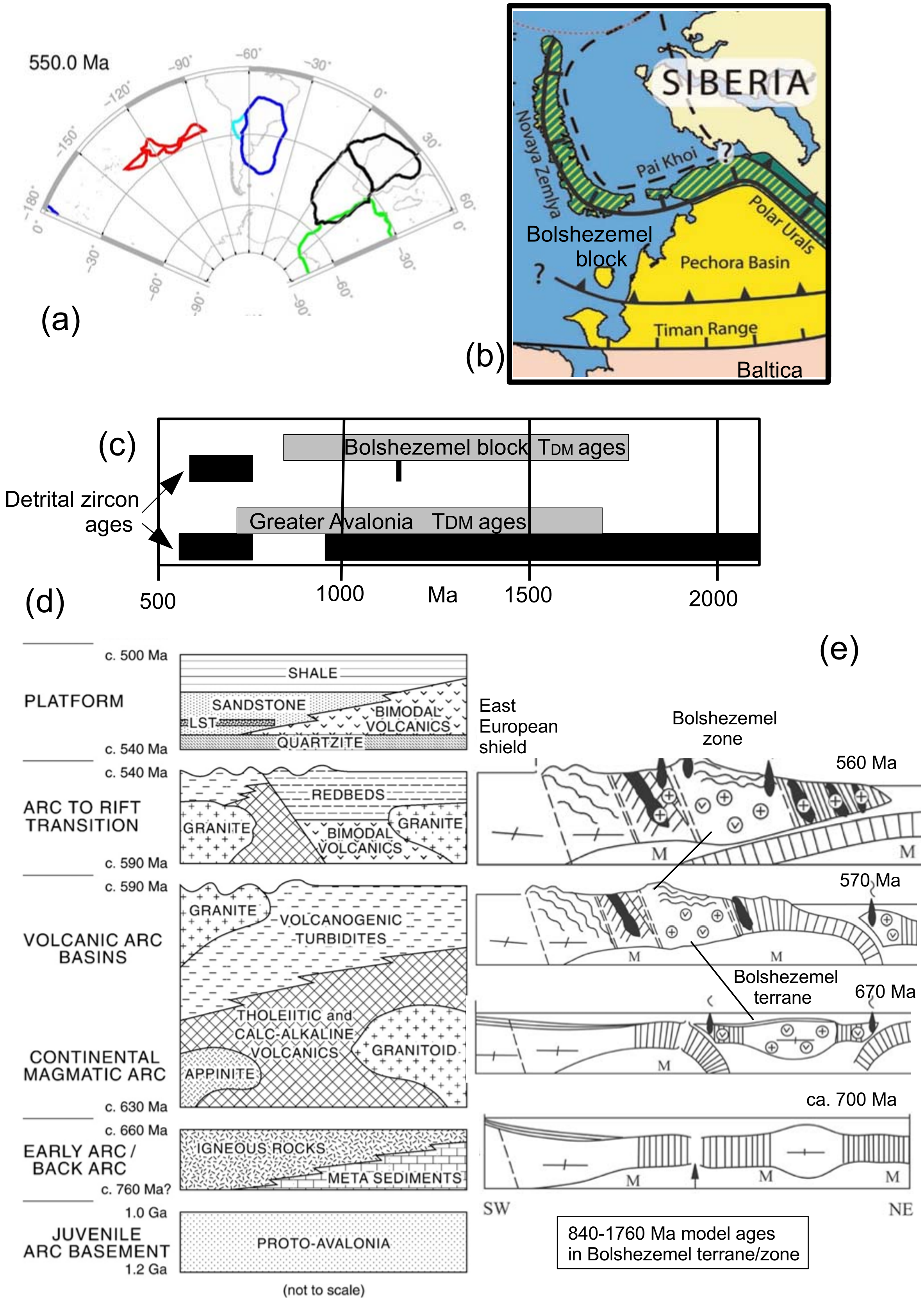

Figure 4. Neoproterozoic–Cambrian relationships between Avalonia and Baltica: (a) paleogeographic reconstruction at 550 Ma (this paper - see Fig. 5 for colour codes.); (b) map showing the distribution of the Timanian orogen in eastern Baltica (after Gee and Pease 2004); (c) comparison of detrital zircon and T_{DM} ages from the Bolshezemel and Greater Avalonia terranes (for sources of data see text); (d) Neoproterozoic–Cambrian geological record of Avalonia (modified after Murphy et al. 2008); and (e) plate tectonic interpretation of the Timanian orogen (modified from Dovzhikova et al. 2004).

(Keppie et al. 2012). Similar T_{DM} ages in Baltica occur in the post-tectonic granite in the 0.9–1.2 Ga Sveconorwegian orogenic belt of SW Scandinavia, which yielded T_{DM} ages of 1.03–1.69 Ga. (Andersen et al. 2001). In the Bolshezemel block (eastern Timanides), $^{176}Lu/^{177}Hf$ ratios of detrital zircon yielded 0.84–1.76 Ga T_{DM} model ages (Kuznetsov et al. 2010) that are similar to those of Greater Avalonia (0.73 to 1.9 Ga; Keppie et al. 2012). Furthermore, the island arc-related, Neoproterozoic geological records of Avalonia and the Bolshezemel block are almost identical only differing in the inference that the Bolshezemel block was involved in an arc–continent collision with Baltica (Dovzhikova et al. 2004), whereas Avalonia is relatively mildly deformed. The similarity of Avalonia and the eastern Timanides has been noted by several other authors who either rotate Baltica through 180º, which places the Timanides adjacent to Avalonia, Armorica and northern Gondwana (Hartz and Torsvik 2002; Cocks and Torsvik 2006; Kuznetsov et al. 2010; Corfu et al. 2010), or roughly in its present relative orientation, which leads to the inference that Neoproterozoic subduction zones lay around the periphery of Rodinia (Scarrow et al. 2001; Amato et al. 2009), and subduction may have started during Rodinia breakup.

Figure 5. Present-day base map showing digitized blocks used in this paper. The Timan–Pechora block corresponds to the Bolshezemel terrane.

PALEOGEOGRAPHIC RECONSTRUCTIONS AND PLATE TECTONIC INTERPRETATIONS

Laurentia, Baltica, NW and NE Africa, the Amazonia and Colorado blocks in South America, and Greater Avalonia were digitized (Fig. 5). Apparent Polar Wander Paths (APWPs) were plotted using poles from Torsvik et al. (2012) supplemented by those from other authors as described above (Fig. 6 and figure caption). Figure 6 shows the APWPs used in making the paleogeographic reconstructions. Figure 6a shows APWPs derived from local data in a local reference frame (i.e. a Laurentian APWP in a Laurentian reference frame). Figure 6b shows APWPs derived from local data rotated into a common South African/Gondwanan reference frame. Figure 6c shows the simplified APWP tree that results if Master Path segments are adopted for Laurussia and Pangea from Torsvik et al. (2012) (i.e. Laurentia and Baltica share a common Laurussian Master APWP for 430 Ma to 320 Ma, and Laurentia, Baltica, and Gondwana share a common Pangean Master APWP for 320 Ma to 0 Ma). Figure 6d shows the simplified APWP tree that results when all APWPs are rotated into the common South African/Gondwanan reference frame: this is depicted diagrammatically at the bottom of Figure 6. The APWPs plotted in Figure 6d underlie the reconstructions shown in Figure 7, which additionally reflect choices for paleolongitude of the various blocks that are either consistent with previous studies or reflecting new interpretations discussed here. Figure 7 shows ten reconstructions from 550 Ma to 415 Ma in 15 Ma intervals.

Curiously, published late Ediacaran and Early–Middle Cambrian positions of Avalonia generally ignore the low paleolatitudes recorded by paleomagnetic data, and instead place Avalonia at high latitudes (e.g. Torsvik et al. 2012, and references therein). Similarly, a latest Ediacaran–Early Cambrian paleogeographic map based on fauna and facies places Avalonia at high latitudes and Gondwana straddling the Equator (Landing et al. 2013a), both of which are inconsistent with Avalonian paleomagnetic data. A more recent 540 Ma reconstruction based on paleomagnetic data (Li et al. 2013) is consistent with low latitudes for deposition of carbonate and evaporite units in the major continental blocks, nevertheless, Avalonia is still placed at high paleolatitudes of 40–70ºS, not the 20–30ºS paleolatitudes documented by the paleomagnetic data. The 580 Ma Gaskiers tillite in the Newfoundland Avalon is generally cited as evidence of deposition at a high latitude, however, they are associated with humid, temperate climate

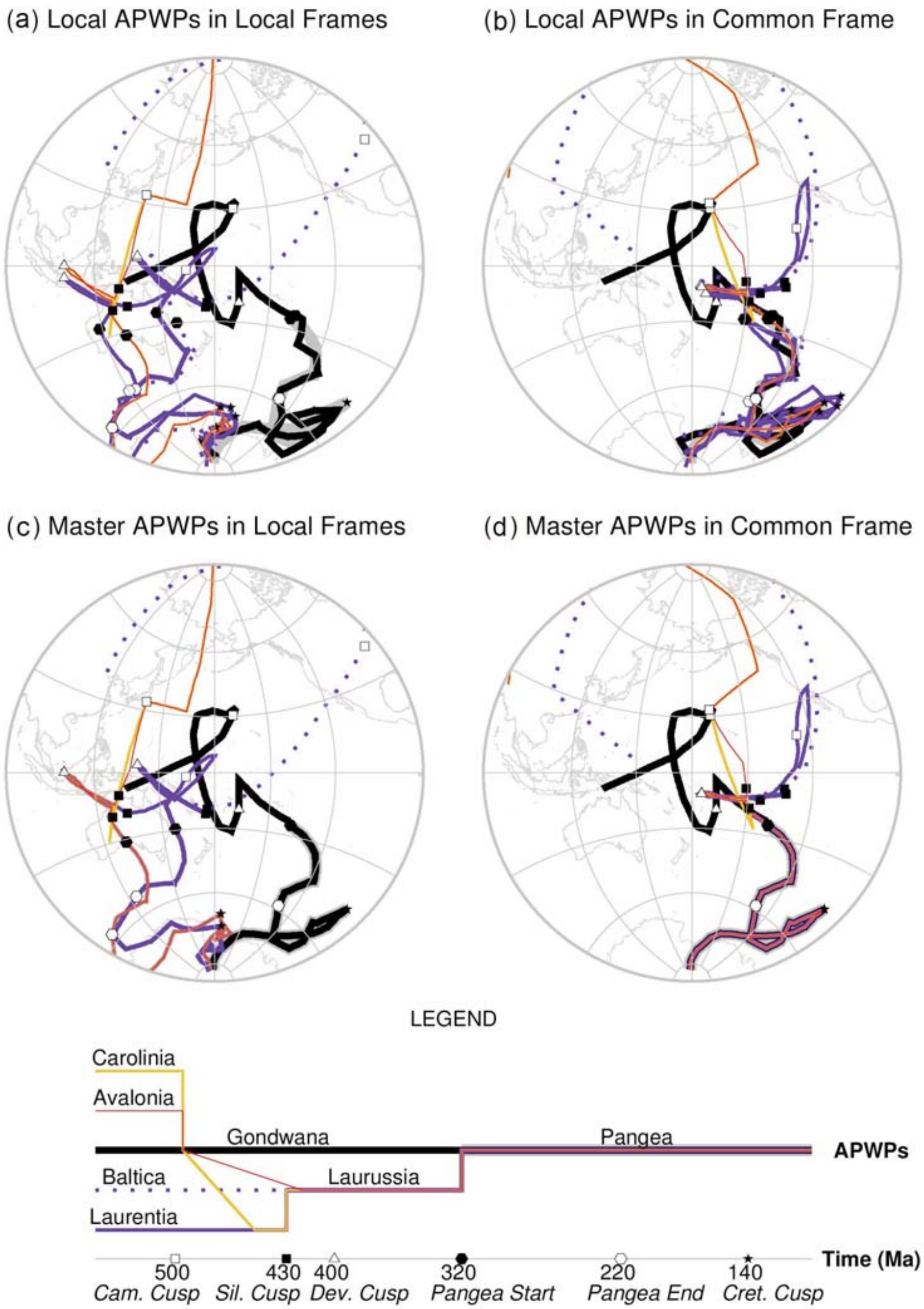

Figure 6. Apparent Polar Wander Paths (APWPs) for Laurentia, Baltica, Gondwana, Avalonia and Carolinia in various reference frames: (a) local Apparent Polar Wander Paths in local frame; (b) local Apparent Polar Wander Paths in common framework; (c) Master Apparent Polar Wander Paths in local frameworks; and (d) Master Apparent Polar Wander Paths in common framework, which leads to the simple reconstruction tree shown at bottom. Post-530 Ma poles for Gondwana, Laurentia and Baltica are from Torsvik et al. (2012). 530 Ma poles for Laurentia and Gondwana are also used for 530–550 Ma, whereas, the 550 Ma pole for Baltica is the f-corrected pole of Meert (2013) who corrected for inclination shallowing in the Popov et al. data (2005). Avalonia poles are from Pisarevsky et al. (2008, 2012), Thompson et al. (2010a, 2012), Johnson and Van der Voo (1985), and Van der Voo and Johnson (1985): the 490 Ma pole was also used for 500 Ma. Carolinia poles are from Vick et al. (1987) and Noel et al. (1988).

paleosols, which has led to their interpretation as glacial moraines deposited in the forearc basin, similar to Japan (Retallack 2013).

550–500 Ma (Late Ediacaran – Middle Cambrian) Reconstructions

At 550 Ma, Greater Avalonia lay at ca. 25ºS and rotated 150º anticlockwise about a vertical axis with a long axis parallel to paleolatitude (Fig. 7: 550 Ma): the Timanian/Uralian margin of Baltica lay at a slightly higher paleolatitude. In this location, Avalonia may be traced along strike into the northeastern Timanides. The Neoproterozoic, 600–540 Ma, geological record of Avalonia is interpreted as an island arc complex, which may be correlated with an Ediacaran arc complex in the Bolshezemel block of the northeastern Timanides both in time, space, and detrital zircon and model ages (Fig. 4; Scarrow et al. 2001; Kuznetsov et al. 2010). The main difference between these complexes is the degree of latest Ediacaran deformation, mild in Avalonia and polyphase in the Bolshezemel block, which may be interpreted in terms of isolation of the Avalonia microcontinent versus collisional between Baltica and the arc-related Bolshezemel block in the Timanides, respectively. In Maritime Canada, the dip of the Ediacaran Benioff zone deduced from geochemistry and Nd isotopes indicates a north-dipping Benioff zone in present coordinates (Keppie and Dostal 1991; Dostal et al. 1996, which is consistent with the ocean to continent transition observed in Greater Avalonia (Keppie et al. 2012). The dip direction of the Benioff zone becomes south-dipping when rotated 150º counterclockwise. At 590 Ma, a mid-oceanic ridge offset by a major transform fault collided with the trench resulting in migration of two ridge–trench–transform fault (R–T–F) triple junctions (figure 7 in Keppie et al. 2003). One R–T–F triple junction starts in Brunia and Britain at ca. 585 Ma (van Breemen et al. 1982; Finger et al. 2000; Pharaoh and Carney 2000) and migrated to Atlantic Canada by ca. 550–570 Ma. The other R–T–F triple junction started at Boston at 590 Ma (Thompson et al. 2010a, b, 2012) and migrated to Carolinia by 550 Ma (Hibbard et al. 2002). Migration of these

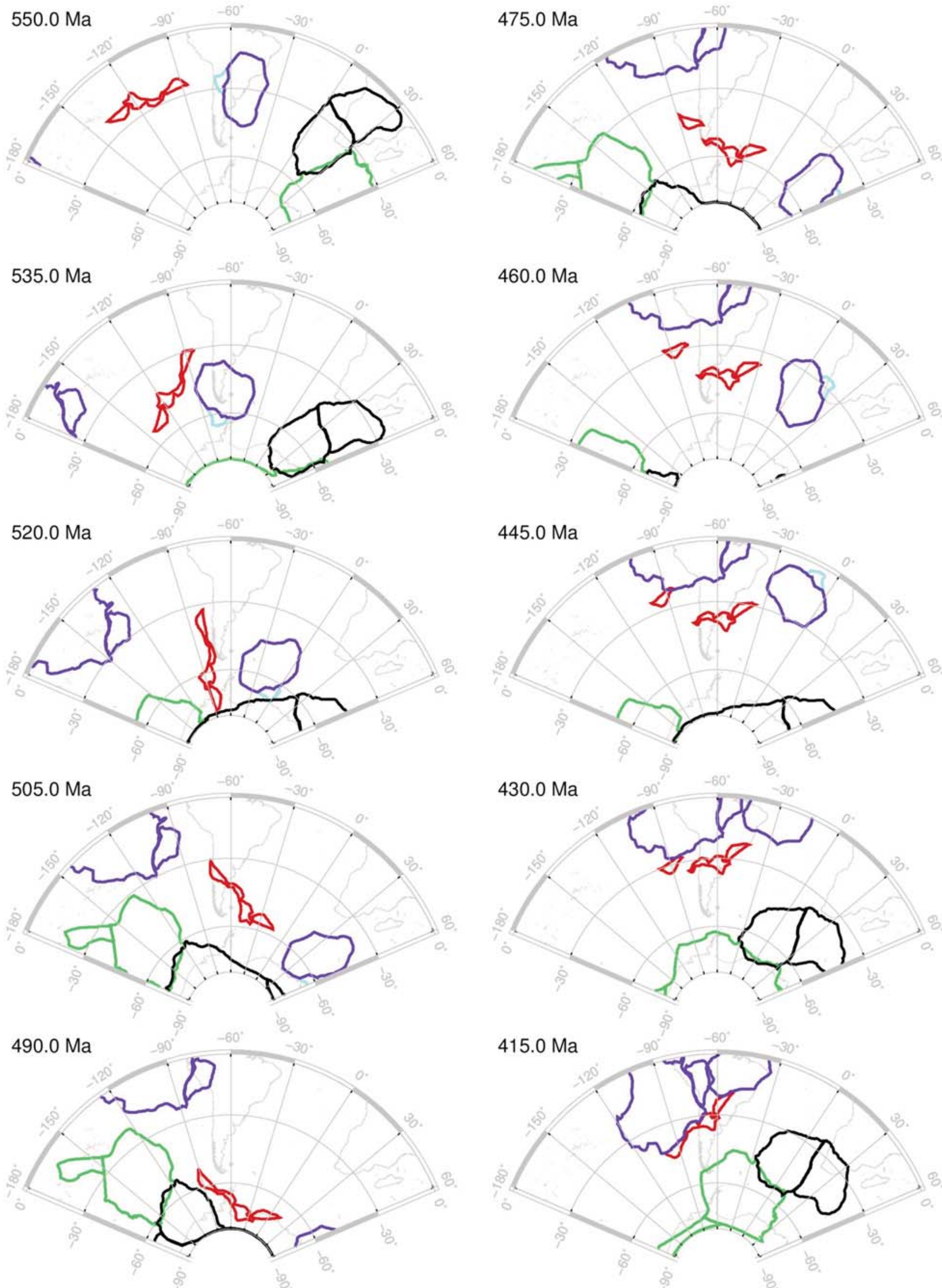

Figure 7. Reconstructions from 550–415 Ma at 15 m.y. intervals showing the migration of Greater Avalonia from Baltica to Gondwana between 550 and 490 Ma and from Gondwana to eastern Laurentia between 490 and 415 Ma. Note that paleolongitude is unconstrained by paleomagnetic data. (see Fig. 5 for colour codes).

triple junctions gradually replaced the trench with a transform fault (Keppie et al. 2003). Sinistral motion on the transform fault led to movement of Avalonia westwards away from Baltica.

The Avalonian arc complex was amalgamated before deposition of the latest Ediacaran–Cambrian overstep sequence (Keppie 1985). The endemism of the Ediacaran–lower Lower Cambrian fauna in Avalonia (Landing 1996b, 2013a, b; Waggoner 2003) indicates that Avalonia was an insular microcontinent at this time and suggests there was an ocean basin between Avalonia and Baltica. Between 550 and 500 Ma, Greater Avalonia rotated counterclockwise through ca. 150º about a pole of rotation at ca. 45ºS, which brought Greater Avalonia off NW Africa at a paleolatitude of 65–75ºS and placing the former Ediacaran trench on the Gondwanan side. A latest Cambrian–lowest Ordovician hiatus without associated deformation in Avalonia suggests that collision with Gondwana did not take place. This counterclockwise rotation appears to have been synchronous with the eastward motion of Baltica relative to northern Gondwana. A modern analog for such synchronous motions may be provided by the relative eastward migration of the Caribbean arc leading to counterclockwise rotation of the Chortis and Yucatan block into the trailing edge of the Caribbean Plate (Keppie 2012; Keppie and Keppie 2012). Arc magmatism is largely absent during this counterclockwise motion suggesting that the movement of Greater Avalonia was parallel to a bounding transform fault.

The partially endemic, Early Ordovician, Avalonian fauna suggests that Avalonia was separated from NW Africa by an ocean basin, which may have become a backarc basin when subduction beneath Greater Avalonia started at ca. 510 Ma. Synchronous onset of subduction on the eastern Laurentian margin at 510 Ma (van Staal et al. 2007) suggests plate reorganisation that initiated the closure of Iapetus. In SE–NW transects across the Ganderian margin, one passes from a passive margin bordering a backarc basin into volcanic arcs (ca. 510–485 Ma Penobscot and ca. 480–450 Ma Victoria arcs): the intervening 485–480 Ma Penobscot orogeny is inferred to represent closure of a backarc basin (Zagorevski et al. 2007, 2010; Schulz et al. 2008; van Staal et al. 2009; Johnson et al. 2012).

490–420 Ma (Ordovician – Middle Silurian) Reconstructions

Between 490 and 420 Ma, Greater Avalonia migrated orthogonally across Iapetus from NW Africa to eastern Laurentia, which is consistent with existing models. It is suggested that an offset between Carolinia and the rest of Avalonia originated during the plate reorganisation, which led to the docking of Carolinia with southeastern Laurentia at 460 Ma followed by sinistral relative motion (Hibbard 2000). Trilobite and brachiopod affinities suggest that the eastern tip of Avalonia approached Baltica at 460–450 Ma (Torsvik and Rehnström 2003) followed by docking with eastern Laurentia at 420 Ma. Closure of Iapetus is reflected in the gradual replacement of endemic Avalonian trilobites and brachiopods by Baltic and Laurentian fauna (Fig. 3).

The new paleogeographic model provides a solution to the apparent contradiction between the SE to NW ocean to continental polarity observed in the Nd isotopic data (Keppie et al. 2012) and the orthogonal transfer of Greater Avalonia across Iapetus where the reverse polarity would be expected (Murphy et al. 2006). This is reconciled in the new model, where 180º counterclockwise rotation of Greater Avalonia during the Cambrian (550–490 Ma) was followed by orthogonal transfer across Iapetus during the Ordovician.

ACKNOWLEDGEMENTS

We would like to thank the editors for inviting us to write a paper for the late Dr. Hank Williams, geologist, friend and fiddler extraordinaire. Reviews of the manuscript by Drs. R.D. Nance and E. Landing are greatly appreciated.

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Received July 2013
Accepted as revised October 2013
First published on the web February 2014