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Early Ordovician rifting of Avalonia and birth of the Rheic Ocean: U–Pb detrital zircon constraints from Newfoundland

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Abstract: Avalonia is the largest accreted crustal block in the Appalachian orogen and comprises a collection of late Neoproterozoic volcano-sedimentary sequences that are overlain by a Palaeozoic platformal sedimentary succession. Detrital zircons from the Conception Group are dominated by 570–620 Ma ages and contain a significant component generated by erosion of coeval igneous arc-volcanic rocks. Overlying samples from the Cuckold and Crown Hill formations are dominated by Neoproterozoic populations with ages between 600 and 650 Ma and are interpreted to be derived from the underlying calc-alkaline arc-plutonic rocks. Early Palaeozoic platform units are dominated by *c*. 620 Ma zircons with lesser Mesoproterozoic and Palaeoproterozoic zircons. The range of detrital zircon ages is inconsistent with a West African provenance and suggests that Avalonia originated along the Gondwanan margin of the Amazon craton. The influx of Mesoproterozoic and Palaeoproterozoic detritus in the Avalonian platform suggests a major change in tectonic regime. The prominent change in provenance is interpreted to be related to separation of Avalonia from Gondwana during the Early Ordovician opening of the Rheic Ocean. The Redmans Formation is interpreted to represent the rift–drift transition of the Rheic Ocean, which imposes important constraints on the palaeotectonic evolution of Avalonia.

Supplementary material: U–Pb isotopic data of LA-ICP-MS analysis of detrital zircons are available at http://www.geolsoc.org.uk/SUP18346.

Avalonia is the largest accreted crustal block in the Appalachian–Caledonian orogen and comprises Neoproterozoic–early Palaeozoic magmatic arc and sedimentary cover sequences that can be traced from the British Caledonides in England SW to Rhode Island (Fig. 1). Lithostratigraphic, isotopic, faunal, and palaeomagnetic data indicate that Avalonia records a Neoproterozoic tectonomagmatic history that predates opening of the Iapetus Ocean and is considered to have formed as a Neoproterozoic arc-related terrane along an active margin of Gondwana (O'Brien *et al*. 1996; Murphy *et al*. 1999; Nance *et al*. 2002). Sometime between the latest Neoproterozoic and Early Silurian Avalonia rifted and separated from Gondwana as a microcontinent where it constituted the boundary between the expanding Rheic Ocean to the south and the contracting Iapetus Ocean to the north (van Staal *et al*. 1998; Murphy *et al*. 2006). Despite its prominence in Palaeozoic palaeogeography, our understanding of such fundamental aspects of Avalonia such as the precise timing of rifting and separation, its source area(s) in Gondwana, and its geometry and relationship to other peri-Gondwanan terranes are poorly constrained. The resolution of these uncertainties bears directly upon our understanding of the timing and nature of opening and the geometry of the Rheic Ocean. To address these problems, a U–Pb geochronological study was conducted on detrital zircon grains in clastic sedimentary rocks from the major lithotectonic units of the type area of Avalonia, the Avalon Peninsula of eastern Newfoundland. New technical developments in high-frequency sampling (e.g. Košler & Sylvester 2003) have led to improved precision and accuracy of zircon geochronology, which is critical to understanding the palaeotectonic evolution of the major Neoproterozoic–early Palaeozoic continents.

Despite its low abundance in sediments and sedimentary rocks, zircon is a common detrital constituent in many sedimentary rocks because it occurs in a wide spectrum of igneous rock types and is one of the few primary igneous minerals that can survive the highest grades of metamorphism and partial melting, as well as erosion, transportation, deposition and diagenesis, and thus can survive in the crust almost indefinitely (Mezger & Krögstad 1997).

Previous studies have shown that single-grain detrital zircon geochronology is a useful method of dating and tracing crustal processes because it can provide information that can be used to: (1) assist stratigraphic correlation of monotonous sedimentary sequences that lack distinctive marker units (Samson *et al*. 2005); (2) determine a maximum limit for the age of deposition of a stratigraphic succession (Barr *et al*. 2003); (3) determine time Gaps in the geological record (Davis 2002); (4) fingerprint source areas with distinct zircon age populations (Cawood *et al*. 2003); (5) constrain the timing of tectonic processes on an orogenic scale (Pollock *et al*. 2007). The ability to utilize zircon to interpret the provenance history of a sedimentary sequence requires that the depositional age of the sequence to be analysed be constrained by either faunal and/or high-precision isotope dilution thermal ionization mass spectrometry (ID-TIMS) data and that the source area(s) of this sequence have a well-defined and distinct U–Pb age signature.

This study is the first zircon provenance analysis of Neoproterozoic–early Palaeozoic rocks from the type area of Avalonia in

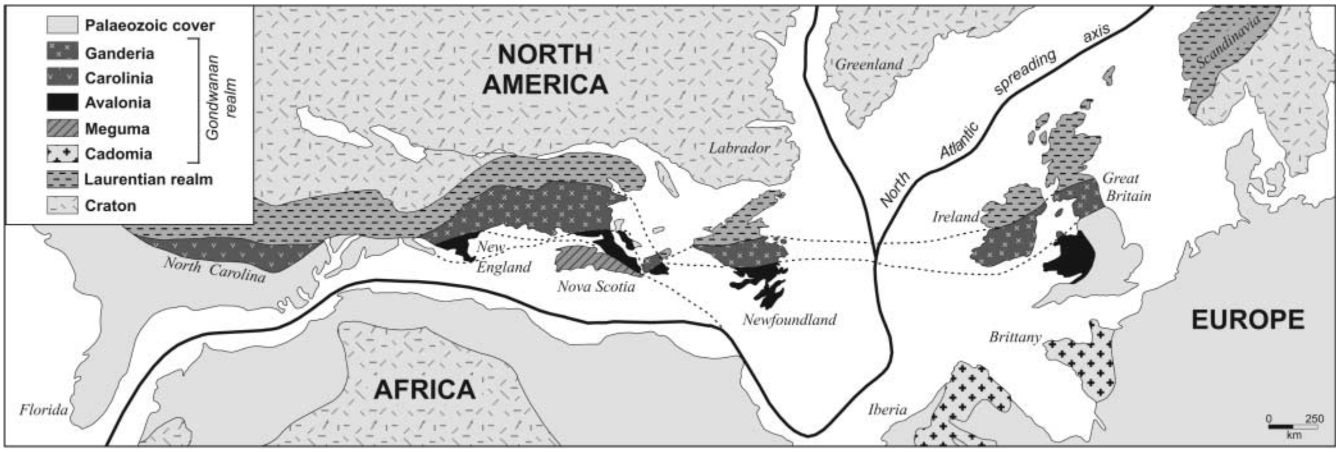

Fig. 1. Early Mesozoic restoration of the North Atlantic region and Appalachian–Caledonian orogen (modified after Williams 1984; Hibbard *et al.* 2007).

Newfoundland. We herein demonstrate the ability of U–Pb detrital zircon geochronology to address two critical problems in Avalonia: (1) the timing of rifting of Avalonia from Gondwana; (2) the provenance and ultimate source craton in Gondwana of Avalonian sedimentary sequences.

Regional geological setting

On the island of Newfoundland the type area of Avalonia (Fig. 2) comprises Neoproterozoic (*c.* 760–540 Ma), largely juvenile, low-grade arc-related volcano-sedimentary sequences and associated plutonic rocks that experienced a prolonged tectonic history before deposition of a terminal Neoproterozoic–early Palaeozoic cover of fine-grained platformal sedimentary rocks that contain Acado-Baltic faunas (Landing 1996; O'Brien *et al.* 1996). The general evolution of Avalonia indicates a protracted and episodic geological history of tectonomagmatic and depositional events that define a four-phase succession comprising: (1) early phases of arc- and rift-related magmatism between 760 and 670 Ma; (2) a main phase (635–570 Ma) of arc volcanism with coeval sedimentary succession dominated by volcanogenic turbidites and cogenetic plutons; (3) rift-related intracontinental volcanism and interlayered clastic sedimentation that records the transition from an arc to a platform without collision between 570 and 545 Ma; (4) deposition of a Cambrian–Ordovician shale-rich platformal sedimentary succession (Nance *et al.* 2002).

Remnants of early arc-related magmatic activity are preserved in three distinct intervals at *c.* 760, 730 and 685–670 Ma. On the Burin Peninsula, a fault-bounded, mixed assemblage of sedimentary and rift-related volcanic rocks and Gabbro of the Burin Group is analogous to basalts and mafic intrusive complexes in modern ocean basins and immature island arcs, and is interpreted to represent an incomplete ophiolite sequence (Strong & Dostal 1980). ID-TIMS ages of 763 ± 2 Ma and 764.5 ± 2.1 Ma from zircon date this Gabbroic succession (Krogh *et al.* 1988; Murphy *et al.* 2008). Vestiges of the *c.* 730 Ma arc are preserved along the southern shore of Conception Bay at Chapel Cove. The Hawke Hills tuff (O'Brien *et al.* 2001) comprises a subaerial felsic to mafic volcanic sequence that is intruded by 630–640 Ma plutonic rocks and unconformably overlain by Neoproterozoic marine siliciclastic rocks of the Conception Group. The Hawk Hills tuff has traditionally been included with the younger Harbour Main Group; however, a U–Pb age from a felsic volcanic tuff sampled immediately below the sub-Conception Group unconformity yields a date of 729 ± 7 Ma (Israel 1998), thereby negating any correlation with the younger volcanic arc sequences. On the Connaigre Peninsula, early arc rocks are represented by low-grade calc-alkaline rhyolite flows and pyroclastic rocks of the Tickle Point Formation that yielded a 682.8 ± 1.6 Ma U–Pb zircon age (Swinden & Hunt 1991). Prior to the deposition of younger Neoproterozoic rocks, the Tickle Point Formation was intruded by granite and Gabbro of the 673 ± 3 Ma Furby's Cove Intrusive Suite (O'Brien *et al.* 1996).

The main phase of Avalonian magmatism records volcanism and plutonism, and coeval sedimentation in arc-related and arc-adjacent basins following an apparent hiatus of *c.* 40 Ma between deposition of the youngest early arc sequences and the main arc phase. Main phase volcanic successions are defined by the widespread occurrence of low metamorphic grade felsic to mafic submarine to subaerial volcanic rocks that are several kilometres thick and formed between 635 and 570 Ma. West to east, these rocks include the Marystown, Love Cove and Harbour Main groups, which have calk-alkaline to transitional and island arc (arc-rift) tholeiitic affinities. Radiogenic isotopic analysis of these rocks yield the following U–Pb ages: 631 ± 2 Ma, 606 + 3.7/−2.9 Ma and 589.5 ± 3 Ma for the Harbour Main Group, and 608 +20/−7 Ma for the Marystown Group (Krogh *et al.* 1988; O'Brien *et al.* 1996). Shortly after their eruption, these sequences were intruded by calk-alkaline plutonic complexes, of which the Holyrood and Simmonds Brook intrusive suites have both been dated at 620 ± 2 Ma (Krogh *et al.* 1988; O'Brien *et al.* 1995). Sm–Nd and Pb isotopic characteristics and ages of xenocrystic zircons indicate that this main phase is juvenile, but erupted on some form of *c.* 1.0–1.2 Ga continental crust (Kerr *et al.* 1995).

These arc-related magmatic rocks are spatially associated with thick successions of consanguineous marine siliciclastic rocks dominated by volcanogenic turbidites that were deposited in intra-arc, inter-arc, and back-arc basins proximal to active volcanic arcs. The Conception, Connaigre Bay and Connecting Point groups are 4–5 km thick sedimentary sequences that are dominated by low-grade, fine-grained siliceous volcaniclastic and epiclastic sedimentary rocks. Field relationships and geochronology (O'Brien *et al.* 1995) demonstrate that deposition of these sequences commenced *c.* 630–620 Ma, locally upon a substrate of 685–670 Ma plutonic and volcanic rocks. Basal interfingering of the Conception Group with the Harbour Main Group, coupled with the occurrence of the Ediacaran index fossil *Charnia* in the

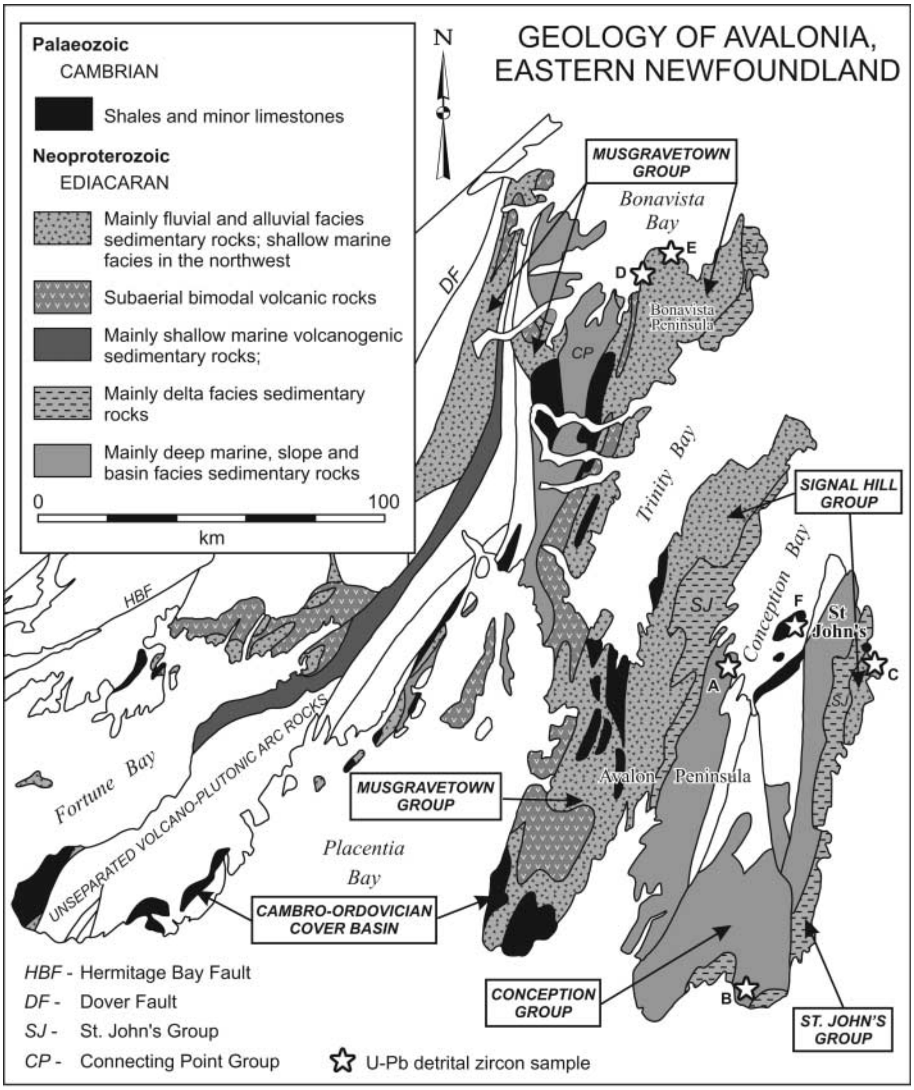

Fig. 2. Regional distribution of late Neoproterozoic sedimentary rocks of Avalonia in eastern Newfoundland (modified after O'Brien & King 2005).

top of the Conception Group, implies a depositional span of *c*. 50 Ma. In the SW Avalon Peninsula, a bimodal volcanic succession, the *c*. 575 Ma Bull Arm Formation and 580–565 Ma calc-alkaline volcanic (Long Harbour Group) and intrusive (Louil Hills granite) complexes, occur stratigraphically above the Connecting Point and Connaigre Bay groups (O'Brien *et al*. 1996).

The *c*. 570 Ma change to bimodal igneous activity is coeval with the cessation of arc-related magmatism and is interpreted to be related to the termination of subduction and the transition to an extensional or transtensional regime (Murphy & Nance 1989). This transition is accompanied by clastic sedimentation in pull-apart basins that first produced thin-bedded, deltaic sandstones and shales (St. John's Group) that pass upwards to fluvial- and alluvial-facies sedimentary rocks (Signal Hill Group) without significant disconformity. Although sedimentation, which continued until the terminal Neoproterozoic, was accompanied by deformation and metamorphism expressed as local thrust faulting, gentle folding and low-grade (prehnite–pumpellyite) regional metamorphism (Calon 2001), there is no evidence for major regional orogenesis and crustal shortening.

The arc–platform transition rocks are overlain by an undeformed, siliciclastic-dominated late Neoproterozoic–early Palaeozoic platform sequence. In the latest Neoproterozoic–Early Cambrian, deposition was dominated by quartz arenite transgressive successions (Chapel Island and Random formations), which pass conformably upward into Middle to Late Cambrian shale and limestone sequences (Adeyton and Harcourt groups) locally accompanied by eruption of alkalic mafic volcanic rocks (Greenough & Papezik 1986). The top of the Avalonian platform is represented by the Early Ordovician Bell Island and Wabana groups, which record tidal-dominated sedimentation of micaceous sandstone, siltstone, oolitic hematite and quartz arenite (Ranger *et al*. 1984).

Sample description

U–Pb ages were obtained from single detrital zircon grains from six samples of Neoproterozoic–early Palaeozoic rocks from eastern Newfoundland in an attempt to constrain the tectonic evolution of Avalonia (Fig. 3). Two samples were collected from the main phase of arc volcanism (635–570 Ma), two samples from the arc–platform transition (590–545 Ma), and two samples from the Palaeozoic platform sequence (Fig. 4). Each sample consisted of *c*. 40 kg of rock that comprised several

Fig. 3. Composite stratigraphic section of Neoproterozoic–early Palaeozoic sedimentary sequences of Avalonia (modified after O'Brien & King 2005).

subsamples collected at varying stratigraphic locations from a single continuous outcrop. This method greatly reduces any potential natural bias that may result from variations in physical sorting and mechanical abrasion that are the result of the hydrodynamic conditions operative during sediment transport and deposition. Previous studies have shown that a single lithostratigraphic unit may contain a diverse zircon population, as significant variations can exist in zircon age distributions at different geographical locations at the same stratigraphic level from the same formation (DeGraaff-Surpless *et al*. 2003), and

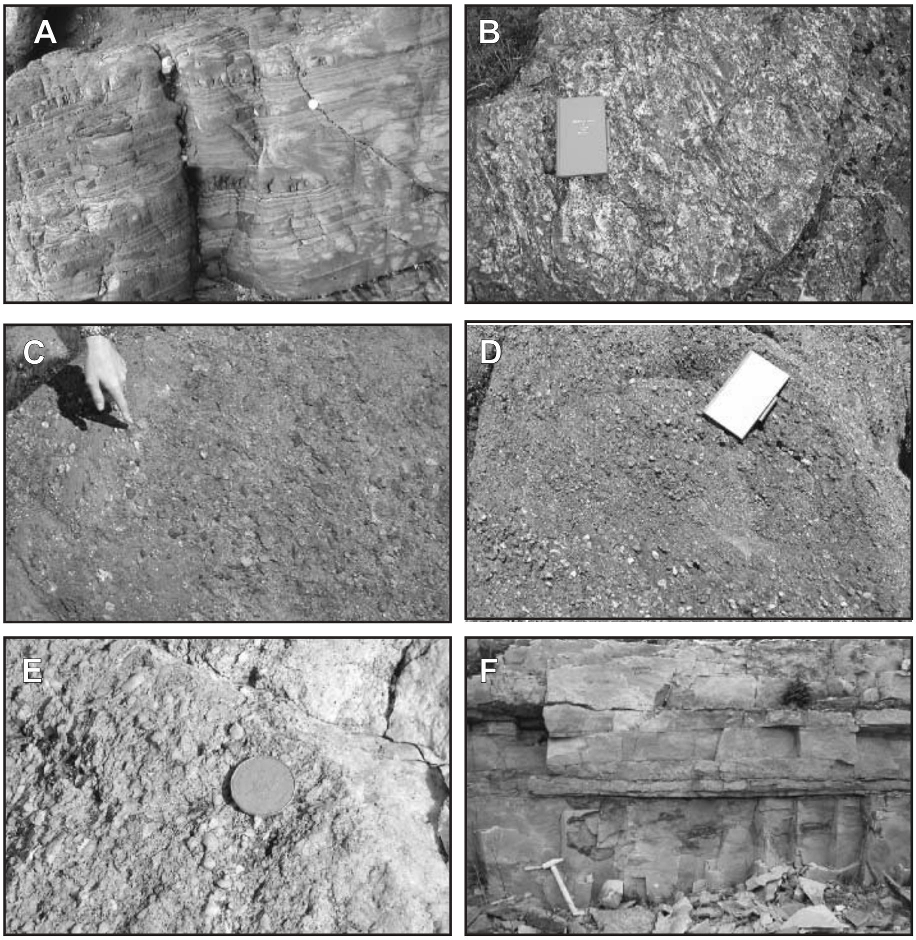

Fig. 4. Representative outcrops for detrital zircon analysis: (**a**) Mall Bay Formation; (**b**) Briscal Formation; (**c**) Cuckold Formation; (**d**) Crown Hill Formation; (**e**) Random Formation; (**f**) Redmans Formation.

other workers have shown that mixed detrital zircon populations may occur throughout the vertical section (Sircombe *et al*. 2001).

Main arc phase

Conception Group, Mall Bay Formation. A sample of a thick-laminated, grey to green siltstone argillite was collected from the lower Conception Group along the eastern shore of Holyrood Bay. At this location the Conception Group comprises *c*. 700 m of rhythmically interbedded fine-grained siliceous sandstone, siltstone and mudstone that show typical Bouma sequence features such as sole marks, rip-up clasts, grading, parallel and cross laminations and structureless mudstone. These features and overall lithology suggest that deposition was controlled by turbidity currents in a deep marine environment (O'Brien *et al*. 1996). The consistency of Conception Group stratigraphy over the entire Avalon Peninsula (Williams *et al*. 1995) invites correlation of the sampled unit with the Mall Bay Formation (Williams & King 1979), which therefore provides an age constraint on the timing of deposition. A maximum age is provided by a U–Pb date of $606 + 3.7/-2.9$ Ma from the Harbour Main Group, which unconformably underlies the Conception Group below the basal Mall Bay Formation (Krogh *et al*. 1988). On the southern Avalon Peninsula, the Mall Bay Formation is conformably overlain by glaciogenic rocks of the Gaskiers Formation (Williams & King 1979; Myrow & Kaufman 1999). Lithostratigraphic correlation of the Avalonian successions of Boston Bay and Newfoundland (Narbonne & Gehling 2003) provides an upper limit on the deposition of the Mall Bay Formation, as the correlative of the Gaskiers Formation in the Boston basin, the Squantum Member diamictite of the Roxbury Formation, is dated at 595.5 ± 2 Ma (Thompson & Bowring 2000).

Conception Group, Briscal Formation. The Briscal Formation was sampled on the southern Avalon Peninsula from well-exposed outcrops on Portugal Cove Brook. At this location the formation consists of 1200 m of coarse-grained, thick-bedded (1–2 m) grey–green sandstone turbidites containing pyroclastic and epiclastic detritus interpreted to have been deposited in a deep marine environment (Williams & King 1979). The Briscal Formation conformably overlies the Drook Formation and is in turn conformably overlain by the Mistaken Point Formation. A late Neoproterozoic age of deposition is suggested for the sequence as all three formations contain the Ediacaran fauna *Charnia masoni* (Narbonne & Gehling 2003) and a minimum age of deposition is constrained by a date of 565 ± 3 Ma from a volcanic tuff in the Mistaken Point Formation (G. Dunning, cited by Benus 1988).

Arc–platform transition

Signal Hill Group, Cuckold Formation (Cape Spear Member). The Cuckold Formation was collected from the type section of the Cape Spear Member at Cape Spear National Park and represents the most easterly onshore formation on the North American continent. The unit comprises *c*. 250 m of gently westward dipping, matrix-supported, pebble to cobble conglomerates that contain predominantly sub-angular red to purple clasts of rhyolite, rhyolite porphyry, ignimbrite and coarse-grained granitoid. Beds in the middle of the formation contain distinctive exotic clasts of quartz–sericite schist, quartzite, vein-quartz and other low-grade metamorphic rocks that locally form less than 25% of the coarse fraction and have been interpreted by King (1990) to indicate a sialic basement source. Diffuse interbeds of pebbly sandstone show large-scale trough crossbeds with a unimodal palaeoflow to the SSW (King 1990).

At Flatrock the Cape Spear Member is disconformably overlain by grey conglomerate of the Flat Rock Cove Formation, which was deposited in response to east-vergent thrusting (Rice 1996). The recognition of this contact as a composite progressive unconformity related to faulting (Calon 2001) indicates that the Cuckold Formation represents a sedimentary succession deposited syntectonically during the earliest phase of deformation. The youngest rocks of the Flat Rock Cove Formation overlie Conception Group strata with angular unconformity and constrain the age of faulting and deposition of the Signal Hill Group to the latest Neoproterozoic (Anderson *et al*. 1975).

Musgravetown Group, Crown Hill Formation. The Crown Hill Formation was sampled from the community of Tickle Cove on the Bonavista Peninsula and comprises a red to maroon pebble to cobble conglomerate that commonly shows medium- to large-scale trough crossbeds. On the basis of similar facies and overall stratigraphy, O'Brien & King (2005) have correlated this unit with the Cuckold Formation of the Signal Hill Group on the Avalon Peninsula. On the Bonavista Peninsula the Crown Hill Formation is conformably overlain by the earliest Cambrian Random Formation. Fluvial and alluvial facies developed within molasse-like rocks of the Cuckold and Crown Hill formations are characteristic of braided river deposits interpreted to have developed in response to major uplift of Avalonia related to the Avalonian orogeny (King 1990).

Platform

Random Formation. The Random Formation is a distinctive grey clastic sequence characterized by white weathering crossbedded orthoquartzite, sandstone and shale that locally attains thicknesses of up to 400 m and is exposed across the entire western half of Avalonia in Newfoundland (Walcott 1900; Landing 1996). A sample of two interbedded rock types of the Random Formation was collected from a 90 m thick section at Keels on the Bonavista Peninsula; a thick- to very thick-bedded, white coarse-grained crossbedded quartzarenite with lenses and thin beds of quartz granule conglomerate from the base of the formation and a dark grey micaceous siltstone that occurs *c*. 30 m higher in the stratigraphic sequence. Facies analysis suggests deposition under macrotidal conditions in an open marine environment (Hiscott 1982). The age of the Random Formation is earliest Cambrian. On the Burin Peninsula the Random Formation conformably overlies the Chapel Island Formation, which contains the Global Stratotype Section and Point for the Neoproterozoic–Cambrian boundary at Fortune Head (Brasier *et al*. 1994); elsewhere in eastern Newfoundland, the Random Formation underlies all exposed fossiliferous Cambrian strata in Avalonia.

Bell Island Group, Redmans Formation. This sample was collected from the type section of the Redmans Formation at Redmans Head on the NE shore of Bell Island. The rock is a medium-grained, white to grey thin- to medium-bedded quartzarenite with minor thin silty interbeds. Most of the sandstones display trough and herringbone cross-bedding, mega-ripple marks and channel and scour surfaces; all features associated with tidal sand wave or barrier island deposits generated by transgression and regression (Brenchley *et al*. 1993). The Redmans Formation conformably overlies the Beach Formation and is in turn conformably overlain by the Ochre Cove Formation. Rare inarticulate brachiopods (van Ingen 1914) and abundant trace fossils in all formations of the Bell Island Group indicate deposition of the Redmans Formation during the Arenig (Ranger *et al*. 1984).

Analytical methods

Detrital zircons were isolated from *c*. 25 kg of unweathered rock using a jaw crusher–Bico disc mill and concentrated using a Wilfley table, diiodomethane (CH_2I_2), and a Frantz isodynamic separator at the Mineral Processing Facility at Memorial University of Newfoundland (MUN). For each of the six samples *c*. 150 zircon grains were selected from a range of non- and paramagnetic fractions to reduce any artificial biasing caused by variations in magnetic susceptibility (Sircombe & Stern 2002). The crystals were mounted with epoxy in 25 mm diameter grain mounts and after curing were ground to a flat surface and polished to expose even surfaces at the cores of the grains so as to remove the outer section of the crystal, which is the principal region where Pb loss occurs in zircon (Krogh 1982). All zircons were imaged with transmitted and reflected light and an SEM to characterize the internal structures of the grains. The data were acquired in back-scattered electron (BSE) mode to illuminate oscillatory zoning and inherited crystals using an FEI Quanta 400 SEM equipped with a solid-state, twin-segment BSE detector. The SEM was operated under high vacuum of $<6 \times 10^{-4}$ Pa with an accelerating potential of 25 keV and a beam current of 10 nA. To minimize potential common Pb surface contamination from the ambient environment, each sample mount was bathed in ultrasonic deionized water and then cleaned with double-distilled HNO_3 followed by a purified Milli-Q H_2O rinse.

Isotopic data were obtained by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the MUN-Inco Innovation Centre. Zircons were ablated *in situ* using a Lambda Physik COMPexPro 110 ArF excimer laser operating at a deep UV wavelength of 193 nm and a pulse width of 20 ns. The 10 μm laser beam was delivered to the sample surface by an automated GeoLas Pro optical beam delivery system and fired at a 10 Hz repetition rate using an energy density of 3 J cm^{-2}. During ablation the sample was mounted in a sealed sample chamber and moved beneath the laser to produce a square 40 μm × 40 μm pit, to minimize the depth of ablation and reduce laser-induced elemental fractionation at the ablation site. Spot analyses were performed on homogeneous BSE domains to ensure that the measured U/Pb ratios did not represent mixtures of two or more age components. A reference grid network for each mount in the SEM was aligned with the grid network in the LA-ICP-MS system and used with the BSE images of each grain to position spots for ablation. The ablated sample was flushed from the sample cell and transported to the ICP-MS system using a helium carrier Gas ($Q = 1.3$ l min^{-1}), which reduces sample re-deposition and elemental fractionation while increasing sensitivity for deep UV ablation. Mercury was filtered from the helium using gold-coated glass wool placed in the carrier Gas line feeding the ablation cell.

All analyses were performed by high-resolution (HR)-ICP-MS on a Finnigan Element XR system equipped with a dual-mode secondary electron multiplier operating in both counting and analogue modes. The operating ranges of these two modes allow for a large crossover range where both modes are simultaneously valid; in this range a cross-calibration is automatically performed for every spectrum acquired, thereby ensuring accurate analysis. Data were collected using a 30 s measurement of the Gas background before activation of the laser followed by 180 s of measurement with the laser on and zircon being ablated. The U and Pb isotopic ratios from the zircon were acquired along with a mixed ^{203}Tl–^{205}Tl–^{209}Bi–^{233}U–^{237}Np tracer solution (concentration of 10 ppb each) that was nebulized simultaneously with the ablated solid sample. Aspiration of the tracer solution allowed for a real-time instrument mass bias correction using the known isotopic ratios of the tracer solution measured while the sample was ablated; this technique is largely independent of matrix effects that can variably influence measured isotopic ratios and hence the resulting ages (Košler & Sylvester 2003).

Raw data for ^{207}Pb, ^{206}Pb, ^{204}Pb and ^{238}U were reduced using the macro-based spreadsheet program LAMDATE (Košler *et al.* 2008). The ^{207}Pb/^{206}Pb, ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ratios were calculated and blank corrected for each analysis. Laser-induced U/Pb fractionation was typically less than 0.05% per a.m.u. based on repeat measurements of the ^{206}Pb/^{238}U ratio of the reference standards. This fractionation was corrected using the intercept method of Sylvester & Ghaderi (1997). For each analysis, time-resolved signals were inspected to ensure that only stable flat signal intervals were used in the age calculation. Measured ^{207}Pb/^{206}Pb ratios were not intercept-corrected; instead the average ratio of the ablation interval selected for the age calculation was used. Analyses were rejected from the final dataset where the ^{207}Pb/^{206}Pb ratio calculated from the intercept-corrected ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ratios did not fall within the 1σ uncertainty of the measured average ^{206}Pb/^{207}Pb ratio. Analyses that fell more than 5% above the ^{206}Pb/^{238}U–^{207}Pb/^{235}U concordia were also rejected. These two conservative filters ensured that any analyses that may have not been corrected for laser-induced U/Pb fractionation properly were eliminated from further consideration.

High instrumental Hg backgrounds prohibited accurate measurement of ^{204}Pb. Thus, in the few analyses where ^{204}Pb was detected above background, the analysis was simply rejected from the dataset rather than to attempt common Pb corrections. In the other analyses of this study, the amount of common Pb present in the zircon represents an insignificant amount relative to the content of radiogenic Pb; as a result, no common Pb correction was applied to the data.

Accuracy and reproducibility of U–Pb analysis in the MUN laboratory are routinely monitored by measurements of natural zircon standards of known ID-TIMS U–Pb age. To monitor the efficiency of mass bias and laser-induced fractionation corrections, standard reference materials 91500 zircon (1065 ± 3 Ma; Wiedenbeck *et al.* 1995) and Plešovice zircon (337.13 ± 0.37 Ma; Sláma *et al.* 2008) were analysed in this study before and after every eight unknowns. Age determinations were calculated using the ^{238}U (1.55125×10^{-10} a^{-1}) and ^{235}U (9.8485×10^{-10} a^{-1}) decay constants and the present-day ^{238}U/^{235}U ratio of 137.88 (Jaffey *et al.* 1971). Final ages and concordia diagrams were produced using the Isoplot/Ex macro (Ludwig 2003). The concordia ages for all analyses of 91500 and Plešovice zircon performed over the course of this study were 1064.2 ± 3.1 Ma ($n = 77$) and 337.61 ± 1.1 Ma ($n = 75$), respectively (95% confidence interval, with decay-constant errors included).

U–Pb results

A total of 398 detrital zircon grains analysed in the six sedimentary rocks Gave results that passed all the analytical data quality screens and were used in the final age compilation. Ages for *c.* 40–80 grains are reported for each of the six analysed samples (40 from the Briscal Formation; 64 each from the Cuckold and Random formations; 68 from the Crown Hill Formation; 81 each from the Mall Bay and Redmans formations). There is some question about the minimum number of zircons that need to be analysed to adequately identify all of the age populations present in a sedimentary rock sample (e.g. Fedo *et al.* 2003; Vermeesch 2004; Andersen 2005). Fedo *et al.* (2003) argued that the analysis of 59 randomly selected zircon grains from a sedimentary rock that has a typical abundance of zircon (given as 5% of the total) reduces the possibility of missing an age population of zircon to 5%. Andersen (2005) suggested, however, that several hundred randomly selected zircon grains would be necessary to give adequate control on the total age probability density pattern, which is impractical for most studies. As a practical alternative he suggested that 35–70 grains be analysed randomly, and a complementary set of non-randomly selected analyses should be added to capture any minor age population too small to be identified by the random data. In this study we have analysed more than the 59 grains suggested by Fedo *et al.* (2003) in all but one sample, and included both random and non-random (targeted for unusual shape and size) analyses as suggested by Andersen (2005).

Age data are displayed in Figure 5 as U–Pb concordia plots, in Figure 6 as age histograms and Gaussian probability density plots, and in Figure 7 as cumulative probability plots. Concordia ages (Ludwig 2003) with 2σ uncertainties are plotted in Figure 6 (rather than ^{206}Pb/^{238}U or ^{207}Pb/^{206}Pb ages as are commonly used) because they make optimal use of all radiogenic U/Pb and Pb/Pb ratios and their uncertainties simultaneously and therefore are more precise than any single U–Pb or Pb–Pb age. The Isoplot/Ex macro estimates the probability of concordance for each calculated concordia age and does not return a result if this probability is less than 1%. An analysis is regarded as discordant when the probability of concordance is less than 5%, and is excluded from the probability density plots in Figure 6. All of the analyses are thus concordant within their stated uncertainties. The use of concordia ages in cumulative probability plots avoids the need to compare ^{207}Pb/^{206}Pb ages, which are most precise for older grains (>1 Ga), with ^{206}Pb/^{238}U ages, which are more precise for younger grains (<1 Ga), on the same plot.

Main arc phase

The Mall Bay Formation is characterized by Neoproterozoic zircons that show one major cluster between 686 ± 22 Ma and 581 ± 14 Ma. Four older Meso- and Palaeoproterozoic components are present as single analyses of 1239 ± 25, 1435 ± 24, 1651 ± 22, and 1823 ± 36 Ma. The detrital zircon age distribution of the Briscal Formation of the Conception Group is similar to that of the Mall Bay Formation and is dominated by a zircon population that constitutes >90% of analyses and comprises Ediacaran zircons that range in age from 562 to 641 Ma. However, in the Briscal Formation this main group is separated by a Gap of 100 Ma from an older (*c.* 730 Ma) Neoproterozoic component. A single zircon grain yielded a Mesoproterozoic age

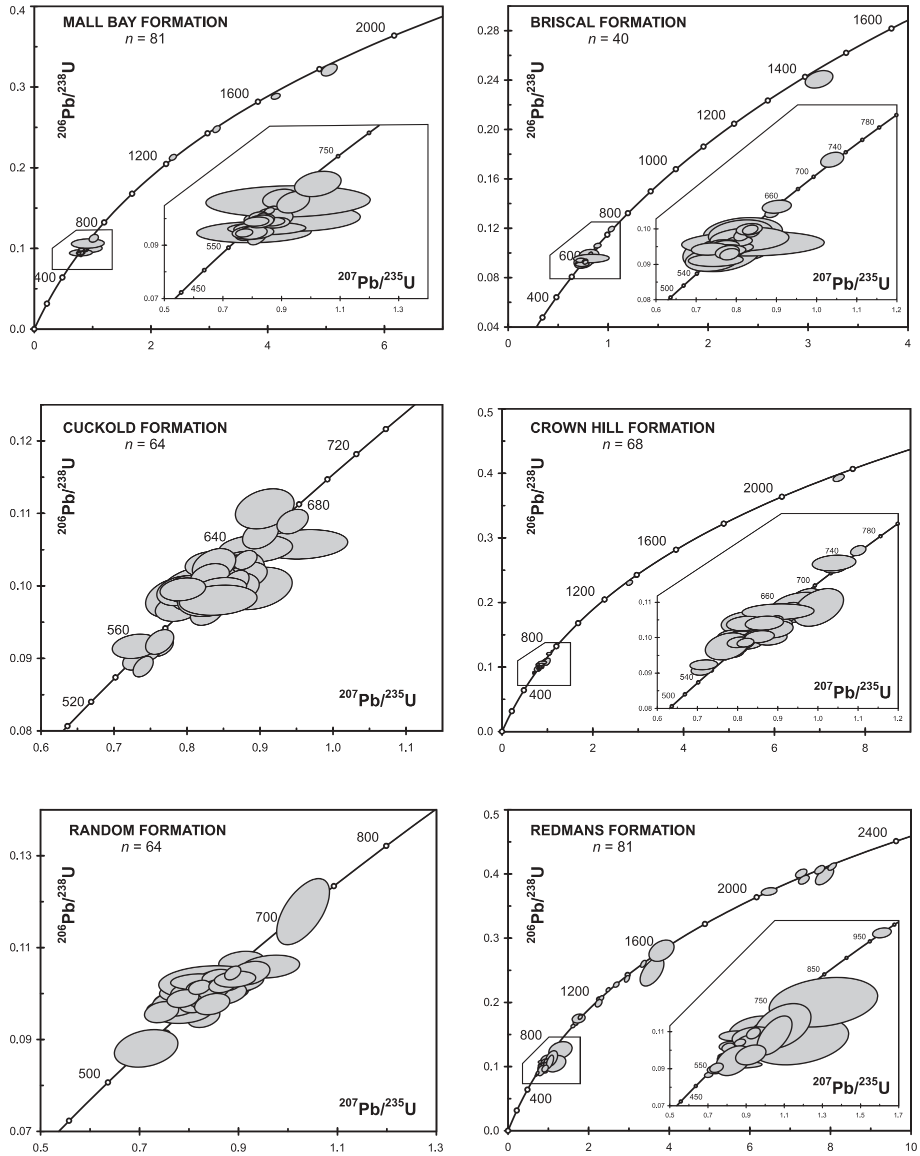

Fig. 5. U–Pb concordia diagrams of dated samples; ellipses are 1σ uncertainties.

of 1414 ± 47 Ma. The cumulative probability curves for both Conception Group samples have a similar shape (Fig. 7), indicating derivation from a common protosource; probability density plots show a single distinct peak at *c*. 590 Ma.

Arc–platform transition

The Cuckold Formation is dominated (82%) by zircons that fall within one broad nearly unimodal peak at *c*. 620 Ma that spans 60 Ma between 590 and 650 Ma. On the probability density plot, there is a minor peak at 565 Ma that consists of six zircons that range from 555 to 572 Ma; the two remaining analyses make up 3% of the total population and yielded older ages of 670 Ma. The zircon signature of the Cuckold Formation is almost identical to the Crown Hill Formation; the latter is characterized by a continuous cluster of zircons (84%) between 590 and 660 Ma and minor components between 557 and 566 Ma (two analyses) and 665 and 682 Ma (four analyses). These components are separated by a Gap of *c*. 60 Ma from older Neoproterozoic zircons of three concordant analyses at 731 ± 20, 734 ± 20, and 755 ± 12 Ma. Although making up less than 2% of the total, two analyses indicate the presence of Mesoproterozoic (1349 ± 27 Ma) and Palaeoproterozoic (2160 ± 24 Ma) components.

Platform

Detrital zircons analysis of the Random Formation yielded ages from 64 zircons, of which 85% cluster in the range from 580 to 655 Ma. A slightly younger grouping of three analyses is separated by a *c*. 20 Ma Gap from the dominant group and contains latest Neoproterozoic to early Palaeozoic zircons between 562 and 542 Ma. The remaining analysis comprises one concordant Neoproterozoic age of 719 ± 44 Ma. The probability density plot of the Random Formation is characterized by a near-unimodal population that has a discrete relative peak at *c*. 620 Ma.

Zircons from the Redmans Formation consist mainly of colourless and brown prismatic grains of variable size. Both colour types range from pristine to strongly pitted, and several

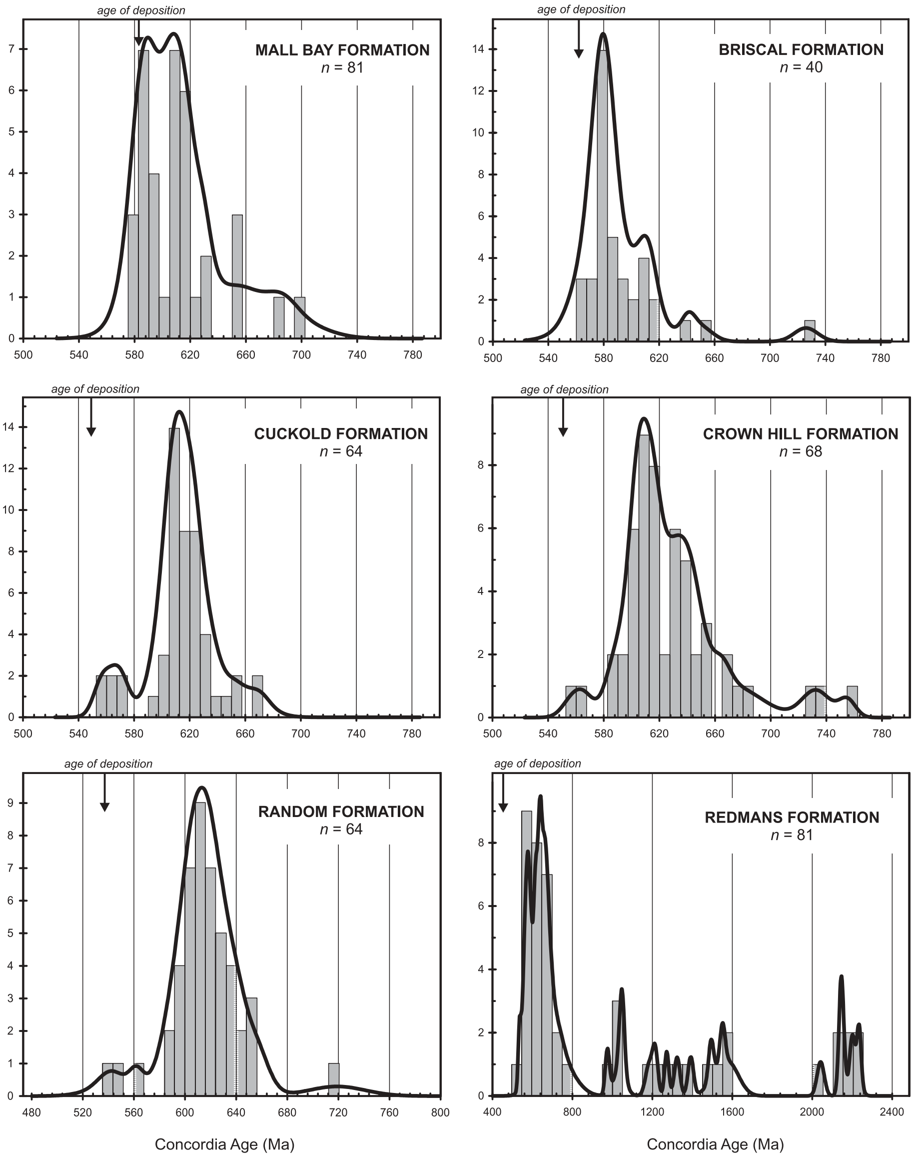

Fig. 6. Age histograms and Gaussian probability density distributions of concordia ages for analysed samples. Only analyses within ±0.05 concordance are plotted.

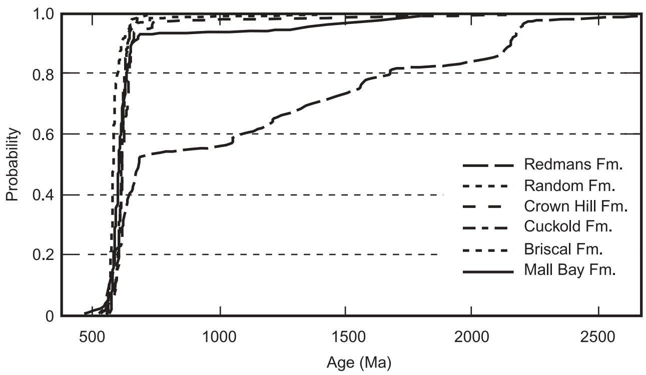

Fig. 7. Detrital zircon cumulative probability distributions for all dated samples.

grains have visible core and overgrowth components. A total of 81 grains representing the entire range of zircon morphologies in the sample were analysed. The data show one major cluster (35%) from 550 to 685 Ma that peaks on the probability density plot at *c.* 620 Ma. A Cambrian component is recognized in a single analysis of 535 ± 13 Ma; four older Neoproterozoic zircons yielded ages of 714 ± 73, 715 ± 99, 779 ± 120 and 975 ± 21 Ma. Statistical comparison (Fig. 7) of the Random Formation and underlying Avalonia samples illustrates that the younger part of the age distribution is very similar between samples; >50% of the ages derive from sources younger than 1 Ga. Significant deviation, however, exists in the older detrital zircon populations as a result of a dramatic provenance change highlighted by a greater abundance of older pre-Neoproterozoic zircons; 19 analyses yielded Mesoproterozoic and Palaeoproterozoic ages between 1036 ± 58 Ma and 2235 ± 19 Ma.

Discussion

Provenance

The new detrital zircon data from Neoproterozoic–early Palaeozoic rocks of Avalonia in Newfoundland demonstrate the temporal controls on zircon heterogeneity in the various sampled stratigraphic successions. The data allow for the deduction of the changing tectonic regimes as the varied provenance can be correlated with discrete sources including contemporaneously generated Avalonian crust and older Gondwanan cratonic crustal sources.

The sedimentary rocks from the main arc phase contain a preponderance of zircons that fall in the *c.* 570–620 Ma range, which corresponds to the period of main phase of magmatic activity in the adjacent Neoproterozoic Avalonian arc. The Conception Group is therefore interpreted to contain a significant detrital component generated by erosion of coeval igneous rocks formed in these arc sequences, which include the Harbour Main and Marystown groups. The lack of zircons in the range *c.* 650–660 Ma and 700–720 Ma in both samples reflects relative periods of little magmatic activity in the early phase of Avalonian arc volcanism; the minor occurrence of *c.* 730 Ma zircons in the Briscal Formation, however, indicates that parts of the early arc were sourced, as these ages correspond to volcanism in the Chapel Cove arc (Israel 1998).

These data indicate that the Conception Group was principally derived from the underlying volcanic main phase arc. The detrital zircon ages are consistent with petrography and chemical composition of the detrital phases that indicate turbidite deposition in submarine fans adjacent to an active evolved magmatic arc (Dec *et al*. 1992). The zircons are probably first-cycle detritus because of the relatively short amount of time between their igneous crystallization and time of deposition. The very high rate of sedimentation, abundant pyroclastic and epiclastic detritus, deep-water environment (Williams & King 1979; O'Brien *et al*. 1996), sedimentation coeval with arc magmatism and detrital zircon ages that are roughly synchronous with the age of deposition all suggest that deposition of these main arc sequences occurred in a tectonically active environment.

The detrital zircon populations in the arc–platform transition (Cuckold and Crown Hill formations) yielded fewer zircons in the 570–600 Ma range and instead are dominated by a group of older zircons between 600 and 650 Ma. Vestiges of 600–650 Ma rocks are exposed throughout Avalonia in Newfoundland and include the Holyrood and Simmons Brook intrusive suites and Connaigre Bay and Love Cove groups. A minor cluster of older Neoproterozoic zircons between 660–680 Ma and *c.* 730 Ma can be attributed to erosion of the underlying early arc sequences (Furby's Cove intrusive suite, Tickle Point Formation, and Hawke Hill tuff) of Avalonia. Such derivation is consistent with facies trends and palaeocurrents (O'Brien *et al*. 1995). The change from siliceous volcaniclastic rocks of the Conception Group to overlying molasse-like red beds of the Signal Hill and Musgravetown groups represents a transition from deep-water turbidite deposition to subaerial fluvial and alluvial plain conditions. The overall coarsening- and thickening-upwards sequences of the Cuckold and Crown Hill formations (King 1990) indicate that deposition occurred in tectonically active fault-bounded basins controlled by major uplift of the underlying arc sequences during the latest Neoproterozoic Avalonian orogeny (Hughes 1970).

The detrital zircon populations in the Random Formation are markedly similar to those in the underlying Crown Hill Formation (600–650 Ma) as both contain Palaeoproterozoic zircons. These data may indicate either a shared protolith and/or the presence of recycled components of the Crown Hill Formation in the Random Formation. The mineralogical and texturally mature quartzarenites, relatively high (up to 25%) plagioclase content and abundance of detrital muscovite argue against significant sediment recycling and suggest derivation from a proximal orogenic source area where detritus was not transported long distances prior to deposition (Jenness 1963). The most likely provenance for the zircons in the Random Formation is the same Avalonian arc-related calc-alkaline plutonic suites as the underlying arc-transition sequences. Stratigraphic variations, however, suggest a change in the depositional environment of the Random Formation. The quartzarenites and interbedded fine-grained siltstones are interpreted to be subtidal sand shoals and intertidal mud flats formed on a macrotidal coastline adjacent to a broad continental shelf or in a large coastal embayment during marine transgression (Hiscott 1982). Early Cambrian transgressive quartz-rich sandstone sequences are present throughout Avalonia in Massachusetts, Maritime Canada, Wales and England (Landing 1996) and were deposited on shallow, wide, shelf platforms during eustatic sea-level rise (Sloss 1963).

Similar to the Random Formation, quartzarenites of the Redmans Formation contain a dominant late Neoproterozoic population (*c.* 620 Ma) and suggest direct derivation from the main arc plutonic suites. Less prominent groupings of zircons between 665 and 685 Ma and 700 and 760 Ma are interpreted to have been derived from the early arc sequences, the Furby's Cove intrusive suite, Tickle Point Formation and Burin Group, respectively. In contrast to other sequences in Avalonia, the Redmans Formation, however, also contains a much wider range of significantly older detrital zircon populations. The pronounced cluster of continuous ages between 1.0 and 1.6 Ga, together with a Palaeoproterozoic component, suggests a significant difference in provenance from all other Avalonian rocks analysed in this study.

The presence of Mesoproterozoic zircons, mainly in the Redmans Formation (but an accessory component in other units) is consistent with the existence of a Mesoproterozoic (*c.* 1.0–1.6 Ga) crustal component in the basement of Avalonia. Although no exposed basement is present anywhere in Avalonia, Sm–Nd (Kerr *et al*. 1995; Murphy *et al*. 1996) and U–Pb (Ayuso *et al*. 1996) isotopic data indicate that the Avalonian magmatic arcs formed upon a dominantly *c.* 1.0–1.2 Ga basement with a minor component of older *c.* 1.6 Ga crust. Palaeoproterozoic grains in the Redmans Formation could also be derived from a local Avalonian basement source, as rare *c.* 2.0 and 2.4 Ga xenocrystic zircons are reported from Avalonian plutonic rocks in the Mira terrane (Bevier & Barr 1990) and New England (Zartman & Hermes 1987).

Source craton

Zircons from sedimentary units in Avalonia show a wide age spectrum with well-defined Palaeoproterozoic, Mesoproterozoic and late Neoproterozoic (Ediacaran) ages. Age patterns of detrital zircon data from main arc and transition samples in Avalonia are dominated by a unimodal population of Neoproterozoic zircons that almost certainly were locally derived from the underlying or adjacent arc sequences of Avalonia and deposited as first-cycle sediments. In contrast, the sequences from the platform contain significant quantities of Mesoproterozoic (1.0–1.6 Ga) and Palaeoproterozoic (1.6–2.3 Ga) components. Although some of these zircons could have been derived from the underlying sequences as second-generation recycled zircons, the large population of zircons and absence of isotopic and geological data for an older basement component in the underlying units, however, suggest that the Meso- and Palaeoproterozoic zircons in the platform sequences were probably derived as first-cycle detritus from basement or from a crustal source that was external to Avalonia.

The Ediacaran zircons provide no palaeogeographical information as they overlap the known age range of underlying

Avalonian igneous rocks. The older U–Pb detrital zircon ages, however, can be compared with potential source cratons that are characterized by Archaean to early Neoproterozoic tectonothermal activity. The detrital zircon population data presented herein to some extent match the age of tectonothermal events in Laurentia, Baltica and Gondwana; hence these cratons are potential sources for the zircons in the rocks of Avalonia.

Although Laurentia and Baltica have comparable geological histories during the Proterozoic, which suggest evolution as a single cratonic nucleus following the amalgamation of Archaean cratons between 1.8 and 1.9 Ga (Hoffman 1988; Gower *et al*. 1990), geological, lithological, faunal, palaeomagnetic and isotopic evidence indicates that Avalonia is a distinct terrane exotic to Laurentia (Williams 1964; Murphy & Nance 1989; Hibbard *et al*. 2007). The detrital zircon data also refute an eastern Laurentian–Baltica source because the analysed rocks in Avalonia contain zircons with ages of 2.0–2.4 Ga and 620–750 Ma, which correspond to major Palaeoproterozoic (2.0–2.4 Ga) and Neoproterozoic tectonic and crust-forming events that are noticeably absent from the geological record of eastern Laurentian and Baltica (Gower *et al*. 1990; Wardle *et al*. 2002). These ages are, however, compatible with a Gondwanan provenance.

The Proterozoic detrital zircons match the age signatures of rocks found along the Neoproterozoic–early Palaeozoic West African and Amazonian margins of Gondwana. The presence of Meosproterozoic–early Neoproterozoic grains in Avalonia is, however, incompatible with a West African source, as the latter contains only minor occurrences of Mesoproterozoic (*c*. 1000 Ma) magmatism (de Wit *et al*. 2005) and no record of any tectonothermal events between 1.1 and 2.0 Ga (Rocci *et al*. 1991). The data are compatible with an Amazonian provenance. Mesoproterozoic and Palaeoproterozoic rocks are present along the Amazonian margin of Gondwana (Fig. 8) and correlate with the Sunsás–Aguapeí (0.9–1.2 Ga), Rondônia–San Ignacio (1.2–1.4 Ga), Rio Negro–Jurena (1.5–1.75 Ga), and Trans-Amazonian (1.9–2.2 Ga) orogenic belts located along the periphery of the Archaean Amazon craton (Sadowski & Bettencourt 1996; Bettencourt *et al*. 1999; Dall'Agnol *et al*. 1999). An Avalonia–Amazonia link is also consistent with Sm–Nd isotope (Murphy *et al*. 1996), xenocrystic and detrital zircon (Zartman & Hermes 1987; Bevier & Barr 1990; Murphy *et al*. 2004), faunal and stratigraphic (Hiscott 1982; Landing 1996) data that are incompatible with a West African provenance for Avalonia.

Timing of rifting

Current palaeotectonic models suggest that Avalonia formed along the Neoproterozoic margin of Gondwana and accreted to Ganderia (the leading edge of composite Laurentia) in the Late Silurian–Early Devonian during the Acadian orogeny (van Staal 2007). Opening of the Rheic Ocean separating Avalonia from Gondwana is therefore constrained to a period between the Neoproterozoic and Silurian. However, there is considerable debate regarding the timing and extent of rifting of Avalonia within this interval. A Neoproterozoic age of separation was proposed by Landing (1996, 2005) based on contrasting Cambrian faunal assemblages and platform sequences between Newfoundland and Morocco, and interpretation of the Cambrian–Ordovician Gander Group as a slope and rise prism of the Avalonia microcontinent. A Neoproterozoic separation of Avalo-

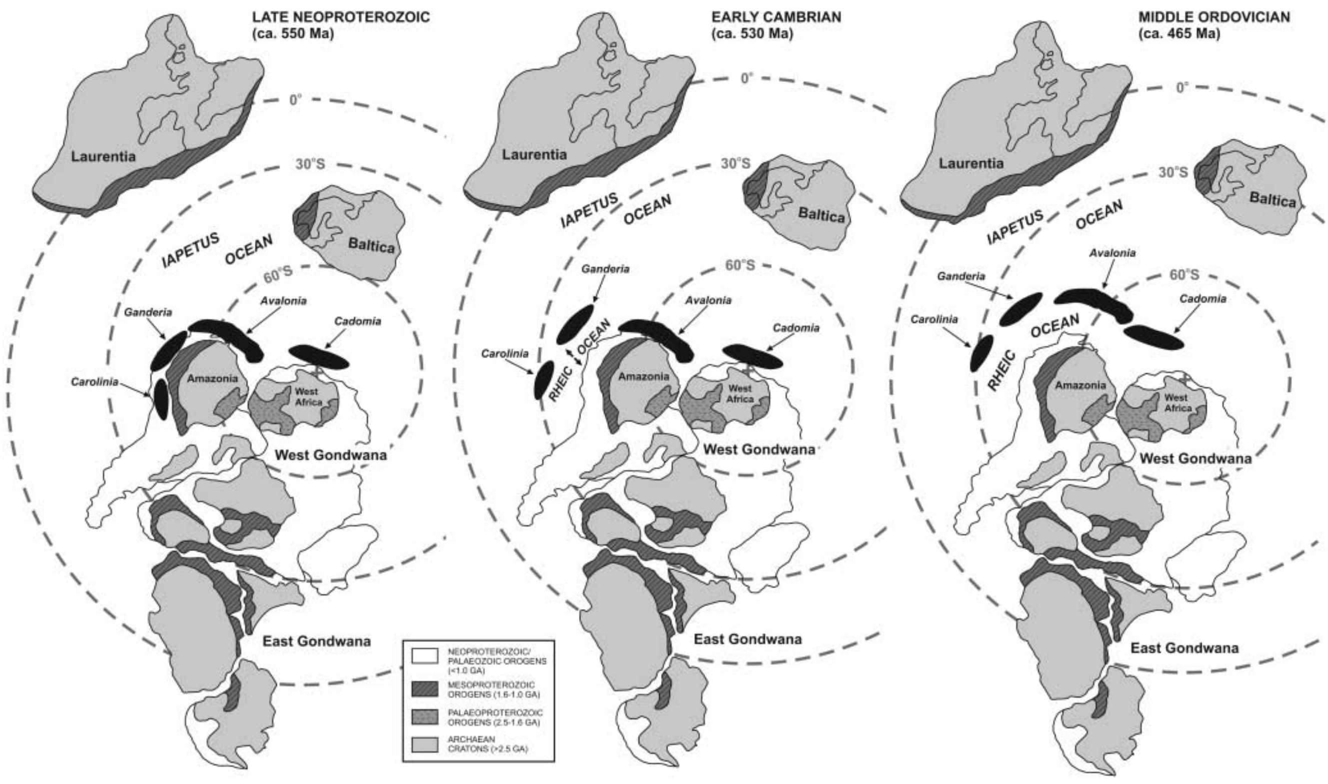

Fig. 8. Late Neoproterozoic–early Palaeozoic palaeomagnetically controlled palaeogeographical continental reconstructions of the southern hemisphere of Torsvik *et al*. (1996). Position of Avalonia, Ganderia, Cadomia and Carolinia from detrital zircon and isotopic data (Samson *et al*. 2005; Hibbard *et al*. 2007; Pollock 2007). Relative position of Gondwana and Laurentia and age provinces from Hoffman (1991) and Murphy *et al*. (2004).

nia from Gondwana is, however, inconsistent with a wide range of palaeomagnetic, faunal, isotopic and geological arguments (O'Brien *et al*. 1996; van Staal *et al*. 1998), as it relies on a pre-rifting connection to West Africa and interpretation of Avalonia and Ganderia as a single tectonic entity. Avalonia is interpreted to have formed along the Amazonian margin of Gondwana and an Avalonia–Ganderia connection is unlikely because even though Ganderia and Avalonia have similar arc-dominated Neoproterozoic basement rocks, they have very distinct magmatic, depositional and tectonothermal histories (O'Brien *et al*. 1996; Hibbard *et al*. 2007; Potter *et al*. 2008) and were therefore almost certainly tectonically decoupled and separated in the early Palaeozoic.

Separation during the Early Ordovician is supported by subsidence analysis (Prigmore *et al*. 1997), comparable faunal assemblages until the Tremadoc (Cocks *et al*. 1997; Fortey & Cocks 2003) and palaeomagnetic data that indicate that Avalonia resided at high southerly latitude near Gondwana from the Middle Cambrian to the end of the Early Ordovician (van der Voo & Johnson 1985; Hodych & Buchan 1998; MacNiocaill, 2000; Hamilton & Murphy 2004). The zircon data presented herein are compatible with a younger timing of separation of Avalonia from Gondwana that occurred in the Early Ordovician (Fig. 9). The absence of significant quantities of Mesoproterozoic and Palaeoproterozoic zircons in Ediacaran–Early Cambrian sequences of Avalonia suggest that zircons of these ages found in Ordovician rocks of the platform represent first-cycle detritus derived directly from Amazonia rather than second-generation recycled zircons from underlying sequences. This interpretation requires that Avalonia lay adjacent to Gondwana throughout the Cambrian until deposition of the Redmans Formation in the Early Ordovician.

Middle Cambrian to Middle Ordovician arc rift-related volcanic rocks in Newfoundland (Spread Eagle Gabbro), Wales (Rhobell volcanic complex), and England (Lake District arc) are generally considered to be related to Avalonia's rifting and departure from Gondwana (Kokelaar 1988; van Staal *et al*. 1998). The separation of Avalonia was followed by widespread Arenig subsidence recorded in the Stiperstone Quartzite of Avalonia in England and the Armorican Quartzite of Cadomia in Brittany, interpreted to reflect the rift–drift transition of the Rheic Ocean (van Staal *et al*. 1998; Nance *et al*. 2002; Murphy *et al*. 2006). The Rheic Ocean may have opened in a manner analogous to the opening of the Iapetus Ocean, where protracted, multiple phases of Neoproterozoic rift-related magmatism were followed by later development of a Palaeozoic rift–drift transition (Williams & Hiscott 1987; Cawood *et al*. 2001; Waldron & van Staal 2001).

The tectonic controls on the mechanisms responsible for separation are uncertain and have been proposed as being related to subduction along an active plate margin with slab roll-back leading to the opening of a back-arc basin in Avalonia (van Staal *et al*. 1998), in a manner analogous to the present-day Okinawa Trough. The Okinawa Trough is a back-arc basin in a prolonged early stage of rifting that formed in the Miocene by NW subduction of the Philippine sea plate causing extension of the Asian continental lithosphere behind the Ryukyu arc system (Shinjo *et al*. 1999).

Alternatively, because most palaeogeographical reconstructions assume that the Palaeozoic proto-Avalonian margin of Gondwana extended into the Iapetus Ocean, the simultaneous subduction on both margins of Iapetus resulted in a major plate boundary reorganization, which may have contributed to the partial break-up and lateral displacement of Gondwanan terranes. Hence, the intra-Iapetus subduction and arc–rifted margin collision on the Laurentian margin (Taconic orogeny) coupled with arc polarity reversal, rapid roll-back, extension and arc-rifting on the Ganderian margin (Penobscot orogeny) may have detached Avalonia

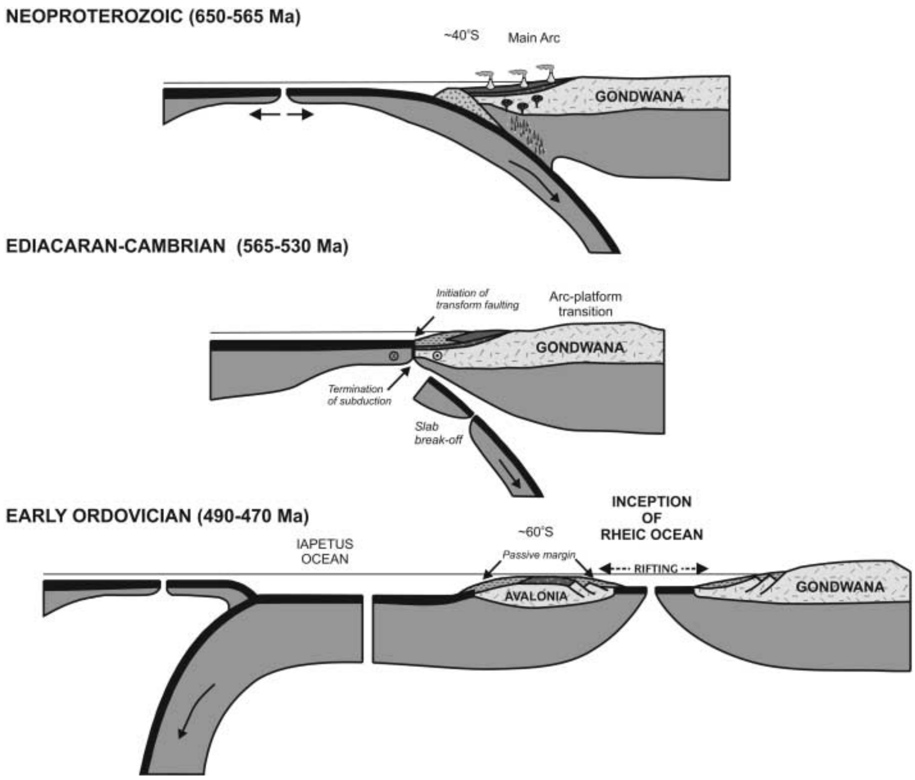

Fig. 9. Late Neoproterozoic–early Palaeozoic tectonic evolution of Avalonia and the west Gondwanan margin.

from Gondwana as a result of increasing slab-pull forces similar to the Permian opening of NeoTethys and separation of Cimmerian terranes from the Eurasian margin by subduction and slab roll-back in PalaeoTethys (Stampfli & Borel 2002; Murphy *et al*. 2006). However, the absence of significant volumes of Early Ordovician volcanic rocks in Avalonia suggests that rifting may have resulted from the propagation of an active, intraoceanic spreading ridge inboard to the edge of the Gondwanan margin in a manner analogous to the rifting of the Jan Mayen and Seychelles microcontinents (Müller *et al*. 2001).

Summary and conclusions

Avalonia comprises a sequence of late Neoproterozoic volcano-sedimentary sequences that are overlain by a Cambrian–Ordovician shale-rich platformal sedimentary succession. U–Pb ages of detrital zircons from Neoproterozoic rocks of the type area of Avalonia in eastern Newfoundland are dominated by Ediacaran populations with ages between 620 and 580 Ma that are interpreted to be derived from the underlying volcanic–plutonic rocks of the main Avalonian arc. These rocks are inferred to have accumulated as a series of submarine fans in restricted fault-bounded, arc-adjacent basins that grade upwards into terrestrial siliciclastic rocks deposited under subaerial fluviatile conditions without a significant change in provenance. Early Palaeozoic platform units show an overall up-section increase in Mesoproterozoic and Palaeoproterozoic zircons that are inconsistent with recycling from underlying Neoproterozoic rocks. The range of detrital zircon ages, combined with isotopic and sedimentological data, argues against Avalonia being proximal to West Africa and suggests that the former originated along the periphery of Amazonia. The rapid influx of Mesoproterozoic and older detritus in the upper sequences of the Avalonian platform suggests a major change in tectonic regime to expose older material that is temporally consistent with Avalonian basement. We conclude from the detrital zircon analysis that, if the rifting of Avalonia was marked by a change in provenance and the rapid influx of Palaeoproterozoic detritus in the upper sequences of the Avalonian platform, then separation of Avalonia from Gondwana and opening of the Rheic Ocean occurred during the Arenig. An Early Ordovician time of separation is also supported by stratigraphic, faunal, palaeomagnetic and tectonic data.

There is close correspondence between lithology, depositional age and detrital zircon signatures of the Redmans Formation and Armorican Quartzite (Ranger *et al*. 1984; Fernández-Suárez *et al*. 2002) and therefore we propose that the Redmans Formation represents the rift–drift transition of the Rheic Ocean. Interpretation of the Redmans Formation as the Rheic rift–drift transition imposes important constraints on the palaeotectonic evolution of Avalonia and opening of the Rheic Ocean. The most significant implication of this observation is the connection between Avalonia and the peri-Gondwanan block of Cadomia in the early Palaeozoic. In this model Avalonia and Cadomia represent two different terranes with distinct basement rocks and contrasting Neoproterozoic histories (Samson & D'Lemos 1998; Samson *et al*. 2005; Murphy *et al*. 2006). The two terranes formed independent of one another on the Gondwanan margin but were juxtaposed along a Neoproterozoic suture prior to the Early Ordovician opening of the Rheic Ocean (Murphy *et al*. 2006; Linnemann *et al*. 2007). Available data suggest that assembly of the Avalonian and Cadomian microplates was accomplished by margin-parallel strike-slip activity caused by the complex interaction of a continental margin transform system with a subduction zone as a result of ridge–trench collision (Keppie *et al*. 2002; Nance *et al*. 2002).

The separation of Avalonia (and Cadomia) and opening of the Rheic Ocean is contemporaneous with, and may be related to closure of the larger Iapetus Ocean. This scenario is similar to the opening of young rifted margins formed behind volcanic arcs that span the closing ages of larger oceans, such as the modern Japan Sea, Okinawa Trough and Tasman Sea, which formed behind arcs of the western Pacific Ocean. Rifting may have initiated as the result of subduction and slab roll-back, slab pull by subduction and ridge–trench collision, or an inboard ridge jump. However, regardless of the actual mechanism of rifting, the timing of rifting and separation is recorded in the changing detrital zircon provenance in the sedimentary record.

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