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# Tethyan, Mediterranean, and Pacific analogues for the Neoproterozoic–Paleozoic birth and development of peri-Gondwanan terranes and their transfer to Laurentia and Laurussia

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## Abstract

Modern Tethyan, Mediterranean, and Pacific analogues are considered for several Appalachian, Caledonian, and Variscan terranes (Carolina, West and East Avalonia, Oaxaquia, Chortis, Maya, Suwannee, and Cadomia) that originated along the northern margin of Neoproterozoic Gondwana. These terranes record a protracted geological history that includes: (1) ~ 1 Ga (Carolina, Avalonia, Oaxaquia, Chortis, and Suwannee) or ~ 2 Ga (Cadomia) basement; (2) 750–600 Ma arc magmatism that diachronously switched to rift magmatism between 590 and 540 Ma, accompanied by development of rift basins and core complexes, in the absence of collisional orogenesis; (3) latest Neoproterozoic–Cambrian separation of Avalonia and Carolina from Gondwana leading to faunal endemism and the development of bordering passive margins; (4) Ordovician transport of Avalonia and Carolina across Iapetus terminating in Late Ordovician–Early Silurian accretion to the eastern Laurentian margin followed by dispersion along this margin; (5) Siluro-Devonian transfer of Cadomia across the Rheic Ocean; and (6) Permo-Carboniferous transfer of Oaxaquia, Chortis, Maya, and Suwannee during the amalgamation of Pangea. Three potential models are provided by more recent tectonic analogues: (1) an "accordion" model based on the orthogonal opening and closing of Alpine Tethys and the Mediterranean; (2) a "bulldozer" model based on forward-modelling of Australia during which oceanic plateaus are dispersed along the Australian plate margin; and (3) a "Baja" model based on the Pacific margin of North America where the diachronous replacement of subduction by transform faulting as a result of ridge–trench collision has been followed by rifting and the transfer of Baja California to the Pacific Plate. Future transport and accretion along the western Laurentian margin may mimic that of Baja British Columbia. Present geological data for Avalonia and Carolina favour a transition from a "Baja" model to a "bulldozer" model. By analogy with the eastern Pacific, we name the oceanic plates off northern Gondwana: Merlin ( ≡ Farallon), Morgana ( ≡ Pacific), and Mordred ( ≡ Kula). If Neoproterozoic subduction was towards Gondwana, application of this combined model requires a total rotation of East Avalonia and Carolina through 180° either during separation (using a western Transverse Ranges model), during accretion (using a Baja British Columbia "train wreck" model), or during dispersion (using an Australia "bulldozer" model). On the other hand, Siluro-Devonian orthogonal transfer ("accordion" model) from northern Africa to southern Laurussia followed by a Carboniferous "Baja" model appears to best fit

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the existing data for Cadomia. Finally, Oaxaquia, Chortis, Maya, and Suwannee appear to have been transported along the margin of Gondwana until it collided with southern Laurentia on whose margin they were stranded following the breakup of Pangea. Forward modeling of a closing Mediterranean followed by breakup on the African margin may provide a modern analogue. These actualistic models differ in their dictates on the initial distribution of the peri-Gondwanan terranes and can be tested by comparing features of the modern analogues with their ancient tectonic counterparts.

*Keywords:* Analogues; Neoproterozoic–Paleozoic birth; Peri-Gondwanan terranes

## 1. Introduction

The Appalachian–Caledonian orogen was once considered a two-sided, symmetrical system that was interpreted in terms of geosynclinal theory in which a major syncline was telescoped into an orogen (Kay, 1951; Williams, 1964). With the advent of plate tectonics, this interpretation was replaced by orthogonal opening and closing of an ocean, now termed Iapetus, between eastern Laurentia and a continental landmass (Avalonia–Carolina: defined below) thought to border Western Europe and northwest Africa (Dewey, 1969). The terms Avalonia, Carolina, and Cadomia are used here to include a collection of terranes previously grouped as the Avalon Zone or Composite Terrane (Fig. 1) (e.g. Williams, 1979; Keppie, 1985), the Carolina Zone, which includes the Carolina, Spring Hope, and Roanoke Rapids terranes (e.g. Williams, 1979), or the Avalonian–Cadomian belt (e.g. Murphy and Nance, 1989). However, data accumulated over the past 25 years suggests that Avalonia–Carolina and eastern Laurentia were not conjugate rift margins during the opening of Iapetus (e.g. Keppie, 1977; Dalziel, 1992; Nance and Thompson, 1996; Keppie et al., 1998). This evidence includes: (1) the recognition that the northwestern margin of Neoproterozoic Avalonia–Carolina–Cadomia was an active margin at the same time that the eastern margin of Laurentia was a developing rift-passive margin (Keppie, 1985, 1989; Cawood et al., 2001); (2) the realization that Neoproterozoic subduction in Avalonia–Carolina–Cadomia was both long-lived ( ~ 170 Ma) and terminated, not in collisional orogenesis, but with a transition to an early Cambrian platform (Keppie, 1982; Murphy and Nance, 1989; Nance et al., 1991); (3) the accumulation of isotopic data indicating that Avalonia and Carolina are underlain by a ~ 1 Ga basement and contain a ~ 1 Ga detritus in Neoproterozoic units that have been linked with ~ 1 Ga orogens that encircle the Amazon craton ( ~ 1 Ga orogens are absent in the West African craton)(Keppie and Krogh, 1990; Murphy et al., 1996, 2000; Keppie et al., 1998; Hibbard et al., 2002); and (4) the evolution of models based on subsidence curves, ~ 1 Ga Rodinia supercontinent reconstructions, and paleomagnetic data, that suggest eastern Laurentia lay adjacent to western South America prior to the birth of Iapetus (e.g. Figs. 2 and 3) (Bond et al., 1984; Hoffman, 1991; Dalziel, 1992; Keppie, 1993; Keppie and Ramos, 1999). Paleontological and paleomagnetic data suggest that Avalonia–Carolina–Cadomia originated as peri-Gondwanan terranes distributed along the northern margin of Amazonia–northwest Africa, although their relative locations along this margin may have varied with time (e.g. Keppie et al., 1996; Keppie and Ramos, 1999). This evidence has spawned a series of models for the transfer of these terranes from Gondwana to Laurentia (from Cambrian separation to Late Ordovician–Early Silurian accretion) (e.g. Keppie, 1993; Strachan et al., 1996; Keppie et al., 1996; Keppie and Ramos, 1999; Murphy et al., 1999; Hibbard, 2000; Linnemann et al., 2000; Franke et al., 2000; Hibbard et al., 2002; Nance et al., 2002). The improved database has reached the stage where more actualistic models may be constructed. This paper presents a summary of the geological records of these peri-Gondwanan terranes from which are derived actualistic plate tectonic models for their transfer to eastern Laurentia and Laurussia.

Potential modern analogues include Alpine Tethys, the Pacific Ocean, and the Mediterranean Sea. We conclude that the Late Paleozoic–Cenozoic plate tectonics of the eastern Pacific Ocean (e.g. Debiche and

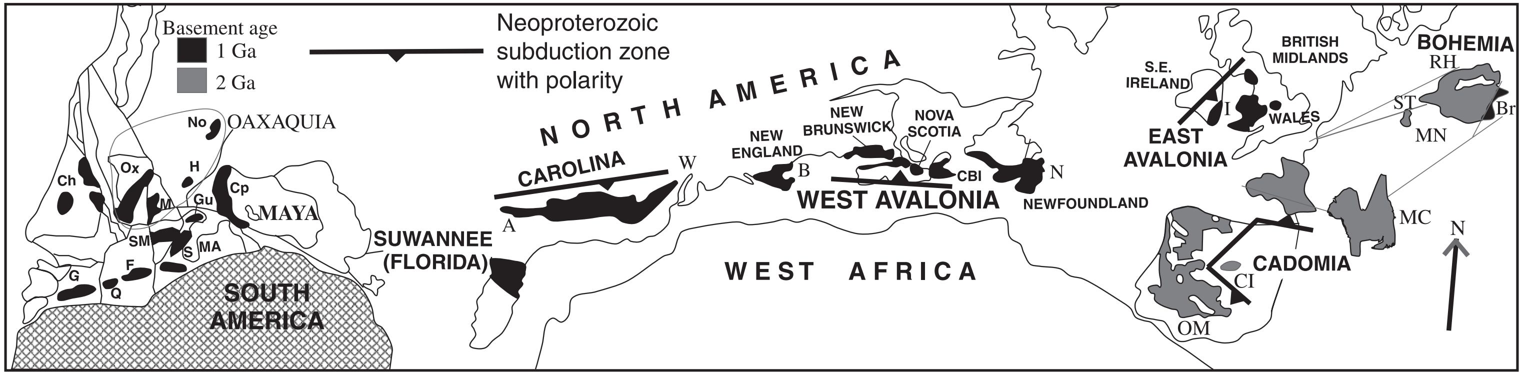

Fig. 1. Pangea A reconstruction (modified after Keppie and Ortega-Gutiérrez, 1999; Weil et al., 2001) showing the location of peri-Gondwanan terranes and the inferred polarity of Neoproterozoic subduction. Abbreviations: A = Atlanta, B = Boston, Br = Brunia (includes Moravo-Silesia and W. Sudetes), CBI = Cape Breton Island, Ch = Chortis, CI = Central Iberia, Cp = Chiapas, F = Floresta, G = Garzón, Gu = Guajira, H = Huiznopala, I = Ireland, M = Mixtequita, MA = Mérida Andes, MN = Moldanubian, N = Newfoundland, No = Novillo, OM = Ossa-Morena Ox = Oaxacan Complex, Q = Quetame, RH = Rheno-Hercynian, S = Santander, SM = Santa Marta, ST = Saxo-Thuringian, W = Washington. OAXAQUIA comprises Huiznopala, Mixtequita, Novillo, and Oaxacan Complex.

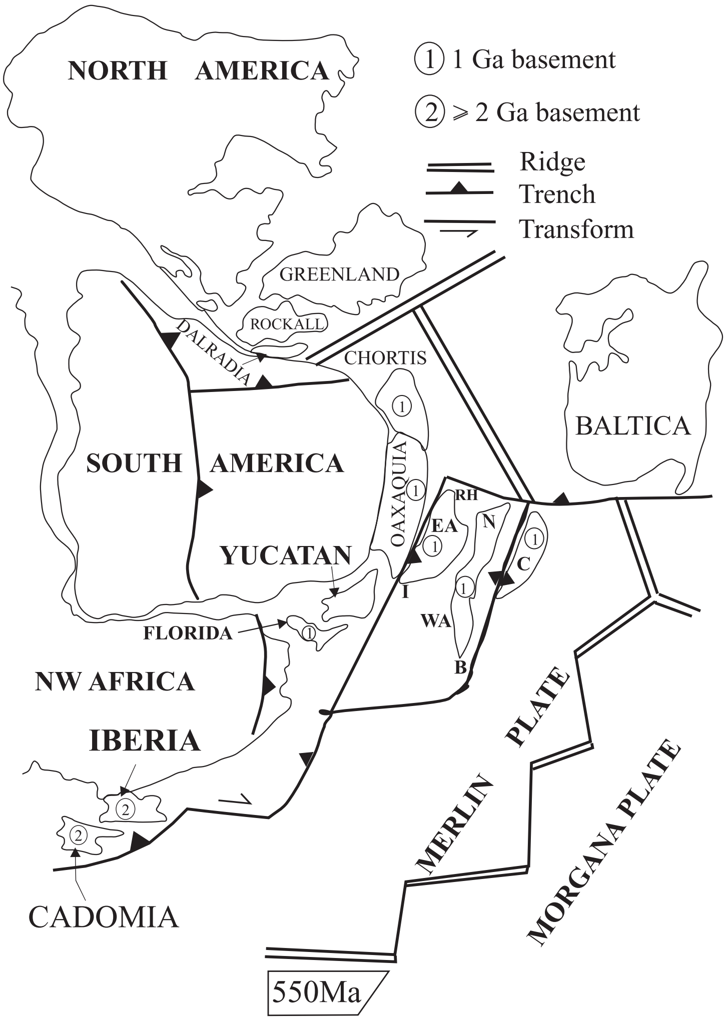

Fig. 2. An end member, side-by-side arrangement of the peri-Gondwanan terranes at 550 Ma (see text for detailed discussion). Abbreviations as in Fig. 1 plus: C = Carolina, EA = East Avalonia, G = Gander terrane, M = Meguma terrane, WA = West Avalonia (modified after Keppie and Ramos, 1999).

Engebretson, 1987; Van Staal et al., 1998) provides the closest analogue for the Neoproterozoic–Early Cambrian history of the peri-Gondwanan terranes, whereas the future history of Australian invasion of the Pacific Ocean provides a reasonable analogue for their Early Paleozoic history. Application of Pacific models to these terranes has an important bearing on their initial arrangement, which can be evaluated using a variety of provenance data including basement signatures, Cambrian faunal provinciality, paleomagnetic data, and detrital zircon ages.

## 2. Peri-Gondwanan terranes

Peri-Gondwanan terranes in this paper are limited to those presently located in the Appalachian, Caledonian, and Variscan orogens that originated adjacent to Amazonia and northwest Africa. These comprise Avalonia and Carolina, which were accreted during the Late Ordovician–Early Silurian (N.B. some authors prefer a Carboniferous time of accretion for Carolina), Cadomia and Bohemia, which were accreted during the Siluro-Devonian, and Oaxaquia, Chortis, Maya, and

Suwannee, which were accreted in the Permo-Carboniferous. Several reviews of the peri-Gondwanan terranes have been published recently (Keppie, 1994; Nance and Thompson, 1996; Ramos and Keppie, 1999; Murphy et al., 1999; Franke et al., 2000; Hibbard et al., 2002; Nance et al., 2002). This paper represents a companion to Nance et al. (2002). Consequently, the summaries presented below will focus on those points essential for establishing actualisitic plate tectonic models: (1) basement age; (2) polarity of Neoproterozoic subduction; (3) timing of the cessation of subduction and the switch from arc to rift magmatism; (4) factors bearing on the provenance of the terranes; (5) timing of separation from Gondwana; and (6) timing of accretion with Laurentia–Laurussia.

## *2.1. ~1 Ga basement terranes*

### *2.1.1. Oaxaquia–Chortis*

The ~1 Ga basements of Oaxaquia and the Chortis block underlie most of Mexico and Honduras, an area of 1,000,000 km$^2$ (Fig. 1). Currently, there are widely divergent views on their provenance. One view holds that they represent an autochthonous extension of the Grenville Orogen of eastern and southern Laurentia (e.g. Karlstrom et al., 1999), whereas another view proposes that they are exotic terranes derived either from Amazonia or northeastern Laurentia (Ortega-Gutiérrez and Keppie, 2000; Keppie et al., 2001, 2003, and references therein). The Oaxacan Complex of southern Mexico, which appears to be representative of Oaxaquia and the Chortis block, consists of (1) a metavolcanic-metasedimentary juvenile arc sequence of unknown polarity and age; (2) a ~1140 Ma, bimodal, within-plate intrusive suite that was deformed, metamorphosed, and migmatized at ~1100 Ma; (3) a ~1012 Ma anorthosite-gabbro that was deformed and metamorphosed in the granulite facies at ~980–1104 Ma; and (4) a ~920 Ma post-tectonic calc-alkaline pluton that has been related to subduction of unknown polarity (Keppie et al., 2001, 2003; Ortega-Obregon, 2002).

This basement complex is unconformably overlain by the Lower Ordovician Tiñu Formation, which contains trilobites of Gondwanan affinity in outer shelf-slope deposits (Robison and Pantoja-Alor, 1968; R. Robison, written comm., 1998). On these grounds, together with their mutually similar Mesoproterozoic geological records, it has been suggested that Oaxaquia and the Chortis block may have been derived from the gap north of Colombia in the circum-Gondwanan, Ordovician facies belts on the northwestern margin of Amazonia (e.g. Figs. 2 and 3) (Cocks and Fortey, 1988; Keppie and Ortega-Gutierrez, 1995; Keppie et al., 2001). The same location was chosen by Keppie (1977) and Boucot et al. (1997) based on the close affinity between Silurian fauna in rocks unconformably overlying the ~1 Ga Novillo Gneiss in northeastern Mexico and those in Venezuela (Fig. 1). Such a provenance is also in accord with the detrital zircon ages (980–1230 Ma) in the Tiñu Formation, which may be derived from the Oaxacan Complex and ~1 Ga basement found in many northern Andean massifs (Gillis et al., 2001). The absence of Cambrian rocks in Mexico coincides with the separation of the peri-Gondwanan terranes, and may be related to the thermal uplift and erosion that commonly precedes thermal requilibration and deposition of rift–drift sequences.

The lower Paleozoic rocks of Oaxaquia (Fig. 1) are unconformably overlain by Carboniferous and Permian rocks that herald the appearance of fauna with Laurentian affinities in the Mississippian (Sour-Tovar et al., 1996; Stewart et al., 1999). This interpretation is borne out by the detrital zircon record, which indicates that Oaxaquia was isolated from the southern margin of Laurentia until the Carboniferous (Gillis et al., 2001). It is also consistent with paleomagnetic data that would locate Oaxaquia off either Amazonia or northeastern Laurentia (Ballard et al., 1989; Keppie and Ortega-Gutiérrez, 1999). Such data led Keppie and Ramos (1999) to place an ocean between Oaxaquia and Laurentia until Permo-Carboniferous times, in contrast to Ortega-Gutiérrez et al. (1999) who propose a collision between Oaxaquia and eastern Laurentia in the Late Ordovician–Silurian.

### *2.1.2. Maya terrane*

The Maya terrane of the Yucatan Peninsula (Fig. 1) represents a block that was rotated ~60° anticlockwise during the Early Mesozoic opening of the Gulf of California (Molina-Garza et al., 1992; Dickinson and Lawton, 2001). Restoration of this rotation suggests former continuity with Oaxaquia (Fig. 1). The Mixtequita inlier near the southern border of the terrane contains ~1.23 Ga orthogneisses metamor-

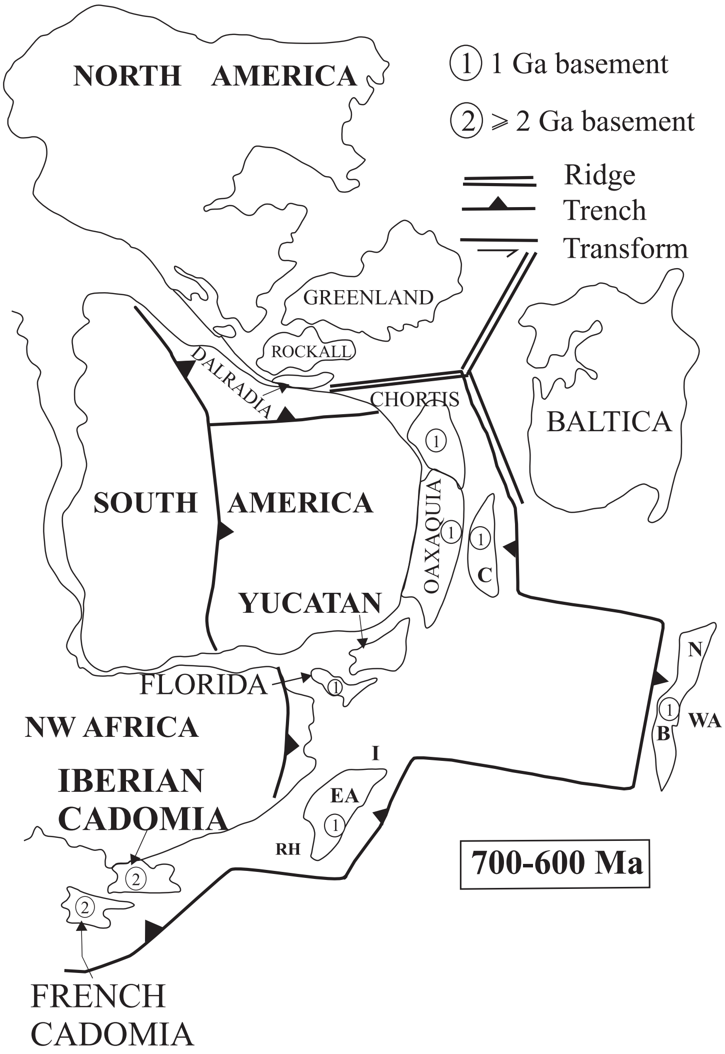

Fig. 3. An end member, end-to-end arrangement of the peri-Gondwanan terranes between 700 and 600 Ma, assuming the present order and subduction polarity applies to the Neoproterozoic, and backward modeled to remove 150–200 million years of subduction (see text for detailed discussion). Abbreviations are as in Figs. 1 and 2. Modified after Keppie and Ramos (1999).

phosed under granulite facies at 990–975 Ma (Weber and Köhler, 1999; Ruiz et al., 1999), factors that suggest it represents part of Oaxaquia. Zircons from plutonic rocks found in boreholes in the Yucatan Peninsula have yielded late Neoproterozoic ages (Krogh et al., 1993), and Late Silurian ages have been recorded in plutons in the Maya Mountains (Steiner and Walker, 1996). The relationship between these units is not exposed. But, if the ~ 1 Ga rocks form the basement beneath the Maya terrane, a history similar to that of Oaxaquia may be assumed (Keppie and Ramos, 1999).

### 2.1.3. Suwannee terrane: Florida

Although the Suwannee terrane (Fig. 1) is covered by Phanerozoic rocks, boreholes have yielded the following sequence: (1) a Mesoproterozoic basement recorded by 1060–1240 Ma $^{207}$Pb/$^{206}$Pb zircon ages in a granitoid (Heatherington et al., 1993) and $T_{DM}$ model ages of 1580–1040 Ma in latest Neoproterozoic igneous suites (Heatherington et al., 1996); (2) ~ 625 and ~ 552 Ma, calc-alkaline igneous suites related to subduction of unknown polarity (Heatherington et al., 1996); and (3) unconformably overlying, undeformed Ordovician–Devonian rocks containing high-latitude trilobite and acritarch fauna of Gondwanan affinity that have generally been correlated with the Bove Basin of West Africa (Whittington and Hughes, 1974; Cramer and Diez, 1974). Such a provenance is consistent with available paleomagnetic data (Opdyke et al., 1987). The Cambrian hiatus may have a similar origin to that of Oaxaquia. The Suwannee terrane was accreted to southern Laurentia during the Permo-Carboniferous amalgamation of Pangea at ~ 300 Ma (Heatherington et al., 1996).

### 2.1.4. Carolina

Carolina comprises many Neoproterozoic terranes (e.g. Carolina, Spring Hope, Roanoke Rapids, etc.) located along the eastern margin of the southern Appalachians. It surrounds on three sides and is in tectonic contact with the ~ 1 Ga Goochland terrane, which has been interpreted as either Laurentian basement or an exotic terrane (Hibbard et al., 2002). Carolina consists of a ~ 635–580 Ma juvenile oceanic-continental arc that was deformed in the Virgilina orogeny prior to the deposition of a ~ 580–540 Ma mature arc sequence (Hibbard et al., 2002). The mature arc is unconformably overlain by Middle Cambrian sedimentary and bimodal volcanic rocks containing mixed Tethyan–Avalonian, cool-water trilobites that share faunal affinities with Armorica, Gondwana, and Avalonia (Theokritoff, 1979; Samson et al., 1995). 1.1–1.8 Ga detrital zircons in these Cambrian quartzites (Samson et al., 1999, 2001) suggest a provenance in Amazonia. The age of the basement beneath Carolina has been inferred from ion microprobe analyses on igneous zircons in Neoproterozoic volcanic suites, which yielded ages of 965–1229 Ma (Mueller et al., 1996). This is consistent with the $T_{DM}$ model ages of 1.1–0.7 Ga reported on the ~ 635–580 Ma juvenile arc sequence (Samson et al., 1995; Wortman et al., 2000). In contrast to the high paleolatitudes of other peri-Gondwanan terranes, paleomagnetic data from latest Precambrian–Cambrian units indicate a low paleolatitude for Carolina (15°S: Vick et al., 1987), but may have undergone remagnetization (Van der Voo, 1993). Based upon arc–backarc spatial geometry, Dennis and Wright (1997) have proposed that subduction was towards the southeast (present coordinates) during the Neoproterozoic. This is consistent with the proposal that the switch in isotopic arc signatures from juvenile to mature was related to eastward thrusting of the ~ 1 Ga Goochland terrane under Carolina during the Virgilina orogeny (Hibbard and Samson, 1995). Although separation of Carolina from Gondwana has not been documented, its oblique sinistral accretion to eastern Laurentia appears to have taken place in the Late Ordovician–Early Silurian (Hibbard, 2000; Hibbard et al., 2002), although other authors argue for Carboniferous accretion (e.g. Hatcher, 1989).

### 2.1.5. Avalonia

Avalonian rocks have been recorded on both sides of the Atlantic Ocean and include West Avalonia from Boston (USA) through Maritime Canada to the Avalon Peninsula of Newfoundland, and East Avalonia from southeast Ireland, Wales, and southern England, through the Rheno–Hercynian zone and the Czech West Sudetes, into the Moravo–Silesian and Brunia zones on the southeastern side of the Bohemian massif (Fig. 1) (Murphy et al., 1999; Freidl et al., 2000; Kröner et al., 2000, 2001; Nance et al., 2002, and references therein). Unequivocal basement is not exposed. However, $T_{DM}$ model ages in Late Neoproterozoic and Paleozoic ( ~ 730–370 Ma) igneous suites range from 0.8 to 1.1 Ga in West Avalonia and from 1.0 to 1.8 Ga in East Avalonia (Thorogood, 1990; Murphy et al., 2000; Hegner and Kröner, 2000; Nance et al., 2002, and references therein). These ages are in accord with the few available SHRIMP analyses of xenocrystic zircons that cluster around 1.2 Ga (Hegner and Kröner, 2000; Freidl et al., 2000, and references therein). However, the model ages older than 1.2 Ga suggest the additional presence of Paleoproterozoic source rocks in East Avalonia. In northwestern Cape Breton Island, an allochthonous ~ 1 Ga basement block (Blair River Complex) has been correlated with both the type Grenville orogen (Miller et al., 1996) and Oaxaquia (Keppie et al., 2000). Ayuso et al. (1996) inferred that the Pb isotopic data from Neoproterozoic igneous rocks across Cape Breton Island represent mixtures of this Blair River basement and typical Avalonian crust implying that they were juxtaposed by the Neoproterozoic. The Blair River Complex consists of gneiss with a protolith age of ≥1.2 Ga that was metamorphosed at ∼1035 Ma, intruded by syenite at 1080 Ma, and then remetamorphosed in the upper amphibolite–granulite facies between 1000 and 970 Ma (Miller et al., 1996).

The Neoproterozoic rocks of Avalonia record three stages of arc development: (1) an early stage (750–635 Ma) represented by isolated inliers with both arc- and rift-related igneous rocks; (2) a main stage recorded in voluminous magmatic arc rocks associated with a variety of intra-arc, interarc, and backarc basin deposits dominated by volcanogenic turbidites that started synchronously at ∼635 Ma but switched diachronously into (3) late stage, rift-related volcanism and sedimentation at ∼590 Ma in New England, ∼560 Ma in southern New Brunswick, ∼550 Ma in Cape Breton Island, ∼570 Ma in Newfoundland, ∼550–540 Ma in Britain, and ∼550 Ma in Brunia (Murphy et al., 1999; Kröner et al., 2000, 2001; Nance et al., 2002). In East Avalonia, south-directed subduction is indicated by the presence of late stage, 550–560 Ma blueschists in Angelsey (Dallmeyer and Gibbons, 1987). In West Avalonia (southern New Brunswick and Nova Scotia), on the other hand, arc to backarc spatial relationships and variations in $\varepsilon_{Nd}$ and rare earth elements during the main and late stages suggest that the subduction zone dipped towards the northwest (present coordinates) (Dostal et al., 1996; Keppie et al., 1998; Murphy et al., 1999). In Cape Breton Island, the apparent northward migration (present coordinates) of the main–late stage arc may be due to shallowing of the subduction zone (Keppie et al., 1998). The possibility that this migration is due to subduction erosion is not supported by the presence of material with velocities of 6.6–6.8 km/s in southern Cape Breton Island, which, if this material is Neoproterozoic (Jackson et al., 2000), suggests that the lower crust has not been removed. A nonaccreting margin is also suggested by the synchronous compressive deformation in the backarc region of mainland Nova Scotia and central Cape Breton Island. In parts of West Avalonia (Cobequid and Antigonish Highlands), 690–630 Ma sinistral transtension produced backarc basins that were inverted by dextral transpression at 610 Ma (Nance and Murphy, 1990; Keppie et al., 2000). In central Cape Breton Island, mainland Nova Scotia, and southern New Brunswick, a ∼550 Ma, initially subhorizontal shear zone (now near-vertical in southern New Brunswick) separating low from high grade (low pressure–high temperature) Neoproterozoic metamorphic rocks (Nance and Murphy, 1990; Raeside and Barr, 1990; Nance and Dallmeyer, 1994) may be interpreted in terms of core complex tectonics (Keppie et al., 1998, 2000), and indicates that the region had passed into extension by this time.

A paleolatitude for West Avalonia of 34° ± 8° at 575 Ma (McNamara et al., 2001) is consistent with a location either off northwest Africa or Amazonia and/or Oaxaquia (Murphy et al., 2002). Ages of 977–1223 Ma for euhedral detrital zircons in locally derived sedimentary rocks of the early and main arc stages favour a nearby source in Amazonia and/or Oaxaquia (Murphy and MacDonald, 1993; Keppie et al., 1998). 980–1255 Ma ages from detrital zircons in the West Sudetes and Moravo–Silesian point to a similar source (Hegner and Kröner, 2000).

Latest Neoproterozoic–Cambrian rocks in Avalonia show a general NW to SE trend from marginal to inner platform (Landing, 1996) associated, in the Antigonish Highlands, with a dextral pull-apart basin (e.g. Keppie and Murphy, 1988). These Cambrian sequences contain a unique Avalonian fauna that is distinct from those in Gondwana, Baltica, and Laurentia (Landing, 1996), suggesting the existence of a barrier to faunal migration in the Cambrian. In Nova Scotia, these Cambrian sedimentary rocks are interbedded with bimodal volcanic rocks that are tholeiitic, where they lie above 580–550 Ma arc rocks, and alkalic, where they rest on older Neoproterozoic arc rocks. In East Avalonia, subsidence curves indicate that the rift–drift transition occurred during the early Ordovician (Prigmore et al., 1997). This is consistent with the increasing faunal endemism (Cocks, 2000) and paleomagnetic data (Trench and Torsvik, 1992).

Accretion of Avalonia to Laurentia and Baltica is indicated by (1) paleomagnetic data, which indicates similar Early Silurian paleolatitudes for Avalonia and eastern Laurentia (Miller and Kent, 1988; Trench and Torsvik, 1992; Potts et al., 1993; Hodych and Buchan, 1994; Mac Niocaill et al., 1997); (2) faunal linkages by the Late Ordovician (Williams et al., 1995); (3) a switch from primitive to mature Nd isotopic signatures in sedimentary rocks at the base of the Silurian in West Avalonia (Murphy et al., 1996); (4) an Early

Silurian sequence interpreted to overstep the entire Canadian Appalachian orogen (Chandler et al., 1987); and (5) Late Ordovician–Early Silurian accretionary deformation with a sinistral transpressional component (Pickering et al., 1988; Currie and Piaseki, 1989; Doig et al., 1990; Soper et al., 1992; Keppie, 1993; Cawood et al., 1994).

Avalonia is tectonically bordered by Cambro-Ordovician continental rise prisms represented by the Gander–Greenore and Meguma (limited to West Avalonia) terranes (Fig. 2). The age of the Gander rocks is constrained between 545 m.y. (youngest detrital titanite) and the conformably to unconformably overlying late Arenig–Llanvirn volcano sedimentary rocks containing a Celtic fauna (Neuman, 1984; Colman-Sadd et al., 1992; Van Staal et al., 1996). Detrital zircons in the Gander rocks have also yielded the following ages: 540–550 Ma, 600–800 Ma, 1.0–1.55 Ga, and 2.5–2.7 Ga (Van Staal et al., 1996, and references therein). In the Meguma terrane, the age of the Meguma Group is constrained between 552 Ma (youngest detrital titanite) near the base, and the Tremadocian (graptolites) near the top: it is disconformably overlain by Silurian–Devonian rocks that have been correlated with the sequence interpreted to overstep the Appalachian orogen (Krogh and Keppie, 1990; Keppie and Krogh, 2000). Detrital zircons in the Meguma Group fall into the following age groups: 560–680 Ma, ~ 2 Ga, and ~ 3 Ga (Krogh and Keppie, 1990). On the other hand, xenoliths in ~ 370 Ma mafic dykes cutting the Meguma terrane yielded upper intercept ages of 880–1050 Ma inferred to indicate a ~ 1 Ga basement (Greenough et al., 1999). Greenough et al. (1999) infer that the source of these ~ 1 Ga zircons lies in Avalonian basement thrust beneath the Meguma terrane in the Devonian. However, the potential presence of a Siluro-Devonian trans-Appalachian overstep sequence in the Meguma terrane suggests that by Silurian times it already lay adjacent to Avalonia and may have been deposited on an Avalonian basement (Keppie and Krogh, 2000).

### *2.2. ~ 2 Ga basement terranes: Cadomia and Bohemia*

Terranes with ~ 2 Ga basements, such as the Central Iberian zone, the Armorican Massif, the Massif Central, and the Saxo-Thuringian and Moldanubian zones, have generally been included in the Armorican Terrane Assemblage (Tait et al., 2000; Linnemann et al., 2000) and are here called Cadomia and Bohemia (Fig. 1). Cadomia includes the Ossa-Morena and Central Iberian zones of the Iberian massif, and the French Armorican and Central massifs. The Saxo-Thuringian and Moldanubian zones in the Bohemian massif of central Europe may also be included in Cadomia.

Cadomian basement is represented by the 2.2–1.8 Ga Icart Gneiss exposed in Brittany (Samson and D'Lemos, 1998). Sm–Nd isotopic data for the crustally derived Neoproterozoic arc rocks of Cadomia in northern France and the Channel Islands record $T_{DM}$ model ages that range from 1.0 to 1.9 Ga and are interpreted to reflect mixing of material derived from the mantle at ca. 600 Ma with the ca. 2.1 Ga Icartian continental basement (D'Lemos and Brown, 1993). This basement is isotopically indistinguishable from that of the ca. 2.0 Ga Eburnian Province in the West Africa craton (Nance and Murphy, 1994, 1996). A similar Eburnian (2.1–1.7 Ga) event has been recorded in U–Pb analyses of zircon from igneous bodies of the Saxo-Thuringian and Moldanubian zones (Wendt et al., 1993; Linnemann et al., 2000).

Two Neoproterozoic magmatic stages are recognized in Cadomia: (1) an early phase represented by the 746 ± 17 Ma Pentevrian orthogneisses in northwest France, which were deformed and metamorphosed at 650–615 Ma; and (2) a main stage that lasted from ~ 615 to 560 Ma and terminated with tectonothermal activity at 570–540 Ma (Quesada, 1990; Chantraine et al., 1994, 2001; Egal et al., 1996; Strachan et al., 1996; Linnemann et al., 2000; Eguíluz et al., 2000; D'Lemos et al., 2001, and references therein). Polarity inferred from the relative locations of the arc and backarc suggests that the subduction zone dipped northwards in France (Chantraine et al., 2001) swinging around the Armorican arc to dip southwards towards the Ossa Morena ( ≡ NW Africa craton) basement in Iberia (Quesada, 1997) (all present coordinates). Weil et al. (2001) published paleomagnetic data that suggest the Armorican arc results from Permo-Carboniferous oroclinal bending of an originally N–S linear belt. Arc magmatism in Cadomia ended with sinistral wrench tectonics, followed by widespread migmatization, and post-tectonic granitoid emplacement at ~570–540 Ma (Rabu et al., 1990; Chantraine et al., 1994, 2001; Strachan et al., 1996; Egal et al., 1996). Proximity of Cadomia to the West African craton is indicated by the presence of residual bauxitic and lateritic sedimentary rocks in Central Iberia that correlate with those in the NW African craton (Quesada, 1997), and 1.8–2.2 Ga and Archean detrital zircon ages (coupled with the lack of ~1 Ga ages) in latest Neoproterozoic sedimentary rocks from the northern part of French Armorica, the Ossa-Morena zone of Iberia, and the Saxo-Thuringian zone (Gebauer et al., 1989; Samson et al., 1999; Gutiérrez-Alonso et al., 2001; Tichomirowa et al., 2001). Such ages are accompanied by 950–1300 Ma ages in detrital zircons from the Central Iberian zone, the Montagne Noire (French Central Massif), and the Moldanubian zone (Bohemian massif) (Gebauer, 1994; Gebauer et al., 1989; Fernandez-Suárez et al., 2000). Since these latter regions are underlain by ~2 Ga basement, the record of ~1 Ga detrital zircons suggests water-borne transport from a Mesoproterozoic source.

The Neoproterozoic rocks are unconformably overlain by Cambrian, bimodal volcanic rocks and sedimentary rocks that contain Tethyan faunas and Archeocyathids, common to the northern Gondwanan margin (Doré, 1994; Robardet et al., 1994). The Arenigian Armorican quartzite is widespread throughout Cadomia and contains 1.0–1.1 Ga detrital zircons (Gutiérrez-Alonso, 2001), which indicates either a primary source in Mesoproterozoic orogens or recycling of underlying sediments, such as those found in the Central Iberian zone. Paleomagnetic data suggest that, by the Late Ordovician, Armorica had rifted away from Africa and lay at 40°S (Tait et al., 2000). This is consistent with the presence of Ashgillian glacial deposits interpreted to represent dropstones from floating ice during a period of global cooling (Brenchley et al., 1991). Late Silurian to Early Devonian paleomagnetic data record paleolatitudes of 20–30°S and indicate a continued northward drift of Cadomia (Tait et al., 2000). Faunal endemism persisted throughout the Silurian and into the Emsian and Givetian, but disappeared in mid-Devonian times with the closure of the Rheic Ocean as Armorica collided with Laurussia (Kriz and Paris, 1982; Tait et al., 2000).

### 2.3. Summary and questions

Peri-Gondwanan terranes may be separated into two groups on the basis of the age of their basement, either ~2 or ~1 Ga (Fig. 1). The ~2 Ga basement of Cadomia extends from Iberia and NW France into the Saxo-Thuringian and Moldanubian zones of central Europe. This distribution matches the areal extent of similar basement in northwest Africa, which, combined with faunal, paleomagnetic, and paleoclimatic data, suggests that these terranes are of local provenance. On the other hand, terranes with ~1 Ga basement may be traced from Mexico through eastern Laurentia (Carolina–West Avalonia), the southern British Isles, and the Rheno–Hercynian zone of northern Europe, around the Bohemian massif into Brunia. With some gaps, a ~1 Ga orogenic belt surrounds the Amazon craton, and one approach has been to derive the ~1 Ga peri-Gondwanan terranes from areas adjacent to the northwest and northern margins of Amazonia (e.g. Nance and Murphy, 1994, 1996; Keppie and Ramos, 1999; Hegner and Kröner, 2000). But at this point, a question arises: is it possible that the ~1 Ga orogen encircling Amazonia had a branch around the northern margin of Africa? This would drastically reduce the amount of lateral motion (up to 7000 km) required to disperse the peri-Gondwanan terranes to their present positions along the Appalachian–Caledonian–Variscan orogen. However, such a branch has not been proposed by anyone and would be difficult to reconcile with the complete absence of ~1 Ga detrital zircons in the Neoproterozoic sedimentary successions of southern Iberia, NW France, and the Saxo-Thuringian zone (Gebauer et al., 1989; Samson et al., 1999; Gutiérrez-Alonso et al., 2001; Tichomirowa et al., 2001). Displacements of up to 5000 km have been proposed for Baja British Columbia along the Cordilleran margin of western Laurentia (e.g. Beck, 1991; Cowan et al., 1997; Keppie and Dostal, 2001, and references therein), and forward modeling of Australia shows that accreted terranes will be bulldozed and dispersed along the side of Australia for up to 8000 km (Van Staal et al., 1998). Could either of these mechanisms be applied to the displacements required for the ~1 Ga peri-Gondwanan terranes?

Current interpretations show that the polarity of the Neoproterozoic subduction zones, in present-day coordinates, changes along the orogen: SE in Carolina, NW in West Avalonia, SE in East Avalonia, and N to SW beneath French and Iberian Cadomia, respectively (Fig. 1). Is this variation an original feature, or have some of the terranes been rotated about a vertical axis? Mesozoic–Cenozoic rotation of terranes about vertical axes has been recorded along the western margin of Laurentia, during both separation and accretion (Nicholson et al., 1994; Johnston, 2002). Could such mechanisms be applied to the ~1 Ga peri-Gondwanan terranes?

Given that all the terranes considered in this paper originated adjacent to the Gondwanan margin, is it possible to locate them more accurately? Two end member configurations can be envisaged: (1) the terranes are arranged side-by-side (e.g. Fig. 2), and (2) the terranes are arranged end-to-end, either as presently observed or in a different order (Fig. 3). As will be shown below, each potential modern analogue for terrane dispersal partly predicts the relative location of the terranes. Thus the analogues may be tested using subtle distinctions in fauna, paleomagnetic data, and detrital zircons suites. In an end-to-end arrangement, for example, the mixed faunal affinities of the Middle Cambrian trilobites in Carolina would favour a model that placed Carolina between Avalonia and Cadomia/West Africa, an arrangement used in Section 3.3 below. On the other hand, backward modeling to ~700 Ma of the side-by-side arrangement to allow for 150–200 million years of subduction would produce three synchronous arc terranes separated by several thousand kilometers, and would place some of the terranes within the peri-Rodinian ocean, far from any continent. This scenario is not in accord with either the presence of continent-derived, Archean, Paleoproterozoic, and Mesoproterozoic detrital zircons in the early arc sediments of West Avalonia, or the close correlation between West and East Avalonia. Note that the presence or absence of ~1 Ga detrital zircons appears to be independent of the basement age: ~1 Ga detrital zircons are found in northern Iberia (~2 Ga basement) whereas they are absent in the Meguma terrane (~1 Ga basement). The mismatch between ages of basement and detrital zircons in overlying clastic rocks is typical of modern drainage systems, such as the Mississippi, Amazon, and Ganges, in which detritus is transported across a continent. Similarly, the potential extent of longshore marine transport is shown by the presence of Archean detrital zircons in Cambrian–Triassic miogeoclinal rocks from Canada to Mexico (Gehrels et al., 1995).

Current estimates for the switch from arc to rift magmatism is diachronous among these peri-Gondwanan terranes: ~540 Ma in Carolina, ~590 Ma in New England, ~560 Ma in southern New Brunswick, ~550 Ma in Cape Breton Island, ~570 Ma in Newfoundland, ~550–540 Ma in Britain, 550 Ma in Brunia, and 560 Ma in Cadomia. In view of this, could termination of the arc be due to flattening of the subducting slab, intra-arc rifting, or collision of a mid-ocean ridge with the trench? Can the rifting be related to the separation of terranes from Gondwana?

In the following section, we present some potential modern analogues for the northern margin of Neoproterozoic–Paleozoic Gondwana, and then apply them to the peri-Gondwanan terranes. These analogues are then evaluated in light of the data.

## 3. Modern analogues

### 3.1. Alpine Tethyan and Mediterranean ("accordion") model

The Mesozoic–Cenozoic history of the Alpine Tethys Ocean involves orthogonal ("accordion") opening and closing of a small ocean basin with some lateral displacements (Stampfli et al., 2001). This could be a modern analogue for the traditional Iapetus model, which involves orthogonal opening and closing of Iapetus between Gondwana and Laurentia (e.g. Williams, 1979; Van der Voo, 1993). But, for reasons presented earlier, this model does not fit the geological data, and current reconstructions of Neoproterozoic Rodinia place eastern Laurentia against western South America (e.g. Dalziel, 1997). In such a reconstruction, the peri-Gondwanan terranes probably faced an open ocean at the time of inception of Iapetus, and so lay beyond the Laurentia–South American suture (e.g. Figs. 2 and 3). But while the orthogonal opening of Iapetus does not appear to be valid, it is possible that (a) Avalonia was transferred orthogonally to Laurentia in the Ordovician once Laurentia lay opposite northwestern Gondwana; and (b) Cadomia was transferred orthogonally to Laurussia in the Siluro-Devonian.

#### 3.1.1. Application of the "accordion" model to Avalonia

An "accordion" model including the orthogonal transfer of Avalonia from northern Gondwana to Laurentia has been proposed by Dalziel (1997), who swings Avalonia around a pole of rotation near the coast of Colombia. In this scenario, the presently observed relative locations and Neoproterozoic subduction polarity reversals in the peri-Gondwanan terranes would be an original feature. Fig. 3 explores this model. Given the 150–200 million years of Neoproterozoic subduction with opposite polarities observed in the geological record, the East Avalonia and Carolina arcs could have lain along the fringe of Gondwana, whereas West Avalonia would have to have lain several thousand kilometers offshore in the circum-Rodinian ocean in order to provide oceanic lithosphere for subduction. Such a possibility seems to be negated by the close correlation between West and East Avalonia during the Neoproterozoic, and by the Archean, Paleoproterozoic, and Mesoproterozoic detrital zircon record in the early arc sedimentary rocks of West Avalonia, which would be unexpected in an intra-oceanic arc (Keppie et al., 1998).

#### 3.1.2. Application of "accordion" model to Cadomia and Bohemia

Tait et al. (2000) have proposed that Cadomia and Bohemia (≡Armorican Terrane Assemblage) were transferred orthogonally from northwestern Africa to southern Laurussia based on paleomagnetic and faunal data. Stampfli and Borel (2002) have placed this scenario in a plate tectonic framework including the following stages: (1) southward subduction of the Rheic–Rheno–Hercynian ocean beneath north Africa and trench rollback triggering detachment of the Gothic (≡Cadomia and Bohemia) terrane in the Late Silurian leaving a widening Paleotethys in its wake; (2) Middle–Late Devonian collision of the Gothic (Cadomia and Bohemia) terrane with Laurussia; (3) latest Devonian jump and flip of the subduction zone to the southern margin of the Gothic terrane; and (4) Carboniferous ridge–trench collision inducing a strike-slip regime analogous to the Gulf of California. The southward polarity of Neoproterozoic subduction throughout Cadomia, after unfolding the Armorican arc, is consistent with orthogonal transfer of Cadomia to Laurussia, followed by oroclinal folding in the Permo-Carboniferous.

#### 3.1.3. Application of the "accordion" model to Oaxaquia, Chortis, Maya, and Suwannee

The Permo-Caroniferous collision of Oaxaquia, Chortis, Maya, and Suwannee, lying along the northern margin of Amazonia, with southern Laurentia may be analogous to the closing of the Mediterranean Sea between North Africa and Europe (Stampfli and Borel, 2002, and references therein). These peri-Amazonian terranes were then stranded on the southern Laurentian margin during the Early Mesozoic breakup of Pangea.

### 3.2. Australian ("bulldozer") model

Van Staal et al. (1998) have compared the development of the Appalachian–Caledonian orogen with the forward-modeled northward motion of Australia into the Pacific Ocean ending in collision with Asia some 45 million years in the future. One potential consequence of this bulldozing motion is that oceanic plateaus, such as the 4000 × 1500 km Caroline–Ontong plateau, are dispersed along the Australian plate margin over a distance of 8000 km (Fig. 4a).

#### 3.2.1. Application of the "bulldozer" model to Avalonia and Carolina

If Fig. 5a is turned over and relabeled, the result is comparable with the present distribution of Carolina and Avalonia along the southeastern margin of Laurentia (Fig. 4b). In fact, Dalziel (1991) has proposed that Laurentia performed an "end-run" around western Gondwana in which Laurentia would act as a "bulldozer". If the peri-Gondwanan terranes were placed in front of the advancing Laurentia, they would be bulldozed and dispersed along its eastern margin. Such a model has implications for the relative positions of these terranes in the Neoproterozoic. Applying this mechanism to the side-by-side arrangement of the peri-Gondwanan terranes would require them to be distributed as shown in Fig. 2, with East Avalonia closest to Laurentia, followed by West Avalonia, and Carolina farthest outboard. During the bulldozing action Carolina would end up farthest south (present coordinates) along the Laurentian margin, as is now the

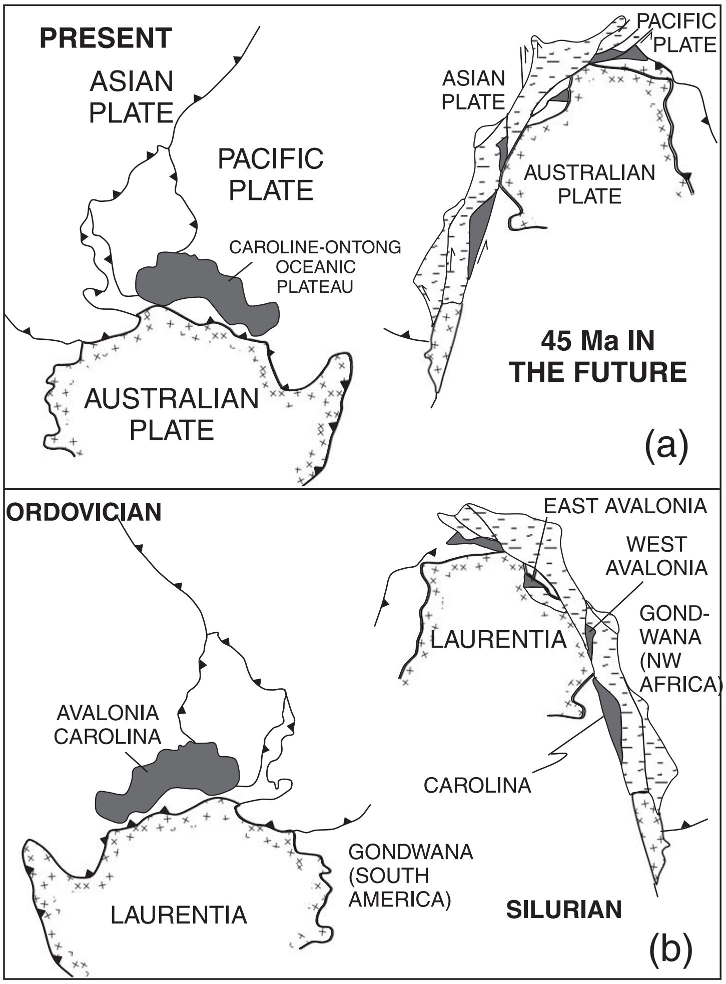

Fig. 4. Australian "bulldozer" model: (a) present and future locations of Australia and the Caroline-Ontong plateau; (b) same diagram reversed and relabeled: Australia to Laurentia, and Caroline-Ontong plateau to Avalonia and Carolina. Dashes = arc and periarc, crosses = Australian plate, dark shade = Caroline-Ontong plateau.

case. On the other hand, applying this mechanism to the end-to-end arrangement of the terranes would require the reverse west to east order (present coordinates): East Avalonia, West Avalonia, Carolina. This is precisely the opposite of that shown in Fig. 3.

### *3.3. Baja California and Baja British Columbia ("Baja") models*

The diachronous switch from calc-alkaline arc to tholeiitic/alkaline rift magmatism in the peri-Gondwanan terranes is analogous to that recorded by the oblique collision of the East Pacific Rise and Cocos Ridge with the Middle America Trench (Dickinson and Snyder, 1979; Protti et al., 1995; Murphy et al., 1999; Keppie et al., 2000). In both cases, the trench is replaced by a transform fault as the ridge is overridden leading to a switch from arc to rift magmatism. As the ridge–trench–transform (R-T-F) triple point migrates, the magmatic switch moves in tandem with the triple point (see Fig. 5 in Dickinson and Snyder, 1979). Where two differently oriented ridges are being overridden, the R-T-F triple points may migrate towards

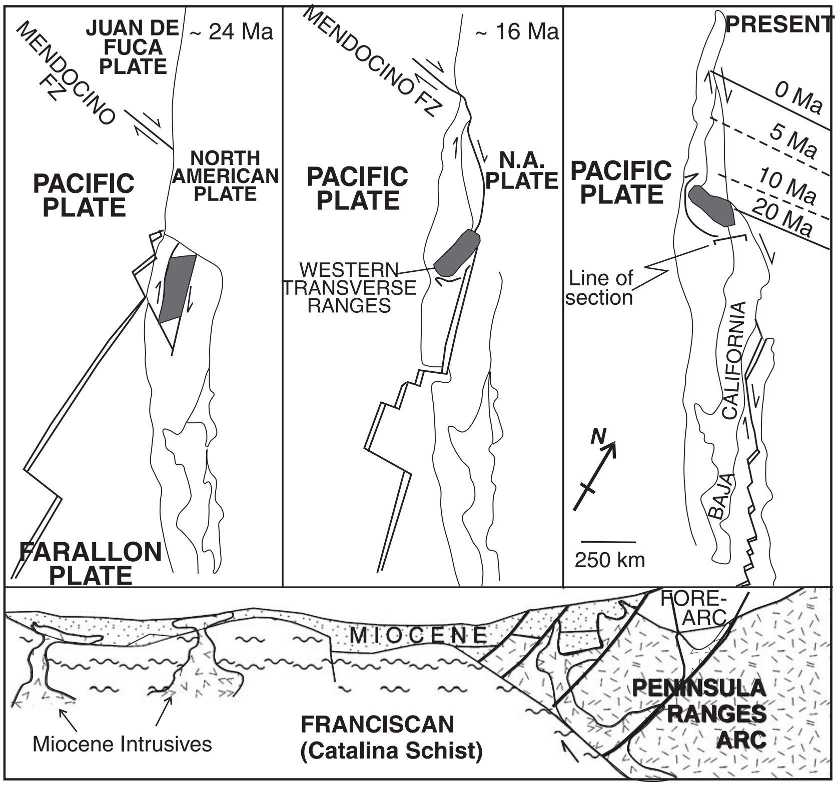

Fig. 5. Tectonic model for the separation of blocks from the North American continental margin after collision of the East Pacific Rise with the trench, showing the rotation of the western Transverse Ranges, and migration of the arc-rift magmatic boundary between 20 Ma and the present (modified after Nicholson et al., 1994; Dickinson and Snyder, 1979). Cross section shows a core complex developed beneath the accretionary complex-arc boundary (after Crouch and Suppe, 1993).

each other (as in Middle America—see figures in Protti et al., 1995), or they may move apart. If the ridge is offset by a transform fault, the F-F-T triple point may also migrate. In the case of the Mendocino transform offset of the East Pacific Ridge, migration occurs in the opposite direction to that of the R-T-F triple point, producing a widening zone of rift magmatism (see Figs. 1–3 in Dickinson and Snyder, 1979). Other features of ridge–trench collision include flattening of the subduction zone prior to collision, the development of a slab window with mantle upwelling, diapirism and eruption of adakites leading to uplift, extension, and increased heat flow (Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989; Goring et al., 1997). Flattening of the subducting slab produces a landward migration of the arc and causes shortening, both of which have been observed in West Avalonia for the 630–550 Ma arcs (Keppie et al., 1998). Such arc migration may also be the result of subduction erosion in which the lower part of the lithosphere is removed, but this is inconsistent with available geophysical data for West Avalonia. If the continental margin is irregular, the R-T-F and T-F-F triple points may be unstable leading to extension or compression, and the separation of blocks. This is the case for the Humbolt, Salinian, and Baja California blocks, which are presently being transferred from the North American plate to the Pacific plate (Fig. 5) (Stock and Hodges, 1989). Such a mechanism might likewise be responsible for the separation of the peri-Gondwanan terranes from Gondwana. The development of such microplates can also lead to the rotation of the blocks, as is the case for the western Transverse Ranges, which have rotated through ~ 120° (Fig. 5) (Nicholson et al., 1994). Such rotation would, in turn, produce apparent subduction polarity reversals like those presently observed in the peri-Gondwanan terranes of the Appalachian–Caledonian orogen. In the North American Cordillera, this extension and rotation is accompanied by the development of Basin-and-Range tectonics, extensional basins, and core complexes in which high temperature–low pressure metamorphic rocks are brought up into contact with low-grade rocks along a sub-horizontal shear zone (Fig. 5 cross-section) (Crouch and Suppe, 1993). Such structures, which can form anywhere between the accretionary prism and the backarc region (Chéry, 2001), have been recorded in the arc–backarc region of West Avalonia in Cape Breton Island (Keppie et al., 1998, 2000).

A more advanced stage in the transport of terranes such as Baja California may be found in Baja British Columbia and Baja Alaska. Some workers believe these terrane assemblages originated off Mexico, were transferred to the Kula Plate in the Late Cretaceous, and transported northwards to accrete to western Laurentia in British Columbia and Alaska in the Cenozoic (for review and figures see Cowan et al., 1997). A potential consequence of such transport is the transcurrent fault slicing of the allochthonous terranes into discrete ribbon blocks (see figures in Keppie and Dostal, 2001). This may be followed by oroclinal folding of a ribbon continent (“train wreck” model of Johnston, 2002) upon encountering a convergent bend in the active margin (Fig. 6), which would produce reversals of polarity. Another result of fault slicing is that initially outboard terranes are transported farther than inboard terranes. Furthermore, sequential transport places originally inboard terranes on the ocean side of originally outboard terranes, as illustrated by the Yukatat terrane assemblage of Alaska (see figures in Plafker and Berg, 1994).

### 3.3.1. *Application of the “Baja” model to peri-Gondwanan terranes*

The shuffling of terranes recorded in Alaska could account for the apparent reversals of subduction polarity deduced from arc–backarc geometry in the peri-Gondwanan terranes. Examination of the peri-Gondwanan terranes in the Appalachian, Caledonian, and Variscan orogens reveals two Variscan oroclines: the Armorican arc through Iberia and France, and the distribution of Avalonia around the eastern border of the Bohemian massif. Although the Armorican arc has been attributed to two orthogonal superposed compressional events (Weil et al., 2001), the application of the “Baja” model by Stampfli and Borel (2002) to the southern margin of Laurussia during the Carboniferous may indicate the operation of a “train wreck” model in Bohemia. However, the oroclines may have been produced by other mechanisms, such as rotation during oblique Gondwana–Laurussia collision. Fur-

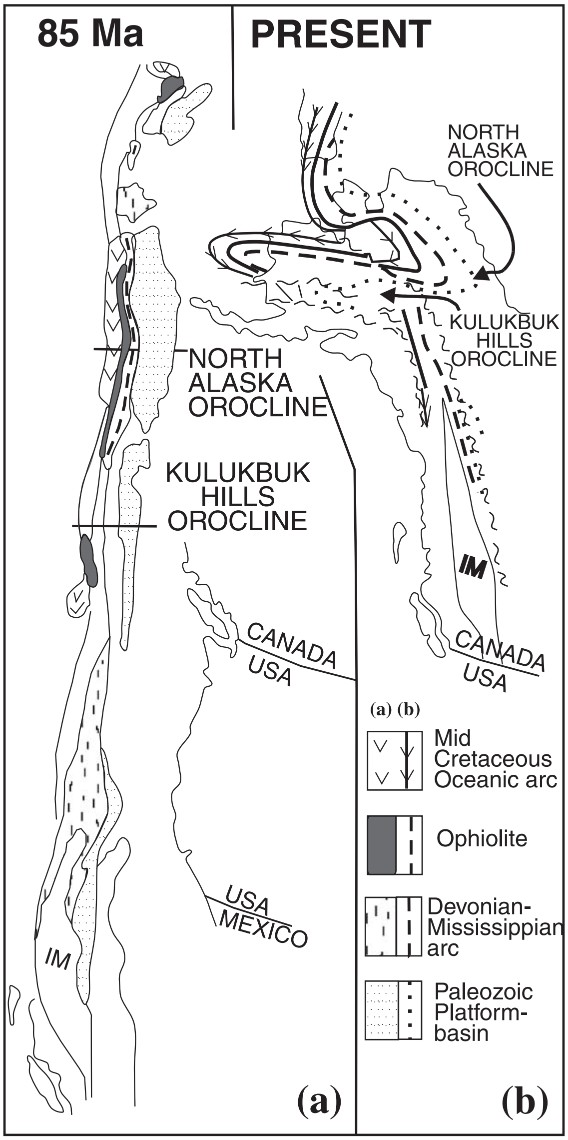

Fig. 6. “Train wreck” model for SAYBIA (Siberia–Alaska–Yukon–British Columbia) ribbon continent (modified from Johnston, 2002): (a) reconstruction of SAYBIA at 85 Ma, and (b) present distribution of SAYBIA. IM = Intermontane domain.

ther analysis is required to evaluate these alternative models. Elsewhere in Carolina and Avalonia, oroclinal folds appear to be absent, although it is possible that subsequent dispersion could have sliced segments apart making their recognition difficult. Thus, the reversals of subduction polarity may be the result of rotation produced either during separation of ribbon blocks or during their accretion to a continental margin.

With the exception of adakites, all the features of ridge–trench collision occur in the geological record of Carolina and Avalonia. Thus it seems appropriate to apply the "Baja" model to the arc–rift transition in the peri-Gondwanan terranes and this has been attempted in Figs. 7 and 8. In this model, several assumptions are made: (1) by analogy with the Pacific Ocean, where subduction polarity is predominantly towards the continents, it is assumed that subduction was beneath Gondwana; (2) it is assumed that Carolina and Avalonia represent several slices that were transferred to an oceanic plate in the Cambrian and transported longitudinally into Iapetus, from which they were accreted to Laurentia in the Late Ordovician–Early Silurian: this dictates that the initial arrangement of terranes from west to east (present coordinates: top to bottom in Fig. 7) along the northern margin of Amazonia was: East Avalonia, West Avalonia, Carolina; (3) it is assumed that ~1 Ga basement was only present around Amazonia; (4) it is assumed that Cadomia originated adjacent to northwest Africa and was transferred orthogonally to southern Laurussia in the Siluro-Devonian with relatively little orogen-parallel transport; and (5) it is assumed that Oaxaquia, and the Chortis, Maya (Yucatan), and Suwannee (Florida) terranes were distributed between northwestern Amazonia and Carolina–Avalonia, and that they were not transferred to Laurentia until the amalgamation of Pangea.

The diachronism in the switch from arc to rift magmatism in the peri-Gondwanan terranes can be

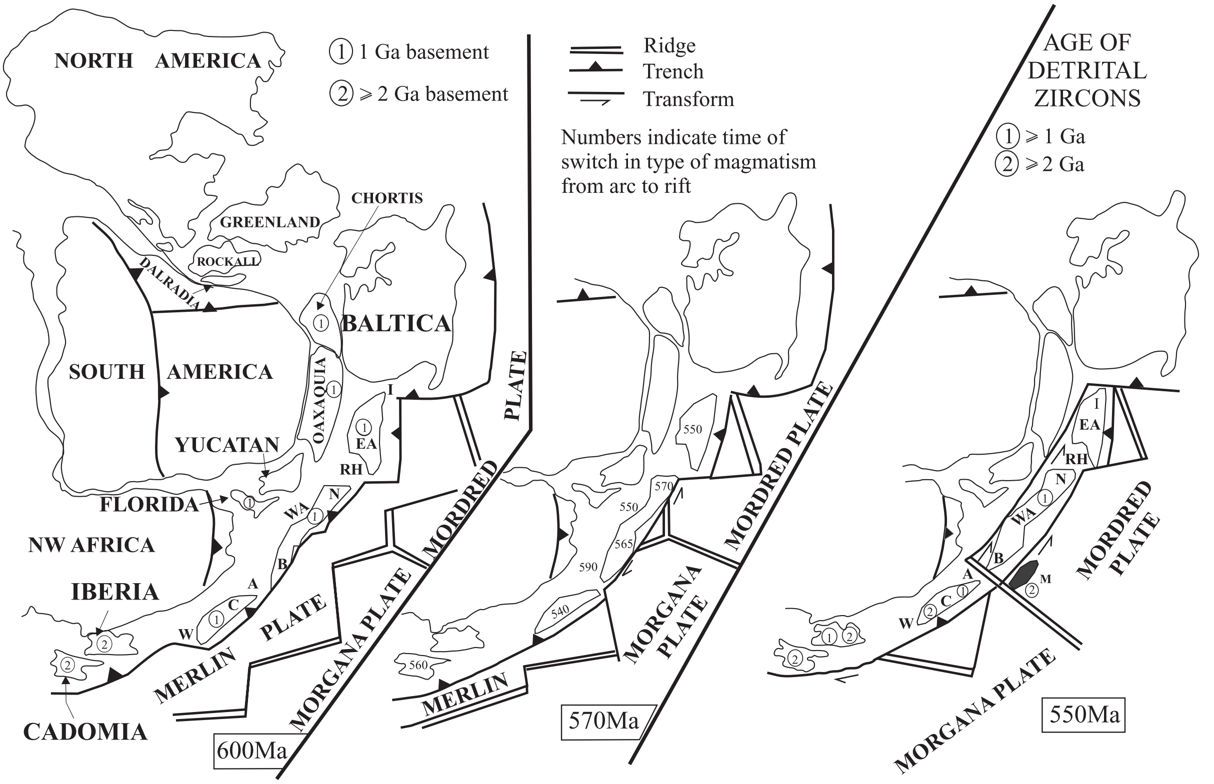

Fig. 7. Neoproterozoic reconstructions using the Baja California analogue for the peri-Gondwanan terranes (modified from Ramos and Keppie, 1999). See text for discussion. Abbreviations as in Figs. 1 and 2.

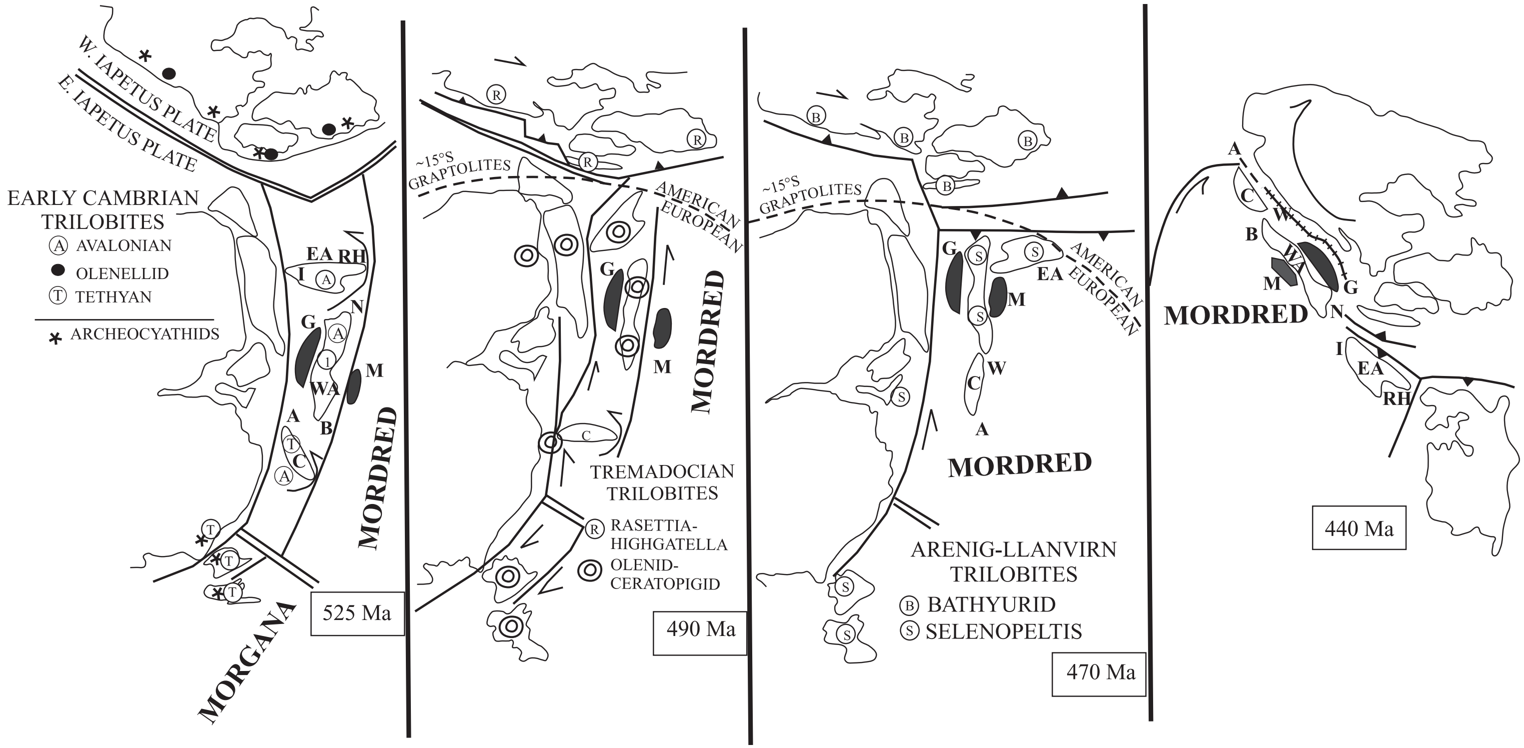

Fig. 8. Lower Paleozoic reconstructions using the Baja California and Baja British Columbia analogue for the peri-Gondwanan terranes (modified from Keppie and Ramos (1999). See text for discussion. Abbreviations as in Figs. 1 and 2.

used to track the movement of R-T-F and T-F-F triple points. In order to simplify discussion of the model, the oceanic plates are given names analogous to those in the Pacific Ocean: Merlin ≡ Farallon, Morgana ≡ Pacific, and Mordred ≡ Kula (Fig. 7). Subduction of the Merlin Plate beneath northern Gondwana prior to 600 Ma is followed between 590 and 540 Ma by collision of the Merlin–Morgana and Merlin–Mordred ridge–transform systems with the northern Gondwana trench, causing a diachronous switch from arc to rift magmatism as subduction was replaced by transform motions. In West Avalonia, this switch appears to be bi-directional, from 590 Ma in New England to 560 Ma in southern New Brunswick, and from 570 Ma in eastern Newfoundland to 550 Ma in Cape Breton Island, and is likened to the subduction of the Cocos Plate (Keppie et al., 2000). On the other hand, the relatively young, 550–540 Ma switch in East Avalonia and Carolina is explicable in terms of a ridge offset by transform faults, which allowed subduction of small remnants of the Merlin Plate to continue until 550 Ma. By analogy with Baja California, it is further inferred that the development of a transform system along the northern Gondwanan margin was accompanied by latest Neoproterozoic migration of the R-F-F (Mordred–Morgana–Gondwana) triple point, microplate capture, and the rifting of East and West Avalonia relative to Gondwana. The separation caused by this rifting was wide enough to produce a faunal barrier and the development of the unique Avalonian fauna by the Early Cambrian (Landing, 1996). This was synchronous with initial deposition of Early Cambrian turbidites in the Gander and Meguma terranes. The Meguma terrane is placed adjacent to West Avalonia and close to northwest Africa to account for its ~1 Ga basement and the North African provenance of its detrital zircons. On the other hand, the Gander terrane may have lain between Oaxaquia and West Avalonia, either of which would be a ready source for the ~1 Ga zircons recorded in the Gander turbidites (Van Staal et al., 1996).

In addition, the Baja-type rifting may have been approximately synchronous with the anticlockwise rotation of East Avalonia and Carolina in a manner analogous to the western Transverse Ranges (Fig. 8). This latter rotational model is favoured over the alternatives (“train wreck” rotation as the leading end of Avalonia encountered Laurentia, or “bulldozer” rotation during dispersion as the terranes were swept along the eastern margin of Laurentia) because oroclinal folds are absent. During the Cambrian and Ordovician, this terrane ribbon was displaced sinistrally along the northern margin of Amazonia into Iapetus, while Laurentia was advancing northwards in bulldozer fashion along the western margin of South America (Keppie and Murphy, 1988; Keppie, 1993; Hibbard, 2000). The Early–Middle Ordovician positions of Avalonia and Carolina south of 15°S are consistent with their graptolite and trilobite faunal provinces (Fig. 8). Following accretion of Avalonia and Carolina to Laurentia in the Late Ordovician–Early Silurian, the terranes were swept along the eastern margin of the Laurentian “bulldozer”. Further advance of Laurussia relative to Gondwana may have dispersed Avalonia around the eastern end of the Bohemian massif.

## 4. Conclusions

Several modern analogues have been presented for the Neoproterozoic and Early Paleozoic evolution of terranes in the Appalachian, Caledonian, and Variscan orogen that were derived from the northern periphery of Gondwana. End member models are (1) the Alpine Tethys (“accordion”) model; (2) the Australian (“bulldozer”) model; and (3) Baja California and Baja British Columbia (“Baja”) models. For Avalonia and Carolina, the “accordion” model is least supported by the geological data: (1) the juxtaposing of eastern Laurentian and western South American in the Neoproterozoic requires vast relative lateral displacements to reach a Pangea A reconstruction in the Permo-Carboniferous, and (2) the synchroneity of a passive eastern Laurentian margin and an active margin along Carolina–Avalonia–Cadomia during the Neoproterozoic implies that they were not opposing margins. Instead, it appears that a “Baja” model for the Neoproterozoic–Early Cambrian followed by a Lower Paleozoic “bulldozer” model best fit the geological data for Avalonia and Carolina. Thus, the development of magmatic arcs along the northern margin of Gondwana, the gradual shallowing of the Benioff zone followed by the diachronous switch to rift magmatism, the accompanying replacement of a trench by a transform plate margin, and the associated extension producing rifts and core complexes, are all analogous to features found in the western margin of Mesozoic–Cenozoic North America. For North America, these phenomena have been related to subduction of the Farallon Plate followed by collision of the East Pacific Rise with the Middle America Trench. Separation and lateral transport of Avalonia and Carolina from Gondwana is likened both to the break-off of Baja California and its transfer to the Pacific Plate, and to the detachment of Baja British Columbia and its transport on the Kula Plate. By analogy, we name the oceanic plates for Neoproterozoic peri-Gondwana: Merlin ≡ Farallon, Mordred ≡ Kula, and Morgana ≡ Pacific (Figs. 7 and 8). In Cambro-Ordovician times, Avalonia and Carolina were transported on the Mordred Plate into the Iapetus Ocean where they encountered Laurentia, which was bulldozing its way northwards (present coordinates) from a position off western South America to one off northwest Africa. This led to the accretion of Carolina and Avalonia to Laurentia in the Late Ordovician, following which they were swept along its eastern margin.

For Cadomia, the "Baja" model also best fits the Neoproterozoic–Cambrian record of subduction terminating in rifting rather than collision. This was followed by orthogonal Siluro-Devonian transfer from northern Africa to southern Laurussia, which is consistent with the relative location of Laurentia–Baltica and North Africa in the mid-Paleozoic. Application of the "Baja" model to the Permo-Carboniferous is supported by strike-slip tectonics adjacent to the Paleotethys Ocean (Stampfli and Borel, 2002).

Permo-Carboniferous, continent–continent collision between Amazonia and southern Laurentia welded terranes along the leading edge of Gondwana (Oaxaquia, and the Chortis, Maya, and Suwannee) to Laurentia. Following the Early Mesozoic breakup of Pangea, these terranes were stranded on the southern Laurentian margin.

Application of these modern analogues provides constraints on the provenance of Avalonia, Carolina, and Cadomia. Thus, we believe they were probably distributed from west to east (present coordinates) off northern Amazonia in the following order: East Avalonia, West Avalonia, and Carolina, with Cadomia located off northwest Africa (Fig. 7). Data bearing on the polarity of Neoproterozoic subduction suggests that certain segments of the active margin have been rotated. This is based upon (1) the presence of continental detritus in the early–main stages of the Neoproterozoic arc; and (2) the close correlation between East and West Avalonia. This requires East Avalonia and Carolina to be rotated through 180° relative to West Avalonia. Such rotation probably took place during separation (by analogy with the western Transverse Ranges), however, rotation either during accretion to Laurentia (by a "train wreck" model: considered unlikely given the absence of oroclines), or during dispersion along the eastern Laurentian margin, or some combination of these mechanisms, is also possible. Data pertaining to the original arrangement of the peri-Gondwanan terranes appears to favour an original, end-to-end arrangement based on the close correlation between East and West Avalonia. But it is possible that, following separation, terranes originally in an end-to-end distribution could have been moved by transcurrent faulting into a side-by-side arrangement before being dispersed by the Laurentian "bulldozer".

The presentation of actualistic models for the Neoproterozoic and Early Paleozoic histories of the peri-Gondwanan terranes provides the basis for tests of the models. For example, the approach and collision of a ridge with a trench produces many tectonic features besides diachronous termination of arc magmatism, such as changes in structural kinematics, opening of slab windows, and complex extension and shortening associated with microplate capture and block rotation. The actualistic model has additionally generated a whole new set of questions for which additional data is required. For example, what evidence is there for block rotation during separation, accretion or dispersion? Can the relative locations of the peri-Gondwanan terranes be more precisely located along the northern margin of Gondwana? Both improved paleomagnetic and geological data can be brought to bear on these and other questions arising from the "Baja, bulldozer, and accordion" models.

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