Opening Iapetus: Constraints from the Laurentian margin in Newfoundland

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ABSTRACT

Late Neoproterozoic to Early Cambrian geologic, geochronologic, and paleomagnetic data from along the Iapetus margin of Laurentia may be reconciled within a multistage rift history that involved an initial separation of Laurentia from the west Gondwana cratons ca. 570 Ma, followed by rifting of a further block or blocks from Laurentia ca. 540–535 Ma into an already open Iapetus Ocean to establish the main passive-margin sequence in the Appalachians. Paleomagnetic data suggest that Laurentia rifted from Amazonia–Rio de la Plata cratons and began its northward movement ca. 570 Ma to produce a wide Iapetus Ocean by 550 Ma. Geologic data from the Newfoundland segment of the Laurentian margin provide evidence for a rift-drift transition ca. 540–535 Ma, as constrained by the youngest rift-related magmatism at 550.5 $^{+3}/_{-2}$ Ma (U/Pb zircon) for the Skinner Cove Formation and 555 $^{+3}/_{-5}$ Ma for the Lady Slipper pluton, and a late Early Cambrian age of ca. 525–520 Ma for the oldest drift-related sedimentation. Rifting between the Laurentia and the west Gondwana cratons was probably distributed among multiple rift systems that fostered the production of a number of terranes (such as the Argentine Precordillera, Oaxacan) as well as the Iapetus Ocean. Development of Laurentian-derived Iapetan terranes during the final breakout of Laurentia from Rodinia may have been facilitated by preexisting 760–700 Ma rift weaknesses and apparently rapidly changing plate vectors during latest Neoproterozoic time.

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INTRODUCTION

Paleogeographic and tectonic reconstructions require precise constraints on the timing of continental rifting and the initiation of ocean spreading, the timing of ocean closure and continental collision, and the position of these tectonostratigraphic elements through time. In this paper we present new data that document the youngest known igneous activity associated with rifting during the development of Laurentia's Iapetan margin, and discuss the relationships between Laurentia's protracted rifting history and the late Neoproterozoic breakup of Rodinia. Two pulses of rifting activity, from ca. 760 to 700 Ma and from ca. 620 to 550 Ma, are recognized along the eastern margin of Laurentia (e.g., Aleinikoff et al., 1991, 1995). We propose that the final pulse, which heralded the initiation of Iapetus seafloor spreading, was a two-stage process involving formation of the Iapetus Ocean between Laurentia and cratonic elements of west Gondwana at 570 Ma, followed by continued rifting along Laurentia's Iapetan margin, which generated a terrane or terranes at 540–535 Ma and formed the Laurentian passive margin stratigraphy.

LAURENTIAN MARGIN SETTING

The Humber zone of the Appalachian orogen represents the eastern margin (miogeocline) of Laurentia and preserves a record of continental margin initiation and destruction associated with opening and closing of the Iapetus Ocean (Kay, 1951; Wilson, 1966; Harland and Gayer, 1972; Thomas, 1991; Williams, 1995). The Humber zone consists of crystalline basement of the Grenville province unconformably overlain by a cover sequence containing rift, continental margin, and foreland basin units that are, in places, structurally overlain by a transported succession (Taconian allochthons). The allochthons include outboard facies equivalents of the cover sequence that are capped by ophiolitic rocks of the Dunnage zone (Figs. 1 and 2). The Humber zone is divided into a western external domain containing rocks that were only weakly metamorphosed and mildly deformed during Appalachian tectonism, and an eastern internal domain containing rocks metamorphosed to upper greenschist and amphibolite (locally eclogite) facies and complexly deformed (Williams, 1995).

Division of the Humber zone rocks into rift and drift cycle successions has been based on stratigraphic and facies characteristics (Williams and Hiscott, 1987). Rift sequences contain mafic to felsic volcanic flows and intrusions emplaced in dominantly siliciclastic sedimentary strata, which show abrupt along-strike changes in facies and thickness, and often unconformably overlie Grenville basement (Fig. 2). Drift sequences of sheet-like, carbonate-dominated lithologies are characterized by lateral continuity of facies types and constant stratigraphic thickness. In Newfoundland, rift-related igneous activity has yielded ages of ca. 620–600 Ma (Stukas and Reynolds, 1974; Williams et al., 1985; Kamo et al., 1989; Currie et al., 1992). Rift activity is also of latest Neoproterozoic age elsewhere in the Appalachians and Scotland (summarized in Rankin et al., 1997; Bingen et al., 1998; Walsh and Aleinikoff, 1999), but includes older events

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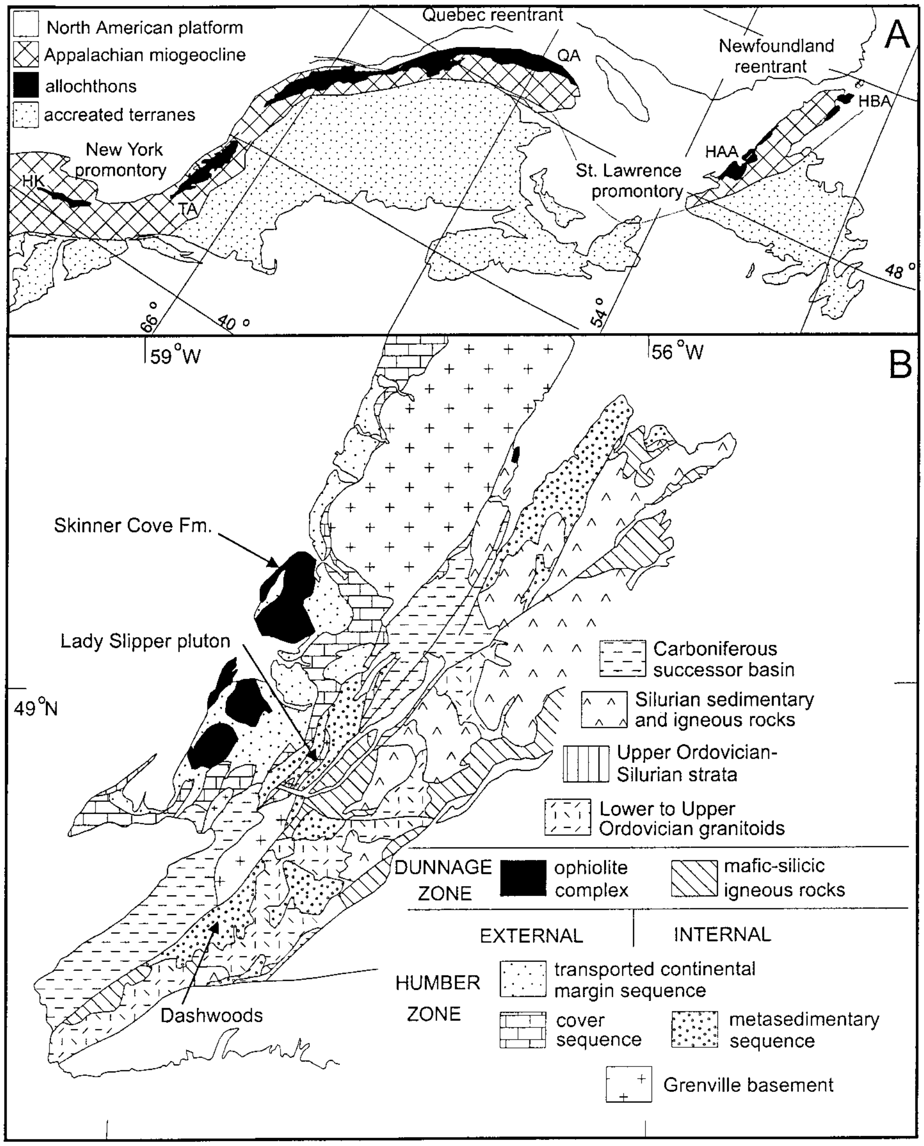

Figure 1. (A) Distribution of northern Appalachian miogeocline, Taconian allochthons, and accreted terranes with respect to promontories and reentrants of the Laurentian margin. (B) Simplified geologic map of western Newfoundland. Abbreviations: HK—Hamburg klippe; TA—Taconic allochthon; QA—Quebec allochthon; HAA—Humber Arm allochthon; HBA—Hare Bay allochthon.

(760−700 Ma) in the south (Su et al., 1994; Aleinikoff et al., 1995). On the basis of analysis of tectonic subsidence curves, Bond et al. (1984) concluded that breakup (rift-drift transition) probably occurred just prior to Cambrian time, ca. 600 ± 25 Ma. Williams and Hiscott (1987), from a detailed analysis of age data and facies relationships in Newfoundland, suggested that the rift-drift transition occurred during earliest Cambrian time. Our data, outlined in the following, in combination with information on the revised Neoproterozoic−Cambrian time scale (e.g., Grotzinger et al., 1995; Tucker and McKerrow, 1995; Bowring and Erwin, 1998), show that magmatic activity along the margin occurred as early as 550 Ma, and was followed by Early Cambrian drift-related sedimentation (cf. Bond, 1997).

YOUNGEST RIFT-RELATED MAGMATISM

Skinner Cove Formation

The Skinner Cove Formation and related rock units occupy an intermediate structural slice within the Humber Arm allochthon (Williams, 1975; Williams and Cawood, 1989) and is well exposed along the coast west of Table Mountain (Figs. 3 and 4). It consists of pillowed and massive alkalic basalt flows that are intercalated with reworked tuff, ankaramite flows, hyaloclastic breccia, and epiclastic sequences, overlain by trachytic flows and crosscut by dikes (Strong, 1974; Baker, 1979; McCausland and Hodych, 1998). Limestone fills the pillow interstices and impure limestones, rich in volcanic detritus, overlie the pillow basalts. The formation is metamorphosed only to zeolite grade and is otherwise little altered.

Previous dating of the sequence is limited to a K/Ar age of 423 ± 6 Ma on ankaramite (D. Archibald, 1973, personal commun., *in* Strong, 1974) and an Ar/Ar age on K-feldspar in trachyte of 358 ± 3.3 Ma (Idleman, 1990), both of which have been related to mid-Paleozoic tectonothermal events. Early Ordovician shelly fossils discovered near the type locality and originally considered to date the formation (Strong, 1974; A.R. Berger and L.E. Fahraeus, personal commun., *in* Williams, 1975) are in melange bounding the formation (Williams, 1995).

An ankaramite flow at the top of an ~100-m-thick volcanic succession was collected for U/Pb dating (Fig. 3). Zircons extracted from the sample are generally large (~100 μm across on average) and euhedral. Two abraded zircon fractions of these euhedral grains (Z1 and Z2, cf. Krogh, 1982) and one unabraded fraction of clear yellow crystal fragments (Z3), probably from the cores of larger grains, were dissolved following the method of Krogh (1973) and analyzed on a Finnigan MAT 262 thermal ionization mass spectrometer in static multicollection mode. The three analyses (Table 1) are 1.8%−7.7% discordant, and define a discordia line that intercepts concordia at 550.5 $^{+3}/_{-2}$ Ma (Fig. 5). This is taken as the age of igneous crystallization of both the flow and the entire unit.

McCausland and Hodych (1998) determined a tilt-corrected paleolatitude for the Skinner Cove Formation of 19° ± 9°S. The formation has been variously interpreted as a product of off-axis igneous activity associated with the Ordovician Bay of Islands ophiolite (Strong, 1974), as seamounts within the Cambrian−Ordovician Iapetus Ocean (Baker, 1979), and as late Neoproterozoic rift facies volcanic rocks (Williams, 1975). Volcanic blocks that are interpreted to correlate with the Skinner Cove Formation occur in rift-related sandstone of the Blow-Me-Down Brook Formation (Fig. 2; Williams and Cawood, 1989), which also contains the trace fossil *Oldhamia* of latest Neoproterozoic to Early Cambrian age (Lindholm and Casey, 1989). This lithological association and the end Neoproterozoic

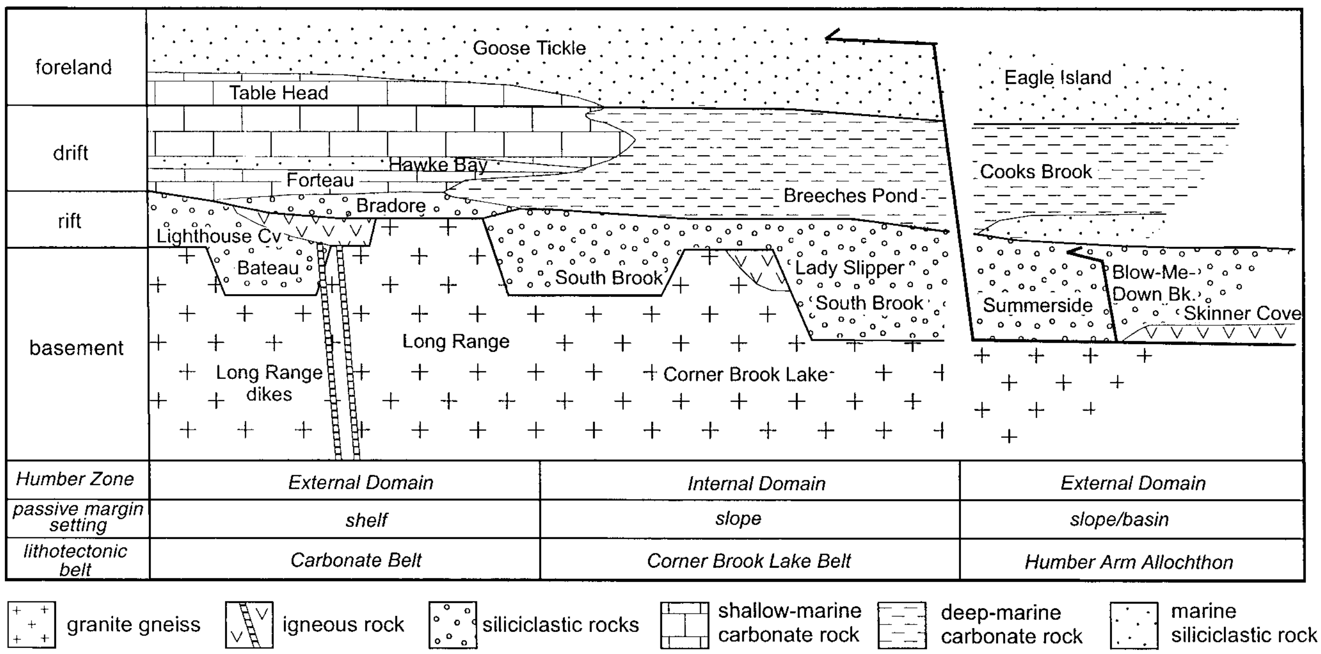

Figure 2. Schematic reconstructed cross section of the Laurentian margin in Newfoundland showing principal lithotectonic divisions and relative position and relationship of major rock units.

age for the volcanics support a rift-setting interpretation for the Skinner Cove Formation.

Lady Slipper Pluton

The Lady Slipper pluton (Cawood et al., 1996; Cawood and van Gool, 1998) is in the internal domain of the Humber zone (Figs. 1 and 2). It is associated with Mesoproterozoic basement gneisses and an unconformable cover succession of quartz-rich siliciclastic rocks and pelites (South Brook Formation), which pass upward into marble, limestone conglomerate, and calc-schist (Breeches Pond Formation; Fig. 4). All rock units were multiply deformed and metamorphosed to mid-amphibolite grade during the Silurian Salinian orogeny (Cawood et al., 1994; vanGool and Cawood, 1994). Primary relationships, however, are sufficiently well preserved to establish that the siliciclastic sequence shows abrupt along- and across-strike variations in stratigraphic thickness and facies, whereas the carbonate succession displays a relatively uniform character. These stratigraphic, lithologic, and facies relations led Cawood et al. (1996) to suggest that the boundary between them corresponds with the rift-drift transition (Fig. 4).

The Lady Slipper pluton consists of tonalitic to granodioritic gneiss with interbanded amphibolite. It crops out at the base of a thrust slice at the southern end of Corner Brook Lake, where it can be traced along strike for ~1 km and has an across-strike width of

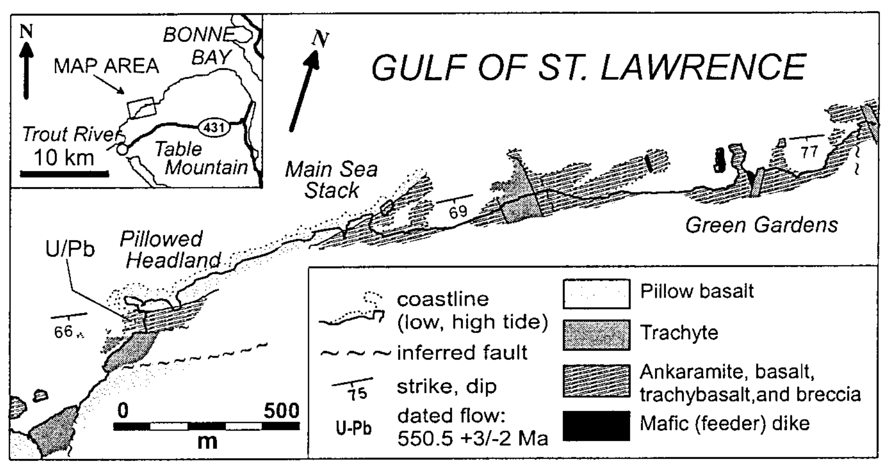

Figure 3. Simplified geologic map of the Skinner Cove Formation at Green Gardens, Gros Morne National Park, showing the U/Pb sampling location in an ankaramite flow.

~300 m (Fig. 4). Along its western margin, the pluton is thrust over calc-schist and marble. It is overlain along its eastern margin by steeply dipping quartzites and siliciclastic rock units with an across-strike width of ~800 m, which pass up into a 300-m-wide carbonate sequence that terminates, to the east, in fault contact against a large overthrust block of siliciclastic rocks. The eastern contact of the pluton with overlying siliciclastic rocks is planar and parallel to the principal foliation in the adjoining rock units. It is considered to represent an original unconformable contact modified by shearing (Cawood and van Gool, 1998).

Zircons from tonalitic gneiss yielded a U/Pb age for igneous crystallization of 555 $^{+3}/_{-5}$ Ma (Cawood et al., 1996) and were slightly discordant along a mixing line with an upper intercept age of 1400 $^{+220}/_{-200}$ Ma. Basement in a nearby outcrop with a U/Pb zircon age of 1510 ± 6 Ma (Cawood et al., 1996) provides a likely source for the inheritance. Hornblende from an interbanded amphibolite yielded an Ar/Ar age of 427 ± 3 Ma that is related to Silurian imbrication and metamorphism of the succes-

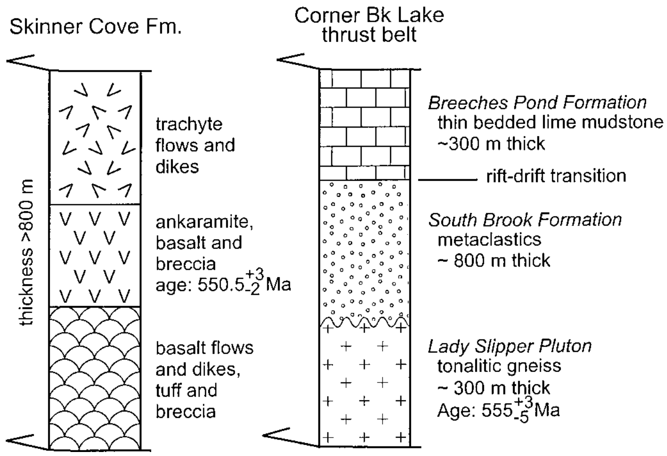

Figure 4. Schematic stratigraphic sections for the Skinner Cove Formation (Baker, 1979) and the thrust slice containing the Lady Slipper pluton in the Corner Brook Lake thrust belt (Cawood and van Gool, 1998).

sion (Cawood et al., 1994; van Gool and Cawood, 1994).

POSITION AND AGE OF THE RIFT-DRIFT TRANSITION

A younger limit on the timing of continental breakup and the initiation of seafloor spreading is provided by the age of the earliest drift-related sedimentation. Williams and Hiscott (1987) placed the rift-drift transition in Newfoundland at the change from terrigenous siliciclastic units of the Bradore Formation to marine carbonate deposits of the Forteau Formation. Structural and stratigraphic relations around the northern end of the Great Northern Peninsula suggest, however, that the boundary is at the base of the Bradore Formation, which marks the termination of both tectonic instability and igneous activity along this segment of the Laurentian margin (Fig. 6). Below the Bradore Formation, coarse siliciclastic and volcanic rocks are confined to fault-bounded grabens within basement. Abrupt thickness variations, particularly of the volcanics, plus probable faulting and tilting of the siliciclastic strata prior to volcanism indicate that this was an active rift system during latest Neoproterozoic time (cf. Bostock et al., 1983). The top of the volcanic succession is extremely oxidized, marked by a ferruginous cap reworked into a granular sandstone (Knight, 1987), which suggests a hiatus between the termination of volcanic activity and accumulation of the Bradore Formation. Placing the rift-drift transition at the base of Bradore is similar to the relationship in the U.S. Appalachians, where the Lower Cambrian Chilhowee Formation blankets various rift-controlled basins of late Precambrian sedimentary and volcanic rock units (Simpson and Eriksson, 1989; Thomas, 1991).

Available age data suggest that the time break represented by the hiatus at the base of the Bradore Formation may be as much as 90 m.y. The flows under the Bradore Formation are dated using feeder dikes from the Long Range swarm (Bostock et al., 1983) at 615 ± 2 Ma (see also Stukas and Reynolds, 1974; Kamo et al., 1989). The Forteau Formation of the drift sequence contains late Early Cambrian trilobites and archaeocyathids (*Bonnia-Olenellus* trilobite zone; Whittington and Kindle, 1969; Debrenne and James, 1981; Knight, 1991) that imply an absolute age of 520–515 Ma (cf. Bowring and Erwin, 1998). The undated, underlying Bradore Formation is as thick as 175 m (Bostock et al., 1983), but its overall coarse siliciclastic nature and fluvial to marginal marine depositional environment (Knight, 1991) suggest rapid accumulation over a few million years; it is probably no older than ca. 525–520 Ma.

IMPLICATIONS FOR LAURENTIA'S IAPETAN RIFT HISTORY

Geochronologic, stratigraphic, and paleomagnetic data for the Skinner Cove Formation and Lady Slipper pluton, together with data on the rift-drift transition in Newfoundland, enable the evaluation of three possible scenarios for the end Neoproterozoic to early Paleozoic final breakout of Laurentia from Rodinia and formation of the Iapetus Ocean: (1) rift-drift transition at 540–535 Ma; (2) rift-drift transition at 570 Ma and younger igneous activity occurring in a passive margin setting (McCausland and Hodych, 1998); (3) rift-drift transition at 570 Ma and a second rifting event at 540–535 Ma.

540 Ma Rift-Drift Transition

The recognition of a rift to drift transition in Newfoundland at 540–535 Ma is based on available geological data, and is consistent with other interpretations for the timing of Iapetan seafloor spreading between Laurentia and west Gondwana (cf. Thomas, 1991; Dalziel, 1997; van Staal et al., 1998).

Igneous activity represented by the Skinner Cove Formation and the Lady Slipper pluton, along with the similar aged Tibbit Hill Volcanics of the Quebec Appalachians (Kumarapeli et al., 1989), indicates that rift-related magmatism occurred as late as 550–555 Ma. Kumarapeli et al. (1989) suggested that the voluminous ca. 554 Ma Tibbit Hill magmatism marked the onset of Iapetan seafloor spreading at the Sutton Mountain triple junction. The age overlap with the west Newfoundland magmatism suggests that this activ-

TABLE 1. U/Pb DATA

Number	Fraction		Concentrations		Measured†		Corrected atomic ratios†				Age (Ma)		
	Zircon attributes	Weight (mg)	U (ppm)	Pb* (ppm)	Total common Pb (pg)	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
Z1	lg clr abr	0.215	290	26.5	32	10 506	0.1721	0.08633 ± 32	0.6970 ± 28	0.05855 ± 6	534	537	551
Z2	lg clr abr	0.053	308	28.6	33	2553	0.2558	0.08222 ± 48	0.6639 ± 38	0.05857 ± 14	509	509	551
Z3	clr frags yel	0.215	308	29.6	38	9655	0.2166	0.08755 ± 35	0.7068 ± 30	0.05856 ± 6	541	543	551

Notes: lg—large; clr—clear; abr—abraded; frags—zircon crystal fragments; yel—yellow.
*Radiogenic Pb.
†Measured values corrected for fractionation and common Pb in the spike; atomic ratios corrected for fractionation, spike, 5–20 pg laboratory blank and initial common Pb, calculated by the model of Stacey and Kramers (1975) for the age of the sample and 2 pg ^{238}U.

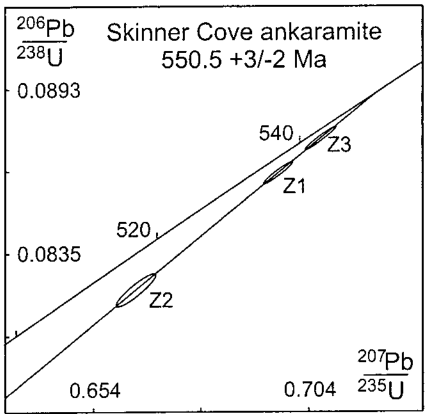

Figure 5. U/Pb concordia plot for zircon from ankaramite of the Skinner Cove Formation.

ity was a more widespread regional event along the Laurentian margin, ~50–70 m.y. younger than tholeiitic continental rift magmatism in west Newfoundland and Labrador, but only ~10–20 m.y. younger than transitional to alkalic and carbonatitic rift-related magmatism in Quebec, Ontario, and New England (Fig. 7).

The breakup of Rodinia and the separation of Laurentia from the west Gondwana cratons ca. 540 Ma conflict with available paleomagnetic data. McCausland and Hodych (1998) argued that the 19° ± 9°S paleolatitude for the Skinner Cove Formation constrains Laurentia to an equatorial position ca. 550 Ma (Fig. 8), while the 547 Ma Sinyai dike in the Mozambique belt of Kenya (Meert and Van der Voo, 1996) places the west Gondwana conjugate margin in the south polar region. Assuming a fully assembled west Gondwana and a Pannotia reconstruction (Dalziel, 1997), Laurentia would occupy a position at the (Sinyai dike) south pole, instead of the equatorial position implied by the Skinner Cove Formation paleolatitude (Fig. 8). Other ca. 550 Ma Gondwana paleopoles from India and Australia (summarized in Meert and Van der Voo, 1997) also require Laurentia to occupy high southerly paleolatitudes in the Pannotia reconstruction. If the assumption of an assembled Gondwana by 550 Ma is abandoned, then the Indian, Australian, and Congo paleopoles no longer provide a constraint upon the position of Laurentia and its proposed west Gondwana conjugate-margin cratons of Rio de la Plata and Amazonia. At the end Neoproterozoic these cratons were separated from the Congo craton and the Mozambique belt by the Brazilide and Adamastor Oceans. Closure of these oceans is generally considered to have taken place by 550 Ma (Trompette, 1997). However, a Laurentia–Amazonia–Rio de la Plata association can only be preserved with respect to the ca. 550 Ma Skinner Cove and Sinyai dike paleomagnetic data if wide Brazilide and Adamastor Oceans accommodated much of the inferred south pole-to-equator paleolatitudinal separation (Fig. 8). Preliminary paleomagnetic data for the Rio de la Plata provide an apparent polar wander path for the period ca. 750 Ma to 500 Ma, consistent with a fully assembled Gondwana by ca. 560 Ma (Bettucci and Rapalini, 1997, 1998).

570 Ma Rift-Drift Transition

To account for the paleomagnetic data for the Skinner Cove Formation with respect to both Gondwana and other Laurentian data, McCausland and Hodych (1998) proposed that Laurentia began a phase of rapid northward drift from the west Gondwana cratons ca. 570 Ma (Fig. 9; Data Repository Table DR1[1]). Paleomagnetic data for the Callander Complex of Ontario, dated by U/Pb zircon as 577 ± 1 Ma, and the ca. 570 Ma Catoctin volcanics in the U.S. Appalachians suggest a south polar location for the Laurentian margin (Symons and Chiasson, 1991; Meert et al., 1994; Aleinikoff et al., 1995; Kamo et al., 1995), adjacent to the west Gondwana cratons. By the time of formation of the Sept Iles anorthosite at 565 ± 4 Ma (Higgins and van Breemen, 1998), Laurentia had begun a phase of rapid apparent northward movement, reaching mid-paleolatitudes by ca. 555 Ma (cf. Meert et al., 1994; Meert, 1999), on the basis of paleomagnetic data for the Johnnie Formation in Nevada (Van Alstine and Gillett, 1979) and low southern paleoaltitudes by the time of formation of the Skinner Cove Formation (Fig. 9; McCausland and Hodych, 1998). In Cambrian time, Laurentia remained at low southerly paleoaltitudes, while the west Gondwana cratons remained at high southern latitudes (Torsvik et al., 1996; Meert, 1999).

Initiation of Iapetus spreading ca. 570 Ma is consistent with currently available paleomagnetic data, but geological relations argue that Laurentian margin igneous activity continued in a rift setting until ca. 550 Ma (cf. Kumarapeli et al., 1989; Williams, 1995; Cawood et al., 1996; Higgins and van Breemen, 1998). McCausland and Hodych (1998) suggested that post-570 Ma magmatism may reflect either igneous activity along the failed Ottawa-Bonnechere rift arm, as in the ca. 564 Ma Mount Rigaud syenite and Sept Iles anorthosite, or passive margin alkalic magmatism similar to that recorded from the Early Cretaceous Atlantic margin of North America (Jansa and Pe-Piper, 1985) for the Tibbit Hill or Skinner Cove volcanics. In the Atlantic margin example, however, the Cretaceous activity was 60 m.y. younger than rift-related igneous activity and formed during a separate tectonic cycle. The possible relation of both the Lady Slipper pluton and correlatives of the Skinner Cove Formation with rift facies siliciclastic rocks suggests continued rift activity.

[1]GSA Data Repository item 2001032, poles used to construct Laurentian margin paleolatitude plot, is available on the Web at http://www.geosociety.org/pubs/ft2001.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: editing@geosociety.org.

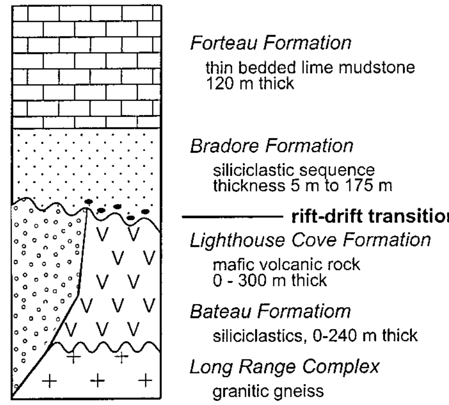

Figure 6. Schematic section through lower and middle Labrador Group highlighting rock relations on Great Northern Peninsula, western Newfoundland, and the position of the rift-drift transition.

Breakup at 570 Ma with Further Rifting from Laurentia at 540 Ma

In an attempt to integrate all available data, we propose that Iapetus spreading commenced ca. 570 Ma with drifting of Laurentia away from the west Gondwana cratons, but that the Iapetan passive margin along the Appalachians only developed ca. 540–535 Ma, when another block rafted off the margin. This model accounts for the paleomagnetic data that suggest that Laurentia began its rapid northward movement ca. 570 Ma (Fig. 9; McCausland and Hodych, 1998) as well as the integrated stratigraphic, sedimentologic, and geochronologic data, which suggest a rift-drift transition after the termination of igneous activity at 550 Ma and prior to the oldest drift-cycle sedimentation at 525–520 Ma. However, it requires a more complex rift history than the previous models.

Recent models of Iapetus formation suggest that supercontinent breakup created a number of terranes along the Laurentian margin and its conjugate margins in Amazonia, Rio de la Plata, and Baltica (Astini et al., 1995; Ramos

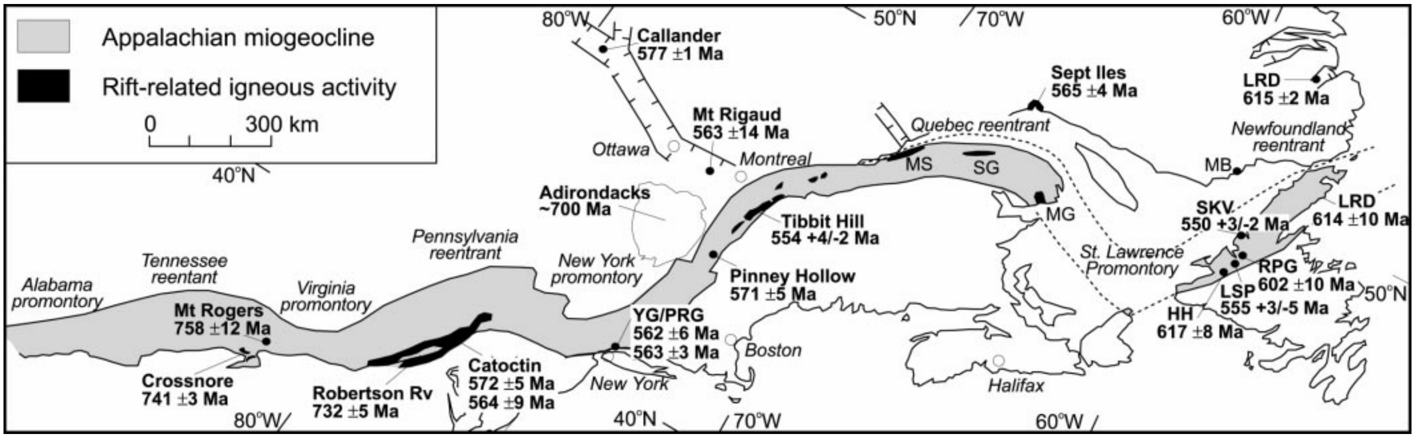

Figure 7. Distribution of late Neoproterozoic rift-related magmatic rocks within the miogeocline of the Appalachian orogen. Abbreviations: HH—Hare Hill Granite; LRD—Long Range dikes; LSP—Lady Slipper pluton; MB—Mutton Bay; MG—Maquereau Group; MS—Mount de St–Anselme Formation; RPG—Round Pond Granite; SKV—Skinner Cove Formation; SG—Shickshock Group; YG/PRG—Yonkers Gneiss and Pound Ridge Granite. Sources for age data: Adirondack Massif—Heizler and Harrison (1998); Callander Complex—Kamo et al. (1995); Catoctin Formation—Aleinikoff et al. (1995); Crossmone Pluton—Su et al. (1994); Hare Hill Granite—van Berkel and Currie (1988); Long Range dikes—Kamo et al. (1989) and Stukas and Reynolds (1974); Mount Rigaud intrusion—Malka et al. (1996); Mount Rogers—Aleinikoff et al. (1991, 1995); Pinney Hollow Formation—Walsh and Aleinikoff (1999); Robertson River Formation—Lukert and Banks (1984); Round Pond Granite—Williams et al. (1985); Sept Iles—Higgins and van Breeman (1998); Tibbit Hill Formation—Kumarapeli et al. (1989); Yonkers Gneiss and Pound Ridge Granite—Rankin et al. (1997). Errors are given at the two sigma level.

et al., 1998; Rapela et al., 1998; Keppie and Ramos, 1999). Potential geological candidates for the block that rifted from the Newfoundland–New England region of Laurentia after 550 Ma include the Argentine Precordillera and possibly the Oaxacan terrane of Mexico.

The Argentine Precordillera is exotic with respect to surrounding units and is considered to have originated along the Appalachian Laurentian margin (Bond et al., 1984; Astini et al., 1995, and references therein). Evidence for a Laurentian origin includes lithostratigraphic similarities with the Appalachian passive margin sequence (Ramos et al., 1986; Astini et al., 1995), faunal evidence showing a shift from exclusively Laurentian forms to Gondwanan forms during Cambrian–Ordovician time (Astini et al., 1995; Benedetto, 1998), and paleomagnetic data for Early Cambrian rift-related strata from the Precordillera, which are consistent with a location along the Laurentian margin (Rapalini and Astini, 1998). Models for the transfer of the Precordillera from Laurentia to Gondwana suggest that it either separated from Laurentia in the Early Cambrian to form a microplate, which drifted across Iapetus to collide with Gondwana in the Middle Ordovician (Astini et al., 1995; Thomas and Astini, 1996; Astini, 1998; Ramos et al., 1998; Thomas, 1998), or that it constituted a marginal plateau off Laurentia until Ordovician time, when continent-continent collision with Gondwana, followed by rifting, left the Precordillera accreted to Gondwana (Dalziel, 1997).

In both models the Precordillera is located in the southern Appalachians outboard of the Ouachita reentrant. Data from the Precordillera do not, however, delimit accurately its original location along Laurentia's margin. The lithostratigraphic character of the Precordillera compares equally well with the Newfoundland segment of the Laurentian margin (Astini et al., 1995), and the timing of the rift to drift transition in the Precordillera (Astini, 1998; Keller et al., 1998) is similar to that in Newfoundland and older than that invoked for the Ouachita margin (Bond et al., 1984; Thomas and Astini, 1996). This discrepancy in age of rifting as well as differences in the thickness of stratigraphic units between the Precordillera and the Ouachita margin have been ascribed to asymmetric rifting (Thomas and Astini, 1999). A lack of igneous activity has been cited as evidence that the Precordillera developed at a nonvolcanic rifted margin (Keller et al., 1998), but an absence of cover strata older than ca. 530 Ma and an unpreserved relationship to basement makes it impossible to establish if the Precordillera developed at a volcanic or nonvolcanic margin. Davis et al. (2000) dated tholeiitic microgabbro in a fault-bounded massive diabase on the western margin of the Precordillera as 576 ±17 Ma. Noting its age similarity with the Catoctin volcanics, they suggested that the massive diabase formed in a well-developed rift or during initial Iapetan separation between the Precordillera and Laurentia at 575–560 Ma.

A terrane such as the Precordillera may not have been restricted to a specific segment but could have extended along the entire Laurentian margin, perhaps in concert with other terranes (Keppie and Ramos, 1999). The relatively consistent Early Cambrian age for the rift-drift transition along the northern and central Appalachians (Thomas, 1991) suggests that if a terrane separated from the margin it would have extended along the entire Newfoundland–New England segment. Unusually flat subsidence curves between New York and Greenland (Bond et al., 1984; Bond, 1997) may also reflect the separation from Laurentia at ca. 550 Ma of a large terrane into an already open Iapetus. The Precordillera alone has an exposed length along strike of ~600 km but may be least 1000 km if it includes the Cuyania composite terrane (Ramos et al., 1998), or greater if the successive Phanerozoic orogenic events acted to obscure or dismember its original dimensions.

The Oaxacan terrane in Mexico is potentially another block that could have originated from the northern Appalachians. Its basement has lithologic, isotopic, and metamorphic signatures that best compare with Grenville orogenic rocks of the Adirondack Highlands and the Colombian massifs (Keppie and Ortega-

Gutiérrez, 1999). The oldest cover sediments on the Oaxacan terrane basement are latest Cambrian to earliest Ordovician platformal strata, which, like those on the Colombian massifs, contain trilobites of Gondwanan affinity (Robison and Pantoja-Alor, 1968; Keppie and Ramos, 1999). A lack of Laurentian fauna suggests that if the Oaxacan terrane was located outboard of the northern Appalachians following Iapetus opening at 570 Ma, its subsequent rifting from Laurentia after 550 Ma and transfer to Gondwana must have been completed by the ca. 500 Ma deposition of strata bearing Gondwanan fauna. The Oaxacan terrane position within Gondwana is suggested to have been marginal to northwest South America before it was transferred back to North America with ocean closure at the end of the Paleozoic (Keppie and Ramos, 1999) or in Late Ordovician−Silurian time (Ortega-Gutiérrez et al., 1999).

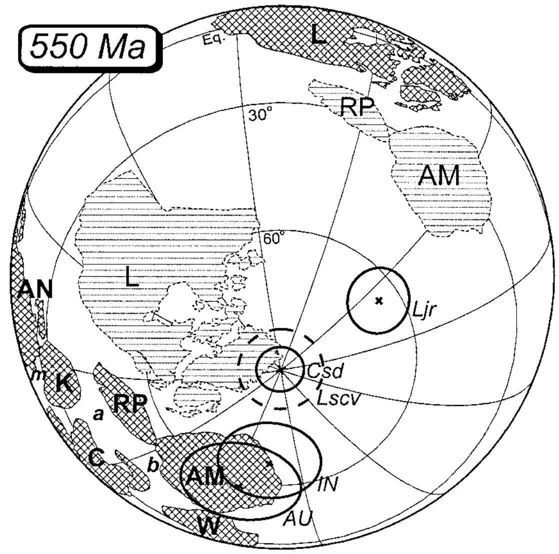

Figure 8. End-member options for ca. 550 Ma paleogeography of Laurentia and the Gondwanan cratons, assuming key relations from the Pannotia supercontinent reconstruction of Dalziel (1997). Cratons shown with cross-hachures are positioned by ca. 550 Ma paleomagnetic data from the Skinner Cove Formation (Laurentia) and the Sinyai dike (Congo–Mozambique belt), and show more than 90° of separation between Laurentia and Amazonia–Rio de la Plata. East Gondwanan ca. 550 Ma poles from India (IN) and Australia (AU) are plotted with reference to the Sinyai dike pole (Csd), and a ca. 555 Ma pole from Laurentia (Ljr—Johnnie Rainstorm Formation, Nevada) is plotted with reference to the Skinner Cove pole (Lscv). Bringing these other Gondwanan and Laurentian poles into coincidence gives lesser but still significant (>45°) separation between Laurentia and an assembled Gondwana, in disagreement with inferred geological and ca. 540 Ma rift relations between Amazonia–Rio de la Plata and Laurentia, on which the Pannotia reconstruction relies. Other abbreviations: a—Adamastor Ocean; b—Brazilide Ocean and orogen; m—Mozambique Ocean and orogen; AM—Amazonia; AN—Antarctica; C—Congo–Sao Francisco; K—Kalahari; L—Laurentia; RP—Rio de la Plata; W—West Africa. Baltica and Siberia are omitted for clarity. Poles are plotted with circles of 95% confidence.

DISCUSSION

The 550–555 Ma Skinner Cove Formation and Lady Slipper pluton represent the last of ~200 m.y. of igneous activity that extended along the east Laurentian margin, associated with Neoproterozoic breakup of Rodinia and the opening of the Iapetus Ocean. Available age data suggest that this activity is divisible into two main pulses, the first from 760 to 700 Ma and a second from 620 to 550 Ma (Badger and Sinha, 1988; Aleinikoff et al., 1991, 1995; Rankin et al., 1993; Li and Tull, 1998). The first pulse is within the Appalachian Blue Ridge (Fig. 7) and is characterized by bimodal alkaline igneous activity in an extensional intracontinental rift setting (Su et al., 1994; Aleinikoff et al., 1995). The Ar/Ar data from K-feldspars in the Adirondack Mountains show evidence for a major thermal event ca. 700 Ma (Heizler and Harrison, 1998), suggesting that the early magmatic pulse extended as far north as New York. In addition, extensive siliciclastic sequences in the East Greenland Caledonides are interpreted to have begun forming in a rift-related setting ca. 760 Ma (Ryan, 1999; Watt and Thrane, 2001). Commencement of rift-related activity in east Laurentia at 760 Ma corresponds with opening of the proto-Pacific between west Laurentia and the East Australia−West Antarctic conjugate margins (Ross, 1991; Powell et al., 1993, 1994; Dalziel, 1997; Karlstrom et al., 2000; Wingate and Giddings, 2000).

Younger magmatic activity occurred from 620 Ma to 550 Ma and is widespread in the northeastern Appalachians. Rifting and separation of Laurentia from the west Gondwana cratons during this time correspond with closure of the Mozambique Ocean and assembly of east and west Gondwana, the initiation of subduction of the proto-Pacific beneath east Gondwana, and the rifting of Baltica and Siberia from Laurentia and Gondwana (Grunow et al., 1996; Dalziel, 1997; Cawood and Leitch, 1998).

Figure 10 presents a series of schematic end Neoproterozoic to Early Cambrian paleogeographic reconstructions showing the distribution of Gondwana, Laurentia, Baltica, and Siberia, and the evolution of plate boundaries between and within these elements. These diagrams are constructed on the premise that rifting along Laurentia's eastern margin to form the Iapetus Ocean was a two-stage process involving drifting of Laurentia from Amazonia−Rio de la Plata prior to the formation of the Laurentian passive margin through the separation of one or several terranes. The distribution and interrelationship of other cratonic elements is adapted from Dalziel (1997), Frost et al. (1998), Grunow et al. (1996), Meert and Van der Voo (1997), Weil et al. (1998), and Torsvik et al. (1996).

The 600 Ma reconstruction (Fig. 10A) highlights a rift system between west Gondwana and Laurentia. Lithospheric stretching probably commenced ca. 620 Ma on the basis of dating of magmatic activity in northeast Laurentia and Baltica (van Berkel and Currie, 1988; Kamo et al., 1989; Kamo and Gower, 1994; Bingen et al., 1998), and proceeded along the west Gondwana−Laurentia boundary following the separation of Baltica, encompassing the future Laurentian-derived Iapetan terrane(s). West Gondwana was being assembled through closure of the Brazilide and Adamastor Oceans, perhaps driven by the collision of east Gondwana with the Congo and Kalahari cratons along the former Mozambique Ocean (Trompette, 1997).

The Iapetus Ocean was initiated between Laurentia and west Gondwana ca. 570 Ma (Fig. 10B), perhaps through propagation of the main proto-Pacific spreading center, and Bal-

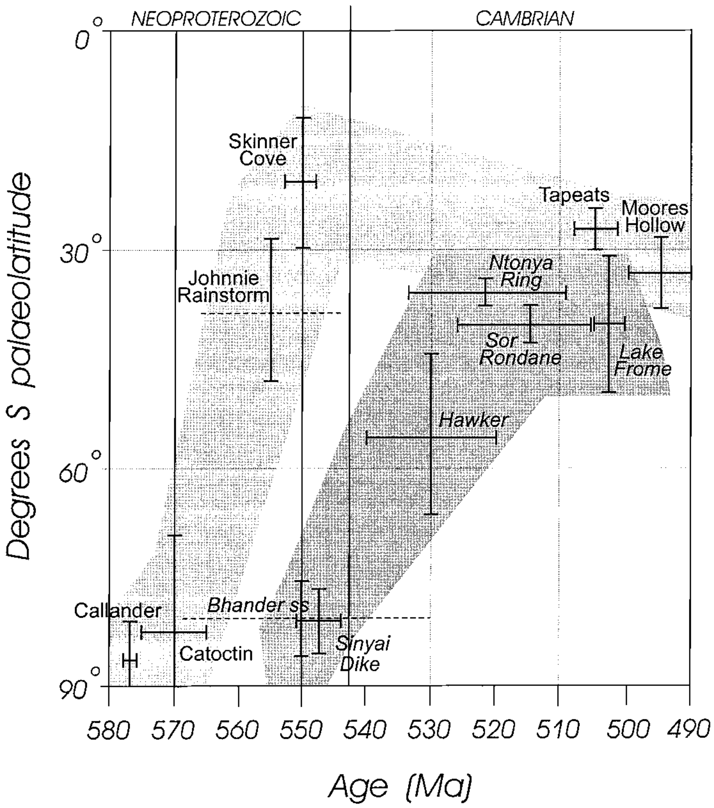

Figure 9. Paleolatitudinal plot of Laurentia's Newfoundland margin, showing an end Neoproterozoic divergence in estimated latitude, as determined directly from Laurentian poles (light gray shading), and from Gondwanan poles (dark gray shading) assuming Laurentia to be in rift relation with Amazonia–Rio de la Plata. Individual paleolatitude constraints are cited as α_{95} (2σ) or equivalent. Dashed lines indicate poor age constraint. Laurentia poles are revised from McCausland and Hodych (1998); Gondwana poles are revised from Meert and Van der Voo (1997) and Klootwijk (1980). Gondwanan poles are rotated to Laurentian coordinates according to Weil et al. (1998) and Lottes and Rowley (1990). See Table DR1 (see text footnote 1) for source data.

tica had already separated from Amazonia and Laurentia (Torsvik et al., 1996). To one side of the incipient Iapetus, the Brazilide belt between Amazonia and Congo–São Francisco cratons was undergoing extensional uplift (Pimentel et al., 1996, 1997), while 570 Ma rifting was renewed along intracratonic rifts separating Laurentia from the inferred outboard microplate. The widespread 620–570 Ma extensional activity between first Baltica, and then Laurentia, and elements of west Gondwana corresponded with the initiation of proto-Pacific subduction along the east Gondwana margin (Cawood and Leitch, 1998). This implies a major 620–570 Ma global rearrangement of plate motions, leading to the rapid northward movement of Baltica and Laurentia and the opening of the Iapetus Ocean.

Paleomagnetic data suggest that by 550 Ma (Figs. 9 and 10C) Laurentia occupied a low-latitude position, relative to a high-latitude position for Gondwana, resulting in a wide Iapetus Ocean (cf. Torsvik et al., 1996). Geologic data suggest that this time frame corresponds with the termination of igneous activity and related tectonic instability along the Laurentian margin. By 530 Ma (Fig. 10D) subduction had commenced along the proto-Andean margin (cf. Rapela et al., 1998), and one or several large microcontinental fragments had rifted off east Laurentia, marking the formation of the Laurentian passive margin. The subsequent position and drift history of this terrane or terranes with respect to the Laurentian margin and Iapetus Ocean are uncertain. Thomas and Astini (1996) proposed that the Precordilleran component of this fragment drifted across Iapetus and was accreted to the proto-Andean margin of Gondwana during the Middle Ordovician, separated from the Laurentian margin by a new spreading ridge, which perhaps developed through a ridge jump. In contrast, Dalziel (1997) proposed that the Argentine Precordillera remained as a marginal plateau outboard of the Laurentian margin that was accreted to South America through oblique collision of Laurentian and Gondwana during the synchronous Taconic and Ocloyic orogenies. A third alternative is that some terranes constituted marginal plateaus that were accreted back onto Laurentia during the Taconian orogeny. The Dashwoods block of southwest Newfoundland (Fig. 1), containing a mixed assemblage of metaclastic and ophiolitic rocks (Cawood et al., 1995), may have developed through such a process (van Staal, 2000, personal commun.). The Pampean terrane may have had a similar relation to Rio de la Plata (Rapela et al., 1998).

A passive margin sequence associated with the inferred first cycle of opening of the Iapetus Ocean (570–540 Ma) has not been recognized along the Laurentian margin. This may be due to rifting associated with this event (and any passive margin sedimentation) occurring well to the east of the current Laurentian margin, along the eastern margin of the displaced terranes. In addition, the Laurentian margin may have remained elevated during this period, perhaps due to thermal effects associated with continued rift-related igneous activity, and did not constitute a site for sediment accumulation. The flat subsidence curves for the Newfoundland to Greenland segment of the margin (Bond et al., 1984; Bond, 1997) may reflect the effects of this two stage, end Neoproterozoic to early Paleozoic rift-drift history.

IMPLICATIONS FOR PALEOGEOGRAPHIC RECONSTRUCTIONS

The presence of rift-related magmatism along the Laurentian margin as young as the Neoproterozoic-Cambrian boundary provides important constraints for evaluating the proposed Pannotian supercontinent configuration (Powell, 1995; Dalziel, 1997). If closure of the Mozambique Ocean occurred after the opening of Iapetus, or assembly of Gondwana was not complete at the time of Iapetus opening, then Pannotia did not exist (cf. MacNiocail et al., 1997). Estimates of the time of closure of the Mozambique Ocean range from ca. 700–600 Ma (Stern, 1994) to the Cambrian (Li and Powell, 1993), but recent work suggests an end Neoproterozoic age of ca. 550 Ma (Meert and Van der Voo, 1996). This overlaps with the age of Iapetus opening and hence, on the basis of available age data, Pannotia was, at best, an ephemeral amalgamation during a period of rapid continental reorganization. However, comparison of ca. 550 Ma paleomagnetic data from Laurentia and Gondwana (Fig. 9;

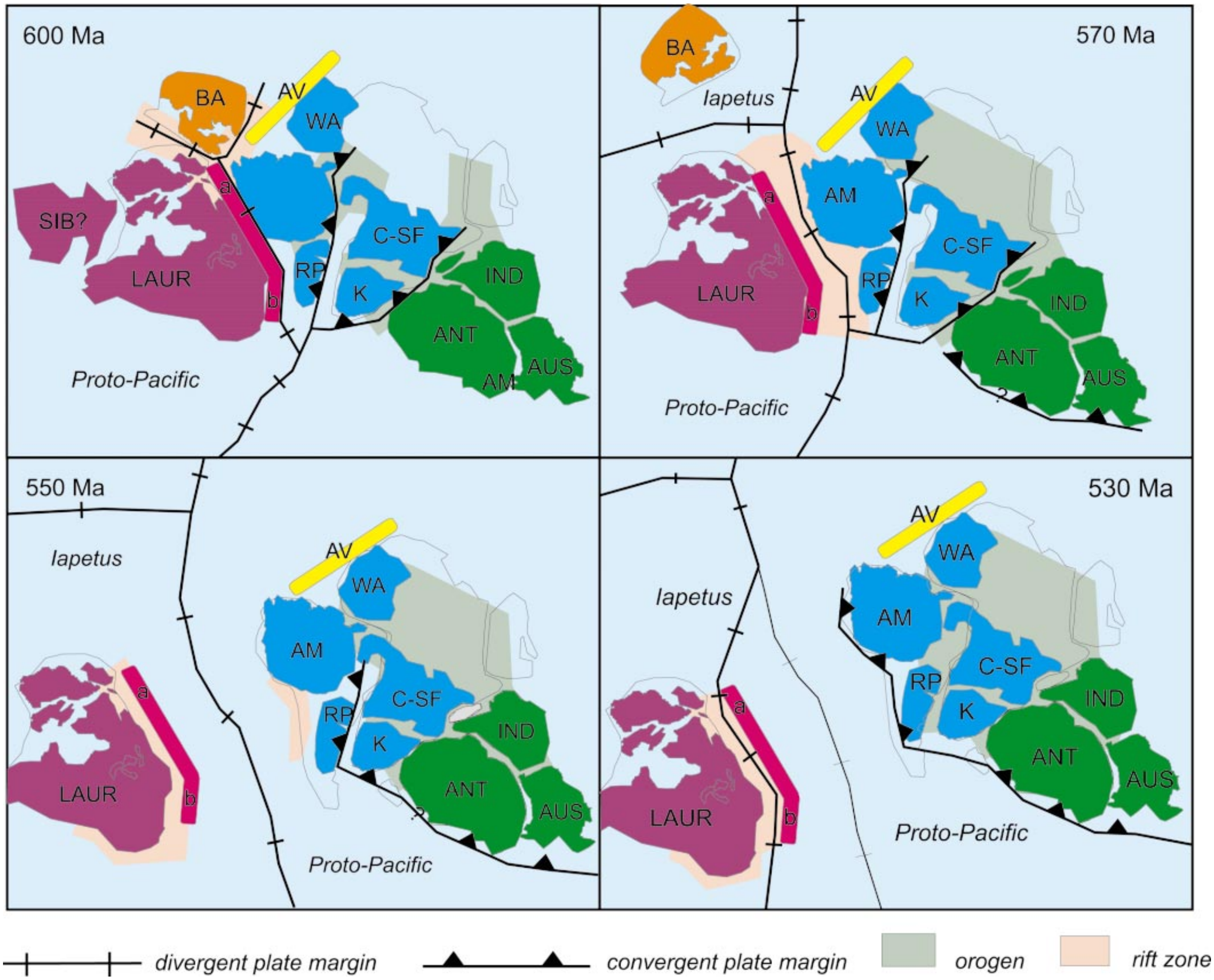

Figure 10. Schematic paleogeographic reconstructions at (A) 600 Ma; (B) 570 Ma; (C) 550 Ma; (D) 530 Ma. Abbreviations: AM—Amazonia, ANT—Antarctica, AUS—Australia, AV—Avalon, BA—Baltica, C-SF—Congo–São Francisco, IND—India, K—Kalahari, LAUR—Laurentia, RP—Rio de la Plata, SIB—Siberia, WA—West Africa. The long linear crustal block (pink) along the east Laurentian margin represents the proposed terrane(s) that rifted from Laurentia prior to its passive Iapetan margin development. The block(s) possibly included the Argentine Precordillera (Astini et al., 1995), the Oaxacan terrane (Keppie and Ortega-Gutiérrez, 1999), and the Dashwoods block. The Pampean terrane may have developed outboard of Rio de la Plata and remained with west Gondwana as a marginal plateau after Iapetus opening (Rapela et al., 1998); a—highlights position of possible terrane off Newfoundland, b—location of Argentine Precordillera proposed by Thomas and Astini (1996) and Dalziel (1997).

Table DR1 [see footnote 1]; Torsvik et al., 1996; Meert and Van der Voo, 1997; McCausland and Hodych, 1998) implies significant separation between cratons across the Iapetus, Mozambique, and/or the Adamastor and Brazilide Oceans and the data do not support the concept of an end Neoproterozoic supercontinent.

Development of a series of crustal blocks along the east Laurentia and west Gondwana margins during the Neoproterozoic breakup of Rodinia (e.g., Fig. 10, A–D) implies that lithospheric extension was not centered along a single continental rift system, but rather dispersed over multiple systems. Possible reasons for this include the extended history of rifting, the development of multiple plate boundaries during this phase of Rodinian breakup, and the intersection, during the latter stages of extension, of a mantle plume with the rift system. Although the current distribution of rift-associated sedimentary and igneous rocks (e.g., Fig. 7) indicates that the 760–700 Ma and 620–550 Ma rift systems in part overlapped, their extent is poorly known and their centers of extension may have differed. The older Laurentian rift system is present in the U.S. Appalachians and the Scotland-Greenland segment of the Caledonian orogen, but is notably absent from the northeast Appalachians. Perhaps this discontinuous rift system records a failed separation of Laurentia from Rodinia in the mid-Neoproterozoic, an event that provided lithospheric weaknesses for the later, successful rift system. Alternatively, the old rift system could have extended through the northeast Appalachians, but the record of its existence was removed during terrane rifting.

As has been pointed out by a number of workers, the final breakout of Laurentia and formation of Iapetus was not a simple two-plate process, but involved the formation of at least three extensional plate boundaries between four cratonic blocks (Laurentia, west Gondwana, Baltica, Siberia) over the period 620 to 550 Ma (Grunow et al., 1996; Pelechaty, 1996; Bingen et al., 1998). Changing plate vectors provide a possible mechanism for shifts in the loci of maximum lithospheric extension along the Laurentia–west Gondwana boundary and the development of a complex, anastomosing rift system in response to weaknesses inherited from older rifting. The intersection of a major mantle plume centered on Sept Iles (Higgins and van Breemen, 1998) may also have facilitated the generation of terranes during rifting (Courtillot et al., 1999).

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