Role of Avalonia in the development of tectonic paradigms

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Abstract: The geological evolution of Avalonia was fundamental to the first application of plate tectonic principles to the pre-Mesozoic world. Four tectonic phases have now been identified. The oldest phase (760–660 Ma) produced a series of oceanic arcs, some possibly underlain by thin slivers of Baltica crust, which accreted to the northern margin of Gondwana between 670 and 650 Ma. Their accretion to Gondwana may be geodynamically related to the break-up of Rodinia. After accretion, subduction zones stepped outboard, producing the main phase (640–570 Ma) of arc-related magmatism and basin formation that was coeval with the amalgamation of Gondwana. Arc magmatism terminated diachronously between 600 and 540 Ma by the propagation of a San Andreas style transform fault, followed by the Early Paleozoic platformal succession used by Wilson to define the eastern flank of the proto-Atlantic (Iapetus) Ocean. This implies the ocean outboard from the northern Gondwanan margin survived into the Cambrian. Avalonia is one of several terranes distributed obliquely with respect to the adjacent cratonic provinces of Gondwana and Baltica, implying that these terranes evolved on different cratonic basements. As a result, their ages and differing isotopic signatures can be used to reconstruct their respective locations along the ancient continental margin.

1960s: from geosyncline to plate paradigms

It is more than 50 years since Wilson (1966) posed the question 'Did the Atlantic close and then re-open?', which was the first application of the emerging plate tectonic paradigm to the pre-Mesozoic world. Before the wide acceptance of plate tectonics, the Appalachian orogen had been interpreted in fixist terms controlled by the evolution of geosynclines (Kay 1951). Geosynclines were viewed as linear troughs characterized by thick deposits of strata, which were subsequently deformed and uplifted to form an orogenic belt. However, the mechanisms responsible for their location, the initiation of subsidence and subsequent mountain-building were enigmatic.

By the early 1960s, field studies in various regions of Atlantic Canada and New England showed that the southeastern margin of much of the northern Appalachian orogen was underlain by a belt of rocks with a shared history characterized by late Hadrynian (Neoproterozoic) low-grade volcanic and sedimentary sequences intruded by *c.* 600 Ma granitoid rocks. This belt of rocks came to be known as the Avalon Platform (Williams 1964; Kay & Colbert 1965) after the type area on the Avalon Peninsula in southeastern Newfoundland where these sequences are well exposed.

Cambrian strata overlying these Neoproterozoic rocks were shown to have Atlantic fauna demonstrably distinct from the Pacific fauna in contemporaneous strata deposited unconformably on the Precambrian Long Range Complex in western Newfoundland (Hutchinson 1952, 1962). Williams (1964) pointed out that these two Cambrian sequences were separated by a symmetrical mobile

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belt of Paleozoic age characterized by: (1) margins consisting of voluminous sedimentary or metasedimentary clastic sequences; (2) ultramafic bodies (now known to be ophiolite complexes) outboard of those margins; and (3) a central zone dominated by polydeformed Ordovician and Silurian volcanic and sedimentary rocks. Williams (1964) concluded that the Appalachian orogen in Newfoundland represented a two-sided symmetrical system and that the occurrence of Late Precambrian rocks in eastern Newfoundland violated the prevailing view that the Appalachian orogen had formed by the continental accretion of an orogenic welt along the southeastern border of ancestral North America (Laurentia) in Paleozoic time. The fact that the Avalon Platform preserved a history earlier than that of the central zone also ran counter to the fixist view in which continents grow by lateral accretion.

Reconciling the geology of the Avalon Platform with the internal zones of the Appalachian orogen was a major catalyst in the development of the Wilson model (Neale 1995). In that model, the faunal differences between the Cambrian platformal rocks of western (Pacific fauna) and eastern (Atlantic fauna) Newfoundland were extrapolated along the length of the Appalachian orogen (and its continuation in the Caledonide orogen of Western Europe) and interpreted to reflect deposition along opposing continental margins of a proto-Atlantic Ocean (now known as the Iapetus Ocean; Harland & Gayer 1972) lying between them. Early Ordovician volcanic complexes (Kay & Colbert 1965) were interpreted as island arcs formed during subduction of this proto-Atlantic Ocean. The mobile belt reflected the closure of this ocean and, like the platformal rocks, was extrapolated along the length of the Appalachian–Caledonide orogen. The Wilson model (Fig. 1) provided a plate tectonic framework for the origin of the orogenic belt and was the first application of plate tectonic principles to pre-Mesozoic orogens. The well-exposed geology of Newfoundland, from the Avalon Platform in the east to the Laurentian foreland in the west, was the lynch-pin of that model. The former continuity of these sequences from the Appalachian orogen into the Caledonide belt was later sundered by the Mesozoic opening of the Atlantic Ocean, as envisaged earlier by Wegener (1912).

The Wilson model was further developed by Dewey (1969) and Bird & Dewey (1970), who took it to imply that the Avalon Platform, along with correlative rocks in Maritime Canada, Britain and NW France, first rifted from Laurentia (ancestral North America) in the Late Precambrian to form the proto-Atlantic (Iapetus) Ocean (Fig. 1b). In this way, the Cambrian platformal sequences were viewed as conjugate passive margins that were re-accreted to Laurentia when the proto-Atlantic Ocean subsequently closed, an event that was considered to have taken place during the Acadian orogeny in the Devonian. Since reconstructions of Pangaea placed the Avalon Platform and its correlatives along the West African margin of Gondwana in late Paleozoic time, the parsimonious interpretation was that the Avalonian Platform formed adjacent to West Africa in the late Precambrian.

The terminology applied to these Avalonian rocks has evolved in lock-step with the development

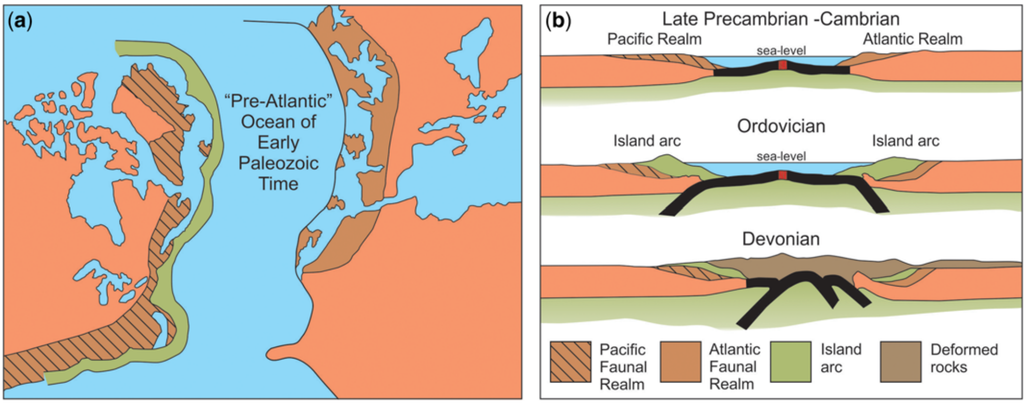

Fig. 1. (**a**) Wilson (1966) model showing the proto-Atlantic (Iapetus) Ocean in Lower Paleozoic time, separating the Pacific (North America) and Atlantic (Europe) faunal provinces. Ordovician island arc sequences develop along the North American margin. (**b**) Plate tectonic evolution of the Caledonide orogen in Britain (simplified from Dewey 1969). A late Precambrian–Cambrian expanding proto-Atlantic Ocean was succeeded by the Ordovician onset of subduction (first beneath North America, followed by subduction beneath Europe) and convergence, culminating in Devonian continental collision.

of new ideas. As new concepts have developed, the term platform has been successively replaced by tectonostratigraphic zone (e.g. Rodgers 1970; Williams 1978, 1979), terrane (e.g. Williams & Hatcher 1982) and composite terrane (Keppie 1985, 1993). Rast & Skehan (1983) referred to Avalon as a microplate, whereas the term Avalonia is now used for the microcontinent (Cocks & Fortey 1990). The terms East and West Avalonia are used for convenience to refer to sequences on opposing sides of the Atlantic Ocean, although, as noted by several researchers (e.g. Landing 1996), Early Paleozoic sequences are virtually identical. Some Late Neoproterozoic and Paleozoic reconstructions show Avalon as a microplate (e.g. Stampfli & Borel 2002), whereas others show it as a microcontinent (e.g. Cocks & Fortey 1990; Scotese & McKerrow 1990; Cocks & Torsvik 2002; Scotese 2009).

The purpose of this paper is to summarize the development of concepts that have guided our understanding of the Neoproterozoic–Early Paleozoic evolution of Avalonia, including those that underpinned and succeeded the model of Wilson (1966) and those that have placed its evolution into a global context. We also outline some crucial areas of uncertainty that remain to be resolved, especially recent evidence that Avalonia may have had more of a connection to Baltica than previously recognized. Although our approach is chronological, more recent references may be cited where they relate to the concepts being discussed.

1970s: testing and refining the model

During the 1970s, the tectonic evolution of the Avalonian rocks became central to testing the Wilson model and understanding the plate tectonic evolution of the Appalachian–Caledonide orogen. The history of these rocks in the Neoproterozoic and early Paleozoic was used to test the rift-to-drift hypothesis implied by their relationship to the proto-Atlantic (Iapetus) Ocean, whereas their Late Paleozoic evolution was used to examine the mechanisms and timing of their accretion to Laurentia.

Building on the mapping of McCartney (1954, 1956, 1957) in the Avalon Peninsula and a meagre Rb–Sr geochronological database (McCartney 1967), Neoproterozoic rocks in the Avalon type area were characterized as a voluminous succession of low-grade volcanic and marine to non-marine volcaniclastic and clastic rocks, which had been tilted and faulted during the Avalonian disturbance/orogeny prior to the deposition of the early Cambrian platformal sequences (Lilly 1966; Rodgers 1970; King *et al.* 1974).

The earliest regional tectonic models initiated a debate as to whether Neoproterozoic Avalon represented a continental rift sequence, an ensialic island arc or some transitional environment between the two. Using major element geochemistry, Papezik (1970) proposed that the Harbour Main Group, one of the principal units of Avalonian magmatism, had an alkalic affinity, probably formed in an extensional, possibly Basin and Range style, setting and was correlative with a coeval volcano-sedimentary sequence in the British Midlands. However, Hughes & Brückner (1971) and Hughes (1972, 1973) pointed out that these Avalonian rocks had suffered extensive metasomatism that would have compromised the use of alkali elements to deduce their petrotectonic affinity. Building on the interpretation by Dewey (1969) of the coeval British sequence, they interpreted the entire Late Neoproterozoic Avalonian sequence as an island arc complex within a pre-existing proto-Atlantic Ocean and proposed correlations with sequences in Morocco.

Rast *et al.* (1976) expanded this analysis by comparing Avalonian rocks in the type area with similar sequences in Maritime Canada and Britain, and with rocks of the Cadomian orogen in Normandy and Brittany. They proposed that the Late Precambrian Avalonian basement rocks formed in a Japan-like ensialic island arc tectonic setting that preceded the Appalachian orogenic cycle. They viewed this arc to have formed above a northwesterly dipping subduction zone and to have rifted from Laurentia. In their interpretation, the Avalonian arc was separated from rocks of the Cadomian orogen by a major ocean.

The proposal that the Avalonian basement was a Late Precambrian microcontinental arc terrane, rather than the opposing passive margin of the Proto-Atlantic to that of eastern Laurentia, constituted a fundamental advance in Appalachian geology, which profoundly influenced subsequent models for the orogen's plate tectonic evolution (Fig. 2). As a result, the evolution of the Avalonian basement also came to play a key part in the understanding of the nature of the global-scale (Pan-African; Kennedy 1964; Kröner 1977, 1984; Collins & Windley 2002; de Wit *et al.* 1988; Stern 1994; Unrug 1996; Kusky *et al.* 2003; Kröner & Stern 2004) orogenesis that accompanied the Late Neoproterozoic–Early Paleozoic formation of Gondwana (Fig. 3).

Given the criticisms that the interpretation of Papezik (1970) was based on unreliably mobile elements, the island arc model began to gain widespread acceptance. However, a geochemical study by Strong *et al.* (1978), which included elements such as Ti and Zr that are more resistant to the effects of metasomatism, concluded that the Avalonian assemblage recorded an aborted rift in which a small ocean basin was abruptly closed with a reversion to continental-type bimodal volcanism. Like the arc model, this interpretation implied that Avalonian

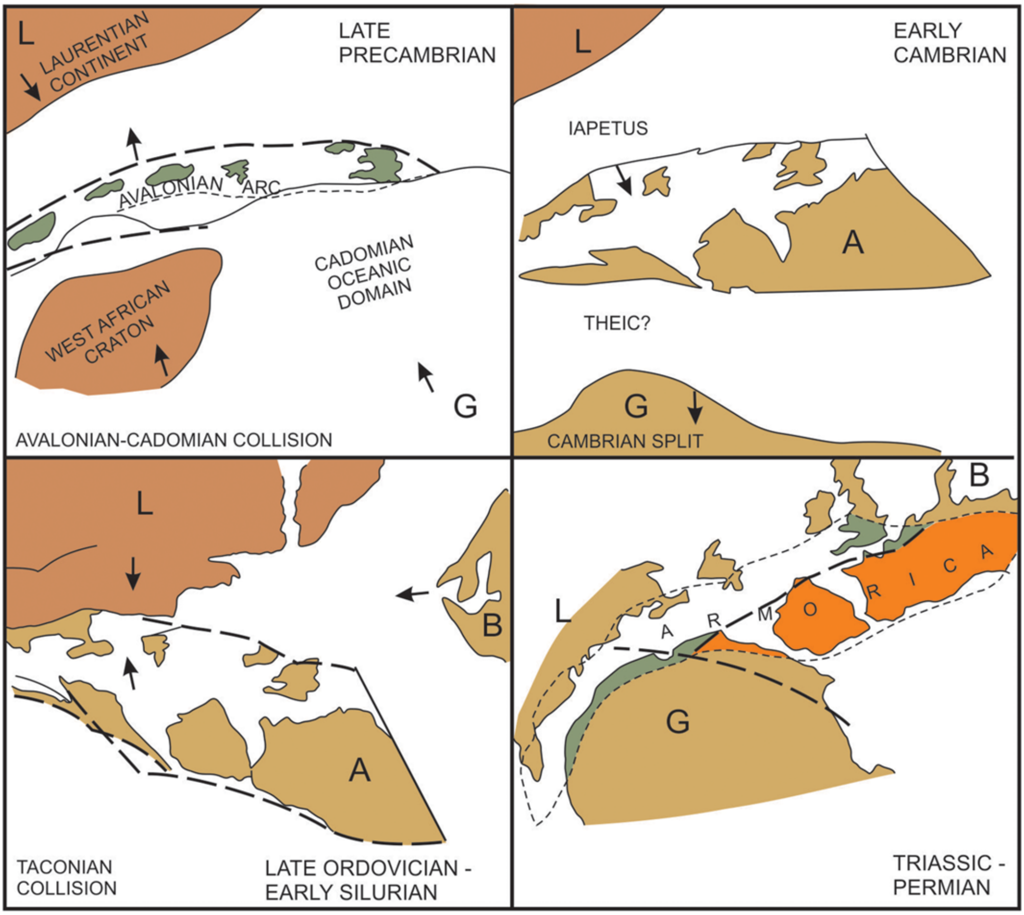

Fig. 2. Model of Rast & Skehan (1983) showing collision of the Avalonian island arc and Cadomian oceanic domain in the Late Precambrian, followed in the Early Cambrian by the development of the Armorican microcontinent with the opening of the Theic Ocean between the microcontinent and West Africa. According to this model, the collision of the microcontinent with Laurentia in the Ordovician caused the Taconic orogeny and was followed by continent–continent collision and the amalgamation of Pangaea. A, Armorica; B, Baltica; G, Gondwana; L, Laurentia.

basement rocks were not conjugate to eastern Laurentia during the opening of the proto-Atlantic Ocean.

The state of knowledge at the end of the 1970s was summarized in two major publications. Building on a zonal subdivision of the Newfoundland Appalachians (Williams 1969), a tectonic–lithofacies compilation map of the entire Appalachian orogen was published (Williams 1978), in which the Avalon Zone was defined as one of five tectonostratigraphic zones stretching from the type area in Newfoundland to New England. In a follow-up synthesis of the orogen, Williams (1979) defined and characterized the five zones shown in the tectonic–lithofacies map based on their contrasting pre-Silurian evolution. The geology of the three most westerly zones (Humber, Dunnage and Gander) was interpreted to record the generation and subsequent destruction of a Neoproterozoic–Early Paleozoic Iapetus Ocean. Williams (1979) summed up the varying interpretations for the tectonic evolution of the Avalon Zone by stating that its Neoproterozoic development could be attributed ‘either to rifting and the initiation of the Iapetus Ocean, or to subduction and a cycle that preceded the opening of Iapetus’. By Cambrian times, however, there was a general agreement that the Avalon Zone was a stable platform. The fifth and easternmost Meguma Zone was interpreted as either a vestige of the continental margin of NW Africa (after Schenk 1971) or as a graben-fill sequence within the Avalon Zone (Keppie 1982; Waldron *et al.* 2009).

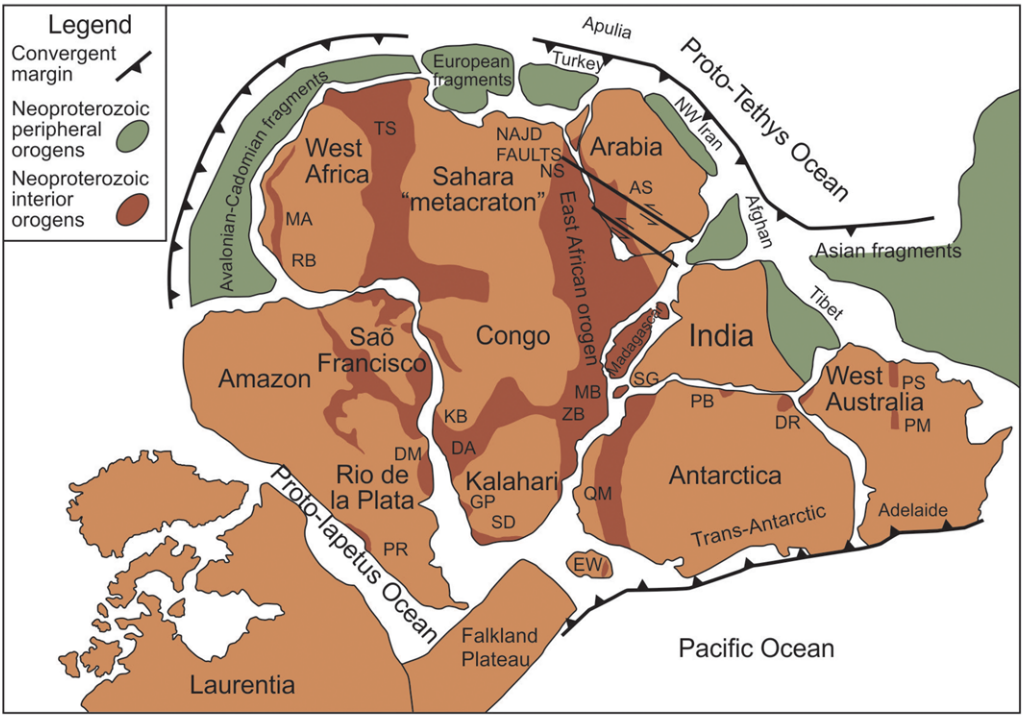

Fig. 3. Late Neoproterozoic–Early Cambrian map of Gondwana showing the distribution of Pan-African orogenic belts (modified from Kusky *et al.* 2003). AS, Arabian Shield; BR, Brasiliano; DA, Damara; DM, Dom Feliciano; DR, Denman Darling; EW, Eilsworth–Whitmore Mountains; GP, Gariep; KB, Kaoko; MA, Mauritanides; MB, Mozambique Belt; NS, Nubian Shield; PM, Peterman Ranges; PB, Pryolz Bay; PR, Pampean Ranges; PS, Paterson belt; QM, Queen Maud Land; RB, Rokelide belt; SD, Saldania; SG, Southern Granulite Terrane; TS, Trans-Sahara Belt; WB, West Congo; ZB, Zarmbezi.

1980s: Avalon as a terrane

After the suspect terrane concept was proposed to explain the exotic nature relative to Laurentia of many Cordilleran assemblages (Coney *et al.* 1980), Williams & Hatcher (1982) re-defined the five Appalachian zones as suspect terranes, implying that the original relationship between them was unclear. Keppie (1982, 1985) defined several Neoproterozoic suspect terranes based on fundamental differences in the Neoproterozoic successions of adjacent fault blocks. However, because they shared a common Early Cambrian passive margin overstep sequence, Keppie (1985) proposed that these terranes became unified into a single composite terrane (the Avalon Composite Terrane) prior to the Early Cambrian. This interpretation had two important implications that still resonate today: (1) every fault block that contains the Cambrian overstep sequence is part of the composite terrane and (2) the Neoproterozoic rocks underlying the overstep sequence could have formed in different locations and tectonic settings. The unification of these potentially independent Neoproterozoic suspect terranes into a single composite terrane was attributed by Keppie (1985) to the latest Neoproterozoic Avalonian orogeny.

1990s: four-part tectonostratigraphy

In the 1990s, advances in U–Pb geochronological techniques, accompanied by the creation of several new laboratory facilities, led to more precise constraints on the age of Avalonian magmatic events. This allowed for the construction of a far more robust tectonostratigraphic framework for the Avalonian succession that consisted of four regional phases (Fig. 4a).

Pre-main phase magmatism: proto-Avalonia (760–650 Ma)

The first precise U–Pb (zircon, thermal ionization mass spectrometry) age from rocks of the Avalon terrane came from a gabbroic sill that intruded the mafic volcanic and interlayered volcanogenic strata

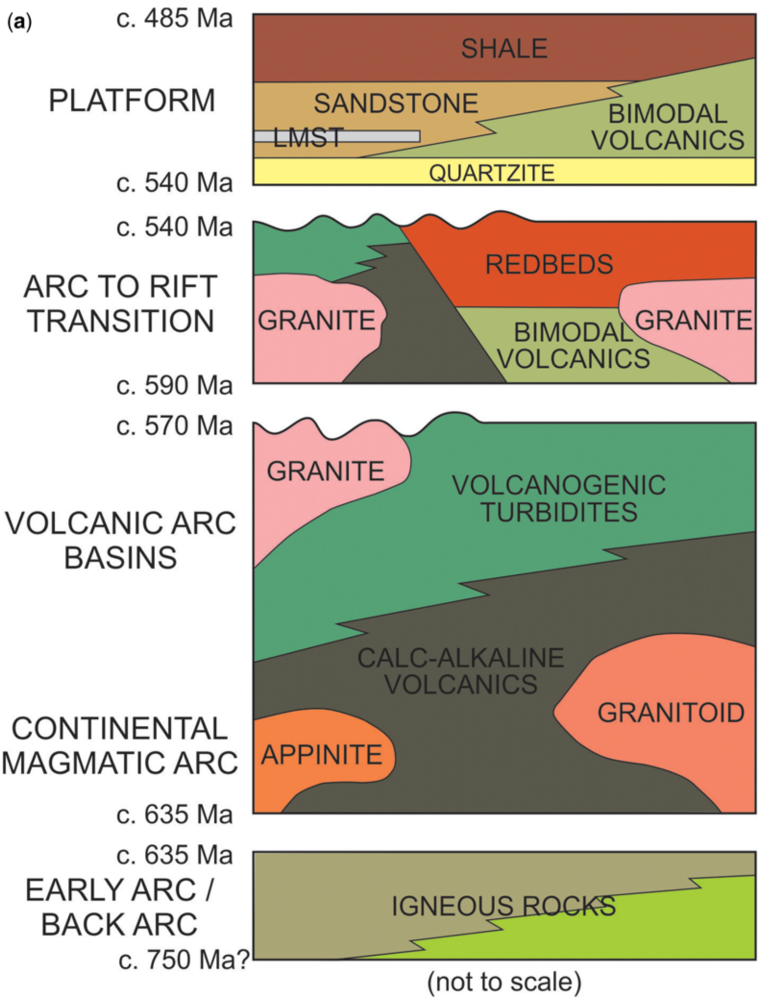

Fig. 4. (**a**) Simplified composite summary of the tectonostratigraphy of Avalonian rocks (modified after Murphy *et al.* 1999; Nance *et al.* 2002). The succession has four main phases: an early (0.76–0.64 Ga) island arc phase during which proto-Avalonia formed outboard of Gondwana within the peri-Rodinian ocean, a main phase of arc magmatism beginning at *c.* 0.64 Ga, which diachronously gave way to an arc-to-rift transition (0.60–0.54 Ga) and was followed in the Early Cambrian by the development of a platformal sequence.

of the Burin Group (Krogh *et al.* 1988). This age (763 ± 2 Ma) was significantly older than the generally accepted 640–570 Ma age for the main phase of ensialic arc magmatism preserved in various parts of the Avalon terrane and has been confirmed by a 764.5 ± 2.1 Ma age derived from a different gabbroic body that likewise intrudes the group (Murphy *et al.* 2008). Both intrusive rocks are thought to be coeval with their mafic host rocks, with which they share a mid-ocean ridge basalt geochemistry (Strong & Dostal 1980; Murphy *et al.* 2008), implying a similar age for the Burin Group. To date, these are the oldest rocks recognized in the Avalon terrane.

Further precise age dating showed that vestiges of magmatic activity predating the main arc phase occur in many parts of the terrane and collectively range from *c.* 765 to *c.* 660 Ma. This early phase of activity came to be known as proto-Avalonia (Murphy *et al.* 2000). With the exception of the Burin Group, however, the complexes have a calc-alkaline chemistry and are widely interpreted to represent subduction-related arc to back-arc plutonic and volcanic complexes. In this context, the Burin Group is interpreted as a back-arc complex, although a coeval arc has not been found.

In the Avalon Peninsula, these complexes include *c.* 730 Ma felsic flows and porphyries near

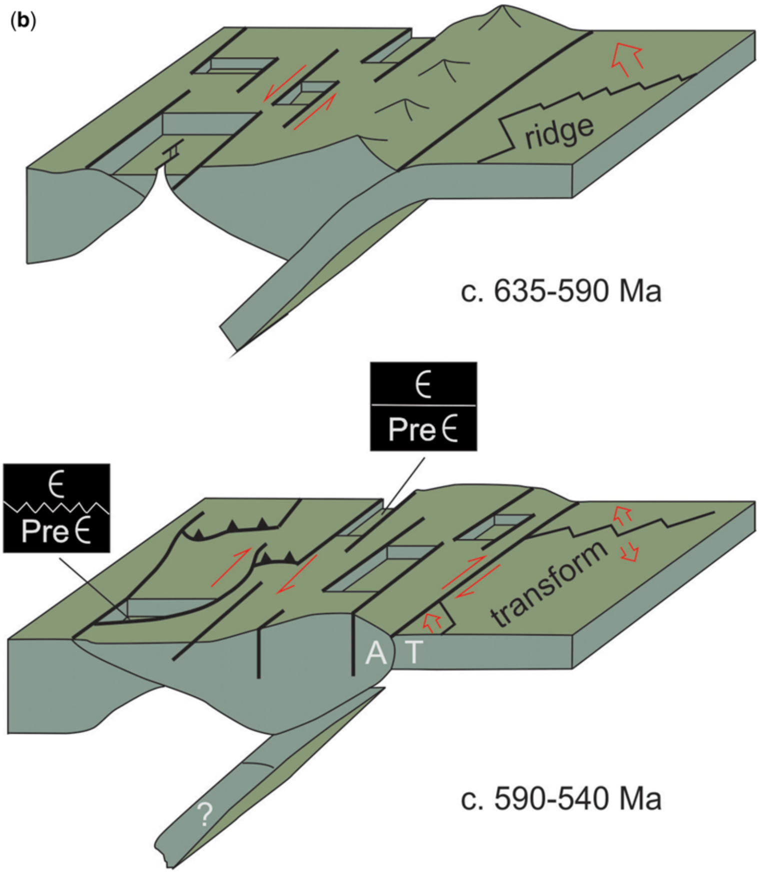

Fig. 4. (*Continued*) (**b**) Model for the Late Neoproterozoic (Np) termination of arc magmatism by ridge–trench collision and the generation of a San Andreas style transform fault (Murphy & Nance 1989).

Conception Bay (Israel 1998; O'Brien *et al.* 2001), 685–670 Ma calc-alkaline volcanic and plutonic rocks in southern Newfoundland (Swinden & Hunt 1991; O'Brien *et al.* 1992, 1995) and, more contentiously, the *c.* 680 Ma Cinq Cerf-Grey River gneiss terrane of the Hermitage Flexure (Dunning & O'Brien 1989; O'Brien *et al.* 1992; Valverde-Vaquero *et al.* 2006).

Early arc complexes in Cape Breton Island include the *c.* 676 Ma Stirling Belt (Bevier *et al.* 1993) and the 700–630 Ma back-arc volcanism in the Creignish Hills (Keppie & Dostal 1998) and, in mainland Nova Scotia, the *c.* 734 Ma calc-alkaline Economy River Gneiss (Doig *et al.* 1993) and the back-arc basin metasedimentary Gamble Brook Formation (Murphy 2002). Similar evidence for an early arc-related event is found in correlative Avalonian rocks in Britain in the form of the *c.* 670 Ma calc-alkaline Malverns Plutonic Complex (Tucker & Pharaoh 1991; Nance *et al.* 1991; Pharaoh & Gibbons 1994; Strachan *et al.* 1996) and the *c.* 711 Ma Stanner–Hanter Complex (Schofield *et al.* 2010).

Each of these complexes was interpreted to have formed in an arc setting: those dominated by felsic rocks in an ensialic arc (e.g. the Malvern Plutonic Complex) and those dominated by mafic rocks (e.g. the Burin Group) in a back-arc setting. Many of these complexes display evidence of deformation and *c.* 670–650 Ma high-grade metamorphism interpreted to reflect an orogenic event that occurred before the onset of main phase arc activity (Strachan *et al.* 1996, 2007).

Main phase arc magmatism (640–570 Ma)

A plethora of precise U–Pb and Ar–Ar age data, combined with geochemical studies emphasizing the abundances of relatively immobile high field strength and rare earth elements in rocks from different parts of the Avalon belt, constrained the main phase of arc-related magmatism to the interval *c.* 640–570 Ma (e.g. Barr & White 1988; Pe-Piper & Piper 1989; Bevier & Barr 1990; Bevier *et al.* 1990, 1993; Dostal *et al.* 1990; Keppie *et al.* 1990; Murphy *et al.* 1990, 1997; O'Brien *et al.* 1990; Strachan *et al.* 1996; Keppie & Dostal 1998). However, it also became clear that this range in age was an oversimplification and that the timing of magmatic activity in each region within Avalon was more restricted. Collectively, these data suggested that arc magmatism varied both in time and location, presumably in response to changes in the nature of subduction (e.g. dip, rate of rollback, upper plate motion relative to the slab) along the continental margin.

It also became evident that the termination of subduction-related magmatism was diachronous along the Avalon belt, varying from *c.* 590 Ma in New England (Thompson *et al.* 1996; Mancuso *et al.* 1996), *c.* 600 Ma in New Brunswick and mainland Nova Scotia (Keppie *et al.* 1990; Barr *et al.* 1994; Murphy *et al.* 1997), *c.* 570 Ma in southern Cape Breton Island (Bevier *et al.* 1993) and southern Newfoundland (O'Brien *et al.* 1996) and as young as 550 Ma in Britain (Pharaoh & Gibbons 1994; Strachan *et al.* 1996).

Early publications on the geochemistry of Avalonian igneous rocks were compromised by petrographic evidence for deuteric alteration and low-grade metamorphism, which implied that the rocks had been affected by elemental mobility during metasomatism. Advances in analytical techniques, together with the seminal work of Pearce & Cann (1973), Winchester & Floyd (1977) and Wood *et al.* (1979), emphasized the importance of using abundances of less mobile, high field strength (e.g. Ti, Nb, Y, Zr, Ta) and rare earth elements to deduce the magmatic affinity and tectonic setting of rocks that had been altered in this way.

Several studies in different parts of the Avalon belt confirmed the arc to back-arc affinities of both the main phase and pre-main phase (proto-Avalonian) igneous rocks. For the main phase, this included studies in the type area in Newfoundland (e.g. Sears 1990; O'Brien *et al.* 1990; Dec *et al.* 1992; Fryer *et al.* 1992), in Maritime Canada (Keppie *et al.* 1979; Pe-Piper & Piper 1989; Dostal *et al.* 1990; Murphy *et al.* 1990; Barr 1993; Doig *et al.* 1993; Barr *et al.* 1994), New England (e.g. Hermes & Murray 1990) and central England (Pharaoh *et al.* 1987; Strachan *et al.* 1996), as well as coeval arc-related rocks in the Cadomian orogen (Cabanis *et al.* 1987; D'Lemos *et al.* 1990 and references cited therein; Egal *et al.* 1996).

In several of these localities, the co-occurrence of tholeiitic mafic and calc-alkaline mafic–felsic suites during the main phase of magmatism, together with stratigraphic relations showing the coeval development of sedimentary basins, were held to signify an important component of extension within the arc that would lead to the development of back-arc or peri-arc basins. The felsic volcanic and plutonic rocks were variously interpreted either as crustal melts or as differentiates from a more mafic parent.

The formation of sedimentary basins coeval with the main phase magmatism – such as those represented by the Conception/Connecting Point groups in Newfoundland (e.g. O'Brien *et al.* 1990), the Georgeville Group in mainland Nova Scotia (Murphy *et al.* 1991) and the Boston Bay Group in New England (Thompson *et al.* 1996) – were attributed to oblique subduction that resulted in strike-slip motion, localized intra-arc rifting and basin development. In each locality, basin-fill detritus was interpreted to reflect cannibalization of the flanking magmatic arc.

Arc to platform transition (600–540 Ma)

With further detailed mapping aided by precise age dating, it became apparent that an important phase of rift-related magmatism and local basin formation occurred after the main phase of arc magmatism, but before deposition of the Cambrian–Ordovician platformal sequences that define the Avalon (composite) terrane. It also became apparent that this transition was not accompanied by any evidence of collisional orogenesis. The rocks that make up the main phase of Avalonian magmatism are generally metamorphosed in the sub-greenschist to greenschist facies. However, features characteristic of continental collision zones – such as pervasive deformation, high-grade metamorphism, crustal shortening, crustal thickening and uplift – are all localized and attributed to the inversion of volcanic arc basin successions, commonly accompanied by strike-slip activity and coeval basin development. In Newfoundland, for example, volcanogenic turbidites of the *c.* 620–600 Ma Connecting Point Group are overlain with angular unconformity by red beds of the latest Neoproterozoic Signal Hill Group (e.g. O'Brien *et al.* 1996). Elsewhere in Newfoundland, however, a conformable sequence of strata spans the same time interval.

The rocks formed within that time interval (now mostly assigned to the Ediacaran Period) include the *c.* 6 km thick Mistaken Point assemblage of southeastern Newfoundland, which is dominated by a conformable sequence of marine to non-marine clastic rocks containing the oldest known diverse assemblage of complex multicellular organisms (Ediacaran fauna; Misra 1969; Narbonne & Gehling 2003). This assemblage lies conformably above the *c.* 580 Ma (Pu *et al.* 2016) Gaskiers Tillite, but unconformably below the latest Ediacaran fluvial Signal Hill Group and Cambrian platformal rocks. As an indication of the diversity of Ediacaran age assemblages, coeval rocks in other areas on the

Avalon Peninsula include both alkaline (rift-related) and calc-alkaline (subduction-related) mafic to felsic igneous suites interpreted as evidence of a transitional arc to rift tectonic environment (e.g. O'Brien *et al.* 1996).

More generally, in Britain, southeastern Newfoundland, southern New Brunswick and southern Cape Breton Island, Ediacaran shallow marine to terrestrial clastic deposits are common in extensional or transtensional basins (e.g. Smith & Hiscott 1984; Pauley 1990; Barr & White 1996; O'Brien *et al.* 1996), whereas magmatism with crystallization ages of *c.* 590–540 Ma is typically bimodal and attributed to intra-continental extension (e.g. Barr 1993; Barr & White 1996; Barr & Kerr 1997). In several of these regions, coeval arc-related magmatism also occurs (e.g. Dallmeyer & Nance 1992; Dostal *et al.* 1996; Barr & Kerr 1997; Keppie *et al.* 1998). In mainland Nova Scotia, magmatism of this age takes the form of small, post-tectonic A-type granitoid bodies emplaced along a major strike-slip zone (Pe-Piper *et al.* 1996; Murphy *et al.* 1998). Conversely, igneous rocks of this age are largely absent in New England. Structural inversion of late Neoproterozoic volcanic arc basins is thought to have been accomplished by a change from sinistral to dextral motion on the basin-bounding faults (e.g. Nance & Murphy 1990; Murphy & Hynes 1990).

The available data suggest that the transition from subduction to the onset of rift-related magmatism in the latest Neoproterozoic began at *c.* 570 Ma in Newfoundland (O'Brien *et al.* 1996), between *c.* 575 and 560 Ma in southern Cape Breton Island (Bevier *et al.* 1993), at *c.* 605 Ma in mainland Nova Scotia (Murphy *et al.* 1997), at *c.* 560 Ma in southern New Brunswick (Bevier & Barr 1990; Barr *et al.* 1994; Currie & McNicoll 1999) and at *c.* 595 Ma in New England (Mancuso *et al.* 1996). Avalonian rocks in Britain underwent this transition between 570 and 560 Ma (Tucker & Pharaoh 1991). These data imply that strike-slip activity was an important feature of the Avalonian arc to platform transition and that such activity in one part of the Avalon terrane was coeval with arc magmatism in another.

Other peri-Gondwanan terranes, such as Carolinia in the southern Appalachians and the Cadomian belt in Brittany and Normandy, which were likewise thought to have been located along the margin of Gondwana in the late Neoproterozoic, also record a transition from an arc to a rift environment: 590–570 Ma in Carolinia (e.g. Hibbard *et al.* 2002, 2007) and 570–540 Ma in France (e.g. Strachan *et al.* 1996).

These data and the lack of evidence of features that would be expected to have accompanied continental collision led to a re-appraisal of the tectonic significance of the Avalonian orogeny. To account for these characteristics, as well as the diachronous transition from arc to rift and the importance of strike-slip faulting in focusing magmatism and opening and closing sedimentary basins, Murphy & Nance (1989) proposed that Avalonian subduction was terminated as a result of the diachronous development of a continental transform fault system in a manner analogous to the Cenozoic development of the San Andreas Fault in western North America (Fig. 4b). This model allowed for the possibility of the along-strike transport of terranes during the late Neoproterozoic–Early Cambrian and was further developed over a series of papers (Nance & Murphy 1996; Murphy *et al.* 1999; Fernández-Suárez *et al.* 2002; Nance *et al.* 2002; Gutiérrez-Alonso *et al.* 2003; Keppie *et al.* 2003) in which the main phase of Avalonian magmatism was attributed to oblique subduction that led to the development of a magmatic arc and coeval volcanic arc basins. The subsequent development of the continental transform system resulted in the diachronous termination of subduction, the inversion of volcanic arc basins, the coeval development of new basins related to rifting and strike-slip movement, and the coeval translation of outboard terranes in the interval *c.* 600–540 Ma.

Platformal succession

The platform succession preserves the Atlantic fauna used by Wilson (1966) to define the eastern flank of the proto-Atlantic (Iapetus) Ocean. Building on several local investigations in Britain and Atlantic Canada (e.g. Hutchinson 1952, 1962; Rushton 1971; Fletcher 1972; Cowie *et al.* 1972; Cowie 1974; Landing *et al.* 1980), detailed stratigraphic and palaeontological studies of the platform succession's uppermost Ediacaran to lower Ordovician rocks (e.g. Landing 1991, 1994, 1996; Landing & Murphy 1991) attest to their impressive similarity across the Avalon terrane from New England, through Atlantic Canada to the British Isles. Landing (1996) recognizes 10 unconformity-bounded sequences from Rhode Island to Britain and advocated a unified stratigraphy for all of them.

These similarities were purported to include the occurrence of the diagnostic shallow marine Acado–Baltic (Atlantic realm) trilobite fauna (Cowie 1974; O'Brien *et al.* 1983; Rast & Skehan 1983). According to Theokritoff (1979), however, the fauna in Avalonian platformal sequences is distinct from that of Cadomia (NW France, Iberia) and Gondwana; differences that Landing (1996, 2005) later emphasized to propose that (1) the Acado–Baltic designation should be discontinued, (2) Avalon was an insular, high-latitude microcontinent (Avalonia) at that time and (3) Avalonia was a distinct faunal province. Despite their faunal and stratigraphic similarities, the Avalonian successions are interpreted to have been deposited in local extensional regimes associated with continued strike-slip activity (Keppie 1982, 1985; Landing 1996). Consistent with this interpretation, some sections contain volumetrically subordinate, early to middle Cambrian bimodal volcanic rocks, the mafic members of which have continental alkaline–tholeiitic chemistry (Murphy *et al.* 1985). Thus the strike-slip regime that became dominant in the late Ediacaran may have persisted into the Cambrian, the older sequences being overstepped by shallow marine strata of the Cambrian platform with rising global sea-levels.

Regional correlations and the Gondwanan connection

By the early 1980s, increasing knowledge of coeval assemblages within the Appalachian, Caledonide and Variscan orogens led to attempts at regional correlations. Similarities between the evolution of the Anti-Atlas of Morocco and the Avalonian belt were described by Leblanc & Lancelot (1980) and Piqué (1981). Rast & Skehan (1983) proposed that correlatives might occur in the southern Appalachians and in the Rokelide and Mauritanide belts of West Africa. They defined Avalon as a microplate, separated from Laurentia by a back-arc basin and from Cadomia by a large ocean. In this model, the Avalonian and Cadomian orogenies were penecontemporaneous events that took place on opposing continental margins (North America and Africa, respectively). O'Brien *et al.* (1983) drew attention to the similarities in age, tectonic evolution and facies development between the Avalon terrane and the Pharusian belt of the Hoggar Shield in West Africa. Building on the syntheses of Martin & Porada (1977*a*, *b*) and Kröner (1977) for the Pan-African belts in North Africa, O'Brien *et al.* (1983) interpreted the Neoproterozoic evolution of the Avalon Zone to be that of a Pan-African belt and its tectonic setting to be transitional between intra-plate and continental margin orogenesis.

Establishing a direct connection between the Avalon terrane and West Africa has since proved to be problematic because the latter is characterized by 2.0 Ga (Eburnian) basement, whereas Avalon is underlain by unexposed basement deemed to be much younger. The oldest known Avalonian rocks are the 760 Ma strata of the Burin Group, which is viewed as the basement to the main arc phase (Krogh *et al.* 1988; Murphy *et al.* 2008). However, rocks similar in age to the 2.0 Ga West African basement have been recognized within the Cadomian orogen of NW France (Auvray *et al.* 1980) and Iberia (Quesada 1990, 2006) and a genetic linkage between Cadomia and West Africa has been proposed by many researchers (D'Lemos *et al.* 1990; Quesada 1990; Strachan *et al.* 1996; Chantraine *et al.* 2001; Linnemann *et al.* 2004).

By investigating a connection with the Pan-African belts of West Africa, the papers by Rast & Skehan (1983) and O'Brien *et al.* (1983) implied a potential genetic linkage between the evolution of the Avalon terrane and the amalgamation of Gondwana, which was responsible for the generation of Pan-African belts in the Late Neoproterozoic-Cambrian (e.g. Kröner 1979).

Avalon as a peripheral orogenic belt

By the late 1980s, it was generally agreed that the Avalon terrane was a distinctive tectonostratigraphic belt along the southeastern flank of the Appalachian orogen (with correlative rocks in southern Britain). The terrane was characterized by late Neoproterozoic (*c.* 640–570 Ma) arc-related volcano-sedimentary rocks and genetically related plutonic rocks succeeded by a 600–540 Ma arc to platform transition and overlain by early Paleozoic platformal successions that contained a distinctive Avalonian fauna (Theokritoff 1979; Landing 1996). Otherwise similar arc-related sequences found in the Armorican massif of northwestern France were referred to as the Cadomian belt and were overlain by platformal successions that contained Tethyan fauna.

An unconformable boundary between the Neoproterozoic arc-related successions and the Cambrian platformal sequence was commonly viewed to be an expression of the Avalonian orogeny. However, this boundary varies from an angular unconformity in some locations to a break-up disconformity in others. Together with the lack of evidence of widespread deformation, crustal thickening or delamination, and large-scale thrusting or foreland basin development, this suggested that the termination of subduction was not due to continent–continent collision and that the ocean subducted to generate the Neoproterozoic arc successions survived into the Cambrian (Murphy & Nance 1989). Available kinematic analyses suggested that Neoproterozoic deformation was related to strike-slip activity (Treloar & Strachan 1989; Nance & Murphy 1990), implying that angular unconformities between the Neoproterozoic and Cambrian successions occur only in areas affected by this deformation.

The realization that the evolution of Avalonia and related peri-Gondwanan terranes required them to have faced an open ocean throughout the Late Neoproterozoic and Cambrian provided important constraints for palaeocontinental reconstructions (e.g. Scotese & McKerrow 1990; Stampfli & Borel 2002; Kusky *et al.* 2003; Scotese 2009). Using the late Neoproterozoic global reconstructions of Bond *et al.* (1984), together with the similarities of these

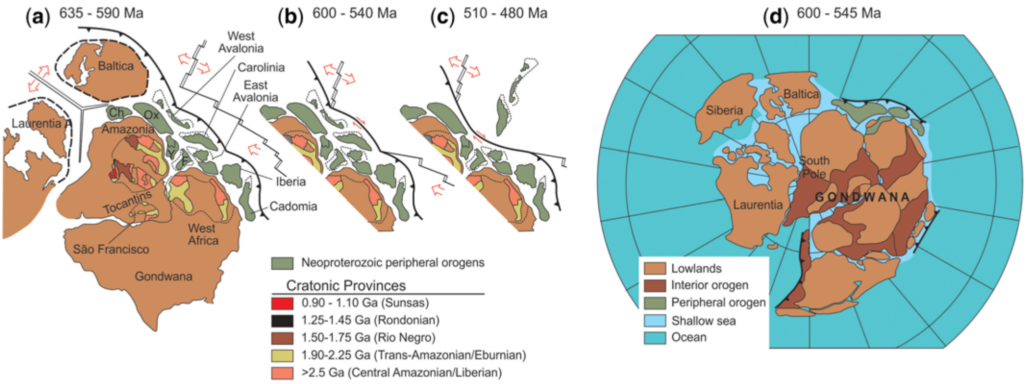

Fig. 5. (**a**) Main arc phase of Avalonia shown as a peripheral orogenic belt along the northern margin of Gondwana (after Nance *et al.* 2002). (**b**) Latest Neoproterozoic (*c.* 600–540 Ma) ridge–trench collision with diachronous termination of subduction and generation of San Andreas style transform fault. (**c**) Early Paleozoic (*c.* 510–480 Ma) continental rifting and separation of Avalonia (and Carolinia) from Gondwana. (**d**) Distribution of Late Neoproterozoic interior and peripheral orogens within the supercontinent Pannotia. Plotted on the continental reconstruction of Dalziel (1997). Ch, Chortis Block; F, Florida; Ox, Oaxaquia; Y, Yucatan Block.

terranes to NW Africa emphasized by O'Brien *et al.* (1983) and Rast & Skehan (1983), Murphy & Nance (1989) positioned the Avalonian and Cadomian orogenic belts along-strike from one another on the northern margin of Gondwana. As the reconstruction of Bond *et al.* (1984) identified South America as the conjugate margin to Laurentia, the proposed location for the Avalonian–Cadomian belt implied a protracted history of subduction of an ocean that preceded Iapetus. The onset of subduction was attributed to the relocation of subduction zones from oceans lying between the converging blocks of Pannotia (Greater Gondwana) to the periphery of this late Neoproterozoic supercontinent. The termination of subduction, on the other hand, was attributed to changes in global plate kinematics triggered by the opening of the Iapetus Ocean.

In this context, the Avalonian–Cadomian orogen was recognized as a peripheral orogenic belt that had formed along the extremity of a supercontinent following its amalgamation, in contrast with the collisional Pan-African orogenic belts, which were termed interior orogens because they came to lie within the interior of the supercontinent following its amalgamation (Fig. 5; Murphy & Nance 1991).

Isotopic tracking

Interpretation of the Avalonian–Cadomian belt as a peripheral orogen terminated by the development of a transform fault implied that the ocean bordering the Neoproterozoic arc survived to border the Cambrian platform. Faunal evidence indicated that the Avalon terrane stretched from New England to southern Britain (Avalonian fauna), whereas terranes with Cadomian affinities (Tethyan fauna) included Armorica (NW France), Iberia and Carolinia (Samson *et al.* 1990). This interpretation was consistent with published Early Paleozoic reconstructions based on palaeomagnetic and biostratigraphic data (e.g. Van der Voo 1988; Cocks & Fortey 1990) and suggested that all of these terranes were peri-Gondwanan in that they were distributed along the periphery of Gondwana. Crucially, these reconstructions also showed that, so positioned, these terranes would have been distributed obliquely with respect to adjacent cratonic provinces and the suture zones of interior Pan-African orogens formed by the continental collisions associated with supercontinent assembly (Murphy & Nance 1991).

Accordingly, the terranes of the Avalonian–Cadomian belt probably evolved on cratonic basements of different ages and, hence, different isotopic characteristics. Consequently, if the basement characteristics of the terranes could be deduced, it would be possible to palinspastically reconstruct the now-dismembered parts of the orogenic belt to their corresponding cratons (Nance & Murphy 1994). However, because limited uplift and erosion is one of the characteristics of peripheral orogens, basement exposures within the Avalonian–Caledonian belt had proved to be rare. At the time, undisputed basement had only been recognized in one of the Cadomian terranes (the Icart gneiss of Armorica) and its U–Pb age of *c.* 2.0 Ga suggested affinities with the Eburnian orogen of the West African craton (Auvray *et al.* 1980). To date, this remains the only unequivocal exposure of ancient basement rocks in the Avalonian–Cadomian belt.

The lack of exposed basement rocks required that determination of its basement isotopic characteristics had to be carried out indirectly. At that time, detrital zircon studies were in their infancy and data from single-grain age determinations were rare. Keppie *et al.* (1998) showed the presence of a wide range of Precambrian detrital zircons in Precambrian Avalonian suites, some of which could be derived from many different cratons. A population of 1.0–1.5 Ga zircons narrowed the potential sources to Amazonia and Baltica and excluded NW Africa. However, although single detrital zircon data provide constraints on the age of adjoining crustal provinces, they do not directly identify the age of the underlying basement. The pioneering work of DePaolo & Wasserburg (1976) and DePaolo (1981) showed that the Sm–Nd isotopic composition of crustally derived igneous rocks could be used to constrain the isotopic characteristics of the basement source.

Nd isotopic data for crustally derived felsic igneous rocks confirmed that the Avalonian and Cadomian terranes developed on basements of different ages (Nance & Murphy 1994, 1996; Kerr *et al.* 1995; Murphy & Nance 2002; Linnemann *et al.* 2004, 2007; Keppie *et al.* 2011). Values of εNd for West Avalonia (Fig. 6a) are strongly positive, which, together with the 0.8–1.1 Ga depleted mantle model (T_{DM}) ages, suggested that the Late Neoproterozoic arc rocks developed by extractions from relatively juvenile crust, similar to that of the Neoproterozoic Tocantins Province of central Brazil, which is located between the Amazon and Sao Francisco cratons (Pimentel & Fuck 1992).

This interpretation was supported by detrital zircon studies (Keppie & Krogh 1990; Keppie *et al.* 1998, 2011; Henderson *et al.* 2016) in Neoproterozoic metasedimentary rocks of West Avalonia. These yielded a wide array of ages ranging from Archean to Neoproterozoic, but included dates of *c.* 1.0, 1.3 and 1.6 Ga, which could have been supplied by the Amazonian craton of South America (Bernasconi 1987; Teixeira *et al.* 1989; Rocci *et al.* 1991) or from Baltica (Keppie *et al.* 1998).

The potential significance of the 0.8–1.1 Ga model ages of the main phase of Avalonian magmatism was investigated by analysing proto-Avalonian 0.66–0.75 Ga crustally derived felsic and 0.76 Ga mafic rocks. The Sm–Nd isotopic signatures of these rocks yielded similar model ages, suggesting that the ages reflected actual tectonic events and that proto-Avalonia had been generated as a series of oceanic arcs between 1.1 and 0.8 Ga (Murphy *et al.* 2000, 2008; Murphy & Nance 2002). Because this interval coincides with the amalgamation of Rodinia, proto-Avalonia was inferred to have been located in the Panthalassa-like Mirovoi Ocean (McMenamin & McMenamin 1990; Pisarevsky *et al.* 2008), which surrounded Rodinia following its assembly. In this context, the proto-Avalonian arc activity was attributed to renewed subduction in the Mirovoi Ocean following the initial break-up of Rodinia, which caused the accretion of these outboard terranes to the Gondwanan margin by *c.* 650 Ma. The main phase of Avalonian magmatism initiated at *c.* 640 Ma when renewed subduction

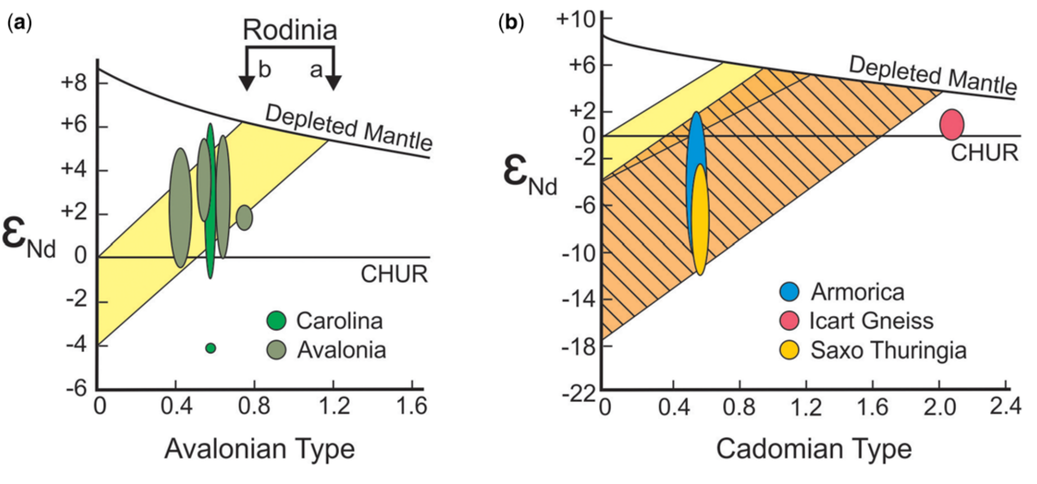

Fig. 6. Compilation of Sm–Nd isotopic data for (**a**) Avalonia (from Nance & Murphy 1996; Murphy *et al.* 2000) and Carolinia (e.g. Samson *et al.* 1995), which have relatively juvenile signatures and (**b**) Sm–Nd isotopic data for Armorica and the Icart Gneiss (Samson & D'Lemos 1998; Samson *et al.* 2003) and Saxo-Thuringia (Bohemian Massif, Linnemann *et al.* 2004), which have more ancient crustal components. Shaded area in part (a) shows field for peri-Rodinian oceanic lithosphere defined by the times of amalgamation and break-up of Rodinia, calculated assuming a typical Sm/Nd oceanic crustal ratio of 0.18 (see Murphy *et al.* 2006). Shaded area in part (b) is the envelope for Avalonia transferred from part (a). CHUR, chondrite uniform reservoir.

occurred outboard of these terranes along the northern Gondwanan margin. In support of this interpretation, accretion of the outboard Avalonian terranes broadly coincided with *c.* 670–650 Ma high-grade metamorphic events recorded in the Malverns Plutonic Suite (Strachan *et al.* 1996) and possibly in southern Newfoundland (O'Brien *et al.* 1996). These data also implied that the Neoproterozoic evolution of Avalonia and other peri-Gondwanan terranes was strongly influenced by the evolution of Rodinia and therefore provides important constraints on the tectonic evolution of this supercontinent.

In contrast with the signature of Avalonia, εNd values for Cadomia were predominantly negative (Fig. 6b), which, together with 1.9–1.0 Ga model ages, suggested significant involvement of ancient crustal material, similar to the Icartian basement exposed in Cadomia and the Eburnian basement of the West African craton (Allègre & Ben Othman 1980; D'Lemos & Brown 1993). At that time, no detrital zircon studies had been published, but subsequent research in Cadomia has consistently supported a linkage to West Africa in the Late Neoproterozoic (Quesada 1990, 2006; Linnemann *et al.* 2000, 2004, 2013; Samson *et al*. 2005; Henderson *et al.* 2016).

εNd values for crustally derived Late Neoproterozoic igneous rocks suggested that East Avalonia may straddle a suture between the West Avalonian and Cadomian basements, consistent with the concept of Keppie (1985) of Avalon as a composite terrane (Nance & Murphy 1994, 1996). εNd values for igneous rocks in the English Midlands are similar to those for Cadomia. They are predominantly negative, with 1.8–1.2 Ga model ages, suggesting that a basement isotopically indistinguishable from that of the Cadomian terranes may extend to southern Britain (Midland microcraton; see also Schofield *et al.* 2010). However, Nd isotopic data from the coeval volcanic rocks of Wales proved to be similar to those of West Avalonia, with strongly positive εNd values and 1.3–1.0 Ga model ages.

Subsequent studies combined Sm–Nd whole-rock isotopes with U–Pb detrital zircon data to produce ever more refined reconstructions of the positions of Avalonia and related peri-Gondwanan terranes along the northern Gondwanan margin (e.g. Linnemann *et al.* 2000, 2004, 2007; Linnemann & Romer 2002; Gutiérrez-Alonso *et al.* 2003, 2005; Fernández-Suárez *et al.* 2002; Samson *et al.* 2005). These studies mirrored advances in the development of laser ablation inductively coupled plasma mass spectrometry and sensitive high-resolution ion microprobe techniques that facilitated the rapid analyses of single detrital zircon grains with sufficient precision for provenance studies. Because of the mineral's robust properties, a detrital zircon may experience several cycles of erosion and deposition before final incorporation into the sample being analysed. However, some provenance studies included Ar–Ar analyses of detrital muscovite (e.g. Gutiérrez-Alonso *et al.* 2005; Murphy & Collins 2008), which is unlikely to survive more than one sedimentary cycle or significant transport and therefore can provide constraints on proximal source areas containing primary muscovite-bearing rocks (Haines *et al.* 2004). These datasets were complemented by detailed work along the northern Gondwanan margin (e.g. Abdelsalam *et al.* 2002; Hirdes & Davis 2002; Avigad *et al.* 2003; Samson *et al.* 2004; Inglis *et al.* 2005; Schofield *et al.* 2006, 2016), allowing more robust comparisons between cratonic Gondwana and the peri-Gondwanan terranes.

A detailed example of the reconstruction of Avalonia and related peri-Gondwanan terranes using these combined techniques is provided by the synthesis papers of Linnemann *et al.* (2007, 2013; Fig. 7). The obliquity between these terranes with respect to the cratonic provinces of the northern Gondwanan margin allowed them to be divided into three basic groups (e.g. Nance *et al.* 2008) reflecting proximity to Grenvillian (east and western terranes, modern coordinates) and West or North African basement (the so-called Avalonian–Cadomian active margin). These reconstructions affirmed Avalonia's location along the northern margin of Gondwana in the late Neoproterozoic, implying that it was not conjugate to the Laurentian margin as early plate tectonic models had envisaged.

As detrital zircon studies to determine provenance became common, it became clear that the matching of U–Pb crystallization ages to tectonomagmatic events in potential source terranes provided non-unique solutions if these terranes preserved coeval tectonothermal events. In the case of Avalonian rocks, several zircon populations could have come from various cratonic sources, including Baltica, Amazonia, West Africa and the Sahara metacraton.

This realization, coupled with advances in analytical techniques, stimulated the application of Hf isotope analysis of the dated zircons, which can constrain the antiquity of the source that melted to produce the zircons (e.g. Smits *et al.* 2014). As more data became available, compilations presented as composite Hf (εHf) arrays plotted against time facilitated the generation of fingerprints for cratons and continental terranes, which could be used to further constrain provenance interpretations (e.g. Collins *et al.* 2011; Smits *et al.* 2014). This approach was especially useful for displaced suspect terranes such as Avalonia, the affinities of which change as they are displaced from one continental margin to another.

For the most part, Hf isotopic analyses from dated zircons in both arc-related igneous and clastic

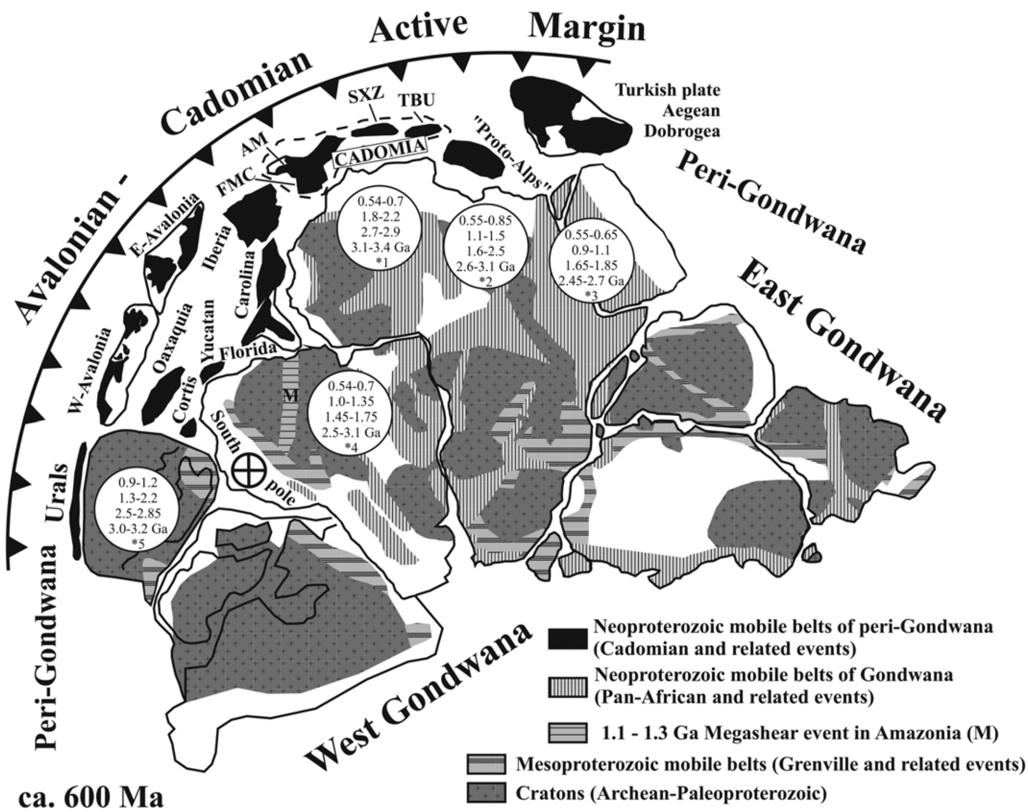

Fig. 7. Palaeogeography of the Cadomian–Avalonian active margin and related major peri-Gondwanan terranes at *c.* 570 Ma. Diagram from Linnemann *et al.* (2007, 2013). Note the continuation of the arc across the Gondwana–Baltica suture. Palaeogeography of the Gondwanan continental plates after Unrug (1996). AM, Armorican Massif; FMC, French Massif Central; SXZ, Saxo-Thuringian Zone (part of the Bohemian Massif); TBU, Teplá-Barrandian Unit (part of the Bohemian Massif). Numbers in circles: zircon ages from the cratons in Ga (see Linnemann *et al.* 2013 for details).

Avalonian rocks yielded results similar to Sm–Nd whole-rock data. The rocks proved to be dominated by high initial $^{176}Hf/^{177}Hf$ values with calculated crust formation (Hf-T_{DM}) model ages ranging from 1.3 to 0.8 Ga, consistent with crust formed by the partial melting of juvenile mantle to form a Neoproterozoic continental arc (Pollock *et al.* 2015) and compatible with the *c.* 1.2–1.0 Ga igneous tectonomagmatic event inferred to have formed the basement to the Neoproterozoic arcs from the Sm–Nd isotopic data (Murphy *et al.* 2000). However, these analyses also identified an older crustal component undetected by the Sm–Nd whole-rock data with Hf-T_{DM} model ages as old as 3.1 Ga and strongly negative εHf values, suggesting that older Proterozoic and/or Archean crust is locally present beneath Avalonia (Pollock *et al.* 2015).

Henderson *et al.* (2016) showed that detrital zircon grains in the late Neoproterozoic–early Cambrian clastic rocks have isotopic characteristics that bear stronger similarities to Baltica than was apparent from the Sm–Nd isotopic record. These researchers reconciled these datasets by proposing that the *c.* 800 Ma juvenile oceanic arc basement indicated by the Sm–Nd data was built on a sliver of Grenvillian-type crust (*c.* 2.0–1.0 Ga) of Baltican affinity at *c.* 800 Ma, prior to accretion with a continental margin at *c.* 640 Ma. A potential modern analogue is provided by the Cenozoic oceanic arcs of Vanuatu in the South Pacific, for which Hf isotopes on zircons in arc-related magmas have identified a thin continental basement that was derived from the Australian margin (Buys *et al.* 2014).

Future considerations

The Neoproterozoic affinity of the peri-Gondwanan terranes was identified before the discovery of the Neoproterozoic–middle Cambrian arc-related sequences of the Timanide and pre-Uralide orogens along the periphery of Baltica (e.g. Gee & Pease 2004; Kuznetsov *et al.* 2007). Thus the potential affinity of some components of Avalonia with Baltica has not been rigorously evaluated, although more recently published reconstructions (Murphy *et al.* 2000; Scarrow *et al.* 2001; Nance *et al.* 2008; Linnemann *et al.* 2013; Fig. 7) suggest a potential relationship by extending Avalonian arc terranes across the suture between Baltica and Gondwana. These data are consistent with faunal and palaeomagnetic data suggesting that Avalonia was an island chain lying at the same palaeolatitude as the Timanide Orogen in northern Baltica (Keppie & Keppie 2014).

Most of the data that imply an intra-oceanic origin for proto-Avalonia at *c.* 0.8 Ga and a northern Gondwanan (Amazonian) affinity by 0.65 Ga come from sequences in mainland Nova Scotia. However, Keppie (1985) pointed out that Avalon was a composite terrane defined by the presence of a Cambrian platformal overstep sequence with diagnostic Avalonian fauna, implying that its Neoproterozoic basement may have been derived from several sources.

In New England, for example, palaeomagnetic, Sm–Nd isotopic and detrital zircon data suggest that this portion of Avalonia had closer affinities to Baltica than to Amazonia (Thompson *et al.* 2007, 2012) in the late Neoproterozoic. The Lu–Hf isotopic data of Henderson *et al.* (2016) also provide evidence of a connection to Baltica, which was not apparent in the Sm–Nd data. In addition, Keppie & Keppie (2014) point out that Avalonia and Baltica may have had similar palaeolatitudes at *c.* 550 Ma. Interpretations based on palaeomagnetic data are complicated by evidence of important intervals of true polar wander during the Late Neoproterozoic–Early Cambrian (e.g. Kirschvink *et al.* 1997; Evans 1998; Meert 1999). Taken together, these analyses suggest that more detailed isotopic tracking of the various Neoproterozoic components of the Avalon terrane is needed.

Summary and conclusions

Deciphering the Neoproterozoic–Early Paleozoic geological evolution of Avalonia has been a major catalyst in the development of the Wilson model and, more generally, has provided an example of how plate tectonic principles can be applied to the pre-Mesozoic world. Early models implying that Avalonian rocks were part of the conjugate margin to Laurentia were soon replaced by those indicating that Avalonia was formed as a Neoproterozoic arc, an interpretation subsequently supported by a wealth of geochemical and field-based studies.

Four main tectonostratigraphic phases are now recognized.

(1) Proto-Avalonia, a 760–650 Ma phase that developed as oceanic arcs within the oceanic (Mirovoi) lithosphere surrounding Rodinia, possibly above thin slivers of continental crust previously detached from Baltica (Henderson *et al.* 2016). Proto-Avalonian arcs probably collided with the Gondwanan margin between 670 and 650 Ma.

(2) The main arc phase began at *c.* 640 Ma and produced voluminous low-grade volcanic and plutonic rocks with arc geochemical signatures, and well as localized basins with arc detritus. The termination of subduction-related magmatism was diachronous along the Avalon belt, varying from *c.* 600 to 550 Ma.

(3) The arc–platform transition produced local basins and coeval volcanic and plutonic rocks, which are predominately Ediacaran in age. This phase began diachronously after the main phase of arc magmatism, but before the deposition of Early Paleozoic platformal sequences. The arc–platform transition was not accompanied by any evidence of collisional orogenesis, suggesting that Avalonian subduction was terminated by the diachronous development of San Andreas type transform faulting.

(4) The Cambrian–Ordovician platform succession contains the Atlantic fauna used by Wilson (1966) to define the eastern flank of the proto-Atlantic Ocean and has an extraordinarily similar stratigraphy from New England through to the British Isles (e.g. Landing 1996).

Avalonia is generally considered to be one of a number of terranes, collectively termed peri-Gondwanan terranes, which were distributed along the periphery of northern Gondwana in the Late Neoproterozoic–Early Cambrian and shared a history of voluminous arc-related magmatism.

Although the main phase of Avalonian arc magmatism was coeval with the collisional Pan-African belts associated with the amalgamation of Gondwana, the Avalonian–Cadomian orogen is widely recognized as a peripheral orogenic belt formed along the northern periphery of Gondwana (Murphy & Nance 1991).

Isotopic analyses confirm earlier suggestions by Keppie (1985) that Avalonian rocks were developed on basements with contrasting compositions and tectonic affinities. Nd isotopic data for crustally derived felsic igneous rocks indicate that West Avalonia developed on relatively juvenile basement. However, detrital zircon studies and the strongly negative εNd values for East Avalonia and Cadomia support a linkage with the West African craton (Nance & Murphy 1996; Schofield *et al.* 2016).

The 1.1–0.8 Ga model ages of the main phase of West Avalonia probably reflect the birth of proto-Avalonia as a series of oceanic arcs within the Mirovoi Ocean. Proto-Avalonian arc activity and the accretion of these oceanic terranes to the Gondwanan margin by *c.* 670–650 Ma may reflect renewed and protracted subduction in the Mirovoi Ocean following the initial break-up of Rodinia. The main phase of Avalonian magmatism initiated when subduction zones relocated outboard of these accreted terranes and was directed beneath the northern Gondwanan margin.

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