Late Paleozoic strike-slip faults in Maritime Canada and their role in the reconfiguration of the northern Appalachian orogen

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Key points

- Late Paleozoic dextral faults dissect northern Appalachians
- NE-SW and E-W dextral faults active at different times
- Restoration of strike slip necessary for understanding orogen

Abstract

Major late Paleozoic faults, many with documented strike-slip motion, have dissected the Ordovician - Devonian Appalachian orogen in the Maritime Provinces of Atlantic Canada. Activity alternated between east-west faults (Minas trend) and NE-SW faults (Appalachian trend). NW-SE faults (Canso trend) were probably conjugate to Minas-trend faults. Major dextral movement, on faults with Appalachian trend, in total between 200 and 300 km, began in the Late Devonian. This movement initiated the Maritimes Basin in a transtensional environment at a releasing bend formed around a promontory in the Laurentian margin, and thinned the crust, accounting for the major subsidence of the basin. Appalachian-trend strike slip continued in the Mississippian, but was accompanied by major movement on E-W Minas-trend faults culminating around the Mississippian-Pennsylvanian boundary, juxtaposing the Meguma and Avalon terranes of the Appalachians close to their present-day configuration. However, strike slip continued during the Pennsylvanian-Permian interval resulting in transpressional deformation that reactivated and inverted earlier extensional faults. A final major episode of transtension, mainly sinistral, occurred during the Mesozoic opening of the Atlantic Ocean. Restoration of movements on these faults, amounting to several hundred kilometres of slip, explains anomalies in the present-day distribution of terranes amalgamated during early Paleozoic Appalachian tectonism. In the restored geometry, the Nashoba and Ellsworth terranes of Ganderia are adjacent to one

another, and the Meguma terrane lies clearly outboard of Avalonia. A restored post-Acadian paleogeography, not the present-day geometry of the orogen, should be used as a basis for reconstructions of its earlier Paleozoic history.

1 Introduction

Major late Paleozoic faults, many of which have documented strike-slip motion [e.g., *Murphy et al.*, 2011], have dissected the Ordovician to Devonian portion of the northern Appalachian orogen in the Maritime Provinces of Atlantic Canada (Figure 1a, b). These faults both bound and dissect the Late Devonian-Permian Maritimes Basin, and many authors [e.g., *Belt,* 1968; *Bradley et al.,* 1982, and references therein] have suggested a relationship between basin subsidence and fault motion. *Stockmal et al.* [1990] and *Hibbard and Waldron* [2009] highlighted the role of inherited irregularities in the Laurentian margin, originally identified by *Thomas* [1977], in subsequent basin development. *Hibbard and Waldron* [2009] suggested ~250 km of cumulative dextral strike-slip motion, that controlled the opening of the Maritimes Basin in a zone of dextral transtension formed at a regional releasing stepover on a fault roughly parallel to the orogen. In their model, motion on orogen-parallel faults was interrupted and overprinted during the Carboniferous by E-W strike slip on the Minas fault zone (MFZ; Figure 1b). Some of these strike-slip faults were also active during Mesozoic rifting and opening of the North Atlantic Ocean [e.g., *Olsen and Schlische,* 1990; *Withjack et al.,* 2009].

Although *Webb* [1969] and *Stockmal et al.* [1990] emphasized the importance of these faults and attempted to restore strike-slip motion on several of them, subsequent reconstructions of the development of the orogen typically have not taken into account the possibility of major strike-slip motion that post-dated the Early to Middle Devonian Acadian Orogeny. Many discussions of the tectonic history of the orogen [e.g., *Bird and Dewey,* 1970; *Williams,* 1980; *van Staal et al.,* 1998, 2009; *Valverde Vaquero et al.,* 2006; *Waldron et al.,* 2011] have been based on maps showing the present-day distribution of units, and cross-sections through the developing orogen approximately orthogonal to regional strike; while acknowledging later transcurrent motion, they do not explicitly restore its effects.

In this paper, we first briefly review major early Paleozoic terranes identified in the Appalachians of Atlantic Canada and adjacent New England. Next, we describe the late Paleozoic fill of the overlying Maritimes Basin, and describe the major fault systems known to have been active during development of the basin. Then, we examine available evidence for the sense and magnitude of strike-slip motion on each fault, testing the model of *Hibbard and Waldron* [2009]. Because of a lack of unequivocal piercing points, in many cases we can only place reasonable limits on the amount of deformation. In a subsequent section we serially restore the suggested movements, starting with the most recent, and propose a post-Acadian configuration of the northern Appalachians. The resulting Middle Devonian paleogeography restores several similar terranes, now separated, to adjacent locations, and thus explains some anomalies in the present-day distribution of rock units. We suggest that a restored post-Acadian paleogeography, not the present-day geometry of the orogen, should be used as a basis for resolving the earlier structural history of the orogen.

2 Early Paleozoic Appalachian terranes

Early Paleozoic divisions [*Hibbard et al.,* 2006, 2007] of the northern Appalachians are summarized in Figure 1b. The most outboard of these, the Meguma terrane, is located south of the Minas fault zone in Nova Scotia and dominated by Cambrian-Ordovician turbidites [*White*, 2010] and ~380-370 Ma granitoid plutons [e.g., *Clarke et al.,* 1997]. The Meguma terrane has no direct equivalents elsewhere in Atlantic Canada; it was correlated with the early Paleozoic of

North Africa by *Schenk* [e.g., 1973], and compared isotopically with younger rocks in Portugal by *Braid et al.* [2012]. On the basis of a detailed stratigraphic correlation, *Waldron et al.,* [2011] grouped the Meguma terrane with rocks in North Wales into the domain Megumia.

Mainland Nova Scotia north of the MFZ, together with the SE parts of Cape Breton Island, Newfoundland, New Brunswick, and New England have been divided into multiple terranes collectively grouped as Avalonia. Avalonia is characterized by Neoproterozoic volcanic, sedimentary, and plutonic rocks [*Hibbard et al.*, 2006, 2007; *Thompson et al.,* 2012], overlain in many places by a distinctive Cambrian cold-water platformal cover succession [*Landing,* 1996]. However, significant differences occur among the areas assigned to Avalonia. For example, the western part of the Avalon terrane in Newfoundland, the Mira terrane of SE Cape Breton Island, and the Caledonia terrane of southern New Brunswick resemble each other in ages and tectonomagmatic evolution [*Barr and White,* 1996*; Barr et al.,* 1998]. In contrast, the Antigonish and Cobequid Highlands of northern mainland Nova Scotia display a dominance of ca. 610-590 Ma plutons, bimodal Ordovician igneous rocks, and an extensive Silurian sedimentary cover succession, features which are less abundant or absent in the other areas [*Barr and White,* 1996; *Barr et al.,* 1998; *Archibald et al.,* 2013]. In SE New England, rocks assigned to Avalonia resemble those of the Antigonish Highlands in their Ediacaran plutonic ages, but lack Ordovician igneous rocks and the Silurian cover succession [*Thompson et al.,* 2010, 2012].

North and west of these Avalonian terranes are diverse components of a continental fragment, with remnants of associated arcs and back-arcs, assigned to the domain Ganderia and interpreted as of peri-Gondwanan origin [*van Staal et al.* 1998, 2009, 2012; *Hibbard et al.,* 2006, 2007; *van Staal and Barr,* 2012]. Ganderia extends west to the Red Indian Line, the suture between peri-Gondwanan and Laurentian components of the orogen [*Hibbard et al., 2006*].

The early Paleozoic Laurentian margin is preserved in western Newfoundland, southeastern Quebec and western New England, and the Blair River inlier of northwestern Cape Breton Island [*Barr et al.,* 1987*; Miller and Barr, 2004*]. In Newfoundland, east of the Cabot fault, are additional fragments of the hyperextended Laurentian margin [*Chew and van Staal.,* 2014], and peri-Laurentian arc rocks (Figure 1) assigned to the Notre Dame and Dashwoods terranes [*Waldron and van Staal,* 2001]; equivalent rocks likely occur in the Chain Lakes massif (Figure 1) of western New England and Québec [e.g., *Hibbard et al.,* 2007].

These diverse terranes were brought together in a series of orogenic episodes starting with the Ordovician Taconian Orogeny, interpreted to have resulted from a complex arc-continent collision affecting the margin of Laurentia [*Waldron et al.,* 1998; *Waldron and van Staal,* 2001]. Subsequent establishment of a west-dipping subduction zone along the margin of Laurentia is recorded in the Annieopsquotch accretionary tract [*Zagorevski et al.*, 2009]. Accretion of peri-Gondwanan fragments (Ganderia) probably drove the Silurian Salinian Orogeny [*Dunning et al., 1990; Zagorevski et al.,* 2007, 2010; *van Staal et al.,* 2009]. Subsequent accretion of Avalonia and Meguma to the margin is commonly interpreted [e.g., *van Staal and Barr,* 2012] to have occurred during the Devonian Acadian and Neoacadian orogenies.

3 Maritimes Basin fill

The Late Devonian to Permian Maritimes Basin (Figure 1b) is a large and complex basin, up to 12 km deep, that overlaps the terranes assembled in Neoacadian and earlier orogenesis. It contains many distinct depocentres, or sub-basins, most of which have stratigraphic elements in common, reflecting basin-wide tectonic events superimposed on the overall northward tectonic drift of Atlantic Canada through the tropics [*Calder*, 1998]. The overall stratigraphy is summarized in Figure 2; readers are referred to *Giles and Utting* [1999] and *Gibling et al.* [2009] for more details.

The oldest units attributed to the Maritimes Basin are volcanic and sedimentary rocks of the Guysborough Group, constrained to Middle Devonian or older [*Cormier et al.,* 1995; *Dunning et al.,* 2002]. Based on petrological characteristics, *Cormier et al.* [1995] suggested a within-plate origin associated with rifting. Roughly coeval intrusive rocks in SE Cape Breton Island may have a similar origin [*Barr and MacDonald*, 1982]. Small areas of Early to Middle Devonian subaerial clastic sedimentary rocks reported in the Cobequid Highlands [*Donohoe and Wallace,* 1985] and Cape Breton Island [*White and Barr,* 1998] lack associated volcanic rocks.

Younger volcanic successions ranging from Famennian to Tournaisian occur at the base of the Maritimes Basin succession in several sub-basins [*McGregor and McCutcheon, 1988; Barr et al.*, 1995a; *Tucker et al.,* 1998; *Dunning et al.,* 2002], including bimodal subaerial volcanic and associated sedimentary rocks in Cape Breton Island (Fisset Brook Fm.), mainland Nova Scotia (Fountain Lake Gp.), and New Brunswick (Piskehagan Gp.). Elsewhere in the basin, the oldest rocks are early to mid-Tournaisian mainly lacustrine clastic rocks of the Horton Group (Anguille Group in Newfoundland). The overlying Sussex Group, confined to New Brunswick, displays similar facies but is separated from the Horton Group by an intra-Tournaisian unconformity. The distinctive Windsor Group (approximately equivalent to the Codroy Group in Newfoundland) is Viséan, and contains marine limestones, thick evaporites, and redbeds. Expulsion of Windsor evaporites has controlled stratigraphy in overlying units [*Waldron and Rygel,* 2005; *Waldron et al.,* 2013]. The Viséan-Serpukhovian Mabou Group represents a return to clastic sedimentation, and is dominated by redbeds. The overlying Cumberland Group, of Bashkirian age, is mainly grey and contains substantial coal. The transition to overlying redbeds of the Moscovian to Permian Pictou Group was diachronous, so parts of the Pictou Group in New Brunswick are contemporary with coal-bearing Cumberland Group in Nova Scotia (Figure 2).

4 Late Paleozoic fault systems

Systems of steep faults with straight or approximately straight traces are prominent in the Appalachians, especially in the Maritime Provinces of Atlantic Canada (Figure 1). In this paper we focus on major faults in the Atlantic Canada (Nova Scotia, New Brunswick, and Newfoundland) that can be traced 30 km or more. The strikes of these faults are strongly grouped; we recognize three major modes in their orientations (Figure 3a).

The most abundant faults strike NE-SW (red in Figure 3a), approximately parallel to the orogen, referred to here as the *Appalachian trend.* In New Brunswick, they include the Bellisle, Kennebecasis, Caledonia and Clover Hill faults (Figure 3b). In Nova Scotia, major faults with this strike include the Hollow, Aspy, Eastern Highlands shear zone, and Georges River faults which bound blocks in northern mainland Nova Scotia and Cape Breton Island, and the Chebogue Point shear zone which transects the Meguma terrane. In Newfoundland, the Cabot fault is the most prominent example, but other NE-SW faults are widespread in central Newfoundland. *Hibbard and Waldron* [2009] suggested that motion on these faults began in the Late Devonian, and that together they account for ~250 km of dextral strike-slip motion, sufficient to explain the subsidence of the predominantly Mississippian-Pennsylvanian Maritimes Basin by transtension at an oblique releasing bend located approximately at the latitude of the present-day Gulf of St. Lawrence.

A second prominent trend is E-W, marked by the major Cobequid, Chedabucto, and parallel faults in mainland Nova Scotia (green in Figure 3a). These faults are major components of the Minas fault zone (MFZ) as defined by *Murphy et al.* [2011], and we refer to this east-west trend as the *Minas trend*. Less extensive E-W faults of late Paleozoic age occur in Cape Breton Island, northern New Brunswick, and possibly southern Newfoundland. Most of these faults had dextral strike-slip motion in the Carboniferous. E-W dextral strike-slip is difficult to relate to the more abundant faults with the NE-SW Appalachian trend using conventional stress and strain analyses, although *Bradley* [1982] included both sets of faults in an overall dextral strike-slip system. In contrast, *Hibbard and Waldron* [2009] suggested that the two trends were active at different times in the late Paleozoic. Portions of the MFZ are also known to have been reactivated with sinistral slip during early Mesozoic faulting that led to the opening of the Atlantic Ocean [e.g., *Olsen and Schlische,* 1990; *Withjack et al.,* 2009].

A third prominent set of faults, with NW-SE to N-S strikes (blue in Figure 3a), occurs in Nova Scotia (e.g., Canso fault, Country Harbour fault), New Brunswick (e.g., Oak Bay fault), and the Gaspé Peninsula of Québec (e.g., Percé fault; Figure 1c). We here refer to this orientation as the *Canso trend*. The Canso fault, extrapolated beneath the Gulf of St. Lawrence, has been interpreted to account for dextral offset of the terranes of southern New Brunswick relative to those of Cape Breton Island, probably during the Early Devonian [e.g., *McCutcheon and Robinson,* 1987; *Barr and Raeside,* 1989; *Stockmal et al.,* 1990]. In the eastern Meguma terrane of southern Nova Scotia the Country Harbour and similar faults have documented sinistral strike slip [*Henderson*, 1986], suggesting a simple conjugate relationship to the dextral MFZ. The timing of motion on these faults is unclear; *Williams et al.* [1995] suggested that most are

Mesozoic. However, their orientations and displacements appear more consistent with inferred Carboniferous kinematics than those of Atlantic rifting.

5 Timing and amount of slip

In this section we consider the major faults and fault zones identified in Figures 1 and 3 in turn, geographically from NW to SE across the portion of the Appalachian orogen exposed in New Brunswick, Nova Scotia, and western Newfoundland. Quantifying the motion on these faults is necessarily somewhat speculative, as unequivocal piercing points involving linear features (Figure 4a) are scarce. Where available, we therefore use major contrasts between contemporary successions on either side of major faults as indicators of strike-slip motion (Figure 4b). Elsewhere, we use area balancing of a strike-slip duplex (Figure 4c) and geometries of thrust faults in plan view (Figure 4d) to place limits on slip. In many cases we can put only a minimum value on slip; larger amounts cannot be excluded. However, we place upper limits on the cumulative slip that can be envisaged based on the interpretation of *Hibbard and Waldron* [2009], who found that offset structural trends in the southern Appalachians, the position of the Hermitage Flexure in southern Newfoundland, and crustal thinning interpreted in the Maritimes Basin beneath the Gulf of St. Lawrence can all be explained by ~250 km of dextral strike slip on an Appalachian trend, between 430 and 320 Ma.

5.1 Norumbega – Fredericton fault zone

The Norumbega-Fredericton fault zone (Figure 1b, c) is the farthest NW of the Appalachian trend faults considered here. Research on the Norumbega-Fredericton fault zone and parallel faults in New England is summarized by *Ludman and West* [1999 and papers therein], *Park and Whitehead* [2003], and *Short* [2006]. These papers demonstrate that the system shows a long history of mainly dextral strike-slip motion but that 384-380 Ma plutons in Maine show minor offsets, suggesting that most of the strike-slip motion occurred before the initiation of the Maritimes Basin. However, *Ludman et al.* [1999] identified a foliation resulting from strike-slip motion in these plutons, and dated the deformation at 376+/-5 Ma. Dextral separation, by about 30 km, of the gently NE-dipping basal unconformity of the Maritimes Basin in the Fredericton area (Figure 1) could be accounted for by Pennsylvanian or younger dextral strike-slip, or by dip-slip (SE-side-down) motion, or by some combination of the two. Mabou Group that occurs along the fault in narrow tectonically bounded zones displays both strike-slip and dip-slip slickenlines indicating Serpukhovian or later movement. We suggest that the dextral strike-slip component does not exceed about 10 km.

5.2 Belleisle fault zone

The thin Carboniferous succession of the New Brunswick Platform is terminated to the southeast at the Belleisle fault zone (Figure 1), which includes the Belleisle and Kierstead Mountain faults (Figure 3), representing a major and long-lived boundary with Appalachian trend. Traced SW, it separates the Silurian Kingston Basin to the south from the New River terrane (part of Ganderia) to the north. In the area of Nerepis (Figure 3c), a conspicuous leftward stepover in the fault is occupied by a contractional strike-slip duplex [*Woodcock and Fisher,* 1986] of at least 13 horses, mapped at 1:50,000 scale by *Johnson et al.* [2005]. The duplex has an area of 93 km^2. Individual faults within the duplex have a total strike length of ~115 km and divide the duplex into horses averaging ~540 m wide. Simple area balancing (Figure 4c) yields a slip estimate of ~157 km. This estimate is only valid if the width of the horses is representative of the width of the duplex prior to deformation, and if the duplex is deformed by plane strain, with no net extension or shortening in the vertical direction; in reality, a contractional strike-slip duplex is likely to display vertical extrusion and therefore a contraction in surface area, in which case the calculation above would under-estimate the total slip.

Although mapping suggests that the westernmost wall of the duplex is intruded by part of the Late Devonian [367 +/- 1 Ma; *Bevier*, 1988] Saint George Batholith, the duplex contains two horses of Devonian-Carboniferous clastic sedimentary rock (Sagwa Fm.) assigned to the Horton Group, suggesting late Devonian or Mississippian displacement.

In the Maritimes Basin, the fault marks a dramatic southward thickening of Mississippian successions (Figure 2). To the NW, on the New Brunswick platform, Famennian (363.4 +/- 1.8 Ma; *Tucker et al.,* 1998] volcanic rocks of the Piskehagan Group at the base of the thin succession represent a major explosive volcanic center. They are directly overlain by thin clastic and locally volcanic rocks of the Mabou Group. Elsewhere on the New Brunswick platform, Famennian to Tournaisian rocks are largely absent, although *Durling and Marillier* [1990] interpreted Horton Group in E-W graben, lying offshore between the Magdalen Islands and the Gaspé peninsula (Figure 1b). The Viséan Windsor Group is represented by only a thin unit of calcrete [*Jutras et al.,* 2007]. In striking contrast, SE of the fault, the Cocagne sub-basin (Figure 3c) displays a thick succession of the Famennian to early Tournaisian Horton Group that spans the same time interval as the Piskahegan Group to the north [*Richardson and McGregor,* 1986; *McGregor and McCutcheon,* 1988]. The overlying succession includes thick Sussex Group, overlain by fully marine carbonates and evaporites of the Windsor Group. The contrast between the explosive volcanic rocks of the Piskehagan Group to the north and the contemporary clastic rocks to the south indicates that the regions currently juxtaposed across the fault must have been widely separated in the latest Devonian, requiring substantial latest Devonian to Mississippian strike slip, consistent with our estimate from the Nerepis duplex. Our reconstruction therefore assigns ~160 km of dextral strike slip to the Bellesisle - Kiersted Mountain fault zone.

The unconformably overlying Pennsylvanian Pictou Group continues across the fault, without major facies or thickness change [*St. Peter,* 2006]. However, the basal Pennsylvanian surface is offset along several fault strands indicating minor post-Mississippian motion.

The Belleisle fault continues in the subsurface beneath Prince Edward Island but is increasingly difficult to trace to the NE [*Durling and Marillier,* 1993], suggesting that its displacement is transferred into extensional horst and graben systems beneath the deepest parts of the Maritimes Basin.

5.3 Kennebecasis – Indian Mountain fault zone

The Kennebecasis fault and associated Berry Mills, Smith Creek and North River faults lie SE of, and roughly parallel to the Appalachian trend of the Bellisle fault (Figure 3c). In SW New Brunswick, this fault zone separates the Silurian Kingston belt from older Paleozoic and Neoproterozoic rocks of the Brookville terrane to the SE, interpreted as part of Ganderia [*White and Barr,* 1996; *van Staal et al.,* 2012]. Faults extend NE in the subsurface, although the correlation of individual faults between New Brunswick and PEI is controversial [*Durling and Marillier,* 1990, *St. Peter et al.,* 1990].

Splays of the Kennebecasis fault bound the Indian Mountain deformed zone (Figure 3c) a complex inlier of Mississippian and older rocks defined by *Park and St. Peter* [2009]. Within this zone, contrasting Mississippian successions are juxtaposed across the dextral North River fault (Figure 3b). To the south, minor Horton Group conglomerate overlies Brookville terrane basement, but the Tournaisian succession is almost entirely Sussex Group (Figure 2). To the north, in the Cocagne sub-basin, a thick predominantly lacustrine succession of the Famennian to mid-Tournaisian Horton Group is unconformably overlain by coarse clastic facies of the Sussex Group, with clasts derived from the New Brunswick platform [*Park and St. Peter*, 2009]. The Horton Group to the north does not show basin-margin facies, which would be expected if it were originally deposited adjacent to the rocks that now lie immediately to the south [*Park and St. Peter,* 2009]. Instead, it resembles in facies the Horton Group in the Moncton sub-basin 60-70 km to the SW (red stars in Figure 3c). Hence, we suggest that the Indian Mountain deformed zone of *Park and St. Peter* [2009] records at least 60 km of post-Horton, dextral strike-slip motion.

A cleavage-forming event occurred in both domains prior to deposition of the Sussex Group, attesting to significant intra-Tournaisian deformation [*Park and St. Peter,* 2009]. Deformed Windsor Group evaporites in the Intervale area (Figure 3c) suggest that movement continued into later parts of the Mississippian, but these structures are truncated by an unconformity at the base of the Pennsylvanian. Minor reactivation occurred in the Pennsylvanian, as indicated by offsets of the Mabou and Cumberland groups at the Berry Mills fault, and by the absence of the basal Pennsylvanian Boss Point Formation across the Indian Mountain deformed zone. A northern splay, the SE-dipping Springhill fault (Figure 3c), places Mississippian Sussex Group rocks over Pennsylvanian Pictou Group. Overall, the Indian Mountain deformed zone thus resembles a positive flower structure. Relationships across the zone indicate Pennsylvanian or younger inversion of a major basin-bounding Famennian-Mississippian fault which combined down-to-the-SE dip slip and dextral strike slip.

Splays of the Kennebecasis fault zone extend southeast into the Moncton sub-basin, linking ultimately to the Caledonia - Clover Hill fault zone (see below). They show a complex relationship to the stratigraphy indicating that different splays were active at different times. For example, the thrust-sense Penobsquis fault [*Wilson and White,* 2006; *Wilson et al.,* 2006] cross-cuts all the strata in the region, including the late Pennsylvanian Pictou Group. The Gordon Falls fault splays southward from the Penobsquis fault, but is truncated beneath the Early Pennsylanian Cumberland Group (Boss Point Fm.). Traced SE, it joins the Clover Hill fault as a dextral strike-slip fault [*Park et al.,* 2007]. The Urney complex of faults forms a duplex that dissects the Moncton sub-basin; these faults were active as thrusts after deposition of the Horton Group. Most are truncated unconformably at the base of the Sussex Group; those that cut the Sussex Group are truncated beneath the Windsor Group. It is thus likely that all these faults propagated upward through the sedimentary cover at different times during progressive movement of the major fault zones in the basement.

5.4 Caledonia – Clover Hill fault zone

The Caledonia - Clover Hill fault zone also follows the Appalachian trend, and coincides in New Brunswick with the boundary between Ganderia and Avalonia. In the west, the Clover Hill fault is near-vertical, and shows abundant indications of dextral strike slip [*Park et al.*, 2007]. A major component of this deformation post-dates the Horton Group but precedes the Sussex Group and therefore occurred within the Tournaisian [*Hinds and Park,* 2009]. Approximate restoration of the strike-slip duplex mapped by *Park et al.* [2007] suggests at least 10 km of movement. Major facies contrasts occur across the fault in the Horton Group; fine-grained facies north of the fault at Elgin have correlatives in the Sussex area to the SW, suggesting about 30 km of dextral strike-slip (green stars in Figure 3c). Minor later reactivation is indicated by facies changes and deformation in the Sussex Group.

Farther east, the Caledonia fault zone dips moderately NW and shows evidence in different places of normal, reverse and strike-slip motion [*Park and St. Peter,* 2005, *Park et al.,* 2007, 2010]. It controlled sedimentation in both the Horton and the Sussex groups, and underwent two episodes of thrust-sense inversion, one after Horton Group deposition and one after Sussex Group deposition [*Park et al.,* 2010]. The whole system of faults disappears under unconformably overlying Windsor Group to the NE.

At the eastern extremity of the Caledonia Highlands the subparallel Dorchester fault also controlled Horton Group sedimentation [*St. Peter,* 1993], but was active later. It was reactivated as a reverse fault placing Precambrian basement over Viséan Windsor Group, but shows only minor offset of the overlying Mabou and Cumberland groups.

Traced to the SW along its Appalachian trend, the Clover Hill fault reaches the coast near Saint John (Figure 3b), where several thrust slices place crystalline rocks above Cumberland Group in the footwall. *Park et al*. [2014] showed that these thrust sheets include Devonian bimodal intrusive and extrusive rocks that were mylonitized during the Mississippian, probably during development of an extensional core complex. Although earlier interpretations of the subsequent thrusting suggested mainly northward translation associated with Pennsylvanian transpression on the MFZ [*Rast et al.* 1984; *Plint and van de Poll*, 1984; *Nance,* 1986; *Park et al.,* 1994], more recent work [*Park et al.,* 2014] indicated that thrust slices were rooted in the Clover Hill fault and show a combination of northward and southward transport directions consistent with a positive flower structure. Thrust translations of up to 10 km suggest that the strike-slip component must have been significantly larger. However, along the Clover Hill fault in the Saint John area calcite mylonites display a dip-slip (SE-side down) sense of movement and several minor NE-trending faults cut the thrust sheets with similar sense of movement. These have been attributed to movement associated with Mesozoic extension [*White*, 1995].

5.5 Cumberland and Sackville sub-basins

To the south and east in the Sackville and Cumberland sub-basins, Tournaisian rocks are unexposed. Subsurface data from the Cumberland sub-basin [*Waldron et al.,* 2013] indicate that a 2-3 km section of Viséan - Serpukhovian Windsor Group and overlying Mabou Group was ponded against an extensional fault with Minas trend at the north edge of the Cobequid Highlands (Figure 1c), suggesting that the basin remained extensional, or more likely transtensional, until at least the end of the Mississippian. Following a period of non-deposition around the Mississippian-Pennsylvanian boundary, the tectonic environment changed to transpression in the Pennsylvanian prompting the expulsion of evaporites into salt-cored anticlines, and the extremely rapid subsidence of the western Cumberland basin during the late Bashkirian (about 320 Ma) [*Waldron et al.,* 2013]. Close to this time, thrusting along the Appalachian-trend Harvey-Hopewell fault (Fig. 3c) duplicated the Mabou and Cumberland Groups, consistent with the postulated dextral transpression in the Nova Scotia part of the sub-basin [*St. Peter and Johnson,* 2009]. *Waldron et al.* [2013] suggested that the change from Mississippian transtension to Pennsylvanian transpression reflects a change from Appalachian-trend (dominantly NE-SW) dextral strike slip to Minas-trend (E-W) dextral strike slip. Total amounts of strike-slip motion are unknown, but available seismic profiles suggest 5 - 10 km of overthrusting at the southern margin of the Cumberland sub-basin, and a similar amount in the Sackville sub-basin.

5.6 Minas fault zone

The faults with Minas trend that extend roughly E-W through mainland Nova Scotia (Figure 1c) were collectively termed the Minas fault zone (MFZ) by *Murphy et al.* [2011], who provided a summary of its important episodes of Paleozoic movement. The faults are best exposed in the Cobequid Highlands (Figure 1), which are divided into a northern Jeffers block and a southern Bass River block with different Neoproterozoic histories [*Pe-Piper and Piper,* 2002], though both blocks are assigned to Avalonia. The two are separated by the Minas-trend Rockland Brook fault, and possibly farther west by the similarly oriented Kirkhill fault (Figure 1c).

Murphy et al. [2011] suggested that the early movements on the MFZ occurred during Famennian-Tournaisian eruption of bimodal volcanic rocks (Fountain Lake Group) on the Jeffers block, and the contemporary predominantly lacustrine sedimentary rocks of the Horton Group, preserved on the Bass River block and elsewhere in southern mainland Nova Scotia. The contrast in facies between these coeval units suggests that the two blocks were widely separated at least until the late Tournaisian, after which major dextral motion on the Rockland Brook fault took place [*Miller et al.,* 1995; *Koukovelas et al.,* 1996; *Murphy et al.,* 2011]. The exposed length of the faults separating the two successions is about 150 km, suggesting motion of at least this amount (Figure 4b), at around 345 Ma, to bring the contrasting older successions into the juxtaposition seen at the present-day.

The Cobequid fault along the southern boundary of the Cobequid Highlands (Figure 1c) is another zone of Minas trend strike-slip motion within the broader MFZ. It, and its probable original eastward continuation, the Chedabucto fault (Figure 1c), underwent major dextral movement close to the Mississippian-Pennsylvanian boundary (~323 Ma). Kilometre-wide zones of mylonite and megabreccia imply at least tens of kilometres of strike slip [*Murphy et al.,* 2011]. Moore and *Austin* [1984] suggested ~35 km of post-Viséan offset to account for facies relationships in the Windsor Group, using a model involving a narrow, two-sided Viséan trough. However a broader Windsor basin would imply an offset much larger than this minimum value. None of the major Mississippian and older structures to the north can be traced on the south side of the zone, nor vice versa. We therefore suggest that the cumulative dextral motion on the MFZ must be at least as large as the currently exposed strike-length of the zone, requiring about 150 km of slip on the Cobequid fault, leading to a restored position of the Meguma terrane south or southeast of Cape Breton Island.

Some of this motion was Pennsylvanian or younger. Dextral motion on the MFZ controlled sedimentation in the transtensional Stellarton sub-basin [*Waldron*, 2004] during the late Bashkirian to late Moscovian. Subsequent overprinting by transpressional strain postdated the youngest (Asturian) sediments in the basin. *Waldron* [2004] suggested that the basin originated at a releasing stepover between the Cobequid and Chedabucto faults at the western edge of the Antigonish Highlands (Figure 1), which requires approximately 25 km of Pennsylvanian slip. Motion of this magnitude explains facies contrasts between the basin fill and contemporary strata that now lie adjacent to the north basin margin [*Waldron*, 2004].

Significant motion on the MFZ also occurred during Mesozoic opening of the Atlantic Ocean. *Withjack et al.* [2009] reconstructed Triassic-Jurassic extension associated with the Fundy rift, and suggested that Mesozoic extension accounted for between 10 and 20 km of motion. The direction was approximately SE during the later stages of rifting (though in the early stages a range of directions between SSW and ESE is possible). A restored section constructed by *Withjack et al.* [2009 Figure 5] along an S-trending line trend shows ~20 km of extension.

5.7 Carboniferous faults in the Meguma Terrane

The Meguma terrane is cut by numerous faults, the majority of which show either the Appalachian or Canso trend. ENE-WSW-striking faults bound and cut the Windsor-Kennetcook, Shubenacadie, and Musquodoboit sub-basins (Figure 1c), where *Waldron et al.* [2010] showed that horsts and grabens controlled sedimentation during deposition of the Tournaisian Horton Group and were inverted prior to deposition of the Viséan Windsor Group. These structures were in turn overprinted by the low-angle Kennetcook thrust as a result of transpression along the MFZ at 320 Ma [*Waldron et al.,* 2007]. Farther west, the early Paleozoic shear zones were reactivated in the Carboniferous as transpressional structures at ~320 Ma [*Culshaw and Liesa,* 1997; *Culshaw and Reynolds,* 1997], probably associated with east-west motion on the MFZ.

A second set of faults, striking NW-SE (Canso trend) is best developed in the eastern part of the Meguma terrane. These faults include the Country Harbour fault (Figure 1c), and several others, which offset Neoacadian E-W folds in the Goldenville and Halifax groups, constraining slip as sinistral [*Henderson*, 1986]. In most cases the slip is less than 2 km. *Williams et al.* [1995] suggested a Mesozoic age for these faults, and associated them with the opening of the Atlantic Ocean. However, the geometry of these faults is consistent with a conjugate relationship to the dextral MFZ, which implies a Carboniferous origin.

Faults with the Canso trend also occur in the western part of the Meguma terrane where some appear to offset the Mesozoic Shelburne Dyke and North Mountain Basalt (Figure 1b, 3c) [*White*, 2012a, b, c]. However, in contrast to the eastern Meguma terrane, the majority of offsets are dextral. We suggest that these faults mainly originated as sinistral faults conjugate to the MFZ during the Carboniferous, but that some were reactivated as dextral strike-slip faults when movement on the MFZ reversed during Mesozoic Atlantic opening.

5.8 Antigonish – Cape Breton Island

The Hollow fault, a zone of deformation with Appalachian trend, extends from the eastern Cumberland sub-basin through the Antigonish Highlands (Figure 1c). It has been correlated along the coast of western Cape Breton Island, either offshore [e.g., *Bradley*, 1982] where it parallels the faulted margin of the deepest portion of the Maritimes Basin [e.g., *Dehler and Potter,* 2002], or onshore [*Durling et al.,* 1995b; *Cook et al.,* 2007] where it connects to the Wilkie Brook and Aspy faults in the northern Cape Breton Highlands (Figure 1c). There the Wilkie Brook fault separates Grenvillian rocks of the Blair River Complex, representing Laurentian crust, from younger peri-Gondwanan rocks of the Aspy terrane [*Barr and Raeside,* 1989; *Barr et al.,* 1995, 1998]. The sub-parallel Wilkie Brook and Aspy faults bound a narrow block of basement suggesting a positive flower structure that cuts the Horton, Windsor and Mabou Groups. A similar configuration is postulated for St. Paul Island (*Barr et al.,* 2014).

Murphy et al. [2001] suggested that the Hollow fault zone originated as a Neoproterozoic transform fault cutting Avalonia. Localized conglomerate adjacent to the Hollow fault suggests that it was again active in the Serpukhovian [*Chandler et al.,* 1998]; traced SW it bounds the Stellarton pull-apart sub-basin of Bashkirian-Moscovian age [*Waldron,* 2004], indicating Pennsylvanian motion.

Some authors [e.g., *Bradley,* 1982; *Hibbard and Waldron,* 2009; *Hayward et al.*, 2014] have suggested major dextral strike-slip motion along the Hollow fault, noting its parallel alignment to other Appalachian trend faults. Others, noting the large vertical offsets of basement along the fault, and the rapid offshore thickening of the Windsor Group [*Keppie et al.*, 1978; *Giles*, 2004], have emphasized normal faulting [e.g., *McCutcheon and Robinson,* 1987; *Dehler and Potter,* 2002; *Cook et al.,* 2007; *Barr et al.,* 2014]. Post-Viséan thrust faults have also been interpreted at depth in St. Georges Bay and west of Cape Breton Island [*Durling and Marillier,* 1993; *Durling et al.,* 1995a; *Hayward et al.,* 2014], suggesting that shortening may also have played a role in the later history of this boundary.

Several observations appear to place limits on the amount of late Paleozoic strike-slip along the Hollow fault and related fault strands. Broadly correlative Silurian successions occur on both sides of the fault in the Antigonish Highlands [*Boucot et al.,* 1974], limiting post-Silurian movement to a few tens of kilometres. A conspicuous magnetic anomaly associated with the Mabou Highlands of western Cape Breton Island (Figure 1c) extends offshore without strike-slip offset at least 12 km, and aligns with other sources interpreted as major plutons by *Cook et al.* [2007]. Farther north, *Dehler and Potter* [2002] correlated a prominent offshore magnetic anomaly with that associated with the onshore Blair River inlier. However, a weakly magnetic zone passes between the northern Blair River inlier and the offshore anomalies correlated with it by *Dehler and Potter* [2002]; this zone may accommodate significant strike slip. Inland, the Aspy fault appears to show less than 10 km of displacement since the Late Devonian, based on offset of the ~365 Ma Margaree Pluton, although the age of that pluton is not well constrained.Southeast of the Hollow fault, the Antigonish Highlands are overlain by the Carboniferous Antigonish sub-basin, which shows a tripartite division along the Morristown and Glenroy faults (Figure 1c). Between these two faults, thick Windsor and Mabou groups rest directly on Avalonian basement. Outside this central zone, basement rocks are overlain by thick sections of Tournaisian Horton Group. This distribution of outcrops implies inversion of two Horton Group grabens that flanked a central horst. During Viséan inversion this horst subsided, accommodating the thick Windsor and Mabou successions between the Morristown and Glenroy faults.

Similar contrasts in Early Carboniferous stratigraphy occur throughout Cape Breton Island. Areas with thick Tournaisian clastic rocks alternate with areas where Windsor Group rocks directly overlie basement. *Durling et al.* [1995b] correlated the Antigonish and Mabou sub-basins beneath St. Georges Bay, suggesting a sinistral offset of about 20 km, distributed over a broad zone with Canso trend. However, the earlier offset of Appalachian terranes across the Canso fault [*McCutcheon and Robinson,* 1987; *Barr and Raeside,* 1989; *Stockmal et al.*, 1990] appears to be dextral, and much larger (up to 250 km, according to *Stockmal et al*. [1990]).

5.9 Cabot Strait and Newfoundland

Using geophysical data, *Langdon and Hall* [1994] traced the Hollow fault across the Cabot Strait, showing it offset by numerous small E-W faults with Minas trend. More prominent Appalachian trend lineaments, which they correlated with the Cabot fault, lie to the SE, connecting with the Wilkie Brook and Aspy faults on-land, and appear less disrupted (Figure 1c). Based on magnetic and gravity modeling, *Barr et al.* (2014) also interpreted that the Wilkie Brook and Aspy faults merge in the Cabot Strait with the offshore extension of the merged Cabot and Cape Ray faults, the latter marking the Laurentian-peri-Gondwanan boundary onshore in Newfoundland.

Evidence is abundant for dextral strike-slip motion on the Cabot fault zone in Newfoundland, including en-echelon folds and faults in the Tournaisian Anguille Group in the Bay St. George sub-basin (Figure 1c) [*Knight*, 1983], and the pull-apart basin history of the Deer Lake sub-basin [*Hyde*, 1988].

Farther north and east in Newfoundland, additional mid-Paleozoic faults with Appalachian trend are abundant, although late Paleozoic stratified units are rare. A swarm of east-west dykes, known from mapping and aeromagnetic data, shows dextral offsets along major faults in the area of the Red Indian Line in central Newfoundland (Figure 1b) [*Oneschuk et al.,* 2001, 2002]. On the Bay Verte Peninsula, older metamorphic rocks at Ming's Bight were rapidly exhumed between 388 and 362 Ma [*Anderson et al.*, 2001] defining a structure that resembles core complex formed at a releasing bend on dextral Appalachian trend faults associated with the Baie Verte Lineament (Figure 1b).

6 Kinematic history of the Maritimes Basin

6.1 Appalachian trend

The history of long-lived Appalachian trend faults in Figures 1 and 3, when viewed at large scale, is consistent with the evolution of a broad zone of transtension at a releasing stepover in a dextral strike-slip system as envisaged by *Hibbard and Waldron* [2009]. Major Appalachian trend faults in SE New Brunswick, including the Belleisle - Kierstead Mountain and Kennebecasis - Berry Mills fault zones, clearly underwent many tens of kilometres of dextral strike slip. Traced NE, however, these faults do not offset intact Laurentian crust of the Canadian Shield. Displacement must therefore have been transferred into extensional or transtensional faults that underlie the Maritimes Basin as shown in Figure 5a.

In contrast, displacement along the Hollow fault zone and its continuation in the Cabot fault of Newfoundland appears to have increased toward the NE. At the south end of the Hollow fault, the slip is constrained to be small by similar Silurian facies on either side of the fault, whereas structures adjacent to the Cabot fault in the Bay St. George and Deer Lake sub-basins of Newfoundland indicate major strike-slip. We therefore suggest that Mississippian displacement was transferred between the Belleisle and Cabot fault zones through a broad zone of transtension (Figure 5b).

Comparable systems have been described elsewhere in the world, notably in the Bohai Basin of NE China [e.g., *Allen et al.*, 1998]. At a smaller scale, similar systems have been described also in parts of Atlantic Canada, where *Waldron* [2005] analysed their kinematics. The bounding faults of the system, as shown in Figure 5b, do not have constant displacement. Displacement is transferred between the two via a combination of extension and rotation of intervening fault-bounded blocks (Figure 5b). Some Minas-trend faults may have originated as extensional features in this zone. During continued transtension, progressive rotation of extensional fault blocks is predicted eventually to bring normal faults into the shortening field, and thus may have led to basin inversion [*Waldron*, 2005].

6.2 Minas and Canso trends

During later stages of Maritimes Basin history, after 350 Ma (approximately the Tournaisian-Viséan boundary), the simple kinematic picture of Figure 5a and b was increasingly disrupted by motion on Minas-trend faults leading to westward translation of the Meguma terrane (Figure 5c). Presumably this was due to Laurentia-Gondwana convergence that eventually gave rise to the Alleghanian orogeny in the southern Appalachians. This process almost certainly contributed to the inversion of earlier extensional basins, even without requiring rotation of fault blocks as envisaged above. It probably accounts for wholesale uplift of the southeastern parts of the Maritimes Basin in the latest Tournaisian, resulting in an unconformity between the Horton and Windsor groups in Nova Scotia, where the Sussex Group and correlative rocks of the *Colatisporites decorsu - Schofites claviger* spore zone are absent [*Utting and Giles,* 2004; *St. Peter and Johnson,* 2009]).

West-directed thrust structures noted at depth beneath St. Georges Bay and the central Maritimes Basin by *Durling and Marillier* [1993], *Durling et al.* [1995a], and *Hayward et al.*

[2014] are kinematically consistent with inferred dextral strike-slip along the MFZ close to the Mississippian-Pennsylvanian boundary (Figure 5c), and may have emplaced Cape Breton Island westward by several kilometres, obscuring the original Mississippian trace of the Hollow fault. Subsequent dextral movement along this long-lived and deep-rooted strike-slip zone may have reconnected to the surface through the upper crust of Cape Breton Island along the trace of the Aspy fault and parallel faults, in part exploiting a former terrane boundary represented by the Wilkie Brook fault, and accounting for perhaps 20 km of Pennsylvanian dextral strike-slip. faults with Canso trend are explained as conjugate sinistral faults, consistent with their observed offsets in the eastern Meguma terrane.

Minas-trend faults were re-activated in the Mesozoic during sinistral transtension associated with the opening of the Atlantic Ocean. Figure 5d illustrates the kinematics of this event, which led to the opening of the transtensional Fundy Graben during inversion of Paleozoic transpressional faults.

7 Palinspastic restoration

Figures 6 and 7 show successive stages in a postulated palinspastic restoration of Atlantic Canada and adjacent areas from the present day (Figure 1b) to its inferred configuration at ~370 Ma, in the Late Devonian. Because of the inherent uncertainties in many of the distances and distortions of units, we have used simple "flat Earth" translations and rotations of projected map units to achieve these reconstructions, and we have rounded translations to the nearest 10 km; a more involved procedure involving Euler rotations on a spheroid is not justified by the limited precision of the available data.

In Figure 6a we remove the effect of Mesozoic deformation associated with the opening of the Atlantic Ocean in the Bay of Fundy region. We have estimated 20 km of N-S extension, based on *Withjack et al.* [2009, their Figure 5], and assume that slip was to the ESE, consistent with their measured extension directions, resulting in a net slip of ~50 km. To close the Hartford Basin in New England we restore ~5 km of extension, in the same direction, based on the cross sections of Schlische [1993].

In Figure 6b we restore deformation that occurred during the Moscovian - Permian interval. Basin formation that is demonstrably attributable to fault motion is concentrated in the Stellarton sub-basin of Nova Scotia, and the Saint John area of southern New Brunswick. *Waldron* [2004] suggested that about 25 km of dextral strike slip along the Cobequid and Hollow faults could account for both the position and subsidence of the Stellarton sub-basin. A similar amount of dextral strike slip, transmitted into the restraining bend in coastal New Brunswick, could account for the observed thrusting. In addition, we restore a small, though poorly constrained, amount of post-Pennsylvanian dextral strike-slip on the Fredericton-Norumbega fault zone, estimated at 10 km. We suggest that most of this motion was carried through Newfoundland on the Cabot fault zone, accounting for localized Pennsylvanian subsidence in the Deer Lake pull-apart sub-basin, and on the Green Bay fault, where *Upadhyay et al.* [1971] and *Marten* [1971] interpreted ~25 km of right-lateral slip based on offset of a syncline in Ordovician rocks. This motion may also have led to extension and subsidence in the Sydney sub-basin between Nova Scotia and Newfoundland, providing accommodation for Pennsylvanian coal deposits in and offshore of Cape Breton Island.

In southern New England, major shortening affected the Narragansett basin and surrounding areas during intense late Pennsylvanian to Permian Alleghanian deformation and metamorphism [e.g., *Walsh et al.,* 2007]; maps and cross-sections by *Wintsch et al.* [2014] imply a total of ~80 km of thrusting along the boundary, though this is spread over the period 340 - 280 Ma. We represent a portion of this this deformation in Figure 6b by restoring a conservative 33% internal shortening of the Narragansett Basin and the rest of Avalonia in southern New England, and ~30 km of thrusting along its western boundary. Prior to this shortening, an episode of dextral strike-slip motion in the late Pennsylvanian led to opening of the Narragansett Basin at a releasing stepover [*Thompson and Hermes,* 2003]. We represent this motion with an amount of slip similar to that on the Fredericton-Norumbega fault zone.

In Figure 6c we restore an extensive and major deformation associated with dextral movement on the MFZ around the Mississippian - Pennsylvanian boundary (~323 Ma). The included deformation ranges from Serpukhovian to Bashkirian, and is most intense in the vicinity of the MFZ [*MacInnes and White,* 2004; *Murphy et al.,* 2011], which must have undergone at least tens and possibly hundreds of kilometres of dextral strike slip. The westernmost Meguma terrane also underwent deformation at this time [*Culshaw and Leisa, 1997*; *Culshaw and Reynolds,* 1997], consistent with significant east-west shortening. Our reconstruction assigns ~150 km of strike-slip motion to this interval, undoing the effects of Mesozoic deformation and placing the Meguma terrane ~100 km east of its present day location. Slip of this order of magnitude is suggested by the width and intensity of the deformed zone along the Cobequid fault [*McInnes and White,* 2004], and effectively separates the Meguma terrane from rocks with strongly contrasting pre-Pennsylvanian structural styles and magmatic histories that currently lie to the north. *Wintsch et al.* [2014] postulate additional thrusting along the western margin of Avalonia in southern New England at ~315 Ma; we restore a further 25 km of thrusting in Fig 6c. We predict a significant region of mid-Carboniferous shortening, or possibly subduction of remnants of trapped Rheic Ocean lithosphere, beneath the Gulf of Maine (Fig 1b); however, this area may instead have been occupied by crust that was already highly extended by Devonian-Mississippian transtension.

At the same time, minor movements (estimated at ~20 km total) occurred along the Country Harbour and related faults in the Meguma terrane. The similarly oriented Strait of Canso fault north of the MFZ offsets the Tournaisian to Serpukhovian successions of the Antigonish sub-basin and southwestern Cape Breton Island. The suggested displacement (20 km) is sufficient to restore this alignment. This motion could account for the tectonic wedging and other indications of shortening interpreted in seismic data west of Cape Breton Island and in St. George's Bay [*Durling et al.,* 1995a, *Hayward et al.,* 2014].

In Figure 7a we restore deformation at ~350-345 Ma, associated with major basin inversion in both southern and northern mainland Nova Scotia, and in Cape Breton Island, that is recorded at the unconformity between the Horton and Windsor groups. This was also approximately the time of movement along the Rockland Brook fault [*Piper and Pe-Piper,* 2001], which separates contrasting volcanic and sedimentary facies of Famennian-Tournaisian age, a contrast that extends almost the entire length of the Highlands, or about 150 km. This distance is therefore used as the minimum displacement on the Rockland Brook fault. The Guysborough block fabric development due to east-west shortening, and metamorphism at this time [*Reynolds et al.,* 2004], interpreted to represent the development of a positive flower structure on the MFZ; we have restored about 50 km of strike-slip motion in placing this block immediately south of Cape Breton Island. In southern New England we have restored a further 25 km of thrusting along the west edge of Avalonia, sufficient to explain the geometry of the boundary and the timing relationships deduced by *Wintsch et al.* [2014].

Other movements occurring at this time include Appalachian-trend motion on the Kennebecasis fault zone of New Brunswick, estimated at 60 km based on contrasting Tournaisian successions, now juxtaposed, in the Indian Mountain inlier (Figure 3b). Additional movement, estimated at 30 km, occurred at this time on the Caledonia fault, where deformation structures affect the adjacent Sussex Group of late Tournaisian age. Motion on all these Appalachian-trend faults, active at 350-345 Ma, was probably transferred eastward through a broad zone of transtension into offshore portions of the Hollow fault – Cabot fault zone, and thence through Newfoundland on the Cabot fault, leading to deformation and subsidence in the Deer Lake sub-basin.

Figure 7b shows the effect of restoration applied to remaining Appalachian-trend faults that may have been active in the Famennian to Tournaisian interval, including the Hollow fault of mainland Nova Scotia and its possible offshore continuation, and the Bellisle fault of New Brunswick. These faults together are inferred to account for over half of the ~250 km of strike slip postulated by *Hibbard and Waldron* [2009]. In many cases evidence is insufficient to pin down the time of movement between ~370 Ma and the start of Windsor Group deposition at ~340 Ma so some of these faults may have been active at the same time as those restored in Figure 7a.

The largest of these fault zones, judging by stratigraphic contrasts, is the Belleisle fault, separating the New Brunswick platform from the Cocagne sub-basin to the SE. In Figure 7b we assign to this zone approximately 160 km of dextral strike slip, consistent with our inferences from the Nerepis duplex. We infer that the Bellisle fault connects to a more east-west boundary within a broad zone of transtension beneath PEI, possibly following the northern edge of the Silurian Kingston terrane [*Cook et al.,* 2007], and thence connects with the Cabot fault in

Newfoundland. Additional slip may be accommodated within Cape Breton Island as shown in Figure 7b. The volcanic belt of the Fisset Brook Formation (375-370 Ma; *Barr et al.,* 1995a; *Barr and Peterson,* 1998; *Dunning et al.,* 2002] shows a dextral offset, which we use as the basis for our restoration of an additional ~20 km of early motion on the Aspy fault. Additional subsidence also occurred in eastern Cape Breton Island, and in the Sydney sub-basin, between Cape Breton Island and Newfoundland. We have accommodated a portion (20 km) of the total strike slip through this region, representing it by strike-slip along the Mira-Bras d'Or boundary (Georges River fault) in Cape Breton Island (though we recognize it was probably distributed over multiple faults.)

In Newfoundland, much of the displacement at this time was probably accommodated in the Baie Verte Peninsula, producing the core complex at Ming's Bight postulated by *Anderson et al.* [2001] and accounting for some of the offset along the Green Bay fault interpreted by *Marten* [1971] and *Upadyay et al.* [1971]. Some of this deformation was possibly also transferred on multiple faults including the Red Indian Line within central Newfoundland, associated with east-west dikes recorded in aeromagnetic maps [*Oneschuck et al.,* 2001, 2002] and interpreted by *van Staal and Zagorevski* [2012].

8 Discussion: Appalachian paleogeography

The restored Late Devonian map (Figure 7c) presents a picture of the distribution of northern Appalachian terranes at the end of the Neoacadian orogeny, and simplifies a number of complexities that appear enigmatic on the present-day map. For example, rocks of the Nashoba terrane (Figure 1b), assigned to Ganderia in southern New England, are brought into juxtaposition with correlative rocks of the Ellsworth terrane (Figure 1b) in NE Maine. In the Canso Strait region, the offset of Appalachian terranes along the Canso fault is aligned with the southern edge of the St. Lawrence Promontory where it can be explained as a simple consequence of terrane accretion against a non-linear continental margin. In Newfoundland and NW Cape Breton Island, Grenvillian rocks (~1.0-1.2 Ga) of Laurentian affinity are juxtaposed without the need for special pleading to explain the outlying position of the Blair River inlier in northwestern Cape Breton Island.

The terranes characterized as Avalonia become organized into two belts, both offset by the Canso fault: an inboard zone, comprising the Avalon terrane of Newfoundland, the Mira terrane of southeastern Cape Breton Island, and the Caledonia Highlands of southern New Brunswick, and an outboard zone, containing the Antigonish and Cobequid Highlands of Nova Scotia and the Avalonian rocks of SE New England. The outboard zone has in common abundant 610-590 plutons mainly absent in the inboard zone; its northern portions also show a Silurian cover succession [*Barr and White,* 1996; *Barr et al.,* 1998; *Thompson et al.,* 2010, 2012]. The outboard zone may well extend east of Newfoundland onto the Grand Banks, where Silurian successions have also been recognized [*King et al.,* 1986; *Durling et al.,* 1987].

The Late Devonian palinspastic reconstruction is remarkably similar to one proposed by *Webb* [1969], based on a much more sparse stratigraphic and geochronologic data set. Our reconstruction was built independently, and we did not become aware of the details of *Webb's* [1969] work until late in the writing of this paper. Webb's reconstruction generated controversy at the time [*Brown et al.,* 1969; *Lock and Webb,* 1969] and was not widely accepted. However, Webb's foresight was remarkable.

Kinematic syntheses of the early Paleozoic evolution of the Appalachians are typically based on present-day maps that do not restore the effects of late Paleozoic strike-slip faults [e.g., *Bird and Dewey,* 1970; *Williams*, 1980; *van Staal*, 1998; *Valverde Vaquero et al.,* 2006].

Diagrammatic cross-sections in these syntheses typically combine segments that may have been substantially offset in the Devonian. Late Paleozoic displacements have important implications for the early Paleozoic relationship between the Meguma terrane and Avalonia, the geometry of Ganderia, and for Alleghanian deformation farther south in the Appalachian orogen. We suggest that the map shown in Figure 7c is a better starting point for the reconstruction of the Cambrian-Devonian evolution of the northern Appalachians.

9 Conclusions

The northern Appalachians of Atlantic Canada and adjoining areas were dissected by strike-slip faults, mainly dextral, during the Late Paleozoic. Together, these faults account for ~250 km of strike-slip motion and define a large transtensional zone formed at a releasing stepover. Three main fault trends are recognizable: the *Appalachian trend* displays NE-SW strike; the *Minas trend* is defined by roughly E-W strike; and faults of the *Canso trend* display NW-SE strike.

Strike-slip faults of the Appalachian trend were active in the Famennian to Tournaisian, while some Minas trend faults may have originated as extensional structures during this time. Coincident bimodal volcanic activity occurred along a belt extending from southern New Brunswick to Cape Breton Island.

Starting at ~350 Ma, continuing to the end of the Bashkirian around ~315 Ma, major dextral movement occurred on the E-W MFZ, bringing the Meguma terrane of southern Nova Scotia close to its present position from a starting point far to the east. Faults of the Canso trend formed as conjugate sinistral shears related to the main dextral motion of the MFZ. Minor dextral motion occurred on both the Appalachian and Minas trends for the remainder of the Carboniferous Period.

The MFZ was reactivated as a sinistral extensional fault in the Mesozoic, during opening of the Atlantic Ocean. Some faults of the Canso trend were reactivated with dextral motion at this time.

Sequential removal of these estimated movements allows construction of an approximate restored configuration of Atlantic Canada to the geometry that it had at the start of the Famennian ~370 Ma. In this restoration, Ganderian rocks of southern New England, northern Maine, and southern New Brunswick are brought into contiguous positions, as are inliers of Laurentian rock in Cape Breton Island and Newfoundland. This kinematic model can account for the overall subsidence of the Maritimes Basin, the juxtaposition of contrasting rocks of the same age across major faults, the inversion of early normal faults, and the distribution of a significant unconformity in the Late Tournaisian. It considerably simplifies the geometry of the early Paleozoic Appalachians of Atlantic Canada and adjoining areas. This reconstruction provides a better starting point than the present-day map for reconstructions of the early Paleozoic northern Appalachian Orogen.

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Figure captions

Figure 1. **(a)** Location of the northern Appalachian orogen within North America. **(b)** Map showing present-day distribution of terranes, other divisions, major rock units and major fault traces (red) in the northern Appalachian orogen, after regional compilations by van Staal et al. [1998] and Hibbard et al. [2006, 2007] incorporating data from Canadian provincial government survey maps [e.g., Colman-Sadd et al., 1990; Keppie, 2000; New Brunswick Department of Natural Resources and Energy, 2000]. **(c)** Enlarged view of the central part of Figure 1b showing detail in the Maritimes Basin. Legend shows stratigraphic subdivisions of Maritimes Basin fill; other colours as (b). Fault traces after Durling and Marillier [1990, 1993], Durling et al. [1995b], Langdon and Hall [1994], Pascucci et al [2000], Pe-Piper et al., [2004], and Hayward et al. [2014]. Major sub-basins of the Maritimes Basin are after Gibling et al. [2009]. Depth-to-basement contours are after Marillier and Verhoef [1989].

Terranes and massifs (boldface): **AH,** Antigonish Highlands; **AsT,** Aspy terrane; **BRI**, Blair River inlier; **BdT**, Bras d'Or terrane; **BvT**, Brookville Terrane; **CaT**, Caledonia terrane; **CoH**, Cobequid Highlands; **EwT**, Ellsworth terrane; **GyB**, Guysborough block; **IHI**, Indian Head inlier; **KnB**, Kingston belt; **MH,** Mabou Highlands; **MiT**, Mira terrane; **NaT**, Nashoba terrane; **SMI**, Steel Mountain inlier;

Carboniferous sub-basins (*lowercase italic*): *an*, Antigonish; *bsg*, Bay St. George; *co*, Cocagne; *cu,* Cumberland; *dl*, Deer Lake; *ma*, Magdalen; *mo,* Moncton; *mu*, Musquodoboit; *nbp*, New Brunswick platform; *sa*, Sackville; *sh,* Shubenacadie; *sm*, St. Marys; *st*, Stellarton; *sy*, Sydney*; wk*, Windsor-Kennetcook.

Fault and other abbreviations (plain text): AF, Aspy fault; BIF, Belleisle fault; BVL, Baie Verte Line; CbF, Cabot fault; CCHF, Caledonia - Clover Hill fault; CHF, Country Harbour fault; CnF, Canso fault; CoF, Cobequid fault; CdF, Chedabucto fault; CPSZ, Chebogue Point shear zone; DHBF, Dover - Hermitage Bay fault; EHSZ, Eastern Highlands shear zone; FF, Fredericton fault; GF, Glenroy fault; GBF, Green Bay fault; GRF, Georges River fault; HF, Hollow fault; Is., Island; KF, Kennebecasis fault; KhF, Kirkhill fault; MF, Morristown fault; MFZ, Minas fault zone; NFS, Norumbega fault system; PF, Percé fault; RBF, Rockland Brook fault; RIL, Red Indian Line; SCF, Spicers Cove fault; SD, Shelburne Dyke; WBF, Wilkie Brook fault.

Figure 2. Diagram showing the main group-level stratified units in the Maritimes Basin, and selected formations, compiled from regional compilations by *Knight* [1983], *Fyffe and Barr* [1986], *Ryan et al.* [1991], *Dunning et al.* [2002], *Gibling et al.* [2009], and *St. Peter and Johnson* [2009]. Additional information from *Keppie et al.* [1978], *Richardson and McGregor* [1986], *McGregor and McCutcheon* [1988], *Barr et al.* [1994], *Utting and Giles* [2004, 2008],

von Bitter et al. [2006], *Jutras et al.* [2007], *Giles* [2009], and *Utting et al.* [2010]; unpublished isotopic age of Cumberland Hill Formation is from New Brunswick Department of Natural Resources bedrock lexicon (accessed 2014 February 26 at http://dnr-mrn.gnb.ca/Lexicon/). Timescales are from *Becker et al.* [2012], *Davidov et al.* [2012], and *Richards* [2013]. Abbreviation: Gp. = Group. Lithostratigraphic names without designation are formation-level units.

Figure 3. (a) Simplified map of major fault systems in Atlantic Canada. Major groups of faults distinguished by strike are distinguished by color. Fault abbreviations as Figure 1. (b) Detailed map of principal faults in southern New Brunswick. For location, see Figure 3a. Abbreviation: F. = Fault

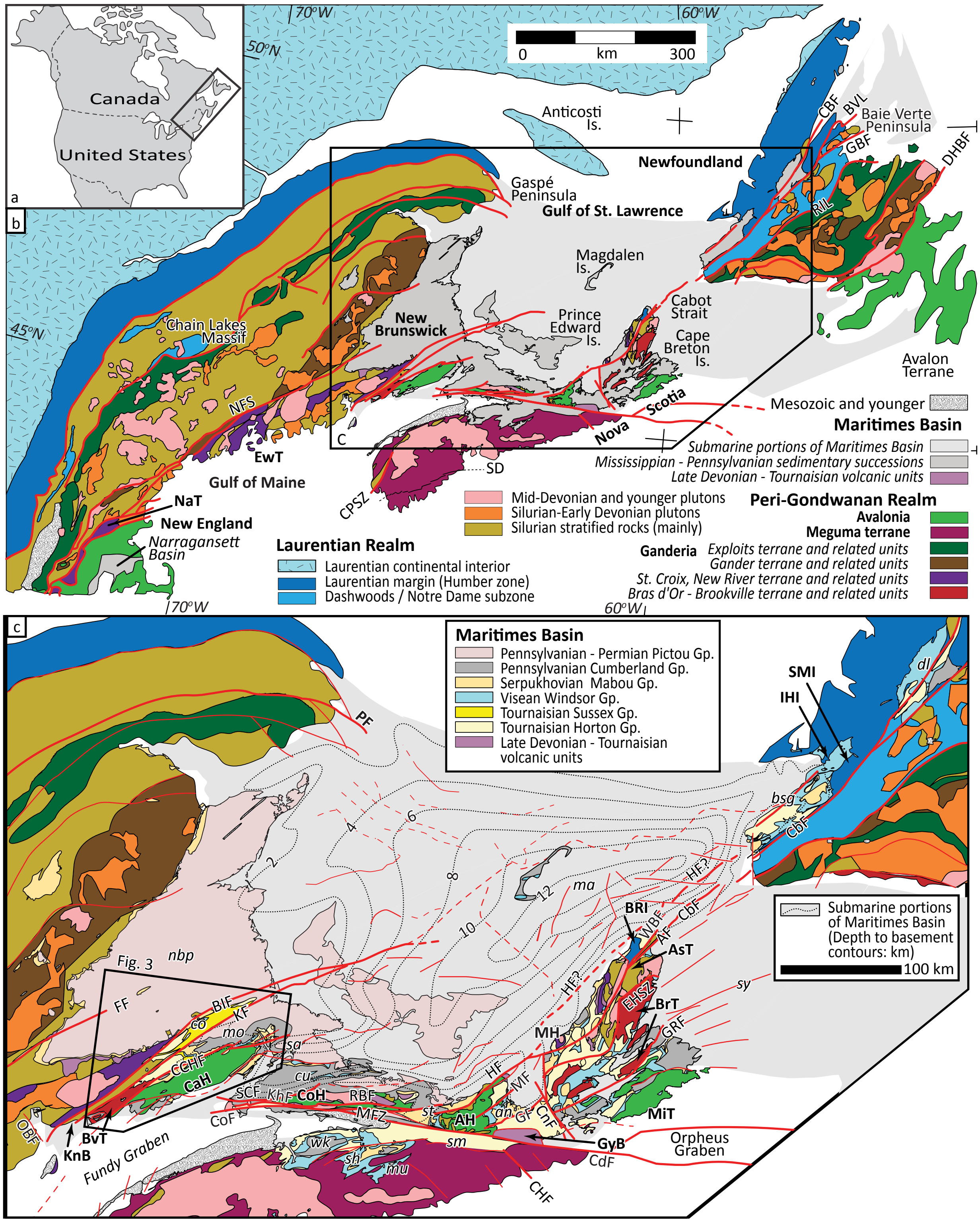
Figure 4. Diagrams to show criteria used to constrain minimum fault slip. (a) Offset facies belts directly constraining strike slip *s*. (b) Contrasting facies across fault (e.g., explosive volcanic rocks and fine lacustrine shale) must be separated by at least *s* in restored configuration. (c) Schematic plan view of a contractional strike-slip duplex, based on Woodcock and Fisher [1986], showing relationship between area *A*, width *w*, number *n* of horses, and mimimum total slip *s*, assuming plane strain area balancing. (d) Sinuous thrust fault trace with fenster, limiting minimum value of heave (and hence slip) to *s*.

Figure 5. Cartoon showing simplified kinematic history of Maritimes Basin region. Ticked lines represent extensional faults; toothed lines represent thrust faults; shear arrows represent strike-slip faults. **(a)** Middle Devonian configuration showing initiation of broad zone of dextral transtension. **(b)** Highly simplified configuration (actual number of fault blocks was much greater) after transtension; fault blocks have subsided and rotated clockwise. **(c)** Mississippian to

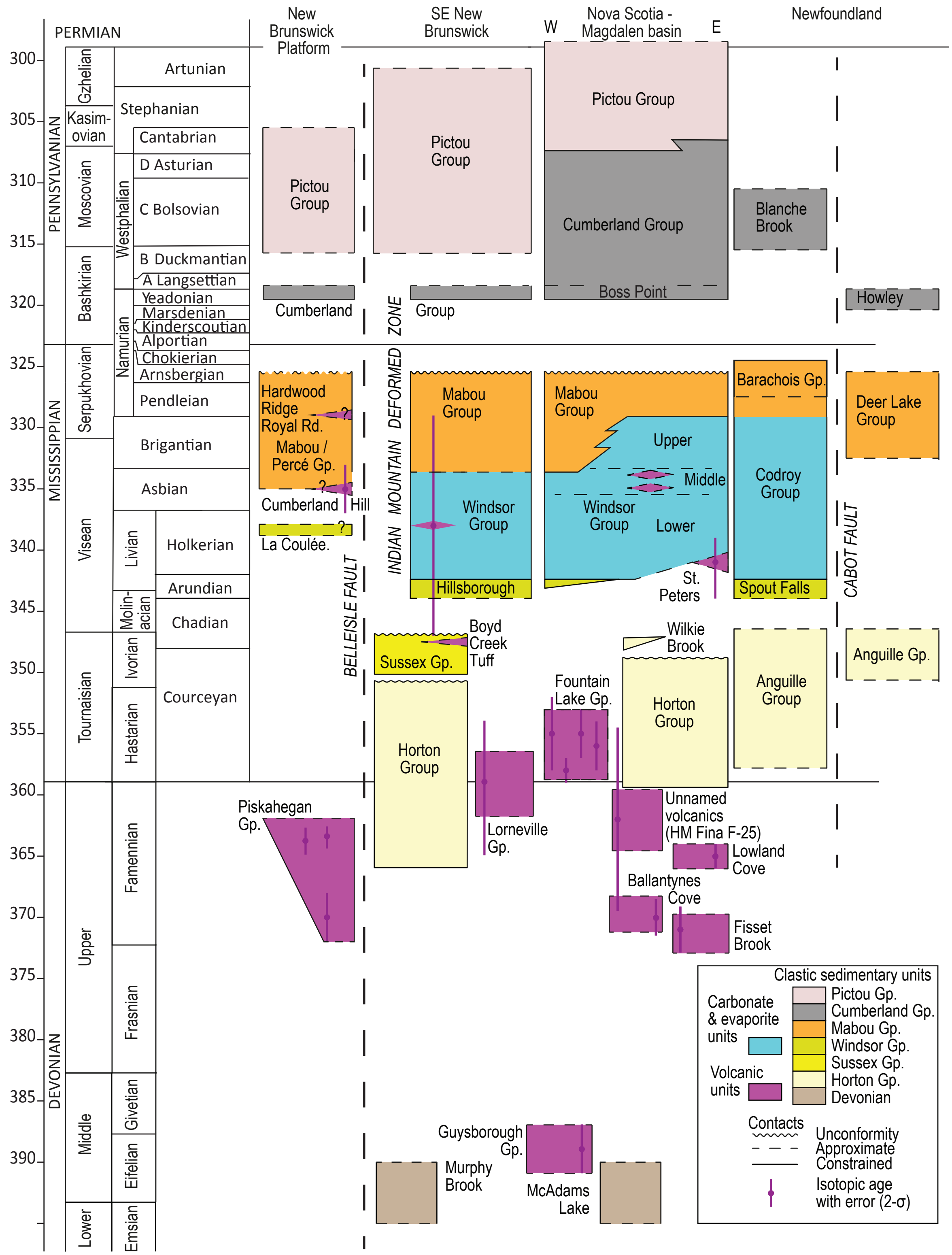
Pennsylvanian westward motion of Meguma terrane on Minas trend faults imposing dextral transpression. **(d)** Mesozoic motion associated with opening of Atlantic Ocean.

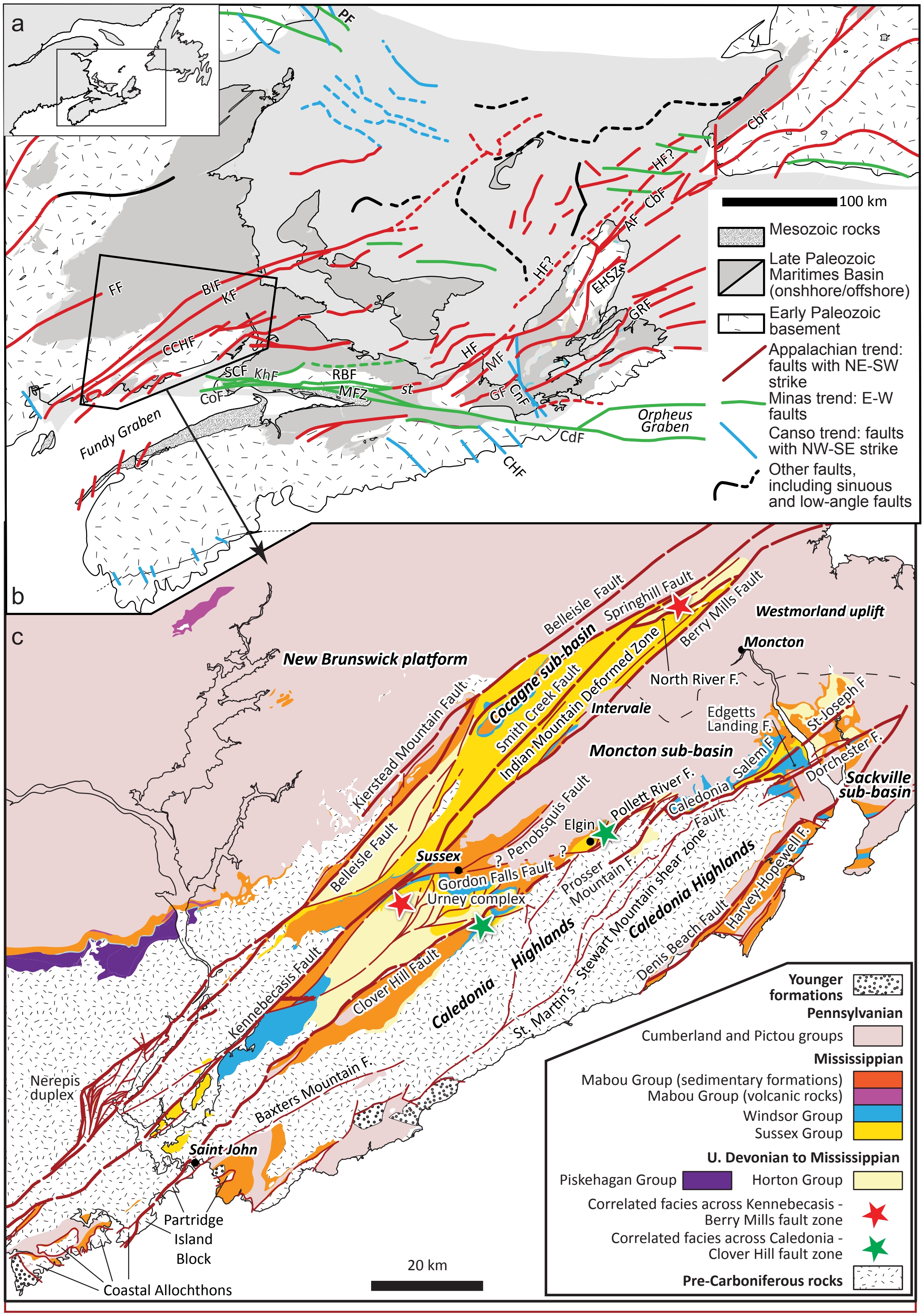
Figure 6. Palinspastic reconstructions of the Northern Appalachians from 330 Ma to the end of the Paleozoic Era. Red arrows show inferred motions relative to continental Laurentia. Black arrows, where shown, indicate relative motions at terrane boundaries. All arrows show motions that have been restored in producing the map, and which therefore post-date the designated time. (See text for details.) **(a)** End Paleozoic (~250 Ma) map, based on Figure 1b but with inferred Mesozoic motion restored. **(b)** Map with Pennsylvanian-Permian and younger deformation removed, showing the configuration at approximately the end of the Bashkirian (~315 Ma). **(c)** Map at ~330 Ma, prior to substantial movement along the Cobequid and Chedabucto faults in the Minas fault zone.

Figure 7. Palinspastic reconstructions of the Northern Appalachians in the Mississippian and Devonian. Arrows as Figure 6. **(a)** Map for the late Tournaisian, ~ 350 Ma, based on Figure 6c with deformation around the Tournaisian-Viseán boundary restored. **(b)** Early Famennian (~ 370 Ma) reconstruction, with known displacements along Famennian-Tournaisian faults restored. **(c)** Map based on (b) showing inferred geometry of Appalachian zones and terranes assembled prior to the Late Devonian.

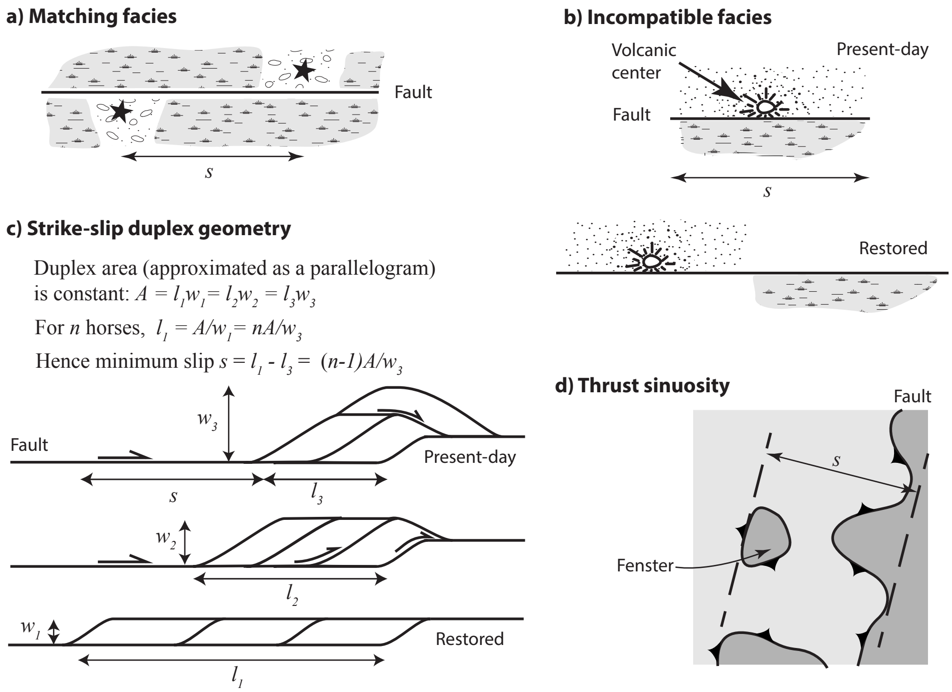


a
Canada
United States
b
70°W
60°W
50°N
45°N
0 km 300
Anticosti Is.
Newfoundland
Baie Verte Peninsula
CBF
BVL
GBF
DHBF
RIL
Gaspé Peninsula
Gulf of St. Lawrence
Magdalen Is.
Cabot Strait
Prince Edward Is.
Cape Breton Is.
New Brunswick
Chain Lakes Massif
NFS
Nova Scotia
Avalon Terrane
EwT
Gulf of Maine
NaT
New England
Narragansett Basin
CPSZ
SD
C
Mesozoic and younger
Maritimes Basin
Submarine portions of Maritimes Basin
Mississippian - Pennsylvanian sedimentary successions
Late Devonian - Tournaisian volcanic units
Mid-Devonian and younger plutons
Silurian-Early Devonian plutons
Silurian stratified rocks (mainly)
Peri-Gondwanan Realm
Avalonia
Meguma terrane
Ganderia
Exploits terrane and related units
Gander terrane and related units
St. Croix, New River terrane and related units
Bras d'Or - Brookville terrane and related units
Laurentian Realm
Laurentian continental interior
Laurentian margin (Humber zone)
Dashwoods / Notre Dame subzone
c
Maritimes Basin
Pennsylvanian - Permian Pictou Gp.
Pennsylvanian Cumberland Gp.
Serpukhovian Mabou Gp.
Visean Windsor Gp.
Tournaisian Sussex Gp.
Tournaisian Horton Gp.
Late Devonian - Tournaisian volcanic units
PF
SMI
IHI
dl
bsg
CbF
HF?
ma
BRI
WBF
AF
CbF
AsT
sy
EHSZ
BrT
GRF
MH
Submarine portions of Maritimes Basin (Depth to basement contours: km)
100 km
2
4
6
8
10
12
Fig. 3
nbp
FF
BIF
KF
co
mo
sa
CCHF
CaH
cu
SCF
KhF
CoH
RBF
MFZ
st
AH
an
GF
CnF
MF
HF
HF?
MiT
GyB
Orpheus Graben
CdF
sm
wk
sh
mu
CHF
CoF
OBF
KnB
BvT
Fundy Graben

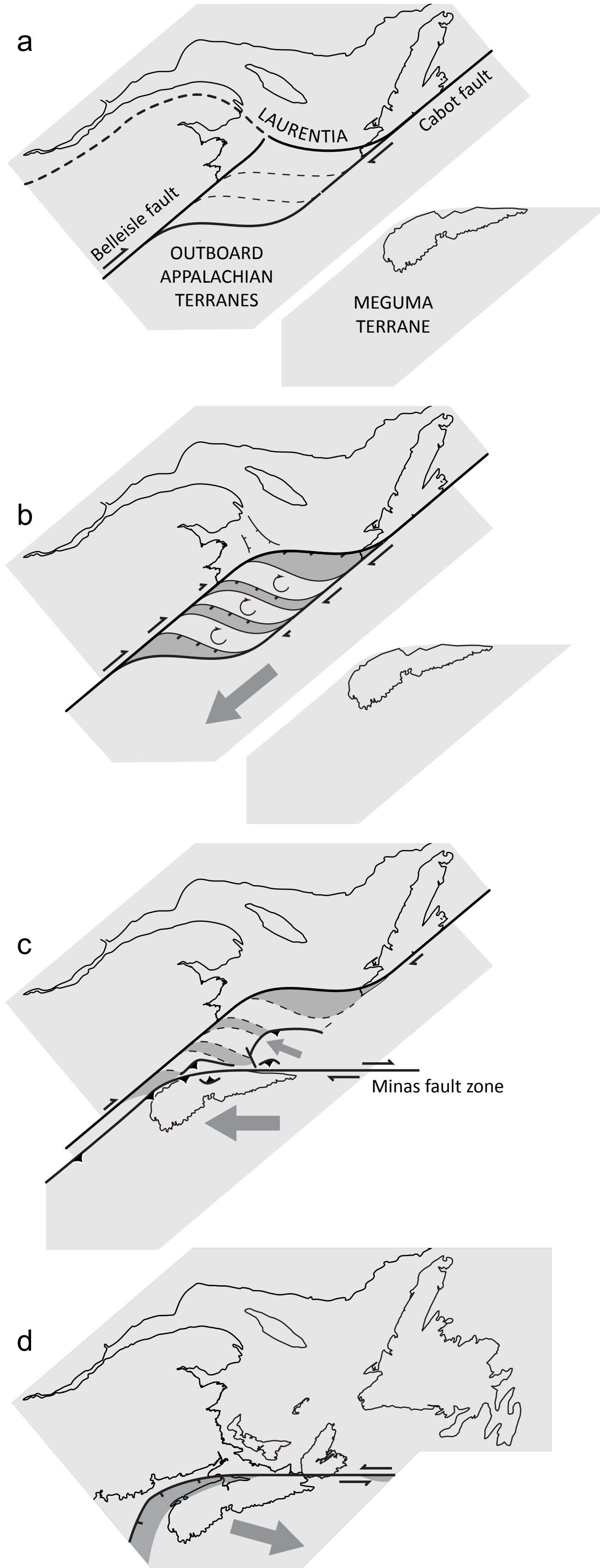

PERMIAN
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
Gzhelian
Kasim-ovian
Moscovian
Bashkirian
Serpukhovian
Visean
Tournaisian
Upper
Middle
Lower
Westphalian
Namurian
Livian
Molin-acian
Ivorian
Hastarian
Famennian
Frasnian
Givetian
Eifelian
Emsian
Artunian
Stephanian
Cantabrian
D Asturian
C Bolsovian
B Duckmantian
A Langsettian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
New Brunswick Platform
SE New Brunswick
W
Nova Scotia - Magdalen basin
E
Newfoundland
Pictou Group
Pictou Group
Pictou Group
Cumberland Group
Blanche Brook
Cumberland
Group
Boss Point
Howley
Hardwood Ridge
Royal Rd.
Mabou / Percé Gp.
Cumberland
Hill
La Coulée.
Mabou Group
Windsor Group
Hillsborough
Mabou Group
Upper
Middle
Windsor Group
Lower
St. Peters
Barachois Gp.
Codroy Group
Spout Falls
Deer Lake Group
INDIAN MOUNTAIN DEFORMED ZONE
BELLEISLE FAULT
CABOT FAULT
Sussex Gp.
Boyd Creek Tuff
Wilkie Brook
Anguille Gp.
Fountain Lake Gp.
Horton Group
Anguille Group
Horton Group
Lorneville Gp.
Piskahegan Gp.
Unnamed volcanics (HM Fina F-25)
Lowland Cove
Ballantynes Cove
Fisset Brook
Guysborough Gp.
Murphy Brook
McAdams Lake
Clastic sedimentary units
Carbonate & evaporite units
Volcanic units
Pictou Gp.
Cumberland Gp.
Mabou Gp.
Windsor Gp.
Sussex Gp.
Horton Gp.
Devonian
Contacts
Unconformity
Approximate
Constrained
Isotopic age with error (2-σ)



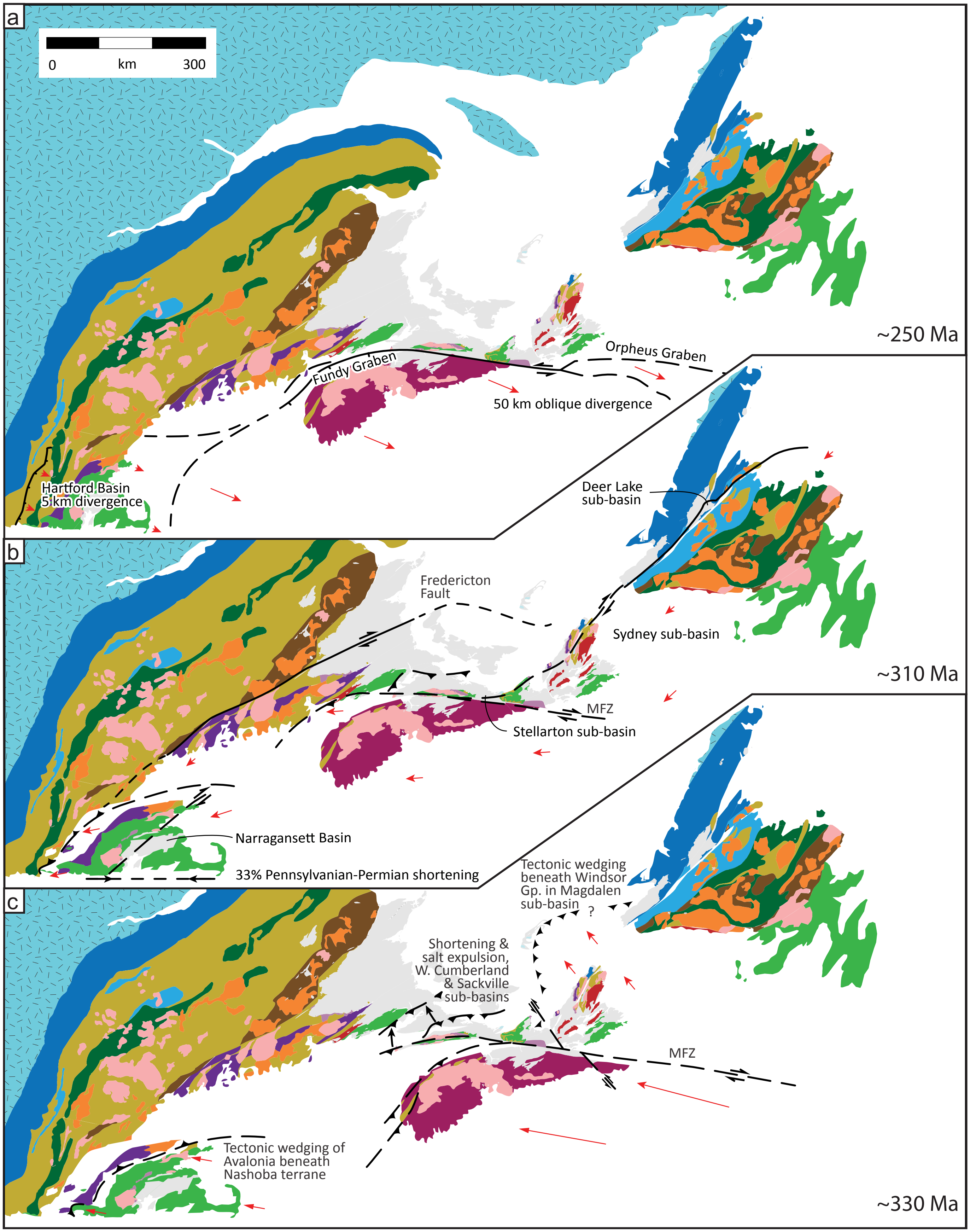
a
PF
CbF
HF?
AF
CbF
HF?
EHSZs
GRF
HF
MF
GF
CnF
FF
BIF
KF
CCHF
SCF
KhF
RBF
MFZ
st
CoF
Fundy Graben
Orpheus Graben
CdF
CHF
100 km
Mesozoic rocks
Late Paleozoic Maritimes Basin (onshore/offshore)
Early Paleozoic basement
Appalachian trend: faults with NE-SW strike
Minas trend: E-W faults
Canso trend: faults with NW-SE strike
Other faults, including sinuous and low-angle faults
b
c
New Brunswick platform
Belleisle Fault
Springhill Fault
Berry Mills Fault
Westmorland uplift
Moncton
Cocagne sub-basin
North River F.
Smith Creek Fault
Indian Mountain Deformed Zone
Intervale
Kierstead Mountain Fault
Moncton sub-basin
Edgetts Landing F.
St-Joseph F.
Salem F.
Dorchester F.
Sackville sub-basin
Pollett River F.
Caledonia Fault
Penobsquis Fault
Elgin
Sussex
Gordon Falls Fault
Urney complex
Prosser Mountain F.
Stewart Mountain shear zone
Caledonia Highlands
Harvey-Hopewell F.
Denis Beach Fault
Kennebecasis Fault
Clover Hill Fault
Caledonia Highlands
St. Martin's
Baxters Mountain F.
Nerepis duplex
Saint John
Partridge Island Block
Coastal Allochthons
20 km
Younger formations
Pennsylvanian
Cumberland and Pictou groups
Mississippian
Mabou Group (sedimentary formations)
Mabou Group (volcanic rocks)
Windsor Group
Sussex Group
U. Devonian to Mississippian
Piskehagan Group
Horton Group
Correlated facies across Kennebecasis - Berry Mills fault zone
Correlated facies across Caledonia - Clover Hill fault zone
Pre-Carboniferous rocks

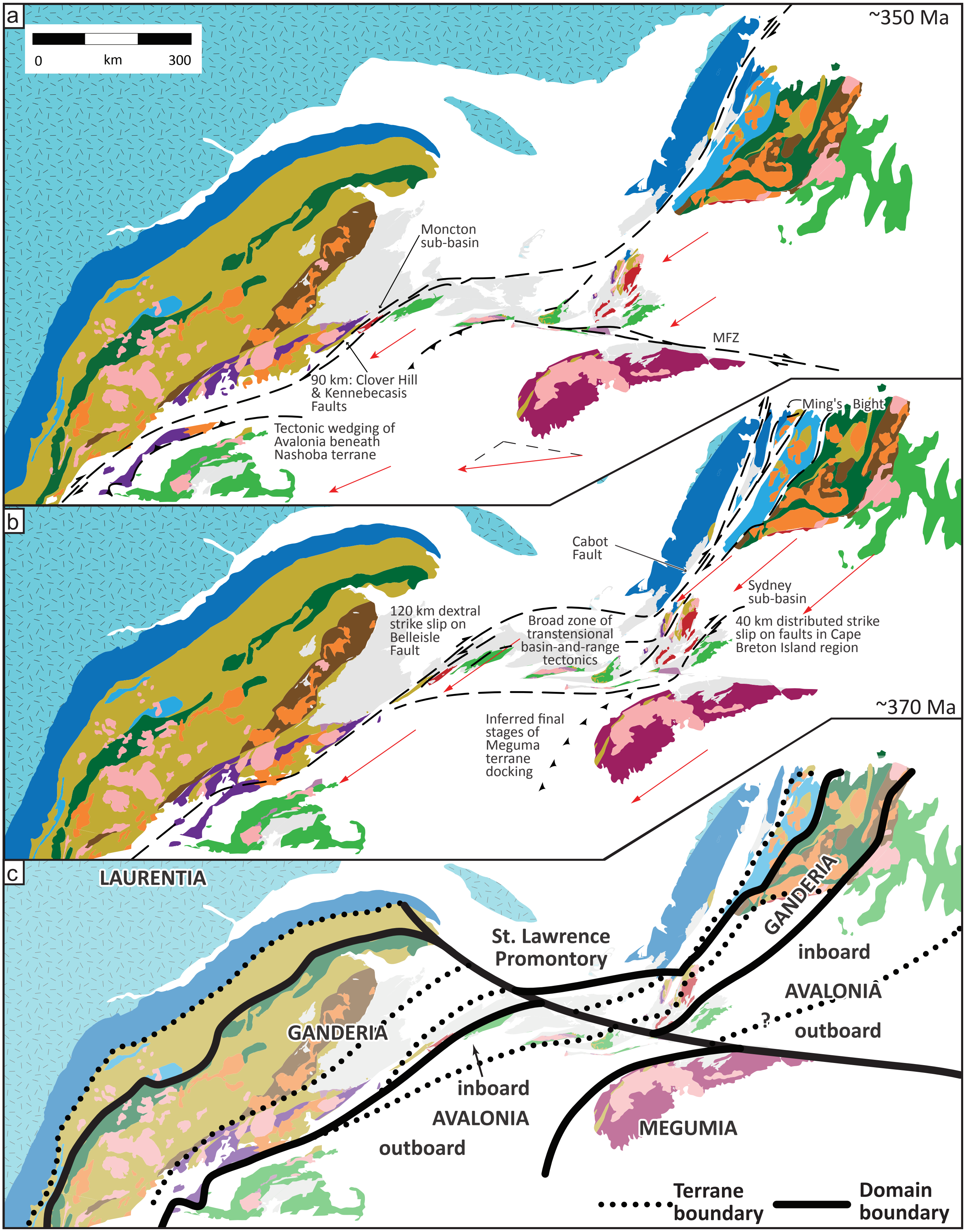


a) Matching facies
Fault
s
b) Incompatible facies
Volcanic center
Present-day
Fault
s
Restored
c) Strike-slip duplex geometry
Duplex area (approximated as a parallelogram) is constant: $A = l_1 w_1 = l_2 w_2 = l_3 w_3$
For n horses, $l_1 = A/w_1 = nA/w_3$
Hence minimum slip $s = l_1 - l_3 = (n-1)A/w_3$
Fault
w_3
Present-day
s
l_3
w_2
l_2
w_1
Restored
l_1
d) Thrust sinuosity
Fault
s
Fenster



a
LAURENTIA
Cabot fault
Belleisle fault
OUTBOARD
APPALACHIAN
TERRANES
MEGUMA
TERRANE
b
c
Minas fault zone
d


a
0
km
300
~250 Ma
Orpheus Graben
Fundy Graben
50 km oblique divergence
Hartford Basin
5 km divergence
b
Deer Lake
sub-basin
Fredericton
Fault
Sydney sub-basin
~310 Ma
MFZ
Stellarton sub-basin
Narragansett Basin
33% Pennsylvanian-Permian shortening
c
Tectonic wedging
beneath Windsor
Gp. in Magdalen
sub-basin
?
Shortening &
salt expulsion,
W. Cumberland
& Sackville
sub-basins
MFZ
Tectonic wedging of
Avalonia beneath
Nashoba terrane
~330 Ma


a
~350 Ma
0
km
300
Moncton sub-basin
MFZ
90 km: Clover Hill & Kennebecasis Faults
Tectonic wedging of Avalonia beneath Nashoba terrane
Ming's Bight
b
Cabot Fault
Sydney sub-basin
120 km dextral strike slip on Belleisle Fault
Broad zone of transtensional basin-and-range tectonics
40 km distributed strike slip on faults in Cape Breton Island region
Inferred final stages of Meguma terrane docking
~370 Ma
c
LAURENTIA
St. Lawrence Promontory
GANDERIA
GANDERIA
inboard
AVALONIA
?
outboard
inboard
AVALONIA
outboard
MEGUMIA
Terrane boundary
Domain boundary